B. T. Fijalkowski

Intelligent Systems, Control and Automation: Science and Engineering

Automotive Mechatronics: Operational and Practical Issues

Volume I

Springer

Automotive Mechatronics: Operational and Practical Issues

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Automotive Mechatronics: Operational and Practical Issues

Volume I

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For my daughter Madeleine

Preface

The purpose of this book is to present operational and practical issues of automotive mechatronics with special emphasis on the heterogeneous automotive vehicle systems approach.

The book is intended as a graduate text as well as a reference for scientists and engineers involved in the design of automotive mechatronic control systems.

As the complexity of automotive vehicles increases, so does the dearth of high competence, multi-disciplined automotive scientists and engineers. This book provides a discussion into the type of mechatronic control systems found in modern vehicles and the skills required by automotive scientists and engineers working in this environment.

Divided into two volumes and five parts, **Automotive Mechatronics** aims at improving automotive mechatronics education and emphasises the training of students' experimental hands-on abilities. The author hopes that this can stimulate and promote the education programme in students' experimental hands-on experience among high education institutes and produce more automotive mechatronics and automation engineers.

Contents

- VOLUME I
  - Part 1 - RBW or XBW unibody or chassis-motion mechatronic control hypersystems;
  - Part 2 - DBW AWD propulsion mechatronic control systems;
  - Part 3 - BBW AWB dispulsion mechatronic control systems;
- VOLUME II
  - Part 4 - SBW AWS diversion mechatronic control systems;
  - Part 5 - ABW AWA suspension mechatronic control systems.

The book was developed for undergraduate and postgraduate students as well as for professionals involved in all disciplines related to the design or research and development of automotive vehicle dynamics, powertrains, brakes, steering, and shock absorbers (dampers). A basic knowledge of college mathematics, college physics, and knowledge of the functionality of automotive vehicle basic propulsion, dispulsion, conversion and suspension systems is required.

Individuals new to the subject matter of RBW or XBW unibody, space-chassis, skateboard-chassis or body-over-chassis-motion motion mechatronic control systems, will have most advantage most the material. This manual is not compulsory for individuals with a basic background in, or knowledge of DBW AWD propulsion, BBW AWB dispulsion, SBW AWS diversion and ABW AWA suspension mechatronic control systems. Into the bargain, please notice that because of proprietary considerations, this book does not present details of algorithm design, algorithm performance, or algorithm application.

I am the sole author of the book and all text contained herein is of my own conception unless otherwise indicated. Any text, figures, theories, results, or designs that are not of my own devising are appropriately referenced in order to give acknowledgement to the original authors. All sources of assistance have been assigned due acknowledgement.

All information in this book has been obtained and presented in accordance with academic rules and ethical conduct. I also wish to state declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this book.

I wish to express my sincere gratitude to Professor Spiros Tzafestas for his interest in the preparation of this book in the Intelligent Systems, Control, Automation (ISCA), Science and Engineering book series. My gratitude is also due to Ms Nathalie Jacobs and Ms Johanna F. A. Pot of Springer for their persistence in making this book a reality.

I am grateful to the many authors referenced in this book from whom, during the course of writing, I learnt so much on the subjects which appear in the book. I am also indebted to my national and international colleagues who indirectly contributed to this book.

Most of all I wish to express thanks the following consortia and institutions: ABIresearch, ABResearch, ACURE Dynamics, ADAMS, ADVISOR, ADwin, AEG, Air Force Research Lab. (AFRL), AIRMATIC, AirRock, AKA Bose Corp., AMESim, AMI Semiconductor, AMT, AMTIAC, AR&C, AROQ Ltd., Audi AG, AUDIAG, AutoPro, AUTOSAR, AUTOTECH, Avio Pro, AVL, Bertone, BizWire, Bobbs-Merril Co., BMW, BOSCH GmbH, Bridgestone Corp., Cadillac, CAFS, California Linear Devices, Carnegie Mellon, Centro Richerche FIAT, CFC, Challenge Bibendum, Chalmers University of Technology, Climatronic, Cleveland State University, Cracow University of Technology, Continental TEVES Inc., Cosc/Psych, Cracow University of Technology, CRL, Chrysler, Daimler-Benz, DaimlerChrysler AG, D&R, DAS, DECOMSYS, Delco Electronics, Delco-Remy, Delphi, Delft Center for Systems and Control, DJH, DLR RoboDrive, DRDC, dSPACE GmbH, Dynamic Structures & Materials LLC, Energen Inc., ERFD, ER Fluid Developments Ltd. UK, eSTOP GmbH, FAA US DoT, FACE International Corp., FHWA-MC Fiat, Fichtel & Sachs, FlexRay Consortium, FMA, FortuneCity, FPDA, US DoT, Ford Europe, Ford Motor Co., Ford SRL, Freescale Semiconductor Inc., FUJI Microelectronics Inc. (FMA), FUJITSU, GM Chevrolet, GM Opel, General Motors Corp., German Aerospace Centre (DLE e.V.), Gothorum Carolinae Sigillium Universita, Graz University of Technology (TUG), Haskell, Hitachi Co., Honda, How Stuff Works, Hunter, I-CAR, IEC, IEEE, IMechE, Intel, Institute of Robotics and Mechatronics, Intelligent Transportation Society (ITS), ISO, IPC website, IPG Automotive GmbH, Istanbul Technical University, Jäger GmbH, JB, JUST-AUTO.COM, Kalmar, Kinetic Suspension Technology, Lexus, Kungl. Tekniska Högskolan (KTH), Land Rover, Lord, Lotus Engineering, Lund Institute of Technology, MagnetiMarelli, Magnet Motor, Mazda, McCormick, Mechanical Dynamics, Inc., Mecel, Messier-Bugatti, MICHELIN, MILLENWORKS, MIT Hatsoupulos Microfluid Lab., Mitsubishi Corporate, MOST Net-services, MOTOROLA, NI, NASA Langley Research Center, National Highway Traffic Administration (NHTSA), Nissan, Office of Naval Research (ONR), Norwegian University of Science and Technology, Oldhams Ltd., OSEK-WORKS, Packard, PACIFICA Group Technologies Pty Ltd., PEIT, PHILIPS, PITechnology, Polski FIAT, Porsche, PSA PEUGEOT CITROËN , Purdue School of Engineering and Technology, SAAB, SAE, Scania, Sensormag, Siemens VDO Automotive, SKF, Star, Studebaker, Subaru, Radatec Inc., Southwest Research Institute (SwRI), Racelogic, Radatec Inc., Renault, Research Team for Technology (CARAMELS), Ricardo, RMSV, Robert Bosch GmbH, Rodmillen, SCANIA, Seoul National University, TACOM TARDEC, Technische Universität Darmstadt, Universität Koblenz, Universität Regensburg, TENNECO Automotive, The Motor Industry Research Association (MIRA), The New York Times, The University of Michigan, Toyota, TRIDEC, Triumph, TRW Automotive Inc., TTPbuild, TTPnode, TTTech Computertechnik AG, Universita ‘di Bologna, Universität Salzburg, University of California Berkeley, University of Leicester, University of Limerick, University of Pennsylvania, University of Queensland, University of Sussex, University of Texas at Austin, University of York (UK), Uppsala University, US Army Research Office, US DLA, US DoD, US DoE, UT-CEM, Valentin Technologies Inc., Valeo, Van Doorne Transmissie BV, VCT, Vienna Institute of Technology, VOLKSWAGEN (VW), VOLVO, Wongkwang University, ZF Sachs AG, and XILINX for their text, figures, or designs included in this book in order to give them due credit and acknowledgement as well as to present their contemporary achievements in automotive mechatronics.

The book is full of advanced statements and information on the technology development of the automotive industry. These statements can be written and may be recognizable by terms such as *‘may be’*, *‘will’*, *‘estimates’*, *‘intends’*, *‘anticipated, ‘expects’* or terms with analogous sense. These statements are derived from presuppositions with reference to the developments of the technology of Europe, Americas and Asia-Pacific countries, and in particular of their automotive industry, which I have prepared on account of the information accessible to me and I think to be realistic at the time of going to press.

The estimates specified implicate a degree of risk, and the actual development may differ from those forecasts. If the presuppositions underlying any of these statements prove incorrect, the actual results may noticeably differ from those expressed or embedded by such statements.

I do not update advanced statements retrospectively. Such statements are valuable on the date of publication and can be superseded.

Whoever has attempted to write such a book in their spare time knows how many weekends and vacation days go into it. I want to dedicate this book to my family for their continual encouragement, constant care, and assistance and infinite patience in making the writing of this book possible, as well as the generous understanding they have always shown me.

Cracow, September 2010 *Bogdan Thaddeus. Fijalkowski*

Contents

PART 1

RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control Hypersystems

1.1 Introduction

The number of active automotive mechatronic control systems based on an integrated mechatronics based **artificial intelligence** (AI) systems approach [FIJALKOWSKI 1987] in an automotive vehicle is rapidly escalating for getting better the performances and the safety of the vehicle, predominantly automotive mechatronic control systems for affecting the motion of the unibody or chassis. **Anti-lock braking systems** (ABS) as well as an **electronic stability program** (ESP) are standard equipment nowadays on automotive vehicles. In the not-too-distant future, it can be expected that vehicles will be equipped with emerging, advanced mechatronic control systems like an integrated unibody or chassis motion mechatronic control hypersystem, which may be normally broken down into longitudinal x axis (*Roll*), lateral y axis (*Pitch*) and vertical z axis (*Yaw*) mechatronic control systems: **drive-by-wire** (DBW), **all-wheel-driven** (AWD) propulsion and **brake-by-wire** (BBW), **all-wheel-braked** (AWB) dispulsion, **steer-by-wire** (SBW), **all-wheel-steered** (AWS) conversion, as well as **absorb-by-wire** (ABW), **all-wheel-absorbed (**AWA) suspension mechatronic control systems. Until now these emerging, advanced mechatronic control systems, when implemented, are controlled independently. However, it is clear that there is a strong coupling between them, coming from of the rubber tyres. Therefore, undesired coupling effects could lead to a severe loss of performance if not taken into consideration. However, with a good mechatronic control strategy, the coupling could be taken into account when reaching the absolute optimum.

The challenge of integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control is to see the automotive vehicle, with all sensors and actuators, as a whole instead of as a combination of sensors-actuators pairs.

Currently, the intention of automotive engineers and scientists is to integrate and optimally control all the active automotive mechatronic control systems of the unibody or chassis to conclusively create the automotive vehicle behaviour more consistent and predictable and simultaneously enhance the handling and riding performance, disturbance behaviour, handling at the friction limit and comfort. Moreover, it is of interest to investigate the added value that wheel-tyre forces sensing can add in mechatronic control. Above all, it is expected to greatly enhance the robustness against the large wheel-tyre/on-off road uncertainties.

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Looking at the motion dynamics of the unibody, space-chassis, skateboard-chassis or body-over-chassis motion, [GERARD 2008] distinguished two levels: the unibody, space-chassis, skateboard-chassis or body-over-chassis level and the wheel-tyre level.

The unibody, space-chassis, skateboard-chassis or body-over-chassis motion is quite slow and linear while the wheel-tyre dynamics is much faster, nonlinear and uncertain. Therefore, an integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic controller will be developed with layer architecture.

This controller will match the unibody or chassis motion to a desired reference model, weight comfort and safety, and distribute the control actions to different automotive mechatronic control systems while respecting the actuation limits. Further, the local automotive mechatronic controllers will apply the set-points, compensate for the wheel-tyre/on-off road uncertainties and estimate the actuation limits.

In [GERARD 2008], three test environments have been used to test the systems approach at various development stages. First, an accurate multi-body vehicle physical model (*Modelica-Dymola®*) has been used for off-line simulation. To further assess how a **human driver** (HD) will react to a control strategy, the **Delft Center for Systems and Control** (DCSC) is developing a moving platform vehicle simulator [GERARD 2008]. Thanks to a real-time vehicle physical model coupled to motion filters and visualisation screens, the driver will get the feeling of sitting in automotive vehicle and interacts with the controller. Conclusion should be drawn by testing it in a fully actuated real vehicle. The more sophisticated and specialised each automotive mechatronic control system gets the number of manufacturers who may be competent of developing these systems.

Automotive scientists and engineers may use integrated unibody, space-chassis, skate-board-chassis or body-over-chassis motion actuation technologies, and may be working to develop **ride-by-wire** (RBW) also known as **x-by-wire** (XBW) integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control advanced technologies, to enhance the fundamental automotive vehicle functions of propulsion (driving), dispulsion (braking), suspension (absorbing/ damping) and conversion (steering).

The over part or central portion of an automotive vehicle, or the like, a fuselage or hull, is termed the vehicle's *'body'*. The body is flexibly bolted to the chassis during the manufacturing process.

The under part or frame of the automotive vehicle, in most designs a pressed steel or an aluminium, rectangular frame that forms a skeleton that provides a mounting place for other parts of the vehicle on which the body is mounted, with a strong metal frame, together with the wheels, powertrain, brakes, shock absorbers (dampers) and steering mechanism, is termed the automotive vehicle's *'chassis'*. The combination of the vehicle's body and chassis absorbs reactions from the motions of the powertrain components, receives the reaction forces and/or torques of the wheels during acceleration (driving) and/or deceleration (braking), absorbs aerodynamic wind forces and road shocks through the suspension and absorbs the major energy of an impact in the event of an accident.

The chassis consists of the vehicle's frame and everything attached to it except the body.

'Body-over-chassis' construction allows chassis parts and body to be bolted to the frame. Thus, the body is bolted to a thick steel frame. The high-strength steel or aluminium *'monocoque'* or *'unibody'* has dominated volume manufactured models throughout the second half of the 20th century.

A unibody construction is a form of body construction that doesn't necessitate a separate frame to secure structural strength or support to the automotive vehicle's mechanical components; also termed *'unitized'* or *'unitary'*. It integrates everything but bolted-on body panels. If an automotive vehicle has a separate frame, the term chassis refers to the frame. It is a related construction technique for automotive vehicles in which the body is integrated into a single unit with the chassis rather than having a separate body-over-chassis. The spot welded *'unit body'* is now the dominant automotive vehicle construction technology, so some vehicles (particularly trucks) still use the older body-over-chassis technique. High-strength steel and aluminium (actually duralumin) reduces vehicle's mass and enhances safety while improving stiffness for towing. A unibody (unitized) construction has sheet-metal body panels welded together to form the body and frame. Thus, the frame is an integral part of the body. Compared to older techniques where a body would be bolted to a frame, monocoque or unibody (unitized) vehicles are less expensive and stronger. Still product life-cycles in the automotive marketplace and escalating fuel efficiency requirements are inspiring vehicle manufacturers to think about other body construction methods in mainstream manufacturing, for instance, *'space-chassis'* or *'spaceframes'*; also termed **independent body and panels** (IBP).

A space-chassis allows the load impact structure of the automotive vehicle to be separated from its exterior panels. These panels can be prepared and painted offline, or manufactured using some other method such as thermoplastic colour injection moulding. This has enabled several vehicle manufacturers to exploit new technology and minimise the impact of the traditional paint shop on both order fulfilment and the environment.

A *'skateboard-chassis'* with the entire DBW AWD propulsion system housed within; in-wheel-hub E-M/M-E motors/generators at the wheels enable DBW AWD propulsion for driving (acceleration) and BBW AWB dispulsion for braking (deceleration) as well as SBW AWS conversion for steering, four electrical mechanical body attachment mounts to lock the body in place onto the skateboard; preconfigured and validated perimeter structural impact zones; external side-mounted optimized cooling fins; a smart single-access docking port to connect and link power, control, heating and cooling systems to the body from the skateboard; a refuelling port for hydrogen, and an exhaust outlet dispersing water in the form of vapour. All of the automotive vehicle components that contribute to the generation, transmission, and distribution of propulsion and/or dispulsion torque to the wheels, are termed the *'powertrain'* or *'drivetrain'*.

The powertrain incorporates all components to convert primary chemical and/or physical (mechanical, electrical, fluidical, or pneumatical), or even nuclear energy, into secondary mechanical energy and deliver it to the wheels.

Thus, in an automotive vehicle, the term *'powertrain'* or *'drivetrain'* refers to the group of components that generate power and deliver it to the on/off road surface. Hence, the powertrain is the part of an automotive vehicle connecting the prime mover, that is, **chemo-thermo-fluido-mechanical** (CH-TH-F-M) **internal combustion engine** (ICE) or **external combustion engine** (ECE), **electro-mechanical/mechano-electrical** (E-M/M-E) motor/generator, **fluido-mechanical/ mechano-fluidical** (F-M/M-F) motor/pump, or **pneumo-mechanical/mechano-pneumatical** (P-M/M-P) motor/compressor to propeller or driven axle, may include **mechano-mechanical** (M-M), **electro-mechanical** (E-M), **fluido-mechanical** (F-M), or **pneumo-mechanical** (P-M) drive shaft, clutch, transmission and differentials, and the final drive (drive wheels, caterpillar tracks, propeller, and so on), as well as exhaust treatment systems and hardware/software used to control the powertrain.

Sometimes the term *'powertrain'* is used to simply refer to the CH-TH-F-M ICE or ECE, E-M/M-E motor/generator, F-M/M-F motor/pump, or P-M/M-P motor/compressor and M-M, E-M, F-M, or P-M transmission, including the other components only if they are integral to the M-M, E-M, F-M, or P-M transmission, respectively.

The modern powertrain may be split into (4) four main sections, namely:

- ❖ The prime mover, that is, the ICE or ECE – The most evident and perhaps major part of the powertrain is the ICE or ECE as it supplies the power that permits the automotive vehicle to be in motion; the conventional powertrain uses as ICE or ECE running on petrol or diesel fuel; there are powertrains where there are (2) two ICEs or ECEs, these are known as hybrids and they must have multipart transmission systems to permit both prime movers to input power at the right time; also as the prime mover may be used, the E-M/M-E motor/generator, F-M/M-F motor/ pump, or P-M/ M-P motor/compressor, frequently, may be of a different type;
- ❖ The M-M, E-M, F-M, or P-M transmission – This is the second major part of getting power to the wheels; it may alter the torque and speed of the power that the prime mover generates; for instance, this is normally executed by using a series of gears at different ratios; for example, the M-M transmission also incorporates the M-M driveshafts and the axles, and any other device that transfers power directly to wheels;
- ❖ Exhaust treatment systems – Very influential in terms of the automotive vehicle's environmental impact, also significant in terms of the prime mover's efficiency as most of the energy run away through the exhaust; most exhaust systems have a catalytic converter and a specific trap to clean the exhaust gases; they may also comprise superchargers to try to use some of the dissipated energy within the exhaust;
- ❖ Hardware and software used to control the powertrain – This is hardware/software that controls various different factors within the powertrain so as to try and maximise efficiency.

In an automotive vehicle, the term *‘driveline’* refers to the parts of the power-train or drivetrain, excluding the CH-TH-M ICE or ECE, E-M/M-E motor/generator, F-M/M-F motor/pump, or P-M/M-P motor/compressor and M-M, E-M, F-M, or P-M transmission. It is the portion of a vehicle after the M-M, E-M, F-M, or P-M transmission that changes depending, whether an automotive vehicle is **front-wheel-drive** (FWD), **rear-wheel-drive** (RWD), or **four-wheel-drive** (4WD).

The brake is a friction mechanism that slows or stops the rotation of the wheels of an automotive vehicle so that wheel-tyre traction slows or stops the automotive vehicle.

The steering mechanism is the one, including gear train and linkage, for the directional control of a vehicle.

The shock absorber (damper) is a spring, a dashpot, or a combination of the two, arranged to minimise the acceleration/deceleration of the mass of a mechanism or portion thereof with respect to its frame or support.

The term RBW, also known as XBW, may refer to the application of a vehicle's *‘mechanics’*, *‘electrics’* and/or *‘fluidics’* through the practice of *‘mechatronics’*.

Mechanics is the science and technology of the application of motion as well as force or torque to transmit mechanical energy and signals.

Electrics is the science and technology of the application of electricity as well as current or voltage to transmit electrical energy and signals.

Fluidics is the science and technology of the application of a fluid or compressible medium to transmit fluidical energy and signals. The physical premises of fluidics are hydraulics and pneumatics, based on the theoretical foundation of fluid dynamics.

In this book, the author uses the term *‘fluidics’* instead of the term *‘hydraulics’* in these cases, when a liquid, is used as another fire-resistant fluid instead of water.

Hydraulics deals with such matters as the flow of water (in Greek: *‘hydrous’*) in pipes, rivers, and channels and their confinement by dams and tanks.

Pneumatics deals with fluid statics and behaviour in closed mechatronic control systems when the fluid is a gas or an air.

Mechatronics is the science and technology of the application of the synergic combination of precision mechanics (*‘mecha’* for mechanisms), electronics (*‘tronics’* for electronics) and AI systems approach (thinking).

Automotive mechatronics has come to mean the synergic application of physics, namely, mechanics, fluidics (hydraulics or pneumatics), electrics, electronics, overall control theory, computer science, and sensor and actuator technology to design improved automotive products and manufacturing (Fig. 1.1) [WASHINO 2000; BALSI 2006; KOOPMAN 2007].

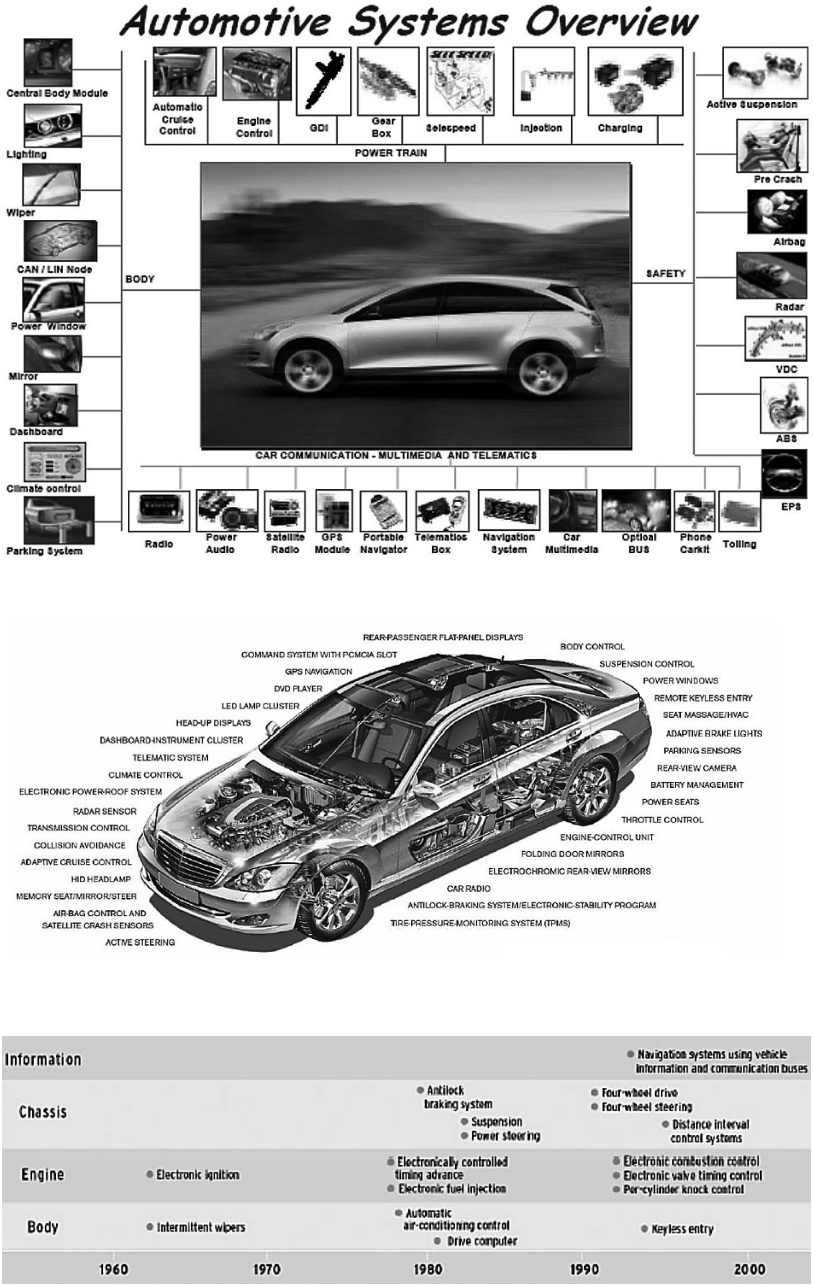

Fig. 1.1 Automotive mechatronics through the years
[BALSI 2006 (Top and bottom images); KOOPMAN 2007 (Middle photo)].

Mechatronic sophistication in automotive vehicles is increasing. For example, *Daimler Chrysler*'s Mercedes S-Class (Fig. 1.1) employs at least 70 networked **electronic control units** (ECU); ten years ago, most automotive vehicles had three ECUs. *Caterpillar 797* (Fig. 1.2) employs a **distributed embedded** (DE) system [KOPETZ 2001] with *195* sensors and actuators plus wireless data link [KOOPMAN 2007].

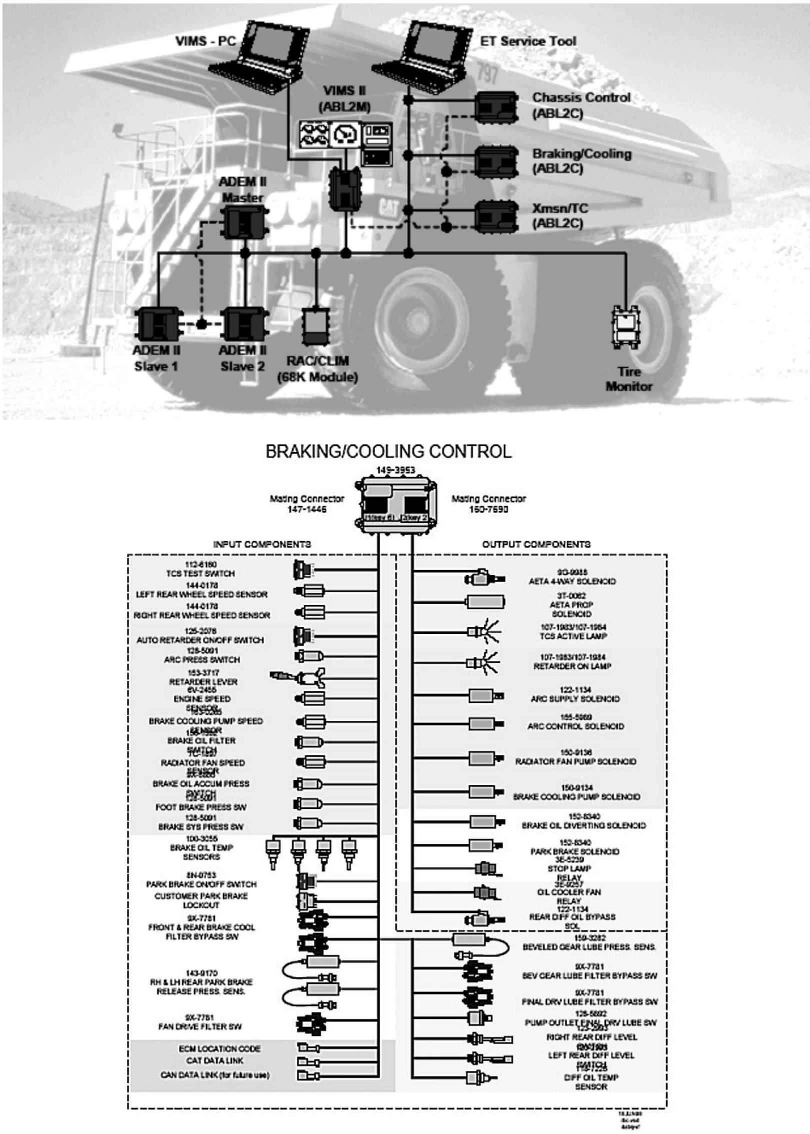

Fig. 1.2 Caterpillar 979's distributed embedded system [KOOPMAN 2007]

The intention of this chapter is to give to the interested reader the background for presentation of safety-related **fault-tolerant** (FT) mechatronic control systems without mechanical backup in automotive vehicles (so-termed *'RBW or XBW integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hypersystems'*).

The *'R'* or *'X'* in *'RBW'* or *'XBW'*, respectively, represents the basis of any safety-related FT longitudinal x axis (*Roll*), lateral y axis (*Pitch*) and vertical z axis (*Yaw*) mechatronic control system application, such as DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems (Fig. 1.3).

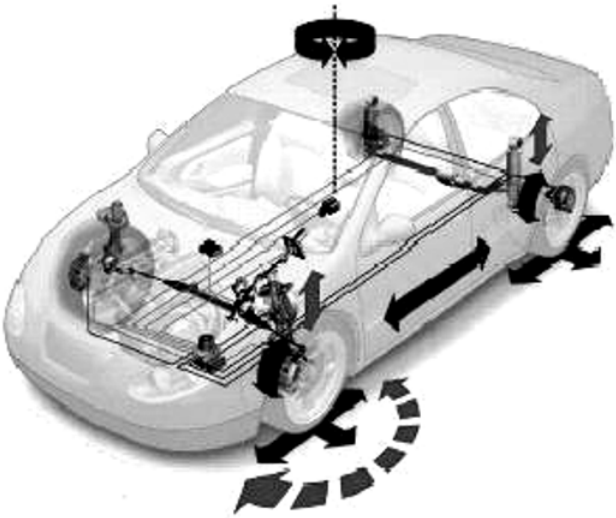

Fig. 1.3 Ride-by-wire (RBW) or x-by-wire (XBW) integrated unibody motion mechatronic control hypersystem [Continental Automotive Systems; RIETH 2006].

These applications may greatly increase overall vehicle safety by releasing the driver from routine tasks and assisting it in finding solutions in critical circumstances. Highly sophisticated future vehicle applications, such as driver assistance or autonomous driving, necessitated computerised mechatronic control of the driving dynamics. This entails that the driver requirement be sensed and interpreted appropriately so as to take proper account of the existing driving circumstances and environmental influences. This requirement has to be interpreted into optimum driving (acceleration), braking (deceleration), and steering manoeuvres.

In the modern automotive industry, mechanical components of conventional construction type are more and more being replaced by mechatronic control systems without direct mechanical connection between controlling and active elements. For this RBW or XBW advanced technology, coming initially from aerospace, there is a series of possible applications, for example mechatronic controlled gears with brakes, steering, and spring systems [MÜLLER 2002].

Unlike in conventional automotive vehicle mechatronic control systems the commands of drivers, for example like *'brake'* or *'steer'* wheels are not passed to the active elements using mechanical components but, instead, exclusively by means of wire-linked data transportation (DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension. The following characteristics motivate the evolution and the introduction of mechatronic control hypersystems *'RBW'* or *'XBW'* by the automotive industry: raised active and passive vehicle safety, less fuel consumption, non-polluting construction of automotive vehicles, and low-cost manufacturing [MÜLLER 2002].

Enhanced Active Safety: Since the commands of the driver on the way to the active elements are compared with the current driving situation and the operational state of the vehicle by a computer, the *'correction'* of these commands in the case of over-reflexes is made possible.

Enhanced Passive Safety: In the case of SBW AWS conversion mechatronic control systems, a wire thus considerably reducing the danger of injury for the driver during an accident, replaces the steering column in the automotive vehicle. By replacing the steering column and other mechanical components, safety concepts may now be equally developed for the passenger compartment. A further factor that positively influences the passive safety, is the by-far lower wear on mechatronic compared to mechanical components.

Less Specific Fuel Consumption: Through the innovative technique of transfer of driver commands through wire in place of mechanical components to the active elements, a much lighter automotive vehicle may be built as a result of which SFC is reduced.

Non-Polluting Construction of Automotive Vehicles: The realisation of BBW AWB dispulsion mechatronic control systems leads to the replacement of the conventional way of passing the driver's command to the brakes. Instead of transferring it by means of a fluidic (hydraulic and/or pneumatic) circuit, the command is now transferred by a wire. The use and disposal of brake fluid or gas (air) is hence no longer necessary.

Low-Cost Manufacture: In addition to the mentioned technical advantages of RBW or XBW advanced technology, such systems are also of great importance from the economic point of view for the automotive industry since vehicles may be manufactured at lower costs, compared to conventional components and, in addition, they simplify the process of manufacture. In spite of all described advantages, a set of risks arises out of the fact that the advanced technology is placed as an interface between the driver and the vehicle.

In order to completely clear these risks or at least to minimise them to a minimal probability of occurring, RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems must satisfy the highest claims concerning real-time behaviour, fault tolerance, and robustness. The probability of a malfunction of the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem is ideally lower than from the corresponding mechanical components, so that a malfunction or failure of the hypersystem may be virtually excluded [MÜLLER 2002].

Examples of mechatronic control systems where RBW or XBW integrated unibody or chassis motion mechatronic control development is occurring include DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension.

The SBW AWS conversion mechatronic control system is neither revolutionary nor a new concept. The stability of automotive vehicles is determined by the combined functions of the vehicle DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems. Traditionally, these **mechano-mechanical** (M-M) systems have been designed and developed by different automotive **original equipment manufacturers** (OEM) in accordance with specifications from automotive vehicle manufacturers. As a result, optimising automotive vehicle stability has been a difficult coordination issue [SEEWALD 2000].

The advent of mechatronic controls has greatly advanced the ability to control stability but has also complicated optimisation issues. A complete range of integrated unibody or chassis motion mechatronic control hypersystems may be available to automotive suppliers and now allows the design of optimised integrated unibody or chassis motion mechatronic control hypersystems. As a result, suppliers now have the ability to focus on synergies in vehicle performance and cost by combining the different mechatronic control systems, such as DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems. Furthermore, other sensors, such as vision or radar, may be added to enhance automotive vehicle control and safety.

The evolution toward integrated unibody or chassis motion mechatronic control hypersystems is the result of a long series of developments in automotive mechatronics. As the reliability of mechatronics in automotive environments has improved and the cost of mechatronics decreased, more and more of the individual mechatronic control functions have transitioned from mechanical systems to electronic systems. Equally important has been the development of automotive vehicle networks and protocols that enable the sharing of sensor and control signals among the various vehicle systems. Together, these developments are enabling the emerging technology of integrated unibody or chassis motion [SEEWALD 2000].

Summing up, RBW or XBW is the collective term for the addition of mechatronic control systems to the automotive vehicle to enhance and replace tasks that were previously accomplished by means of mechanical and fluidic (hydraulic and/or pneumatic) mechatronic control systems. New data network-conscious automotive technologies are being introduced because they enhance safety, economy, and functionality of the automotive vehicle. Automotive vehicle manufacturers are facing increasing challenges from all facets of the industry. They strive to reduce manufacturing costs and maximise efficiencies in the design process while simultaneously meeting increasing demand for vehicle safety systems.

The introduction of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems into the automotive environment is gaining rapid momentum, and RBW or XBW examines this industry-wide movement to replace fluidics (hydraulics and/or pneumatics) and mechanical systems with mechatronics.

In the early days of automotive vehicle design and manufacture, the chassis was the frame over which the vehicle body was mounted, and below which the axles were mounted by means of their springs, together with any associated steering and braking systems.

During the 1920s, automotive pioneers began to study the implications of eliminating the chassis frame, attaching the wheels – whether mounted on axles or independently – directly to the vehicle body. It quickly emerged that to achieve similar orders of stiffness in bending and (especially) in torsion, a load-carrying vehicle body could be made lighter and more compact than an unstressed vehicle body mounted on a chassis frame. By the 1950s, the stress-carrying *'unitary'* vehicle body had become the industry's standard.

The term *'automotive vehicle's integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion'* had not disappeared, but rather had been transferred to those mechatronic control systems between the vehicle body and the on/off road surface – the ABW AWA suspension linkages, springs, and shock absorbers (dampers), and the wheels themselves – together with the closely associated SBW AWS conversion, and BBW AWB dispulsion, as well as DBW AWD propulsion mechatronic control systems essential for integrated mechatronic control of the automotive vehicle.

Some observers regard RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems and ABW AWA suspension mechatronic control systems as synonymous, but this disregards the interdependence of ABW AWA suspension, SBW AWS conversion, as well as BBW AWB dispulsion and DBW AWD propulsion mechatronic control systems, the fact that they are integrated to an increasing degree, especially at the mechatronic level.

It may also be argued that even in the early days of motoring when complete chassis were delivered to coach builders for vehicle body installation, the steering and the brakes (such as they were) were already installed.

In present-day terms, therefore, the terms *'automotive vehicle's integrated unibody, space-chassis, skateboard chassis, or body-over-chassis motion engineering'* or *'automotive vehicle's integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control hypersystems'* embrace a hierarchy of technologies and features that may be outlined below.

This book considers the topics of DBW AWD propulsion (driving) and BBW AWB dispulsion (braking), SBW AWS conversion (steering), as well as ABW AWA suspension (absorbing/damping) functions, **time-triggered protocol** (TTP) offerings, the role of 42 V_{DC} in-vehicle **energy-and-information networks** (E&IN), and the integration of these systems, along with navigation and infotainment systems, along common data buses (Fig. 1.4).

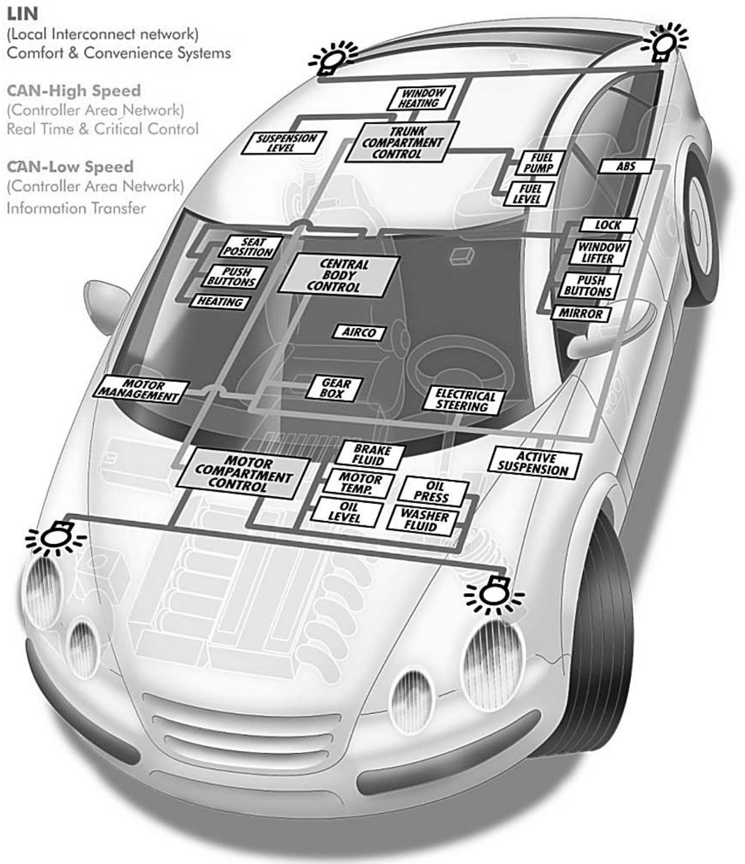

Fig. 1.4 **In**-vehicle energy-and-information networks (E&IN) [AMIS 2004].

Expanded emphasis is placed on emerging in-vehicle communication protocols such as **local interconnect network** (LIN), SAE J1850, IEEE 1394, **controller area network** (CAN), **time-triggered protocol** (TTP), **media oriented systems transport** (MOST) and FlexRay™.

This part of the book forecasts the main target technologies and takes advantage of communication protocols, divided by region, through 2010 [ABI-RESEARCH 2004; AMISEMICONDUCTOR 2004].

What is RBW or XBW?

- ❖ Hypersystems for integrated unibody or chassis motion mechatronic control;
- ❖ Replace automotive mechanical and fluidic (hydraulic and/or pneumatic) linkages with electrical wires;
- ❖ Originally integrated aerospace aircraft mechatronic control hypersystems termed fly-by-wire (FBW);

- ❖ Passionate research and development (R&D) area for integrated unibody, space-chassis, skateboard-chassis or body-over-chassis mechatronic control hypersystems:
  - ➢ Drive-by-wire (DBW) or throttle-by-wire (TBW) plus shift-by-wire (SBW) propulsion mechatronic control system – since 1986;
  - ➢ Brake-by-wire (BBW) dispulsion mechatronic control system;
  - ➢ Steer-by-wire (SBW) conversion mechatronic control system;
  - ➢ Absorb-by-wire (ABW) suspension mechatronic control system.

Why RBW or XBW?

- ❖ Recent automotive mechanical solutions are good;
- ❖ But, if one can eliminate them:
  - ➢ Can reduce mass → greater liquid fuel efficiency;
  - ➢ Reduce cost over many automotive vehicles;
  - ➢ New functionality from mechatronic controls:
    - Anti-lock braking system (ABS) -- although this is not really BBW;
    - In the automotive industry, control of unstable automotive vehicles.
  - ➢ Can eliminate *'passive failure modes'*.
- ❖ Improve automotive vehicle handling (change steering in steep curves to keep the vehicle on the road, similar to ESP);
- ❖ More flexible automotive vehicle design, since no steering column;
- ❖ Fully autonomous driving;
- ❖ Some issues can already be achieved by active steering, including *'wake-up rattle'* for driver using *'lane departure warner'*.

Why is Fault-Tolerance Important?

- ❖ Mechanical systems being replaced are very reliable;
- ❖ Customers demand equal level of reliability in new designs;
- ❖ Government Regulation.

For instance, the RBW or XBW integrated unibody or chassis mechatronic control hypersystem being developed by *Hitachi Ltd.* represents the first generation of autonomous driving. As for the first generation, it is necessary that the automotive vehicle accurately` follows the driver's intentions.

Consequently, as regards realising actions *'RBW'* or *'XBW'* -- namely, cutting out the mechanical linkage between the input devices such as brake pedal and steering HW and actuators -- a key issue is improving the reliability of the actuators and controllers. It is also important to improve the reliability of the sensor recognition technology that connects to the decision-making process. In respect to the evolution from the first to the second generation of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems, it is considered necessary to guide automotive vehicles to a safer direction by means of autonomous decision-making. To achieve this, it is necessary to advance automotive vehicle mechatronic control by integration of individual DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, to expand co-operation with humans (namely, extracting the driver's intention) and the mechatronic control domain under circumstances that cause no discomfort to the driver [YOSHIDA ET AL. 2004].

RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems should enhance safety by releasing drivers from routine tasks and assisting the driver to respond to critical circumstances. The on-board AI should allow driver instructions such as steering in a particular direction or accelerating at a given point, to be translated into the optimum manoeuvre for the prevailing driving conditions or environmental influences.

The RBW or XBW advanced technology also has the potential to make automotive vehicles more environmentally friendly and less expensive. For instance, Citroën is presenting an advanced technology demonstration passenger vehicle, *'C5 by Wire'*. This vehicle reflects two of the objectives: to develop a vision of the automotive future and to continuously devise new solutions to improve driving pleasure, safety, and interior layout [CITROËN 2005].

Developed by the automotive industry, *'RBW'* or *'FBW'* advanced technology involves replacing the mechanical connections between controls (steering wheel, pedal assembly, etc.) and systems (driving, braking, steering, absorbing/damping, etc.) with mechatronic connections. First, the steering **hand wheel** (HW) groups the steering, braking, and acceleration controls, and second, there is no accelerator and brake pedal assembly in the automotive vehicle. The multifunctional steering HW (Fig. 1.5) thus plays an essential role.

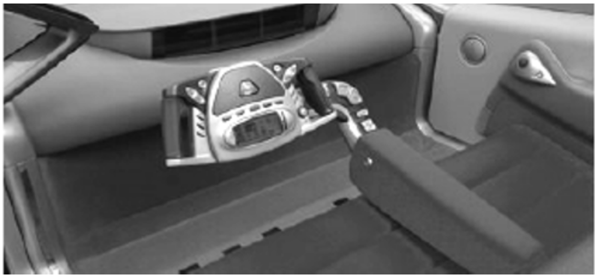

Fig. 1.5 Principle layout of the driver's mechatronic control system consists of left and right steering control yokes for mechatronic control of throttling (acceleration), gear shifting, and clutch actuation, as well as braking (deceleration) [SKF and Bertone -- *Guida-Filo*].

Previously automotive vehicles' *'RBW'* or *'XBW'* advanced technology was being partly trialled on the Citroën *C5*.

'RBW' or *'XBW'* advanced technology opens new possibilities in interior design by replacing mechanical components such as the accelerator and brake pedal assembly and the steering column. Grouping all the driving controls on the steering HW is an ergonomic solution that also promotes easy use. As a result, controls may be activated more quickly for enhanced safety [CITROËN 2005].

Operating Principle of the driver Interface -- The driver, who holds the steering HW in the *'quarter-to-three'* position in order to activate the controls, manages essential driving functions. The lower and upper parts of the steering HW hoop have been removed, allowing full use of the all-electric variable-ratio steering, which is particularly sharp at low values of vehicle velocity.

The driver uses the right or left thumb to reach the forward-facing acceleration paddles on either side of the wheel. It was necessary to provide two paddles in order to allow the driver to accelerate and, at the same time, to activate the lighting on the left and the windscreen wipers, headlamp washers, and horn on the right. *'Triggers'* located at either end of the steering HW control the brakes. The driver uses the right or left index finger to reach these controls. Brake force is applied intuitively. These controls are all highly ergonomic. They feel completely natural to use after just a short time behind the wheel [CITROËN 2005].

Passivity-Based RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control - With the introduction of driver-assisting control systems and RBW or XBW technology, the automotive industry is now able to redesign the interface between the driver and the vehicle's dynamical behaviour. The RBW or XBW unibody or chassis motion mechatronic control hypersystems help to make the vehicle more consistent, predictable and therefore safer to operate. Besides that, the vehicle can easily be designed to have a specific *'driving feel'* [KOOPMAN 2008]. However, increasing the degrees of control freedom often results in a complex conglomeration of DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems within the automotive vehicle. It is desirable that a single integrated RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem is developed, possibly having a structural hierarchy.

Other relevant complicating factors are:

- ❖ Uncertain on/off road surface conditions;
- ❖ Changing loading conditions;
- ❖ Highly nonlinear wheel-tyre behaviour.

The **research and development** (R&D) work aims at applying constructive, physics-based nonlinear control techniques to the problem of integrated RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control. It is the objective to shape the vehicle's dynamical behaviour by applying:

- ❖ Four-wheel steering (4WS);
- ❖ Differential braking and traction;
- ❖ Active suspension control.

Closed-loop controller synthesis methods can help to keep the controller as simple as possible and preferably physically interpretable. The closed loop should be robust to changes in, e.g., friction and loading conditions. In [KOOPMAN 2008], **passivity-based control** (PBC) is used.

The area of PBC focuses on shaping the closed-loop's

- ❖ Energy;
- ❖ Interconnection;
- ❖ Damping.

In a port-Hamiltonian description of a system

$$\dot{x} = \left[J(x) - R(x)\right]\frac{\partial H}{\partial x}(x) + g(x)u \quad ,$$

this corresponds to shaping *H(x)*, *J(x)* and *R(x)*.

The system's passivity properties play a key role in this kind of controller design. One of the key advantages of PBC is the fact that nonlinearities can be treated in a natural way.

An interesting open issue is a general methodology to incorporate performance specifications into the controller synthesis. First results will be validated using the full-vehicle simulation environment of *Modelica-Dymola®* [KOOPMAN 2008].

The RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control Hypersystem: An Advanced Technology Serving Safety - The multifunctional steering HW plays an essential role. Easy to use, it allows the driver to concentrate on the road, thus clearly contributing to safety which ought to be an essential factor in the development of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems for the automotive industry. The absence of the accelerator and brake-pedal assembly and steering column considerably enhances safety, since the risk of injury in the event of impact is significantly reduced. In addition, the space freed up for the legs improves ergonomics and postural comfort. Also, having the controls on the steering HW increases the speed of execution, particularly when braking. Precious time is gained, since the driver no longer has to reach for the brake pedal [CITROËN 2005].

Variable-Ratio SBW AWS Conversion Mechatronic Control System -- The all-electric steering system provides a variable steering HW angle/wheel angle ratio, adjusted automatically to suit the driver's requirements and the vehicle velocity [CITROËN 2005]. In particular, this function makes parking much easier, thanks to the more direct steering ratio (between one and two turns of the steering HW compared with three turns in general). This feature also ensures pin-sharp steering at high values of the vehicle velocity-considerable latitude in adapting and defining steering parameters in terms of torque (controlling wheel vibration, for example), angle (small turns of the wheels) and vehicle behaviour (overall chassis motion mechatronic control).

BBW AWB Dispulsion Mechatronic Control System - The BBW AWB dispulsion mechatronic control system is **electro-fluidical** (E-F). There is no brake pedal assembly but the electric button on the steering HW plays exactly the same role as a conventional system. Brake force is applied progressively in an intuitive and natural way. To brake, the driver simply applies pressure to one or both of the steering HW handles. With the *'C5 by Wire'*, Citroën is exploring advanced technological options. By elimination of mechanical limits and constraints, it suggests creating more attractive and ergonomic cockpit design that adapts to the necessities of each driver and brings significant progress in active safety [CITROËN 2005].

Optimization of RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control Hypersystem's Variables **--** Application of modern actuators **-- active rear steering** (ARS), active **torque vectoring differential** (TVD), **active limited-slip differential** (ALSD), suggests novel possibilities of getting better active vehicle stability and performance.

However, the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem becomes more complex, which calls for application of advanced controller optimization methods [KASAĆ ET AL. 1994].

Advantages of using the nonlinear open-loop optimisation:

- ❖ Estimation on the degree of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's enhancement realised by introducing different actuators;
- ❖ Getting of an insight into how the state controller can be extended by feedforward and/or gain scheduling actions to get a better performance.

In this chapter a gradient-based algorithm for optimal control of nonlinear multivariable hypersystems with mechatronic control and state vectors constraints may be estimated.

RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's application – the double lane change manoeuvre executed by using control actions of active rear steering and active rear differential actuators [KASAĆ ET AL. 1994].

Summing up, a **back-propagation-through-time** (BPTT) exact gradient method for optimal control has been applied for control variable optimisation in RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems. The BPTT optimisation approach has proven to be numerically robust, precise (control variables are optimised in 5000 time points), and computationally efficient [KASAĆ ET AL. 1994].

Recent algorithm improvement:

- ❖ Numerical *Jacobians* calculation;
- ❖ Implementation of higher-order *ADAMS* methods.

The future R&D work ought to be directed towards:

- ❖ Using of more accurate wheel-tyre physical and mathematical models;
- ❖ Application of a human driver (HD) physical and mathematical models for closed-loop manoeuvres;
- ❖ Physical model extension with roll, pitch, and heave dynamics;
- ❖ Implementation of different gradient methods for convergence speed-up.

1.2 Integrated Unibody or Chassis Motion Advanced Technology Roadmap

Just as **local area networks (**LAN) connect computers, control networks connect an automotive vehicle's electronic equipment. These networks facilitate the sharing of information and resources among the distributed applications. In the past, wiring was the standard means of connecting one element to another. As mechatronic content increased, however, the use of more and more discrete wiring hit a technological wall. Added wiring increased vehicle mass, weakened performance, and made adherence to reliability standards difficult. For an average well-tuned vehicle, every extra 50 kg of wiring -- or extra 100 W of power -- increases SFC by 0.2 l for each 100 km travelled. Also, complex-wiring harnesses take up large amounts of vehicle volume, limiting expanded functionality. Eventually, the wiring harness became the single most expensive and complicated component of vehicle electrical systems. Fortunately, today's control and communications networks based on serial protocols, counter the problems of large amounts of discrete wiring. For example, in a 1998 press release, Motorola reported that replacing wiring harnesses with LANs in the four doors of a BMW vehicle reduced the mass by 15 kg while enhancing functionality.

Beginning in the early 1980s, centralised and then distributed networks replaced point-to-point wiring [LEEN ET AL. 1999].

Figure 1.6 shows the sheer number of systems and applications contained in a modern vehicle's E&IN architecture [LEEN ET AL. 1999; XILINX 2006].

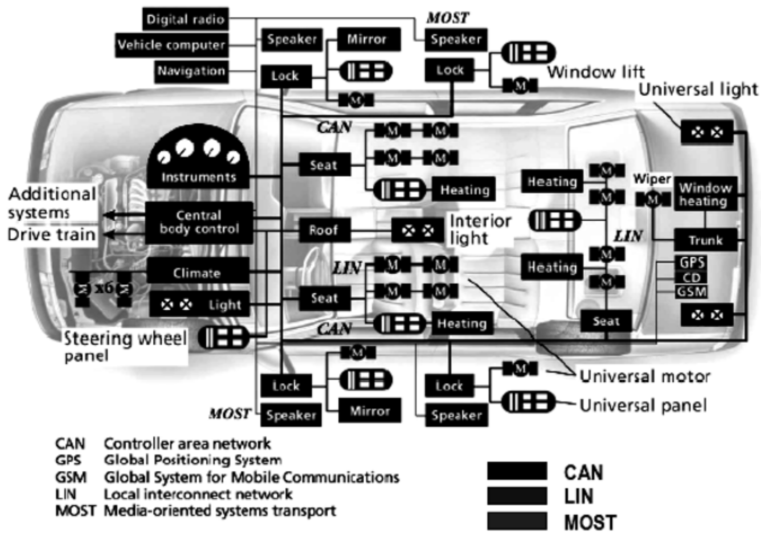

Fig. 1.6 One subset of a modern automotive vehicle's E&IN architecture, showing the trend toward incorporating evermore extensive electronics [LEEN ET AL. 1999; XILINX 2006].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
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DOI 10.1007/978-94-007-0409-1_2,

The trend toward the increasing application of mechatronics is reflected in the integrated unibody or chassis motion advanced technology roadmap in Figure 1.7 [SEEWALD 2000].

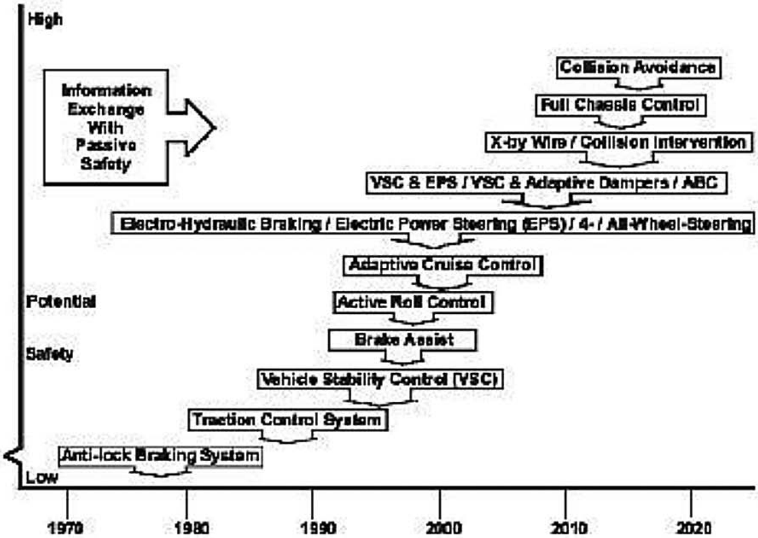

Fig. 1.7 Integrated unibody or chassis motion advanced technology roadmap [SEEWALD 2000].

Anti-lock braking systems (ABS) were launched in the 1970s, followed by **traction control systems** (TCS) in the mid-1980s. Between 1990 and 2000, **vehicle stability control** (VSC), **brake assist** (BA), and **active roll control** (ARC) were introduced. Today, the first **adaptive cruise control** (ACC) systems are being launched.

Looking forward to the next 10 years, several innovative systems are in discussion, that is, BBW AWB dispulsion (braking), SBW AWS conversion (steering), followed by mechatronically controlled ABW AWA suspension (absorbing/damping).

Complete RBW or XBW, a term used in the automotive industry to denote mechatronic control of the various automotive vehicle functions, is envisioned to be operable by 2010. This would also facilitate the first steps toward collision intervention. Integrated unibody or chassis motion mechatronic control and collision avoidance would then follow [SEEWALD 2000].

The integrated unibody or chassis motion advanced technology roadmap in Figure 1.7 reflects a general time line, as seen by the major automotive OEMs. These new functions would be linked to the passive safety systems to optimise occupant safety.

Radar and optical sensors would also serve pre-crash situations and would deploy safety measures earlier than current crash sensors, which are based on acceleration/deceleration measurements obtainable only after a crash has started to occur [SEEWALD 2000].

A more detailed integrated unibody or chassis motion advanced technology roadmap showing several phases of development is depicted in Figure 1.8 [SEAWALD 2000].

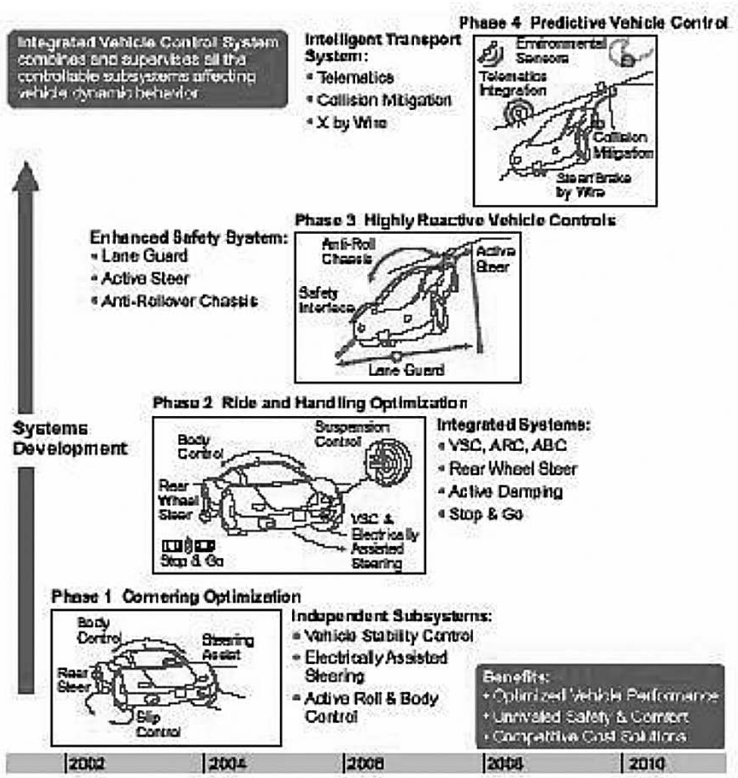

Fig. 1.8 TRW integrated unibody or chassis motion advanced technology roadmap [SEAWARD 2000].

Phase 1, building upon prior work in longitudinal stabilisation (ABS and TCS), may focus on cornering and lateral optimisation. During this phase, our priority may be on optimisation within the different independent systems such as VSC, **electrically assisted steering** (EAS), and **active roll and body control** (AR&BC). The benefits of this optimisation may result in improved manoeuvring stability, reduced steering effort, optimised roll, and reduced body motion [SEAWALD 2000].

In Phase 2, with the priority on **ride and handling** (R&H) optimisation, the independent hyposystems may be linked as an integrated system.
Adaptive cruise control, which in its initial form is inactive only above 56 km/h (35 mph), may be extended by a **stop-and-go** (S&G) function.

are reduced cost via hardware integration and sensor sharing, and enhanced stability, ride comfort, and road handling [SEAWALD 2000].

Phase 3 may be directed toward highly automotive vehicle's reactive integrated unibody or chassis motion mechatronic control with the focus on enhanced safety systems. These include lane guard (an active lane-keeping control), active steer, and an anti-roll chassis.

Additionally, there may be a strong interface with passive safety systems, particularly with seat-belt pretension. Front, rear, and side vision sensors may be necessitated to provide control signals for active steering and lane keeping. Active steering requires an overlay of steering commands, which, in turn, requires limited decoupling between the steering HW and the steering gear. The active mechatronic control of steering may maximise wheel-tyre-to-on/off-road adhesion, may aide in rollover prevention, and may perceptibly reduce the occurrence and severity of accidents [SEAWALD 2000].

The highest level of integrated unibody or chassis motion advanced technology may be achieved in Phase 4 by means of the automotive vehicle's predictive RBW or XBW integrated unibody or chassis motion mechatronic control.

Automotive vehicles with a RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem may be ready to be integrated into an **intelligent transport system** (ITS) to achieve a high degree of collision mitigation and improved traffic flow. However, much R&D work may be required in sensors, optimised controls, and in the entire transportation infrastructure [SEAWALD 2000].

1.3 RBW or XBW Philosophy

The development of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems is a major area of current interest in automotive research. Roughly speaking, research on this topic has been motivated by the desire for increased vehicle safety, increased comfort, and better performance by taking into account and using the interactions that exists between the different active DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems of the automotive vehicle.

While research on this topic has progressed along several lines of inquiry, it appears to be the case that almost no effort has been devoted toward the construction of vehicle emulators that are based on an RBW or XBW integrated unibody or chassis motion mechatronic control systems.

For example, automotive vehicles equipped with active DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems may, in principle, be constructed to emulate any reasonable given set of automotive vehicle dynamics. Arguments for the design of such automotive-vehicle emulators are compelling.

In particular, automotive vehicle designers should, in principle, be able to use vehicle emulators to test prototypes before their construction and at lower expense than by using vehicle simulators and actual prototype vehicles.

The intention of this chapter is to present an RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem with the capacity to emulate an automotive vehicle with a given set of longitudinal (x), lateral (y) and vertical (z) motion dynamics using the vehicle's active DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems (and taking into account the interaction between these active mechatronic control systems).

The concept of generic prototype automotive vehicles has emerged as a promising solution to an outstanding challenge in the development of the **ride and handling** (R&H) characteristics for advanced passenger vehicles: the bridging of the gap between numerical simulations based on the physical model of a vehicle -- a virtual prototype -- and experiments on a proof-of-concept prototype vehicle.

A generic prototype vehicle would be equipped with advanced computer-controlled *'actuators'* enabling it to modify its ride and handling characteristics.

Examples of such advanced *'actuators'* are active DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems.

An integrated unibody or chassis motion microcontroller would command those *'actuators'* to track a set of reference signals corresponding to a desired R&H behaviour.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
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DOI 10.1007/978-94-007-0409-1_3,

Currently, moving-base driving simulators are used to emulate the R&H behaviour of virtual prototypes prior to building real ones. However, the achievable accelerations of such simulators severely constrain their ability to realistically recreate the full range of automotive-vehicle motions.

Generic prototype vehicles could allow for the realistic recreation of the R&H characteristics of virtual prototypes, thereby enabling automotive scientists and engineers to experience and evaluate their behaviour prior to making the decision to build expensive proof-of-concept prototypes.

A defined RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem, shown in Figure 1.9 [WINNER ET AL. 2003], replace the conventional mechanical or fluidical (hydraulical and/or pneumatical) linkages between the driver controls as well as the driving (DBW AWD propulsion) and braking (BBW AWB dispulsion), steering (SBW AWS conversion), as well as absorbing/damping (ABW AWA suspension) mechanisms with various E-M actuators, pedal and steering feel emulators, and a **distributed embedded** (DE) network of mechatronic control modules.

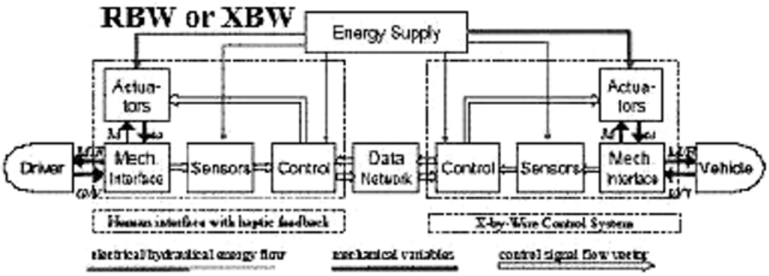

Fig. 1.9 Structural and functional block diagram of a RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem [WINNER ET AL. 2003].

Conventional steering and brake mechanism components, such as the steering column, intermediate shaft, pump, hoses, fluids, belts and brake power booster/ master cylinder, are completely eliminated. For instance, SBW AWS conversion and BBW AWB dispulsion mechatronic control systems may provide improved fuel consumption.

The elimination of the fluidical oily-fluids or gas (air) is more environmentally friendly. Fewer components simplify assembly and allow for significant flexibility in the design of the cockpit. With no mechanical connection constraints, enhancements to the driver controls become a possibility. Further, its adaptive design allows the mechatronic controls to be easily changed from left-hand drive to right-hand drive.

The RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem also supports the vehicle manufacturers' efforts to improve crash worthiness [DELPHI 2001].

As fully programmable mechatronic control systems, RBW or XBW offers vehicle manufacturers rapid tuning capability, significantly reducing development time and effort.

Programming flexibility and rapid tuning strategies permit RBW or XBW to quickly and precisely meet a wide variety of vehicle handling and steering feel specifications, allowing the vehicle manufacturers to program in the brand character they desire. While RBW or XBW advanced technologies promise many benefits, they must be carefully analysed and verified for safe operation.

A system-safety program for RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems must be closely co-ordinated between the vehicle manufacturer and their OEM. System safety is an overriding priority for OEMs [DELPHI 2001].

An RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem permits true co-ordinated mechatronic control of driving and braking, steering as well as absorbing/damping dynamics and offers additional integration capability with other automotive vehicle functions.

These mechatronic control hypersystems are fully programmable and provide the maximum opportunity for optimising the R&H and active safety performance, including VSC, rollover prevention assistance and collision avoidance [DELPHI 2001].

As part of an **integrated safety system** (ISS), RBW or XBW advanced technology together with, e.g., Delphi's *FOREWARN*™ collision-warning sensor systems represent the critical elements of dynamic vehicle safety management.

When a potential collision is detected and deemed avoidable, RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems may be automatically activated to supplement the driver's actions if necessary. This integrated approach may enable safety-enhancing features such as lane keeping, enhanced lateral control, and, ultimately, true collision avoidance. Together, RBW or XBW and *FOREWARN*™ advanced technologies may enable Delphi's vision of helping to better-protect the driver and the vehicle's occupants with a mechatronic cocoon [DELPHI 2001].

Next-generation RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems -- safety-related **fault-tolerant** (FT) automotive vehicle mechatronic control hypersystems -- may play a critical role in vehicles. They might be the only link between the driver and the vehicle, performing a number of functions autonomously to increase vehicle functionality.

For instance, RBW or XBW integrated unibody motion mechatronic control hypersystems, as shown in Figure 1.10, offer a number of advantages to mechanical or fluidic (hydraulic and/or pneumatic) systems, namely [SHENOY 2006]:

- More efficient motoring;
- Automotive industry standardisation;
- Less specific fuel consumption (SFC);
- Safety, comfort and reliability;
- Design freedom.

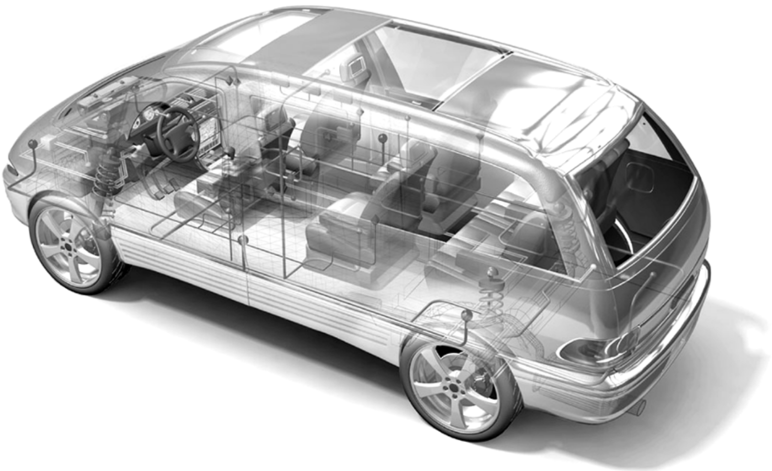

Fig. 1.10 Layout of an exemplary RBW or XBW [SHENOY 2006].

They are lighter, easier to manufacture and maintain, and they enable further functions. In a BBW AWB dispulsion mechatronic control system, for example, a digital data bus may replace the fluidic (hydraulic and/or pneumatic) lines from the brake pedal to the wheel brakes.

A sensor at the pedal then measures driver input, while at the other end of the control loop, an E-M motor applies the required brake force to the wheel. Similarly, mechatronics may replace or enhance other systems, such as DBW AWD propulsion, SBW AWS conversion or ABW AWA suspension mechatronic control systems [NOSSAL AND LANG 2002].

Computer DE systems are the key qualifiers of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems and mechatronic control-system functions.

While developers can validate the correct operation of the communication and operating systems and the silicon implementations -- the basis of computer DE systems -- once and for all, they cannot validate the application-dependent software and data structures in these systems in the same manner.

The developer must configure the communication system for the respective application, create middleware codes to access the communication system, and, last but not least, implement the application software. Because this is necessary for every new application, the authors of [NOSSAL AND LANG 2002] necessitate a well-defined process and a complementary set of tools to minimise error and support a high-quality development life cycle. An exemplary physical model of the DE system that uses an arbitrary partitioning boundary selected between the input and control blocks is shown in Figure 1.11, but other partitioning is also possible [EMAUS AND GRUSZCZYNSKI 2003].

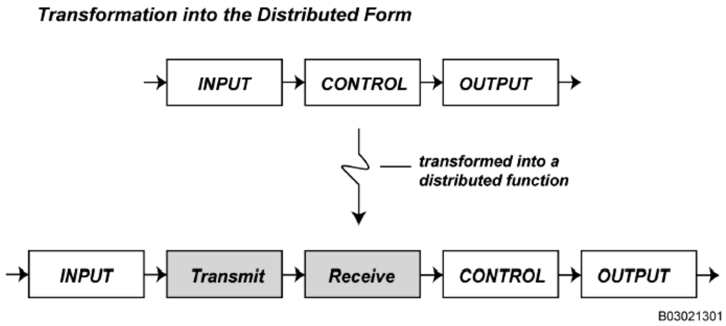

Fig. 1.11 Origin – from the distributed function
[EMAUS AND GRUSZCZYNSKI 2003].

It is well known, for example, from EMAUS AND GRUSZCZYNSKI [2003] that software establishes the speed of operation – not protocol transfer speed as shown in Figure 1.12.

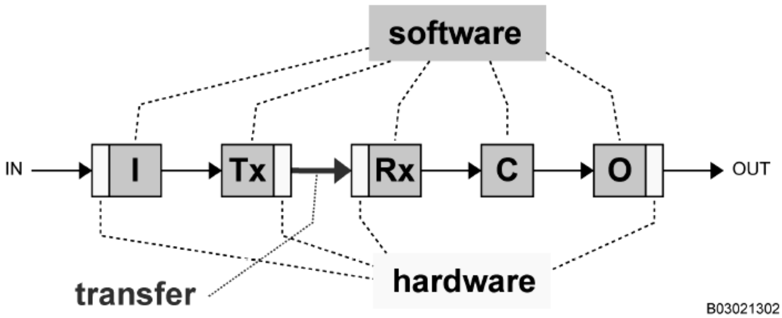

Fig. 1.12 Software in the distributed function: I – input; Tx – transmitter; Rx – receiver;
C – controller; O -- output [EMAUS AND GRUSZCZYNSKI 2003].

SAE Embedded Software Task Force – Goals [EMAUS AND GRUSZCZYNSKI 2003]
More target goals:

- ❖ Increase efficiency in the procurement of software;
- ❖ Optimise the software development lifecycle shared between the OEM and supplier;
- ❖ Minimise mistakes made by entry-level software engineers;
- ❖ Decrease the cost of software development through reusable software building blocks and algorithms;
- ❖ Develop common methods for ask scheduling, I/O handling, loss of communication, and so on;
- ❖ Develop generic distributed embedded software (DES) requirements;
- ❖ Raise industry awareness of issues that pertain to the system – the distributed embedded (DE) system;

- ❖ Develop common methodologies for vehicle network software (if OEM supported);
- ❖ Develop common software testing methods.

In NOSSAL AND LANG [2002], the authors propose a physical model-based process -- the *'A'* development process. It consists of a sequence of physical models, each of which serves a specific purpose and thus contains only those pieces of information it requires for this purpose. The physical models are linked to each other by process transitions that either add information to or extract information from their predecessors. The *'A'* development process guides the developer from one physical model to the next and is supported by a set of tools.

In NOSSAL AND LANG [2002], the authors discuss development process physical models, in general, and their physical model-based process in particular.

The *'A'* development process builds on a number of related physical models, each of which is used at a specific process stage. NOSSAL AND LANG [2002] define the physical models according to two characteristics:

- ❖ A physical model is a dedicated abstraction of the real world;
- ❖ A physical model may help explain certain real-world phenomena.

The developer faces a serious challenge here. Since each physical model serves a specific purpose, the developer necessitates various physical models throughout the development process. Yet, when several physical models represent different aspects of the same system, they may contradict each other in certain respects.

A straightforward approach to remedying this problem might be to create a comprehensive virtual system physical model. This model would be a perfect representation of the original system. It would model all properties of the real-world system, and users could derive various development physical models from it. Obviously, the model would be very complex and thus incomprehensible.

NOSSAL AND LANG [2002] necessitate a more practical approach. To serve different purposes during the development process, the virtual system physical model is instantiated at various levels of abstraction without actually being built. Each physical model instance type -- that is, each development physical model -- is best suited for a certain process step and contains only those pieces of information required for that step. Two main constraints guide the process definition [NOSSAL AND LANG 2002]:

- ❖ The proposed process serves only as a role physical model that developers may adapt to specific needs;
- ❖ The process must reflect the OEM-supplier relationship typical of the automotive industry.

NOSSAL AND LANG [2002] do not necessitate the virtual system physical model as long as the development process adds information to a physical model at a specific point in the process and passes this information to all subsequent models.
Thus, they focus on two issues of a development process:

- ❖ A series of process steps are carried out in a defined order;
- ❖ Design data -- all pieces of information used in one of the physical models -- are added throughout the process and must not be removed.

At first glance, these statements might seem trivial, but unfortunately they are not. The development approaches in current automotive systems rarely adhere to these principles.

Rather, they apply *'ad hoc'* methods, create different physical models for different purposes without considering the others, or -- worst of all -- they do not use modelling or simulation.

While this might be sufficient for man applications, RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems call for a different approach.

In NOSSAL AND LANG [2002], the authors' physical model-based development process adheres to these principles. It defines a sequence of process steps corresponding to a sequence of physical models dedicated to different purposes.

NOSSAL AND LANG [2002] derive the physical models from each other and add specific information to each.

When adding information, NOSSAL AND LANG [2002] perform consistency checks to avoid contradicting information.

By passing on every piece of information from one process step to the subsequent step, NOSSAL AND LAND [2002] cannot lose any piece of information during the process.

The *'A'* development process consists of four physical model types, namely [NOSSAL AND LANG 2002]:

- ❖ Functional physical model;
- ❖ Architecture-allocated functional physical model;
- ❖ Virtual prototype;
- ❖ Architectural physical models -- that may be classified according to the respective level of abstraction.

The *DECOMSYS*' *'A'* development process physical model tracks the development life cycle of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems' applications. \

The designation, *'A'* development process, stems from the sequence of development physical models, starting with the architecture-allocated functional physical model on top and the interaction patterns of the physical models that are derived from it [NOSSAL AND LANG 2002].

Figure 1.13 illustrates the *'A'* development process and Table 1.1 lists the '*A'* development process information-flow details [NOSSAL AND LANG 2002].

Information that is passed from one physical model to another is listed in the appropriate cell with the rows being the source and the columns being the destination of the information.

Information may be entered (normal font) or created (*italic font*) in the respective physical model. Blank boxes represent physical models that do not interact directly. Only physical models that are adjacent to each other in the *'A'* may pass on information.

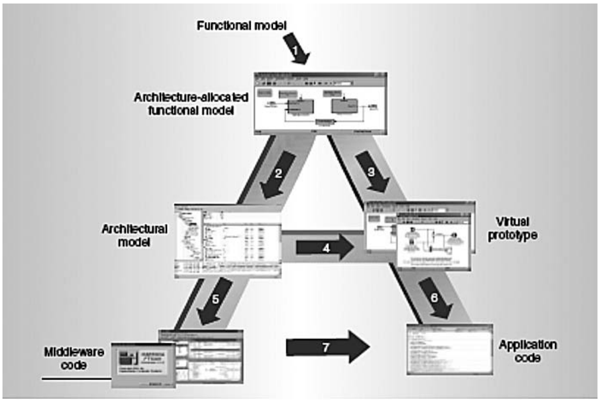

Fig. 1.13 The *'A'* development process; the *'A'* process model tracks the development of RBW or XBW applications from functional model to middleware and application code [NOSSAL AND LANG 2002].

The configuration of a real-world system is based on architectural physical models. Configuration data are the hardware-specific representation of the data set required to run the real-world system. A schedule, for example, describes the communication pattern abstractly [NOSSAL 1997].

Table 1.1 Physical model relationship [NOSSAL AND LANG 2002].

	DESTINATION			
Source	**Functional model**	**Architecture-allocated functional model**	**Virtual prototype**	**Architectural models**
Functional model	Closed loops*)	Closed loops*)		
Architecture-allocated functional model		Task allocation, node allocation, message transfer relation	Control loops, task allocation, node allocation relation*)	Task allocation, node allocation, message transfer relation*)
Virtual prototype				
Architectural models			Message schedule, task schedule per node, network topology	*Message schedule, task schedules per node, Network topology***)

***) Control loop period**
****) Signal transmission period, task offset, signal transmission offset**

Note: Information (as objects and relations) is passed from one physical model to another. Normal font represents information that is entered in the respective physical model; italic font represents information that is created.

The data for configuring a specific communication controller's buffers, which are derived from the schedule, are part of these configuration data. RBW or XBW integrated unibody, space-chassis or body-over-chassis motion mechatronic control hypersystems; there is a clear trend toward a time-driven system architecture consisting of a time-driven communication system, such as FlexRay™, and a time-driven operating system, such as *OSEKTime* (www. osek-vdx.org). Both require a schedule that must be created before runtime and loaded to the system nodes. For message schedule creation, a message scheduler uses the sender-receiver relations, the software physical model signal periods and signal sizes, and the allocation information in the hardware physical model. In a second step, a task scheduler uses the communication schedule and the task set information to derive the task schedules for each node. For instance, to assist users in system development, DECOMSYS has implemented the *xDesigner* (www.decomsys.com/htm/frs/2_xd.htm), a tool for handling the architectural models. Wizards that carry out the core development functions, operate on the architectural physical models.

For example, the *xDesigner* includes a *ScheduleWizard* for creating the communication schedule. It realizes a variation of the bin-packing algorithm to automatically derive a communication schedule for FlexRay™ [NOSSAL AND LANG 2002]

Intensive discussions with major OEMs in the automotive market proved that our model-based *'A'* process meets the needs of developers of future RBW or XBW integrated automotive vehicle mechatronic control hypersystems' applications. Because these applications have stringent requirements, developers necessitate gathering information about the systems and gaining confidence in them through modelling and simulation before actually building a system.

Once developers have derived an appropriate physical model, they should turn the model into a real-world system with no gaps in the process. Thus, a gap-free tool chain from the physical model to the real-world system, including automatic ECU code generation and system configuration, is a good approach. Most companies already have a working development process or use a certain set of tools [NOSSAL AND LANG 2002].

Thus the scheme that NOSSAL AND LANG [2002] discuss may be meant to be a role physical model rather than a dogmatic process. The process and the tools may be adapted to the particular requirements of an OEM or a supplier to fit in a given process environment. The tools presented are part of DECOMSYS's tool chain for Flex Ray™ systems and a first step toward a seamlessly integrated tool chain. While extending the tool chain to offer better user support, DECOMSYS may at the same time incorporate means for dealing with the prevalent relation between OEMs and suppliers in the automotive domain. Reflecting the organizational setting, the extended process may allow individual process participants to develop ECUs or parts thereof in relative autonomy [NOSSAL AND LANG 2002].

Recent advances in dependable, embedded systems advanced technology, as well as continuing demand for improved vehicle handling and active safety improvements, have led automotive vehicle manufacturers and OEMs and suppliers to pursue development of computer-controlled by-wire systems.

As a result, automotive OEMs and suppliers have combined development efforts on RBW or XBW to more effectively serve the emerging needs of the automotive industry.

Combining efforts in the areas of systems architecture, control algorithms, system safety and vehicle dynamics development, allows automotive scientists and engineers to concentrate their considerable expertise to expeditiously bring integrated unibody or chassis motion mechatronic control hypersystems to customers. There is an increasing demand for automotive OEMs to increase vehicle safety and performance, while simultaneously reducing manufacturing costs and maximising efficiencies in the design process [LEEN AND HEERNAN 2002].

The introduction of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems into the automotive environment is gaining rapid momentum, and RBW or XBW examines the global movement toward replacing fluidics and mechanical systems with mechatronics for safety-critical applications.

The RBW or XBW represents the basis of any safety-related application, such as DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic controls and/or even multi-airbag systems. These applications aim to increase overall vehicle safety and performance by releasing the driver from routine tasks and assisting in finding solutions in critical circumstances.

The objective of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem is to make the average driver as skilled as a professional driver in stabilising the vehicle. Integrating RBW or XBW may create both functional and infrastructure improvements.

Functional improvements include [DELPHI 2002]:

- ❖ Improved ride comfort and road handling – RBW or XBW computer control of integrated automotive vehicle dynamics allows DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems to work together;
- ❖ Enhanced stability control -- sensors and microcontrollers work together to detect and then correct increased yaw movements that could result in spin-outs or rollovers;
- ❖ Safety-enhancing systems – RBW or XBW advanced technology provides the communication link necessary to enable safety systems like lane keeping and collision avoidance.

Through modular design and the elimination of hardware, RBW or XBW offers several infrastructure improvements [DELPHI 2002]:

- ❖ Increased modularity – fully functional by-wire modules reduce automotive OEM assembly time and cost;
- ❖ Improved driver interface – the elimination of mechanical connections to the steering column gives automotive OEMs more flexibility in designing the driver interface with regard to location, type, feel, and performance;
- ❖ Enhanced passive safety – A RBW or an XBW cockpit may simplify and improve occupant restraint management;

- ❖ Added flexibility – vehicle designers may have more edibility in the placement of hardware under the hood and in the interior to support alternative power trains, enhance styling and improve interior functionality;
- ❖ Lead-time reduction – automotive OEMs may be able to use a laptop computer to perform soft tuning capabilities instead of manually adjusting mechanical components.

The following chapter has been partially extracted from LEEN AND HEERNAN [2002]. In the past few years, there has been a tendency in automotive vehicle construction to increase the safety of vehicles by introducing AI assistance systems, e.g. ABS, BA, ESP, and so on, which help the driver to cope with critical driving circumstances. Typical for these functions are the active mechatronic control of the driving dynamics by distributed assistant systems, which therefore necessitates a communications network.

The mechatronic components that control these functions are safety-critical. However, the assistance functions deliver only an add-on service in accordance to a failsafe strategy for the mechatronic components. If there is any doubt about the correct behaviour of the assistance system, it may be shutdown.

For *'by-wire'* mechatronic control systems without mechanical backup, a new dimension of safety requirements for automotive mechatronics is reached. After a fault, the system has to be fail-operational until a safe state (e.g. automotive vehicle standstill) is reached.

Figure 1.14 shows how dynamic driving-control systems have been steadily adopted since the 1920s [PETERSEN 2003].

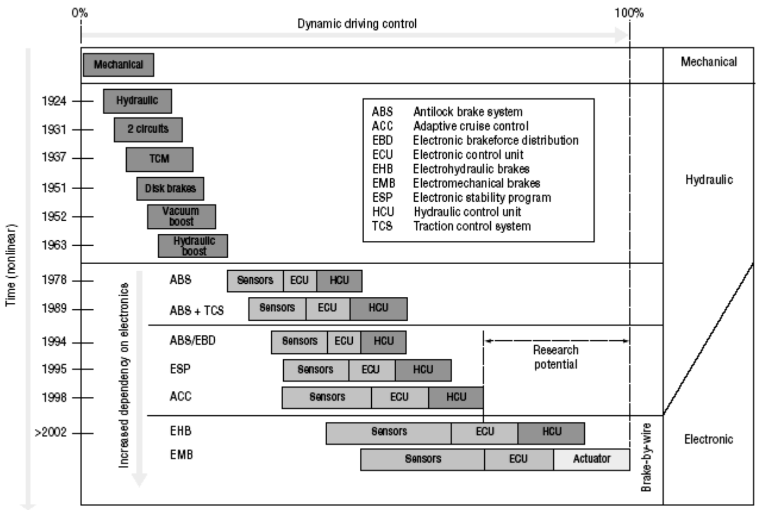

Fig. 1.14 Past and projected progress in dynamic driving control systems [LEEN AND HEFFERNAN 2002; PETERSEN 2003].

Increasing customer demands for improved ride comfort, road handling, and stability, have lead automotive vehicle manufacturers to concentrate enormous efforts on R&D of the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems.

In late years, the VSC system and the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems, such as DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, have been proposed.

In RBW or XBW integrated unibody or chassis motion mechatronic control hyper-systems without any mechanical backup, the fault, caused by the malfunction of sensors, actuators, and communication systems, endangers the safety of passengers.

To cope with the fault, it is necessary to develop the failsafe system in integrated unibody or chassis motion mechatronic control hypersystems. The hypersystems, which supply the information on the occurrence of fault or failure, are termed the **fault detection and isolation** (FDI) systems [PETERSEN 2003].

Future RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems may require both fault tolerance and a reliable power supply. These properties or systems, which so far have been developed as system-specific and are often separate from the application, must, in future, be integrated into a universally applicable development process in order to ensure seamless integration of the process. This is possible using a mathematical model-based software development process.

By adding simulation models of the in-vehicle E&IN and the hardware architecture (for example, redundancies), system behaviour may be evaluated as a whole, and its interactions with other systems analysed, even in the early phases of development. Several protocols are suitable for RBW or XBW applications.

Time-triggered protocol (TTP), for example, is a promising and available protocol geared toward improving driving safety. However, the FlexRay™ and **time-triggered controller area network** (TTCAN) protocols may start to compete with TTP when manufacturers look for more flexibility and lower costs [LEEN ET AL. 1999].

Figure 1.15 shows the past and potential future improvements from active and passive safety systems such as air bags and road-recognition sensors. Advanced mechatronic control systems and the RBW or XBW infrastructure may enable potential active safety improvements.

Summing up, RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems consist of DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems, and so on (Fig. 1.16) [SNU 2000].

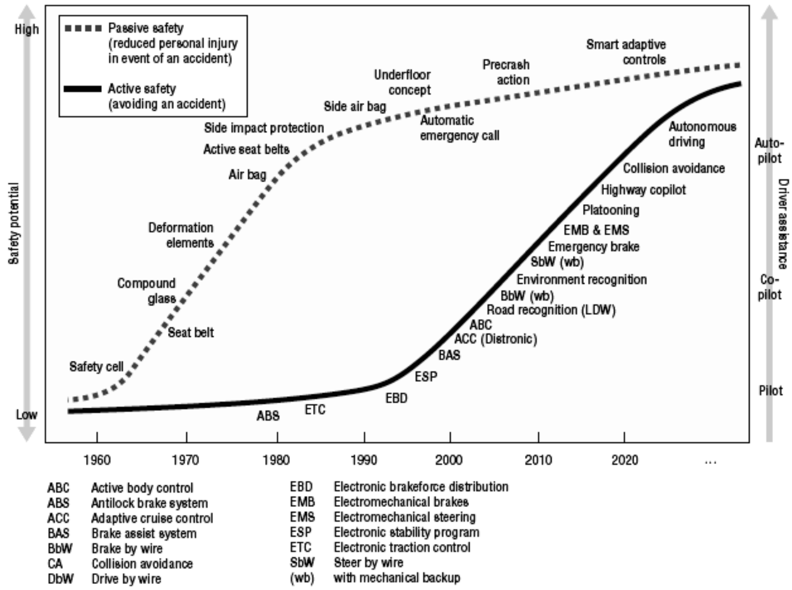

Fig. 1.15 Past and future active and passive safety systems: advanced mechatronic control systems and the RBW or XBW infrastructure may enable active safety improvements [LEEN ET AL. 1999].

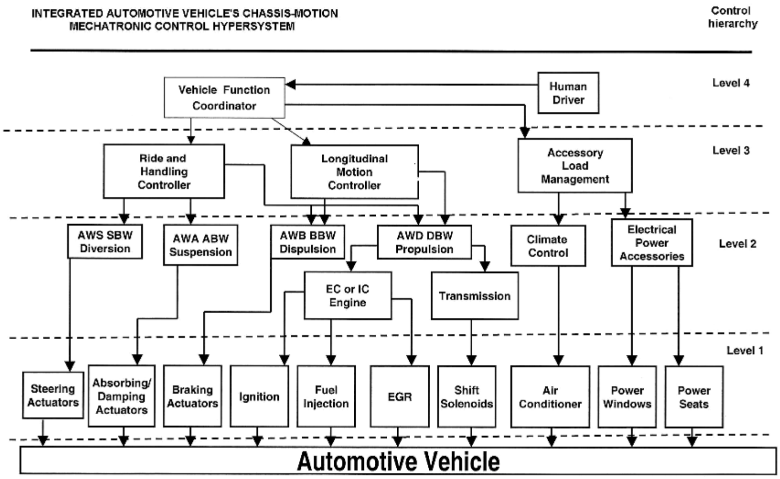

Fig. 1.16 Mechatronic control hierarchy of RBW or XBW [SNU 2000].

This R&D may consider a target RBW or XBW integrated unibody motion mechatronic control hypersystem (see Fig. 1.17) with mechatronic control systems, such as DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems, and so on [SNU 2000].

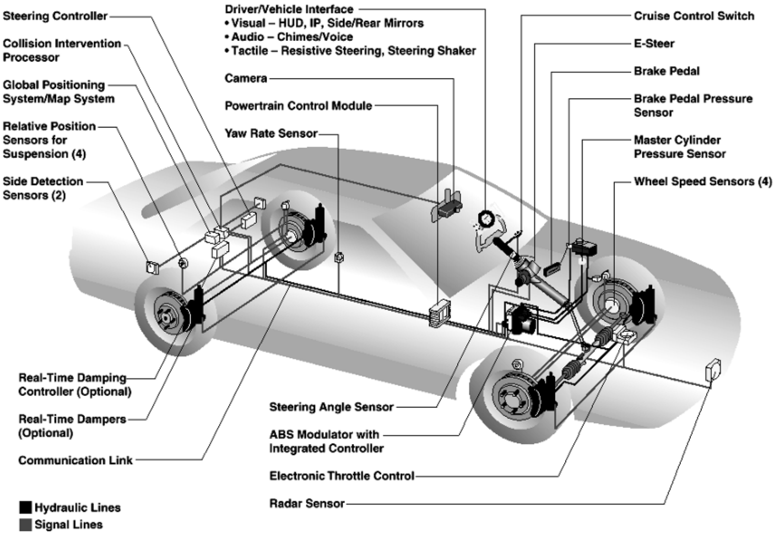

Fig. 1.17 Structural and functional diagram of RBW or XBW [SNU 2000].

If RBW or XBW integrated unibody or chassis mechatronic control hyper-systems are to deliver on the safety promise of reducing deaths and injuries in accidents, the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems in a vehicle must be able to communicate with one another. That means there must be a communication network that may enable RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems to work individually and together, smoothly, safely, and efficiently. RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems integrated in one network offer a functional advantage as well. To control the vehicle requires a combination of driving (DBW AWD propulsion) and braking (BBW AWB dispulsion), steering (SBW AWS conversion), as well as damping/absorbing (ABW AWA suspension), thus coordination is the key.

Having one network of microcontrollers for all the DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA mechatronic control systems, is clearly more efficient than having a separate network for each, because signal delay is reduced and system resources are shared. To handle the communication needs of the RBW or XBW network, the automotive industry seems to be converging on a **time-triggered architecture** (TTA).

Time-triggered architecture (TTA) simply means that actions are carried out at well-defined points in time. So all the nodes, in such a network have a common time reference based on their synchronised clocks. Messages are prioritised so that time is made available to higher-priority actions on the network, even if another message is being sent about another action or event. The two leading TTA candidates are TTP and FlexRay™. TTP has been around for some twenty years and is backed by Audi, Volkswagen, and TTTech Computertechnik AG, among others.

In 2003, a consortium formed by BMW, DaimlerChrysler, Motorola, and Philips Semiconductors announced its own TTA, dubbed FlexRay. A third protocol candidate, TTCAN, is considered a remote possibility as it was begun in 2004 [BRETZ 2002]. For instance, the next-generation automotive vehicle BMW *X5* is said to implement the first application of FlexRay in the automotive world, using the relatively new networking protocol for its mechatronically controlled shock absorbers (dampers). This may take place approximately two years before the manufacturer rolls out its first platform that uses FlexRay as the main automotive vehicle communications backbone [BRYANT 2005].

The CAN-C systems currently in place are limited to 500 kb/s, which many vehicle manufacturers are finding isn't fast enough. Even more problematic, CAN isn't deterministic; that is, it cannot be assured that a message may be successfully transmitted at a particular point in time. There are ways of asserting priority on the network, but this involves playing favourites -- not acceptable when it comes to deciding, e.g., whether the braking or steering is more important, and while those two were arguing, the automotive vehicle electrical valve system just crashed. FlexRay solves both problems by increasing the data rate and implements a low-cost means of establishing a network clock so that each module is given a discrete slice of time in which it may do its own thing. There is a decent introduction to it in this chapter for those looking to learn more. Expect to hear a lot more about it in the next few years.

In the meantime, those of OEMs heavily invested in CAN development tools may hopefully get their money's worth [BRYANT 2005]. Still, it cannot be ruled out because it builds of the protocol governing the networks that control such systems as power windows and door locks in vehicles today. At first glance, FlexRay and TTP seem almost identical. Both are time-triggered architectures but have different data rates and transmission media. FlexRay is designed for optical fibre for a 10-Mb/s data transmission rate; but it may also run on copper. TTP uses copper for only 2 Mb/s, though developers at the University of Vienna are exploring fibre.

FlexRay™ first appeared on copper, which is today's state-of-the-art in automotive vehicles. But fibre is likely to be the future state-of-the-art.

It offers speedy data transmission plus mass and electromagnetic compatibility advantages over copper; but bending fibre to run throughout an automotive vehicle is not yet practical. Interestingly enough, FlexRay was designed for both copper and fibre because BMW and DaimlerChrysler, the two automotive vehicle manufacturers in the consortium, are backing different options.

The thinking behind FlexRay that is based on a BMW protocol called *Byteflight* goes something like this: The wires must provide the same safety as a mechanical system. So what is safeguarded in a mechanical system? The oily-fluid or gas (air) that it provides the working force. The information the wires carry is the equivalent of the oily-fluid or gas (air), so it must be protected.

The protocol controls and organises the information. The information must arrive at a clearly deterministic point of time -- that is to say, at the correct time. To avoid an indeterministic point in time requires predictability [BRETZ 2002].

'Deterministic' simply means that data is sent at a predetermined time (time-triggered), in contrast to any time (event-triggered). In terms of FlexRay and TTP, the data messages to and from each node on the network are scheduled against the network's global clock.

Thus, clock synchronisation and periodic resynchronisation are required to keep all network nodes on the same schedule and in the same timeframe. TTP and FlexRay have built-in mechanisms for clock synchronization [BRETZ 2002].

The RBW or XBW protocol must also be fault-tolerant. An automotive vehicle operates in a rugged environment. Wires run from a very hot **external combustion engine** (EEC) or **internal combustion engine** (ICE) compartment to an icy-cold boot. And as the vehicle moves, things shift, including wires and connectors.

So both the bus system (that is, the wires) and the protocol must safeguard against wire breaks, corrosion at connectors, and shorts. It does so with redundant systems. The dark-horse protocol candidate is TTCAN.

Basic CAN (without the time trigger) is used in vehicles currently for control and communication at up to 1 Mb/s by way of serial data transmission. But it is an **event-triggered protocol** (ETP), meaning that it processes commands, as they occur, not by priority.

Because of its slow speed and inability to prioritise, vehicle manufacturers think CAN is not compatible for safety-critical applications like mechatronically controlled driving, braking, steering, or absorbing (damping).

Whether TTCAN developers are able to overcome these problems is unknown up to now. It's always difficult to expand a protocol to something it wasn't originally designed for [BRETZ 2001, 2002].

Summing up, the automotive industry is always concerned with safety-related issues. It is always trying to develop methods that keep increasing safety standards, for example, intelligent driver assistance.

However, such systems necessitate being computer-controlled to deliver maximum efficiency. With this comes the necessity to replace all of the mechanical or fluidical (hydraulical and/or pneumatical) backups with mechatronic components. This may only be done when it has been ascertained that the systems that are replacing the mechanical or fluidical backups are very safe. Such systems are known as RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems [MOST 2003].

A consortium comprising Daimler-Benz, Centro Ricerche Fiat, Ford Europe, Volvo, Robert Bosch GmbH, Mecel, Magneti Marelli, the University of Chalmers and Vienna Institute of Technology has carried out work in this field.

Examples of a RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem are DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems.

Figure 1.18 illustrates an exemplary application of a RBW XBW integrated unibody or chassis motion mechatronic control hypersystem [SHRINATH AND EMADI 2004].

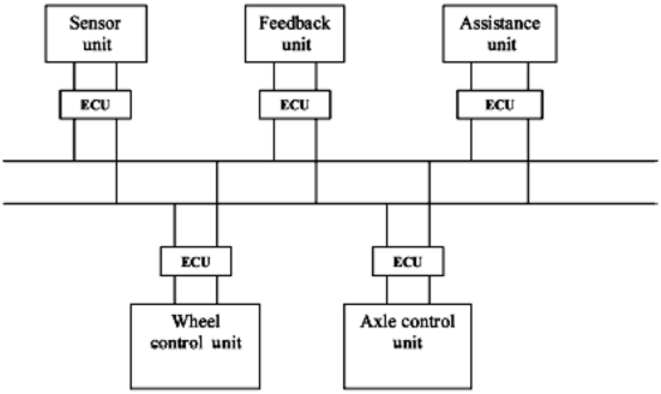

Fig. 1.18 An implementation of the RBW or XBW integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hypersystem for BBW AWB dispulsion and SBW AWS conversion mechatronic control systems [SHRINATH AND EMADI 2004].

An exemplary application of a RBW or XBW integrated unibody, space-chassis or body-over-chassis mechatronic control hypersystem is comprised of actuators and sensors connected to the ECUs. The sensors and actuators are used for taking measurements which are, in turn, fed to the ECUs for driver feedback. Based on the measurements taken, the driver may make suitable modifications, which are then relayed to the actuators for implementation. It must be ensured that the measurements taken are always accurate. If the readings taken by the sensors are not accurate or the response of the driver given to the actuator is not accurately interpreted, it could lead to very serious losses. Another problem with implementing this technology for mass manufacture is its economic feasibility. In addition, associated with this technology are problems such as reliability and maintainability [SHRINATH AND EMADI 2004].

The entire architecture of the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem is based on a time-triggered approach. Here, all the activities are carried out at a specific instant of time. Time is divided into slots of equal duration. A specific task is assigned for each time slot.
All the nodes are synchronised to one global sense of time. This is achieved by the transmission of a synchronisation pulse by a master node. This pulse is periodic in nature.

At specific instants of time, all the sensors capture their measurements which are, in turn, transmitted on the bus. These measurements are used to update certain variables. The new values overwrite the old ones. These new values are then used for control applications.

A main feature of the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem is what is known as composability. It means that whatever properties are exhibited by DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, the same properties are exhibited by when the various mechatronic control systems are integrated to offer some function or application.

Another important feature is the ability of the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem to handle errors that are generated when nodes *'talk'* during a slot that is not allotted to them. This node is known as a *'babbling idiot'*. This error may be avoided because, in a time-triggered system, it is known beforehand which node is supposed to transmit at which time interval. The bus access is controlled by a **time division multiple access** (TDMA) scheme broad-cast topology is used.

As mentioned before, information regarding which node may transmit at which interval is stored in the memory. This information is stored locally in every node. Every node is supposed to follow this timetable. The protocol used is the **time-triggered protocol/class-C** (TTP/C) [Shrinath and Emadi 2004].

The node architecture is based on what is known as a *'fail-silent'* mode of operation. This means that if a node is detected as having an error, it is asked to stop transmission. This is done so that the erroneous node does not interfere with the normal performance of the network. Sometimes, two nodes are used as a pair for fault tolerance. If one node has gone silent, then the other node may continue to perform the task in an error-free way. This technique has many distinct advantages. First of all, the necessity for complex circuitry to implement other **fault-tolerant** (FT) mechanisms is avoided. Second, combined with software fault detection, the fail-silent architecture would be able to cover the entire range of possible errors comprehensively. Third, this mechanism may be tested to test its full functionality. Each ECU, as mentioned before, is made up of some sensors and actuators, such as is presented in Figure 1.19, in the **system-on-chip** (SoC) [Balsi 2006].

It must be ascertained that in a node comprising two ECUs, there should not be any disparity in the decision finally taken. This may mean that each ECU exchanges sensor values with the other on the common bus, so that a common decision is reached. An alternative to using the common system is using a sensor bus. Also, if a digital sensor is used, each ECU may have the same values. If the two ECUs are located far away from each other, then the sensors are connected to the closest ECU. If on the other hand, they are situated close to each other, the sensors may be connected to the ECUs by means of a sensor bus, as mentioned above.

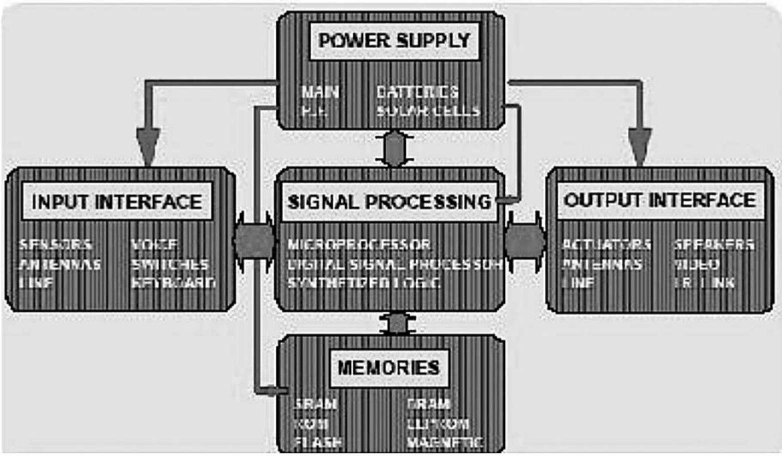

Fig. 1.19 Electronic control unit (ECU as the system-on-chip (SoC) [BALSI 2006].

Figure 1.18 demonstrates the concept of a RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem in an automotive vehicle. The software physical model consists of two layers: the system software layer and the application software layer. The system software layer is used to provide services to the application software layer. Services such as fault tolerance and detection are implemented in the system software level. The language used to write codes is the *ANSI* C subset with certain modifications, such as exclusion of exception handling. Efficient design, higher fault tolerance, ability to be tested and easy-to-synchronise are the main advantages. The RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem is being developed by the European Consortium to provide a standard that is accepted all over Europe for the development of intelligent driving aids for drivers [SHRINATH AND EMADI 2004].

The new bus controller TINA from NEC Electronics (Europe) ideally supports the development of TTP systems This standard protocol is especially suited for safety-critical automotive applications (like lane-change assistant, automatic emergency brake, traffic signs recognition, autonomous tracking) and emerging RBW or XBW applications like DBW, BBW, SBW and ABW. With TINA, NEC developed a bus controller based on TTTech's TTP-IP *'C2S'* which fulfils the high demands of developers on the controlling of **fault-tolerant** (FT) mechatronic systems in vehicles. TINA is the first TTP controller that totally undertakes the protocol functions by means of an integrated sequencer core and thereby relieves the host CPU. Data transmission to the host CPU is by means of a versatile bus interface (8, 16 or 32 bit). TINA may thus be used with a wide range of micro-controllers, e.g., many of NEC's 32 bit V850 family.

With RBW or XBW applications, the mechanical or fluidical (hydraulical and/or pneumatical) fallback system is dropped, which in previous steering and braking systems has simply been complemented by mechatronics. With that, the security and reliability requirements of the mechatronic control systems are extremely high [D&R 2003].

The mechatronic control system must secure that the transmission of signals (e.g. driving, braking, steering and absorbing/damping signals) occurs within a defined time slot. Therefore a fault-tolerant, deterministic bus system like TTP is required. *TINA* is an ASIC microcontroller that fulfils these requirements.

The asynchronous data rate is up to 5 Mb/s at 40 MHz. *TINA* is equipped with 2 channels, 4 kbytes RAM for **communication network interface** (CNI) for data storage and 8 kbytes RAM for scheduling information.

Single power supply is 3.3 V_{DC}, inter-frame gap is < 5 μs. *TINA* is suitable for operating temperatures from -40 to +85 ^{0}C and is supplied in a 100-pin QFP package. *NEC*'s TTP bus controller *TINA* facilitates large development flexibility for the designers of automotive vehicles as well as OEMs and suppliers for entirely novel innovative system concepts for future automotive vehicles.

At present, safety-critical applications and RBW or XBW integrated unibody or chassis motion mechatronic control functions are being developed which are based on *TINA* [D&R 2003].

As an example, a horse senses the rider's intentions and, while judging the surrounding conditions, avoids obstacles in order to ensure its own safety as well as the rider's. Similarly, in the case of an adaptive driver-assistance system, responding to the sudden appearance of another automotive vehicle, pedestrians, or animals, a group of sensors (such as the vision sensors) recognises the surrounding circumstances; a controller evaluates the driver's intention at the same time as it determines the appropriate evasive action; steering control avoids spinning or skidding, while suspension control adjusts the downward force on the tyres; and independent control of the left and right brakes assists the evasive action and controls the vehicle's velocity. The result of these actions is that crash avoidance is safely completed.

In regards to the establishment of future adaptive driver-assistance systems, as well as electronising the operation of the actuators, improving the reliability of the sensors and controllers is a key issue. It is thus thought that the trend toward making best use of the integrated technologies developed by Hitachi Ltd. will continue. An example of such a vital technology -- which may realize functions analogous to man and horse as one -- is the RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control hypersystem being developed by Hitachi [YOSHIDA ET AL. 2004].

In addition, a **human-machine interface** (HMI) advanced technology that enables the automotive vehicle and driver to cooperate in a natural way (so intervention of the adaptive driver-assistance system does not cause any sense of discomfort to the driver) and that this may cooperate with the infrastructure is thought to be an important part of the evolution process toward autonomous driving.

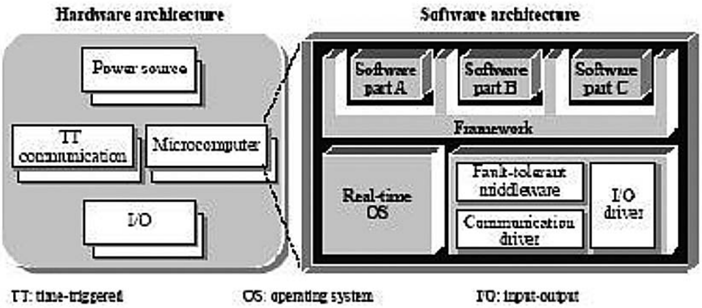

Fig. 1.20 Example configuration of high-reliability controller [YOSHIDA ET AL. 2004].

An example configuration of a high-reliability controller is shown in Figure 1.20 [YOSHIDA ET AL. 2004]. Duplicating the hardware ensures that the controller can continue to operate as a whole unit even if one part of it is damaged.

The software architecture is configured in such a way that application software resources are utilized as software components and the reliability of communication and I/O is ensured in the middleware layer. Previously accumulated software resources can be used, as a result of this layered configuration, and the reliability of the whole software configuration may be easily ensured [YOSHIDA ET AL. 2004].

Structural and Functional Integration for RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control Hypersystems -- As a consequence of relationships that developed previously and for reasons associated with acquisition strategies, RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems incline to be dealt with principally as stand-alone systems by the R&D centres of vehicle manufacturers and OEMs [SEMMLER ET AL 2006].

This may direct to a state in which, for example, a vehicle with DBW AWD propulsion (active powertrain) and BBW AWB dispulsion (active braking), SBW AWS conversion (active steering), as well as ABW AWA suspension (active suspension) mechatronic control systems is equipped with as many as four independent driving state estimators, reference behaviour calculators and driving-state controllers.

In addition, several sensors are normally set up to measure the same variable -- lateral acceleration for example. This kind of architecture may be referred to as the *'coexistence functional approach'* is shown in Figure 1.21 [SEMMLER ET AL. 2006].

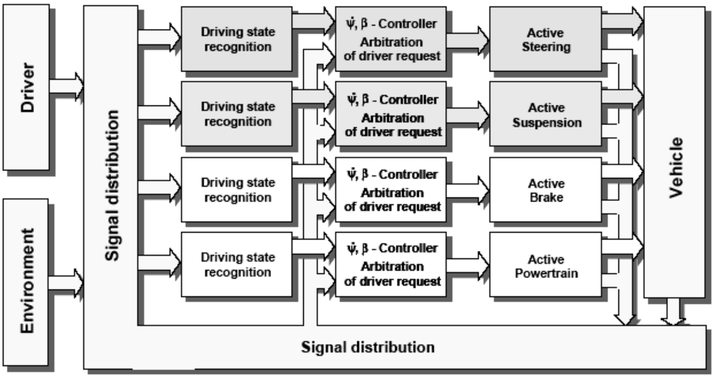

Fig. 1.21 Methods for function distribution: coexistence functional approach [SEMMLER ET AL. 2006].

In consideration of the overlaps in the subjects of the action of the numerous actuators, they must be directed in a coordinated method to prevent counterproductive effects with a detrimental impact on dynamic stability. As this is not always possible with the coexistence functional approach, the overall result gained may be less than ideal.

Another decisive drawback of this approach is the exponential increase in the R&D effort required as a function of the number of stand-alone systems involved. This tendency is incompatible with demands for even shorter R&D times and the constrained availability of archetypes [SEMMLER ET AL 2006].

In response, for instance, Continental Teves has developed methods for function distribution: *'integrated functional approach'* shown in Figure 1.22 [SEMMLER ET AL. 2006].

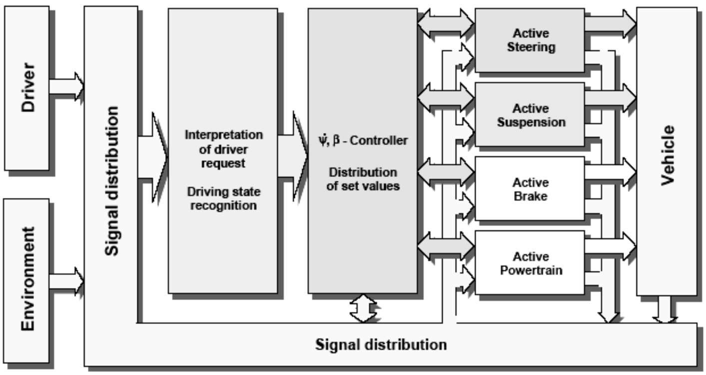

Fig. 1.22 Methods for function distribution: integrated functional approach [SEMMLER ET AL. 2006].

In this architecture, each of the chassis mechatronic control systems has one basic function, such as a variable ratio function in the case of the SBW AWS conversion mechatronic control system.

In contrast to the coexistence functional approach, there is only one driving-state estimator, one reference behaviour calculator and one driving-state controller. Conditional on the necessary and actual behaviour of the vehicle, the SBW AWS conversion mechatronic control system computes the corrective yaw torque necessary to continue the course set by the driver. The actuators that may ensure the best overall optimisation of active safety, ride quality and driving pleasure always allowing for the adjustment and dynamics reserves of the actuators concerned by applying this torque. For instance, steering interventions are given priority over brake interventions.

Mechatronic interfaces may be used between the DBW AWD propulsion (active power-train) and BBW AWB dispulsion (active brake), SBW AWS conversion (active steering) as well as ABW AWA suspension (active suspension) mechatronic control systems, and interaction between those mechatronic control systems may be optimised to create an optimum overall effect [SEMMLER ET AL. 2006].

Upcoming Technologies for RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control Hypersystems [NOLTE ET AL. 2004]

- Time-Triggered CAN (TT-CAN):
  - Time-triggered session layer on top of CAN;
  - Same limitations as CAN.
- Time-Triggered Protocol (TTP):
  - Pure TDMA;
  - 25 Mb/s;
  - Fault tolerant mechanisms:
    - Membership service;
    - Bus guardians;
    - Clock synchronisation (distributed).
- FlexRay™:
  - Mixed TDMA/FTDMA;
  - 10Mb/s;
  - Fault tolerant;
  - Flexible.

1.4 Harnessing Energy and Information Networks

1.4.1 Foreword

In recent years, OEMs have added a steady stream of convenience, safety, telematics, and entertainment features to their vehicles [YAZAKI 2006].

At the same time, macrocommutator- and microprocessor-based on integrated macro- and microelectronics-based systems approach technologies are replacing many conventional fluidical and mechanical systems.

In this environment, the demand for supporting power and data distribution has multiplied dramatically. The conventional wire harness continues to provide the foundation for the in-vehicle energy and information distribution [high-power **application specific integrated matrixers** (ASIM) that drive **electro-mechanical** (E-M) motors, locks, etc., low-power **application specific integrated circuits** (ASIC) that carry data such as speed, temperature, and so on].

By adopting a more advanced in-vehicle **energy-and-information network** (E&IN), OEMs may provide the enhanced driving experience customers want while addressing pressing issues of space, mass, and cost. E&INs are an evolution in automotive mechatronic technology that spans nearly 80 years.

New strategies and technologies share the stage with proven approaches to energy and information distribution.

Advances in energy and information distribution have not eclipsed previous technologies but have refined them, adding important options to the engineer's tool chest.

Cost may be a major factor in determining how advanced technologies are implemented. System designers must be able to draw on the best of existing and new approaches to achieve the desired results within given cost parameters.

The challenge may be to add greater functionality and more vehicle features, while minimising or eliminating corresponding increases in the physical infrastructure. In many ways, this is as much an art as it is a science.

An automotive in-vehicle E&IN (Fig. 1.23) incorporates the ASIM macroelectronics, ASIC microelectronics, physical media, and supporting technologies that deliver energy and/or information (data) used to activate and control various automotive vehicle functions [FUHRMAN 2002].

In application, this takes the form of a local system of interconnected devices and supporting components such as controllers and gateways.

Several hyponetworks may be integrated to form the vehicle's power and data infrastructure.

This integration is the job of gateways that allow data sharing while preventing unwanted interference between different networks; and bridges, which provide data filtering between similar networks.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_4,

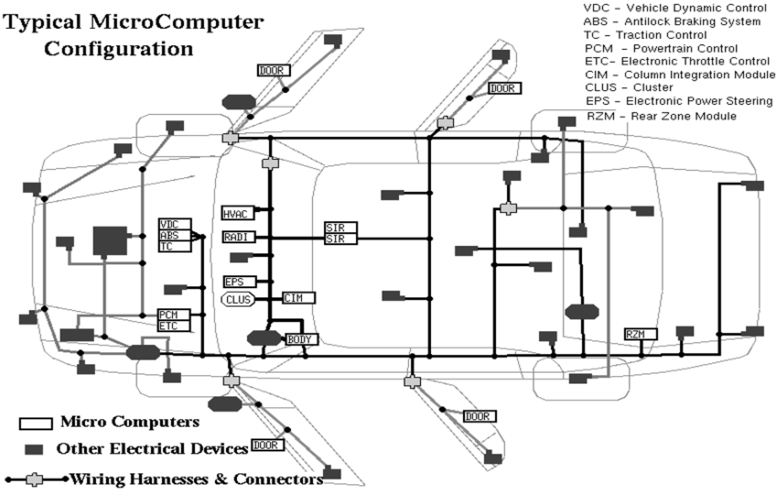

Fig. 1.23 Typical in-vehicle energy-and-information network (E&IN) microcomputer configuration [FUHRMAN 2002].

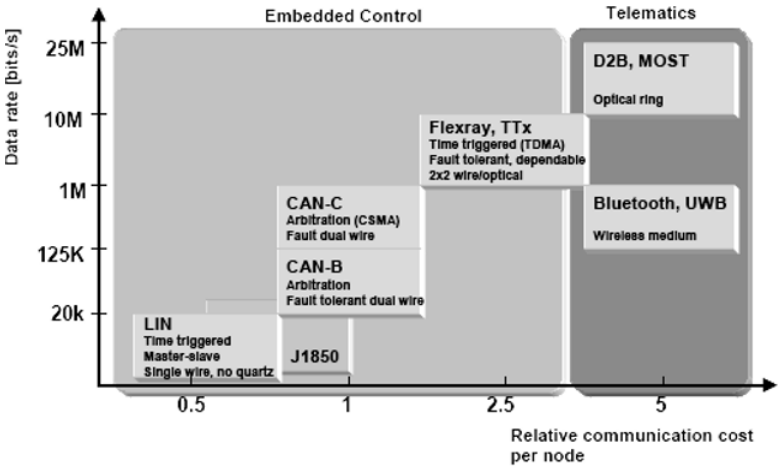

Fig. 1.24 The automotive busses: LIN, J 1850, CAN-B, CAN-C and FlexRay™ [SONG 2005; YAZAKI 2006].

Different E&IN architectures are employed to connect the different devices and hyponetworks in an automotive vehicle. It is even possible to have two architectures in the same automotive vehicle (ring architecture could be used for a hyposystem the node on a bus network).

Automotive E&IN solutions must satisfy a number of requirements [YAZAKI 2006]:

- ❖ Reliability – the network must be able to perform error-free under adverse conditions for the life of the vehicle;
- ❖ Flexibility -- content variation across models and compatibility with after-market devices requires network scalability and upgradeability;
- ❖ EMC -- unwanted electromagnetic fields may disrupt the network and nearby devices;
- ❖ Connector optimisation -- number of connectors, connector size and functional integration are critical variables in network design;
- ❖ Cost -- performance and other benefits must be carefully balanced against cost and competitive impact;
- ❖ Fault tolerance -- susceptibility to faults and the necessity for system redundancy are major issues;
- ❖ Modularity -- standardised modules mean shorter design cycles and lower costs.

1.4.2 SAE In-Vehicle Energy-and-Information Network Classes

In-vehicle E&INs may be differentiated by data-handling speed. This, in turn, governs the types of devices served and data-communication protocols applied. In general, as network data speed rises, technical sophistication and costs increase accordingly (see Fig. 1.25) [KIRMANN 2005; SONG 2005; YAZAKI 2006].

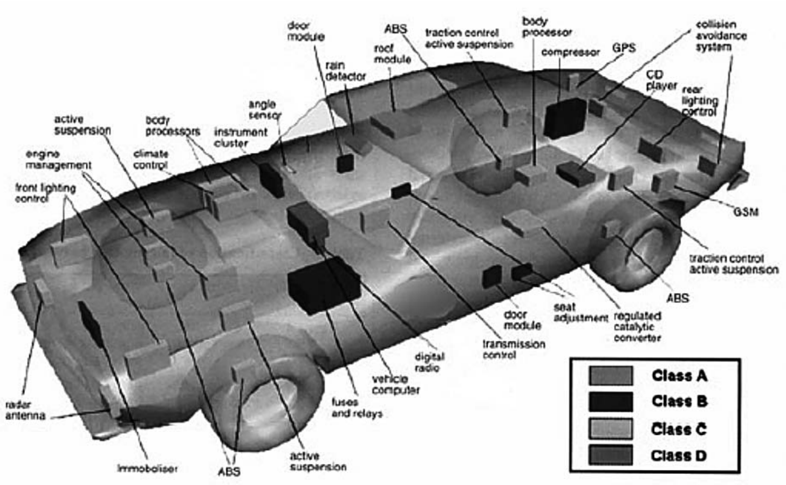

Fig. 1.25 Applications of in-vehicle energy and information network (E&IN) [SONG 2005].

This is one reason why devices with relatively modest data needs are often networked separately, as is shown in Figure 1.25 [SONG 2005].

Class A networks, for example, include devices that operate through simple on/off control of power loads. These copper-based networks generally run at speeds below 10 kb/s and include devices such as seat controls, power mirrors and trunk releases.

Class A data protocols include a **local interconnect network** (LIN) and **time triggered protocol/class-A** (TTP/A). Class B networks are designed to allow sharing of basic information between various vehicle devices, thereby eliminating redundant sensors. Operating at 10 -- 125 kb/s, these networks commonly include instrumentation, emissions systems, speed-control systems, and other devices dependent on routine operating data.

Protocols applied to Class B networks include J1850 and ISO 9141-2. Class C networks operate at speeds from 125 kb/s to 1 Mb/s to support large data requirements and/or real-time control. Typical applications include vehicle dynamics and powertrain control.

Protocols in Class C include the **controller area network** (CAN) and J1039. Class D networks operate at speeds above 1 Mb/s and are used for safety-critical systems, such as RBW or XBW, and high-bandwidth multi-media applications. Class D protocols include FlexRay™ and **media-oriented systems transport** (MOST) in either copper or optical media [YAZAKI 2006].

The four-layer **network infrastructure** (NI) physical model recognises natural network sub-divisions based on broad functionality, data transmission speed, and corresponding data protocols. A given layer may be made up of two or more hyponetworks.

The energy layer includes power generation, storage and distribution elements (typically a generator, storage battery, and under-bonnet power distribution centre). The safety and mobility layer incorporates airbags, engine control modules, HVAC system, steering, transmission and RBW or XBW. These systems are supported by SAE Class C and Class D networks, which provide real-time control, with operating speeds from 125 kb/s to 1 Mb/s and greater.

The vehicle-body layer provides control of lighting, HVAC, door and seat functions, and also includes velocity (speed) control, instrumentation, and emissions systems. These functions are supported by low-speed SAE Class A networks operating at less than 10 kb/s, and SAE Class B networks running at 10 -- 25 kb/s.

The infotainment layer includes advanced audio and video devices, wireless phone, voice-activated systems, instrumentation sensing, and other systems requiring SAE Class D data transfer speeds (>1 Mb/s).

The infotainment layer incorporates an optical fibre network scenario based on the MOST data protocol. The four-layer NI physical model is conceptual, and not intended to suggest physical reality. Rather, its purpose is to help illuminate the challenges, relationships, and opportunities inherent in an integrated power and data infrastructure. Application of these concepts plays a central role in the development of advanced E&INs [YAZAKI 2006].

1.4.3 Scalable Modular Architecture

During much of the last century, growing automotive vehicle electrical requirements led to a steady increase in specialised power, diagnostic, control, and fault-prevention components. Successful efforts to integrate many of these functions into centralised modules has delivered both cost and performance benefits.

However, the advantages of centralisation must now be balanced against dramatic expansion of the physical distribution infrastructure to support added energy consumption and data processing [YAZAKI 2006].

The challenge is to deliver the benefits of integrated functionality with a new infrastructure model, one capable of delivering greater capacity and increased efficiency with a compact, cost-optimised physical package. For example, consistent with the four-layer conceptual physical model, Yazaki's **scalable modular architecture** (SMA) is an instrumental step in this direction. This architectural methodology places multi-functional nodes strategically throughout the automotive vehicle. Each node is fed power from the under-bonnet node and interconnected by means of a data bus. Power and control of devices are localised in physical zones while leveraging network communications and distributed processing. Each node integrates communications, junction block, gateway, power switching, fault detection, fault handling, and body control functionality. This system of nodes provides intelligent, software-driven control, with diagnostics that provide the optimal solution for the automotive vehicle.

In the Yazaki SMA solution, the primary power distribution and under-bonnet body controls are housed in an integrated power module. The under-bonnet node uses bus bar and printed circuit board technologies and is microcontroller- based. The interior nodes are completely solid-state, based on a common digital core board design that is deployed in all nodes. Smart connectors are also used when appropriate for mechatronic-based hyposystems such as seats and doors [YAZAKI 2006].

Mechatronics are embedded in these connectors to provide highly localised control of E-M motors, E-M actuators, and sensors. Smart connectors are interconnected by means of a LIN bus network and are slaves to an interior node master. Interior nodes also provide necessary LIN/CAN gateway functions.

The SMA methodology may easily be extended beyond 14 V_{DC} based systems to 42 V_{DC} and **hybrid-electric vehicle** (HEV) applications. This may be accomplished by adding additional functions such as **pulse-width modulation** (PWM), voltage conversion, battery **state of health/state of charge** (SoH/SoC) monitoring and control, jumpstart provisions, and arc detection/prevention to the basic building blocks or *'form factors'* [YAZAKI 2006].

All SMA nodes are scalable, allowing a single platform design to serve automotive vehicles with differing content profiles. Common hardware form factors may be populated/ unpopulated and reconfigured through customised software algorithms. Features may be added or deleted with minimal impact to the nodes. The result: dramatically reduced development cycles and realisation of economies of scale. Other benefits include reduction of wiring, simplified assembly, and intelligent power delivery.

1.4.4 Optical Fibre Technology

In certain vehicle network applications, **optical fibre** (OF) may offer significant advantages over copper. By using pulsed light instead of electrical current, OF has the ability to transmit large amounts of data at very high speeds. In addition, OF advanced technology permits multiple inputs and multiple outputs to share data simultaneously as members of a common ring network. OF can, therefore, meet specific data-handling requirements more efficiently than copper, while saving on both weight and space [YAZAKI 2006].

OF may also operate successfully in crowded electronic environments, with virtually no degradation of data transmission. Further, it meets strict **electromagnetic compatibility** (EMC) requirements: unlike copper, OF is not susceptible to electrical interference generated by the operation of nearby electronics. At speeds above 1Mb/s, it is an efficient and cost-effective medium for use in-vehicle E&INs.

Its unique operating characteristics and relatively simple architecture make it a strong choice for high-bandwidth applications such as multimedia, telematics and *Internet* access.

Equivalent copper-based networks typically require many more connections and a physical layer with considerably greater mass. For all its strengths, the current OF used in vehicles today has its limitations. Fibre applications are restricted by thermal environment and network configuration. Thermal ratings and optical attenuation of the fibre constrains network architecture design and routing flexibility. These issues can be addressed with **polymer clad silica** (PCS) fibre. PCS is an advanced material that has minimal optical attenuation and may withstand more demanding environmental conditions. PCS has two more features that make it more attractive than current OF: a higher bandwidth, which allows for faster transmission of data (up to 1Gb/s), and greater physical flexibility, which provides optimal packaging solutions for E&IN designers [YAZAKI 2006]. Well-designed OF networks may be discrete, but they are not isolated. Like other in-vehicle networks, they must be designed as part of the total vehicle infrastructure and optimised with respect to the power networks they parallel. This requires full integration of physical-layer components, software and network architecture – a process best undertaken in the earliest stages of automotive vehicle development.

1.4.5 Wireless Technologies

Today's E&INs must allow for connecting to the external world like never before. To reach the full potential of telematics, for example, call centres must be able to access information directly from the automotive vehicle's data bus. This requires precise application of suitable wireless technologies [NÜSSER AND PELZ 2000].

Similar technical requirements apply to in-vehicle e-mail and *Internet* browsing. Data-interface electronics, based on **wireless application protocol** (WAP), allow these and other web-based functions to be successfully integrated into the vehicle's data-management system [YAZAKI 2006]. Hands-free and portable systems also depend on wireless technologies.

E&INs for automotive vehicles, employing voice-activated cell-phones for data sharing with E&INs and laptops, use *'Bluetooth'* wireless technology interface (Fig. 1.26) to achieve efficient connectivity [KELLERER ET AL 2001; KIRMANN 2005; SONG 2005].

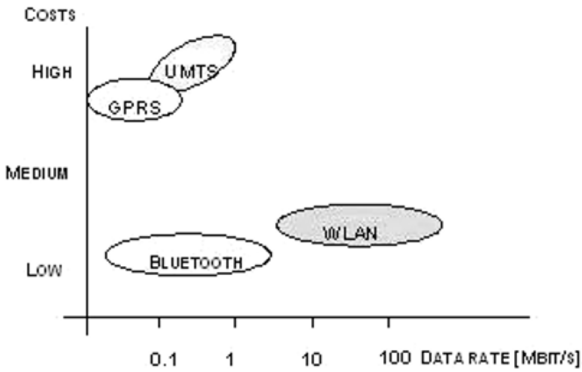

Fig. 1.26 Wireless technologies [KIRMANN 2005 (Aktuelle Technik, 4/05)].

An in-vehicle *Bluetooth* connection would eliminate the necessity in for a cradle to connect a telematics portable device to the automotive vehicle. **Cambridge silicon radio** (CSR) launched a *Bluetooth*-enabled hands-free vehicle kit termed *AutoSira*.

The design is based on CSR's *Bluetooth* silicon, called *BlueCore* that includes all the software, data, and schematics that designers require [HAARSTEN 2000; FREDRIKSSON 2001; WUNDERLICH ET AL. 2000A, 2000B].

1.4.6 Conclusion

Advanced E&INs enable, and are driven by, rapid expansion of vehicle features and functionality. This accelerating development is uniting vehicle control, information and entertainment through on-board computers and specialized application software.

New and more sophisticated E&IN architectures are moving control closer to the devices they serve, using technology such as integrated power/control modules and connectors with embedded microprocessors.

E&INs are poised to bring a new world of multimedia and telematics to drivers and their passengers, while supporting next-generation advances in safety, operating convenience, and vehicle diagnostics. The end deliverable is more in-vehicle capability, better communication in the power and data network and reduced development time, with corresponding reductions in size, mass, and cost [YAZAKI 2006].

1.5 Local Interconnect Networking

Local interconnect network (LIN) is a communication protocol that has been established for automotive vehicles [KOPETZ ET AL. 2003]. This protocol is based on the SCI (UART) data format with single master/multiple slave architecture. A consortium formed in 1998, comprising AUDI, BMW, DaimlerChrysler, Volvo, Volkswagen, VCT, and Motorola worked on establishing a specification for this protocol. The development of LIN was based on the necessity for a communication protocol that was very cost effective and not only addressed the issue of the specification for communication, but also other issues like signal transmission, programming, and interconnection of nodes. It basically takes an all-round approach for the development and consolidation of an automotive protocol.

The basic advantage that LIN enjoys is that it is very economical compared to protocol such as CAN (Fig. 1.27). However, this advantage is negated by its inherent limitations, such as low bandwidth and performance, and the single master topology of the network [SHRINATH AND EMADI 2004; MOTOROLA 2007].

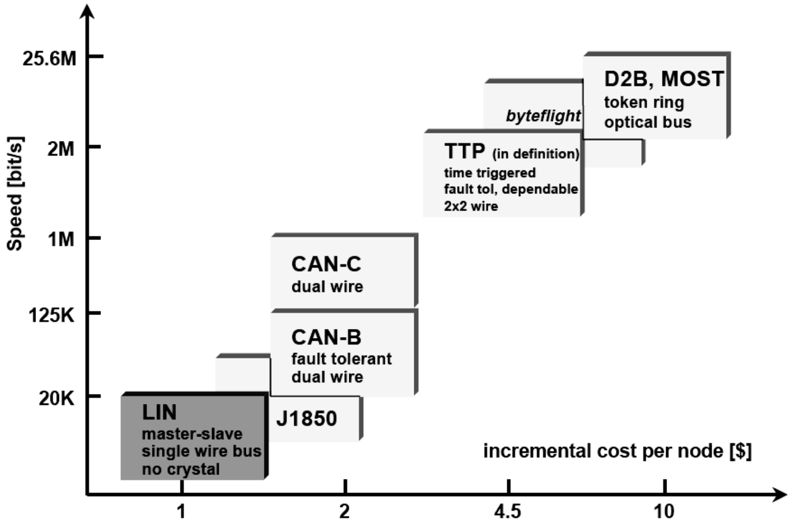

Fig. 1.27 MUX Standards (Costs and Data Rates) [MOTOROLA 2007].

There are quite a few criteria that have to be taken into consideration when a network is designed. Factors such as bandwidth, security, latency, **electromagnetic interference** (EMI), fault tolerance, and cost should be balanced in order to design a network to suit requirements. There are basically two different approaches that could be taken to design a network.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
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One approach is to divide the sensors and actuators in a zonal manner, connected to a central ECU. Various main ECUs are connected to each other by CAN links. This extensive use of CAN is to enable the usage of high-bandwidth for signal exchanges. The other approach is to totally abolish the zonal concept. Here, all the actuators and sensors are connected to the central ECU by means of LIN links. This has the advantage of being scalable. No major changes have to be done to the network in order to accommodate additional nodes. As mentioned before, LIN is based on the SCI (UART) byte word interface. The network has a single master/multiple slave topology [SPECKS AND RÁJNAK 2000].

All the slaves have the job of transmitting and receiving. The master node, apart from the task of transmitting and reception, has the additional task of maintaining the synchronisation in the network. This is done by means of a message header that consists of the synchronisation break, synchronisation byte, and a message identifier. The message identifier is used by the nodes to identify the messages meant for them. Each identifier is unique to the node. This way the node knows the messages meant for it. It has to be remembered that the message identifier indicates the content of the message and not the destination. Once the node has reached the message meant for it, it then sends back a response that contains data with the size ranging from 2, 4 or 8 bytes of data with one checksum byte. One message frame consists of the header and the response parts [SHRINATH AND EMADI 2004].

Each message frame is made up of a byte field that has 10 bits. These 10 bits include a dominant *'start'* bit, 8 bits of data and recessive *'stop'* bit. The message frame consists of the header sent by the master node and the response sent by the slave node. The header sent by the master node consists of a synchronisation break, synchronisation field, and the identifier field. Each message frame is built on the *8N1*-coding scheme. The synchronisation break must be a minimum 13 bits in length to ensure proper synchronisation. The synchronisation field is a string of bits with an equivalent hexadecimal value of 0×55. With this type of synchronisation pattern, it is possible for nodes not equipped with quartz stabilisers to resynchronise themselves. There are basically two levels of synchronisation that are defined for the LIN: unsynchronised, in which the slave clock time differs from the master clock time by less than $\pm$ 15 % and synchronised, in which the slave clock time differs from the master clock time by less than $\pm$ 2% [SHRINATH AND EMADI 2004]. There are four identifiers reserved for special purposes. Out of the four identifiers, two are used for uploading and downloading purposes. The only way they differ from the normal data frame is that in these frames, instead of data, there are user-defined command messages. The other two special identifiers are used for ensuring upward compatibility with the future versions of the LIN protocol. These identifiers are termed *'extended identifiers'*. There is three types of communication mode there are supported: master to slave or multiple slaves, slave to master, and slave-to-slave: the slaves may talk each other without routing the transmission through the master. This is illustrated in Figure 1.28 [SHRINATH AND EMADI 2004]. A typical LIN has a single master with as many as 2 -- 10 nodes contained in the network. Typical data speeds range from 2.4 to 19.6 kb/s. The voltage level that may be supported by the buses is around 13.5 V_{DC}.

Each data frame contains 2 -- 8 bytes of data with a six-bit identifier. Single-wire transmission, low cost of implementation, and no resonators are the advantages. Low bandwidth and a single-bus access scheme are the main disadvantages.

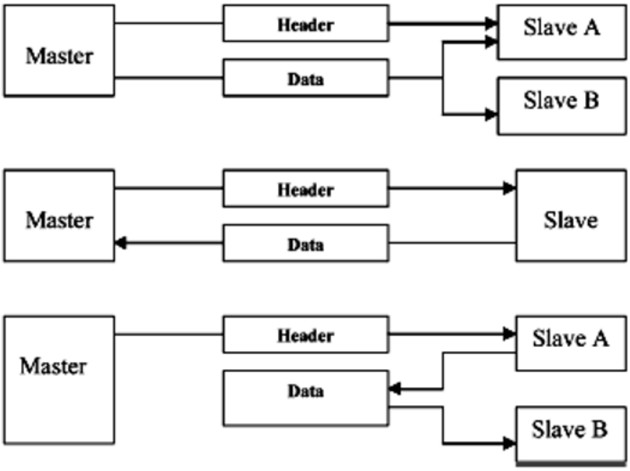

Fig. 1.28 **Data** communication in LIN [SHRINATH AND EMADI 2004].

LIN is usually used for door and roof control, as well as for the steering HW and column (Fig. 1.29) [MOTOROLA 2007].

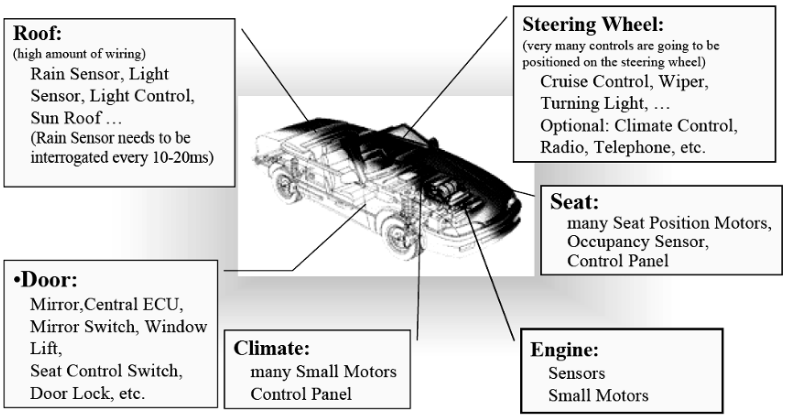

Fig. 1.29 Classic LIN applications [MOTOROLA 2007].

Other implementations include smart wiper E-M motor, sensors and switch panels, seat control, and heating [SHRINATH AND EMADI 2004; MOTOROLA 2007].

1.6 SAE J1850 Protocol

The SAE J1850 protocol has been defined by SAE to a class-B protocol whose definition is given as *'A system whereby data, e.g., parametric data, is transferred between nodes to eliminate redundant sensors and other system elements. The nodes in this form of a multiplex system typically already existed as a stand-alone module in a conventionally wired automotive vehicle'* [WIEGAND 1998].

Class-B networks are essentially used for communicating between modules supporting a data transfer rate of around 100 kb/s. Though this data rate is insufficient for real-time safety critical processes, class-B networks are ideal for non-real-time mechatronic control processes and communication.

The SAE J1850 protocol is based on a bus-level topology wherein the bus is a masterless **peer-to-peer** (P2P) protocol. Just like the CAN, messages are broadcast in the sense that whatever messages have to be sent are sent in the form of frames to all the nodes, irrespective of the desired destination. This protocol supports two modes. One is a 41.6 kb/s pulse-width modulated mode supporting a dual wire and the other is a 10.4 kb/s variable pulse-width mode supporting a single-wire configuration. Data may be sent on the bus by way of either time division multiplexing or frequency division multiplexing. In time division multiplexing, messages are sent on the same bus at different instances of time whereas in frequency divisions, multiplexing two or more messages are sent at the same time [SHRINATH AND EMADI 2004].

Changing the amount of time each transition lasts on the bus transmits data on the bus. For example, according to VPW J1850 protocol definition, a *'1'* bit is a bus driven at a high potential (active) state for 64 μs or low potential (passive) state for 128 μs. Alternatively, a *'0'* bit is defined as a bus in high potential (active) state for 128 μs or low potential (passive) state for 64 μs. A high potential is usually any voltage from 4.25 V_{DC} to 20 V_{DC}. A low potential is any voltage from ground voltage to 3.5 V_{DC} [SHRINATH AND EMADI 2004]].

Using electrical valves (*e.g.,* transistors) may achieve the transition between the voltage levels. Even when the bus is in idle state, it is at low or ground potential. When a node wants to transmit, it uses the electrical valve (e.g., transistor) to push the bus to a *'high'* state, thereby overriding any node wanting to pull the bus to a *'low'* state. Here, those nodes wish to transmit in the first sense, the bus for a fixed amount of time. If they sense the bus to be idle, they start transmitting. If they sense the bus is busy, they wait for a certain amount of time before trying to start transmission once again.

Let us assume that a node transmits a passive symbol. If there is no challenge, it goes ahead and transmits the message. It has to be noted here that even during transmission each bit is checked to make sure that there is no other node with higher priority waiting to transmit. This is termed bit-by-bit arbitration. This process is carried out until only one bit is left. However, before transmission, if there is a node transmitting an active symbol, the node with the passive symbol looses control of the bus and starts functioning as a receiver.

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The node with passive symbol is then said to have *'lost arbitration'*. Thus, one may see why the arbitration scheme used is termed **carrier sense multiple access/collision resolution** (CSMA/CR). It is termed multiple accesses because it is possible for multiple nodes to gain equal access to the bus. Bits at the beginning of the messages indicate the priority of the messages. A CRC is implemented in the protocol for error correction [OLIVER 2003].

Once the transmitting node has finished transmitting, the nodes that had lost arbitration again try to gain access the bus and the whole arbitration procedure is repeated again. Invariably, it is seen that nodes that have more active symbols in the starting of the message compared to others, gain access to the bus earlier than the other messages. However, it must be stressed that, due to the nature of the bus access, it is impossible to specify instants of time at which certain nodes may transmit or receive, unlike the TTCAN presented before [SHRINATH AND EMADI 2004].

The entire SAE J1850 protocol is implemented on a silicon single chip, for instance, the data link controller developed by Delco Electronics for General Motors [LUPINI ET AL. 1991]. This single chip has an 11-byte transmit **first-in-first-out** (FIFO) buffer and a 20-byte receive FIFO buffer as well as an 8-bit parallel data interface. It also has a transceiver built in. This transceiver provides a 7 V_{DC} waveform for transmission on the bus. Wave shaping is done to reduce RFI emissions. The logic section that includes host interface, error detection, and correction codes, and all kinds of logic performs functions, such as filtering, timing, and symbol definitions.

A functional and structural block diagram of the DLC single chip is shown in Figure 1.30 [SHRINATH AND EMADI 2004].

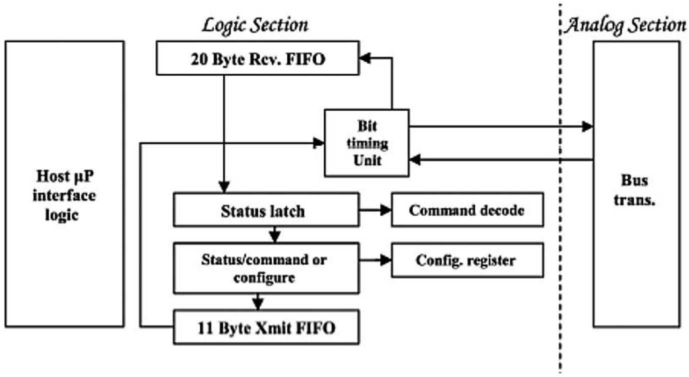

Fig. 1.30 DLC single chip's functional and structural block diagram [SHRINATH AND EMADI 2004].

The advantage of the SAE J1850 is that it is an open architecture. There are no stringent restrictions in its implementation and development and, hence, it gives automotive designers sufficient leeway in developing applications. It is mainly used for diagnostic and data-logging functions.

1.7 IEEE 1394 Protocol

The IEEE 1394 is an up and coming bus standard that may provide a high rate of data communication between electronic devices. The bandwidth offered by an IEEE 1394 serial bus is usually from 2^i to 98.304 MB/s, with i taking on the values of $i = 0, 1, 2, 3, 4, 5$ [RABEL ET AL. 2001]. It has a 64-bit addressing system, out of which the *16* most significant bits make up the node ID [BALTAZAR AND CHAPPELLE 2001]. Out of these 16 bits, 10 bits are used for bus Ids that give rise to $2^{10} - 1 = 1023$ buses and the remaining six bits giving rise to $2^6 - 1 = 63$ nodes. A typical application for this protocol is for in-vehicle infotainment purposes. The protocol stack implemented in the IEEE 1394 is shown in Figure 1.31 [SHRINATH AND EMADI 2004].

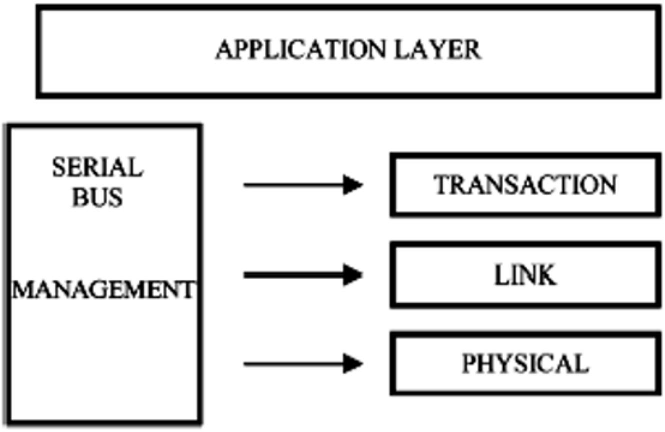

Fig. 1.31 IEEE 1394 protocol stack [SHRINATH AND EMADI 2004].

Just like the OSI physical model that is used widely in the TCP/IP protocol, each level in the IEEE 1394 stack has certain functions assigned to it.

The physical layer is in charge of sending electrical impulses to the bus that are translated into data at the other end. The link layer is associated with addressing as well as data checking. It is in this layer that error detection takes place.

The transaction layer basically provides the set-up mechanisms for communication to take place. The serial management bus has management functions associated with it. It is linked to all three layers. Finally, the application layer is the layer in which codes for specific applications are written [SHRINATH AND EMADI 2004].

The 1394 protocol supports a variety of features, such as high data rates and **plug-and-play** (P&P) compatibility, as well as support for asynchronous and isosynchronous data types [SCHOLLES ET AL. 2001].

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Asynchronous data transfer is mainly used for guaranteed data delivery that some protocols, such as the SAE J1850 protocols, offer (the in-frame response). Messages are short and are mainly used for control and set-up purposes.

Isosynchronous data transfer is used for mass transfer of data. However, reliability is not a major criterion in this case. Constant speed and bandwidth are the major factors taken into consideration for this kind of data transfer. Messages are sent in the form of packets, which are sent out every 125 μs. A typical application is video streaming [SHRINATH AND EMADI 2004].

The IEEE 1394 protocol provides for automatic configuration of the tree topology implemented. The three basic steps are bus initialisation, three identification and self-identification. In the case of dynamically changing IDs, the devices must implement a group of registers defined by the **control and status register** (CSR) architecture specification. The devices themselves are generally of two types: low-cost devices and high-end devices [RABEL ET AL. 2001].

Another important characteristic of the IEEE 1394 protocol is that the management functions are distributed. This means that the nodes have no master and each node operates independently. Therefore, even if one part of the network ceased to function for some unforeseen reason, the rest would continue to function irrespective of the failure of a part of the network. Main applications include the aerospace and automotive industries handling CNI waveforms, industrial cameras for industrial inspection systems for quality control, and multimedia applications in automotive vehicles.

1.8 Controller Area Networking

1.8.1 Foreword

It was in 1983 that *Robert Bosch GmbH* started an internal project in Germany to develop an in-vehicle E&IN that would serve to connect all the electronic components in an automotive vehicle. In 1986, they introduced the concept of the serial bus-based **controller area network** (CAN) for the first time at the **Society of Automotive Engineers** (SAE) Congress [SHRINATH AND EMADI 2004].

The CAN protocol is based on the principle of the broadcast transmission technique in which data to be transmitted on a network is sent to all the nodes including the one for which the data is intended. The nodes look inside the data packet to see if the message was meant for them. If not, they simply discard the packet. The node to which the data was intended then downloads the data and processes it [NAVET 1998].

Some of these features that have made CAN go up to 1 Mb/s. This is very helpful in real-time mechatronic control systems that can afford very low latency. Thus, due to the high speed offered by CAN, low latency and, hence, time-efficient control may be achieved. CAN frames are also short in length, because of which there is minimal delay in the reception of messages.

CAN is basically an **event-triggered protocol** (ETP) mechanism. This means that the transmission of data is prompted only when a specific event occurs. For example, data transmission might take place when a button is pressed or a lever pulled. Owing to this property, the bandwidth available is made maximum use of because of the minimum load put on the bus system. The combination of high speed and short message length results therefore in a low delay, owing to which CAN is implemented in mechatronic control systems that have a very low tolerance for delays (Fig. 1.32) [NI 2007].

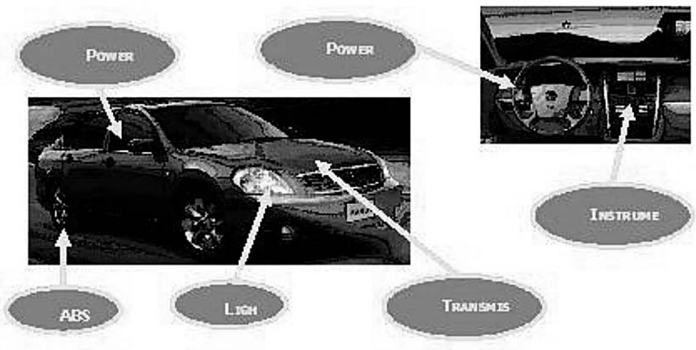

Fig. 1.32 Classic CAN applications [NI 2007].

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The addressing system is based on message identifiers rather than on physical addresses for nodes. Every CAN message has a unique identifier that assigns a priority to the respective message based on the binary value of the identifier. A lower binary value is assigned a higher priority and vice versa. Any node wishing to transmit sends the message to the CAN controller that, in turn, broadcasts the message. All the other nodes then get ready to receive and the nodes that have no use for the message discard it [SHRINATH AND EMADI 2004].

1.8.2 CAN Arbitration

A problem that arises in a network is the problem of collision avoidance. There could be a possibility that with so many messages going around in the network, messages could collide that could lead to a loss of messages. CAN overcomes this by a simple method known as **carrier sense multiple access/collision detection** (CSMA/CD). In this method, the nodes first listen to the bus to see if it is free and then they transmit [SHRINATH AND EMADI 2004].

1.8.3 CAN Error Detection

The errors that occur in a network may be at either the bit level or at the frame level. Fortunately, CAN is equipped to handle both kinds of error [CAN 2003]. The major types of error that may be handled by the CAN protocol are bit, stuffing, **cyclic redundancy check** (CRC), form, and acknowledgement errors. CRC is employed to detect any errors occurring during transmission. Here both the receiver and transmitter would have stored a mutually agreed polynomial *P(x).*

The transmitter then represents the data to be transmitted by a polynomial *G(x)* that is then divided by *P(x)*. The remainder is the transmitted in the frame to the receiver. The receiver then performs the same division to see if it gets the same remainder. If not, then the receiver may infer an error has occurred [SHRINATH AND EMADI 2004].

1.8.4 CAN Architecture

A basic CAN protocol consists of three layers: physical, data-link, and application. The **data-link layer** (DLL) is implemented in an electronic component known as the CAN-controller. There are many ways, in which CAN may be implemented in vehicles. In a more generalised manner, CAN is used to network vehicle body mechatronic control modules and infotainment networks.

Figure 1.33 graphically depicts an example of how CAN may be implemented in automotive vehicles [KIRMANN 2005; SHRINATH AND EMADI 2004].

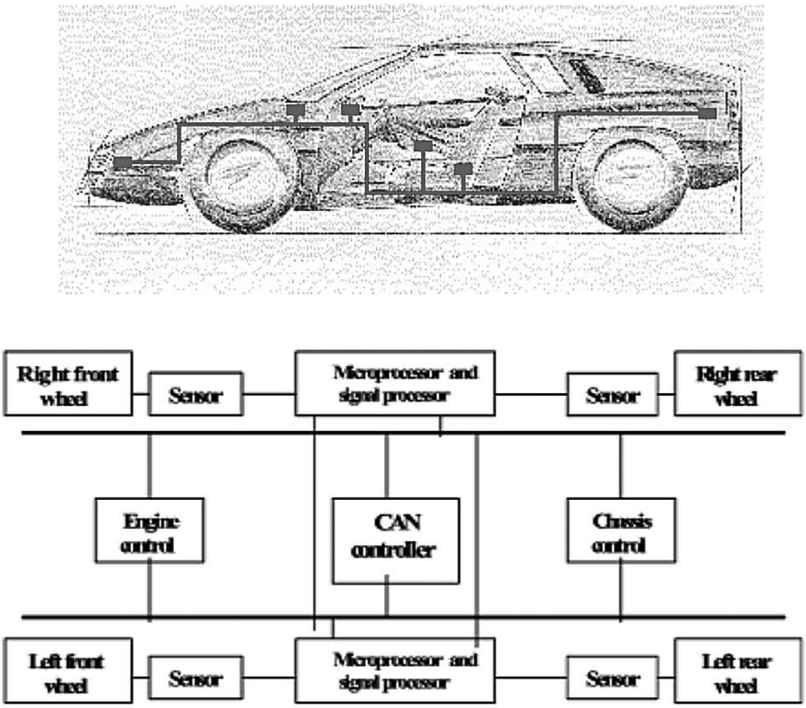

Fig. 1.33 CAN mechatronic control system overview
[KIRMANN 2005 – Top image; SHRINATH AND EMADI 2004 – Bottom image].

Several semiconductor manufacturers, such as Intel, Motorola, and Philips, make it. The CAN controller consists of the following: **CPU interface logic** (CIL) that handles the data transfer on the bus; **bit stream processor** (BSP) that handles the streaming of data between buffer and bus line; **error management logic** (EML) that is involved with error management; **bit timing logic** (BTL) that is responsible for the synchronisation of bit streams; **transceiver control logic** (TCL) that handles error detection and correction, transmission, and reception of the data and *arbitration; and* ***message buffer memory*** *(MBM) that is used to store messages* for future transmission. Recently, a variation of the CAN protocol, termed the *'CAN open'*, has been developed [FARS ET AL. 1999; XING ET AL. 1999].

1.9 Time Triggered Controller Area Networking

Communication protocols may be divided into two classes: event triggered and time triggered. Both these methods vary as far as their operating principles are concerned [Leen and Heffernan 2001].

Time-triggered controller area network (TTCAN) is a communication protocol based on CAN, though the difference is that it uses a time-triggered mechanism rather than the event-triggered mechanism used in CAN. The specifications of TTCAN are defined in ISO standard 11898-4. It uses all the error detection mechanisms as well as the soundness of CAN [Shrinath and Emadi 2004]. The event-triggered physical model is known as an asynchronous physical model, whereas the time-triggered physical model is known as a synchronous physical model. In the event-triggered physical model, data transmission takes place when a certain event takes place, for example when a button is pressed or a lever pulled. Here data transmission takes place at random on the time line. However, in the case of the time-triggered physical model, data transmission takes place at specific intervals on the timeline. In this mode, all the nodes are synchronised to a master clock so that all of them have the same sense of time. Each node is allotted a slot time. It is only during its allotted slot time that the node may transmit. This is something akin to the **time division multiple access** (TDMA) scheme. Transmission of data takes place due to the progression of time. But how do the nodes know when to start transmitting their data? In the static scheme, nodes are allotted slots in time, but in the time-triggered CAN, this problem is solved by the transmission of a special frame known as the reference frame. This is distinguished from other frames by virtue of the identifier. This reference message has a bit termed the **start-of-frame** (SoF) bit. The reception of this bit denotes the instance of time at which the data transmission may take place. The TTCAN has two levels of operation defined in the specification. Level 1 is by virtue of the property of the reference message. This reference message ensures the time-triggered operation of the CAN. Level 2 ensures the global time synchronisation of the nodes in the network. The difference is that for the level 1 implementation, the reference message carries one byte of information necessary for control purposes, whereas for implementation level 2, the reference message contains about four bytes of control information with the other four bytes being usable for data transfer. The advantage that it enjoys over CAN is that during operation cycle, TTCAN permits the transmission of the regular time-triggered messages as well as event-triggered messages. Certain time slots are reserved for the event-triggered messages [Shrinath and Emadi 2004].

The RBW or XBW integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hypersystem (which integrate sensors and actuators for performing certain critical real-time mechatronic control functions) necessitates TTCAN. This leads to a predictable behaviour of the network that is very important owing to the distributed architecture of many networks.

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A distributed network consists of many systems organised into hyponetworks. Each hyponetwork may be implementing a different protocol. Therefore, a protocol that clearly defines the transmission procedure to be followed at well-defined time slots would clearly reduce the complexity of the network, as well as fully use the available bandwidth. In addition, it would reduce the time required, however small, for the arbitration procedure in the CAN that grants the nodes access to the bus for the transmission of messages. It would also reduce the probability of a message with low priority being restrained from transmitting that message for a long time. Many of the hyponetworks in up and coming automotive vehicles may be highly crucial for the safety of the vehicle; for example, the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems being implemented in vehicles. In these mechatronic control hypersystems, the control of the automotive vehicle would be decoupled from the process to which it is attached [FÜHRER ET AL. 2003].

Therefore, in these cases, the deterministic nature of the network, as well as its reliability to deliver messages to sensors and actuators on time, is very essential.

Figure 1.34 illustrates the communication physical model adopted by TTCAN [SHRINATH AND EMADI 2004].

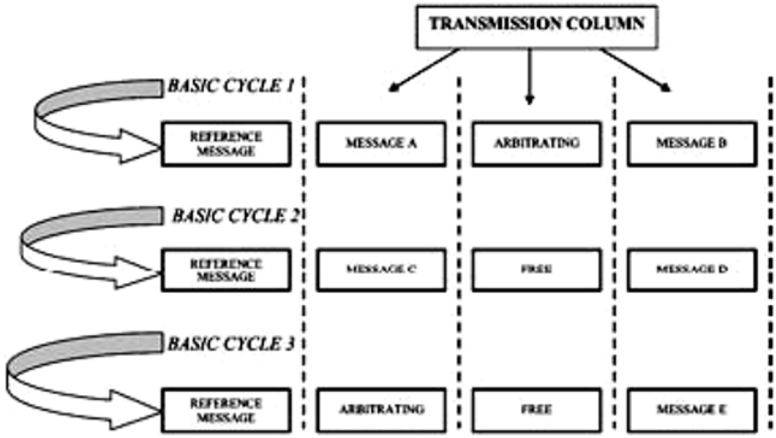

Fig. 1.34 Matrix cycle in TTCAN [SHRINATH AND EMADI 2004].

The matrix cycle essentially describes the transmission schedule of the entire network. It defines which node should be transmitting at any given instant of time. In this way, each node knows when exactly it is supposed to transmit. The matrix cycle is repeated over time. Each basic cycle consists of several exclusive and/or arbitrating and free windows. This structure is highly common oriented. Each column in the matrix cycle is known as a transmission column. All the windows belonging to a single transmission column are equal in length. A counter *Cycle_Count* is used to indicate the number of the current basic cycle.

One implements it every time a basic cycle is completed. Apart from the exclusive and arbitrating window, another window, know as the *Tx Enable*, is used. This is contained within the exclusive and arbitrating windows. It is used to indicate to the node the time at which it is supposed to start transmitting. This is done so that the message following the current one may not be delayed due to the delayed transmission of the current message [SHRINATH AND EMADI 2004].

The time unit used in any network transaction in the TTCAN is known as the **network time unit** (NTU). It may be either CAN-bit duration in the level 1 TTCAN or a fraction of a second when implemented in the level 2 TTCAN.

A **message state counter** (MSC) is attached to every message transmitted or received. An error to this message is responded to by an increment in the MSC. A node then flags an error if either the MSC reaches a value of seven or the difference between two MSC is greater than two. Implementation of the TTCAN protocol is handles by the TTCAN IP module that implements not only the TTCAN protocol (ISO 118998-4) but also the CAN protocol (ISO 118998-1) [TTCAN 1998]. Bit rates of up to 1 Mb/s are achievable by this module. This module provides all the requirements of a time-triggered network, including global time synchronisation and clock-drift compensation.

Message objects and message masks are stored in the message RAM for operation in a CAN. For TT-CANs, the trigger object is stored in the trigger RAM. The message handler deals with all message-handling instructions.

It is possible to change the message handler core as well as certain other cores by having an interface card connected to the module and an external CPU [SHRINATH AND EMADI 2004].

In summary, with the addition of a session layer to the protocol stack of a CAN, it is possible to have a time-triggered physical model of the CAN that lends flexibility as well as deterministic behaviour to the network.

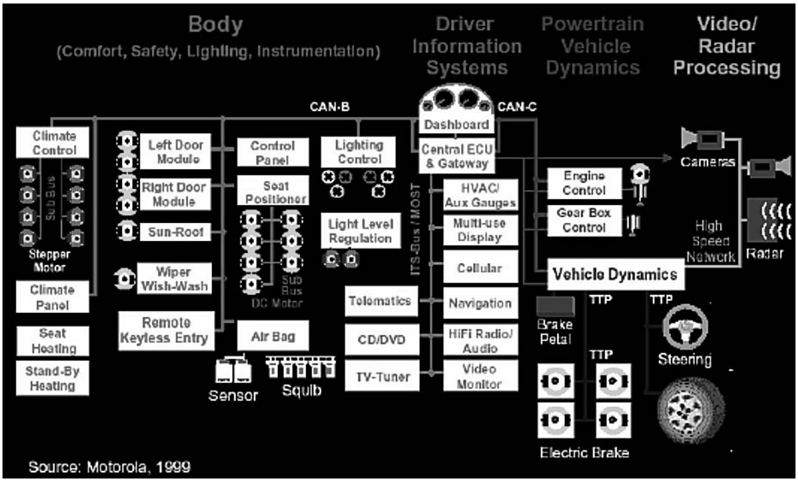

Fig. 1.35 Total connectivity in the automotive vehicle of the time-triggered protocol (TTP) [MOTOROLA 1999].

This fact may be exploited by RBW or XBW integrated unibody or chassis motion mechatronic control hyper-systems. Slowly, such networks would be added to the existing mechanical and/or fluidic (hydraulic and/or pneumatic) back-ups to ensure the complete safety of the operating mechatronic control system.

The advantage of using a **time-triggered architecture** (TTA) is that the system would not be overloaded with events (see Fig. 1.35). It would take additional circuitry to resolve pending scenarios [SHRINATH AND EMADI 2004].

1.10 Media Oriented System Transport (MOST) Networking

The development of the **media oriented systems transport** (MOST) network [SCHOLLES ET AL. 2001; MOST 2003] stemmed from the necessity for a P2P network that had high data speeds, but was also cost effective. The MOST networks were essentially designed for multimedia applications in the automotive environment; however, due to its efficiency, it is being increasingly used for home networks too. Also, the implementation of optical fibres at its physical layer ensures high reliability under adverse circumstances. Some of the key features of the MOST networks are ease of use; cost effectiveness, availability of synchronous and asynchronous data transfer mode, flexibility, and a wide range of applications [SHRINATH AND EMADI 2004].

As pointed out before, the MOST networks are P2P networks. The P2P network connection may be established using either of the ring, star, or daisy chain topologies. Two approaches may be used for administrative tasks: centralised and decentralised. In the centralised approach, a single node handles all the tasks. In the decentralised approach, all the administrative tasks are distributed throughout all the nodes.

A MOST network is essentially made up of MOST interconnect, system services, and devices. The MOST interconnect is essentially concerned with the establishment of connections between the devices at the start-up phase. It is also during this phase that device addresses are distributed throughout all the devices. Synchronisation between all the nodes by means of a bit pulse is achieved during this phase. The MOST system services are comprised of low-level system services. Functions such as data routing, channel allocation, fault detection, or delay detection are performed by the low-level system services.

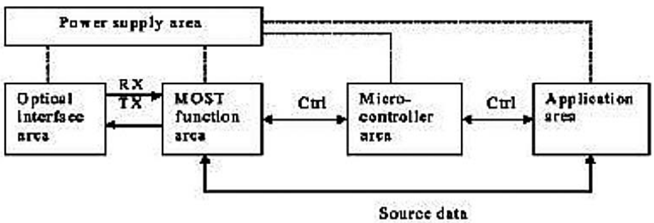

Fig. 1.36 MOST devices in a typical configuration [SHRINATH AND EMADI 2004].

The application socket and the basic-layer system services make up the *MOST Netservices*, which are basically concerned with the transmission and reception of different kinds of data, as well as providing standard interfaces to access various network management functions.

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MOST devices may vary from simple displays to complex applications. They have the capability of bandwidth allocation, as well as packet and control data capacity handling. Figure 1.36 illustrates the implementation of a MOST device in a typical configuration [SHRINATH AND EMADI 2004].

The data types supported by MOST are control data and burst data. All the transactions taking place on the MOST networks involve the generation of a synchronous frame by a frame generator or timing master. Each node has an internal timing device that locks onto this signal by means of a **phase-locked loop** (PLL). By locking onto this synchronisation frame, all the nodes are synchronised to the timing master [MOST 2003].

MOST networks are designed to use **fibre optical** (FO) cables as the medium of transmission. Therefore, the network is designed to accommodate all the possible complex topologies that may implement applications based on FO cables. This provides enhanced capacity, as well as security features. It also enables the MOST networks to support the P&P mode of operation. The signal lines that compose the physical structure are *RX*-receive data and *TX*-transmit data. Other optional lines are power, ground, and wake-up. As the name suggests, the wake-up line is used for waking-up the target device. In this network, each node has a set of functions that are to be carried out. The most important ones are synchronisation, managing data flow, decoding addresses, detection of system start-up, and power management [SHRINATH AND EMADI 2004].

These are the functions that are implemented in each node. However, the software too has many functions that are important. Some of them are physical addressing, channel allocation, control, data transfer, packet data transfer, and system monitoring. Since this network may support real-time data transmission, it may be used for networking CD audio drivers, set-up boxes, and TV sets.

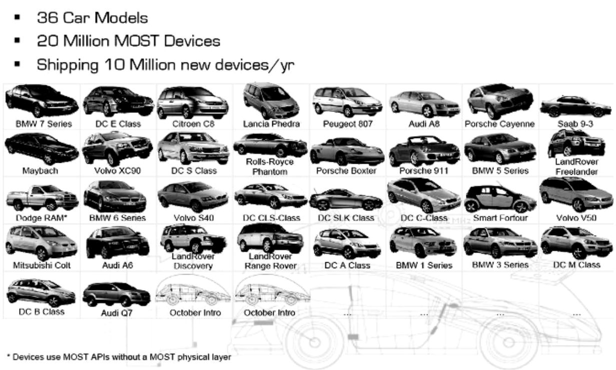


Fig. 1.37 MOST automotive vehicles: 2001 – 2005 [MOST; SAUTER ET AL. 2007].

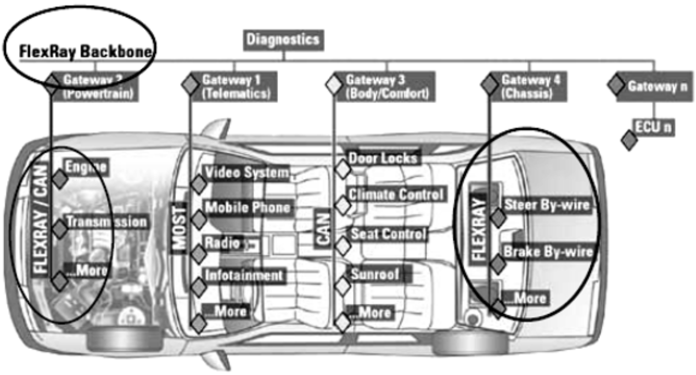
In the automotive field, MOST is applied for implementing infotainment networks (see Fig. 1.37) [MOST; SAUTER ET AL. 2007].

Data, such as door status or illumination property signals, are transmitted to the vehicle's body control module using MOST technology.

1.11 FlexRay™ RBW or XBW Networking

The FlexRay™ protocol is expected to be a comprehensive communication system providing speed, flexibility, and scalability for complex networks.
The protocols key features include [Case 2005]:

- ❖ Time and event-triggered communication schemes;
- ❖ Support of **fault-tolerant** (FT) systems;
- ❖ High-error detection and error-diagnosis capability;
- ❖ Support of different network topologies for cost-effective and safety-enhanced partitioning of the system;
- ❖ Dedicated automotive electrical physical layer with sophisticated power-down and wake-up mechanisms;
- ❖ Flexible extend ability and full scalability to enable upgrades.



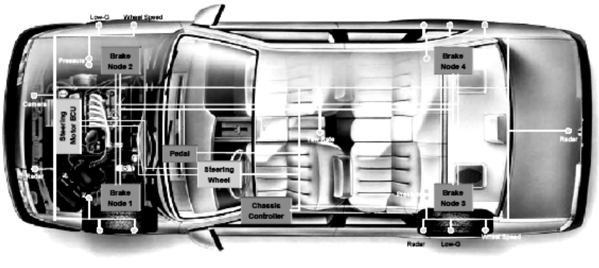


Fig. 1.38 FlexRay™ architecture examples [Hansen 2005].

Among the applications that the FlexRay protocol is expected to make possible are RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems such as DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems (Fig. 1.38) [Hansen 2005].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
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RBW or XBW removes the necessity for fluidical and mechanical systems, connecting the driver to these systems using sophisticated mechatronic systems that are less expensive to build and easier to maintain. Other applications that the FlexRay protocol is expected to facilitate include active and passive safety systems, collision avoidance systems, powertrain management systems and driver assistance systems, for example, as shown in Figure 1.39 [CASE 2005].

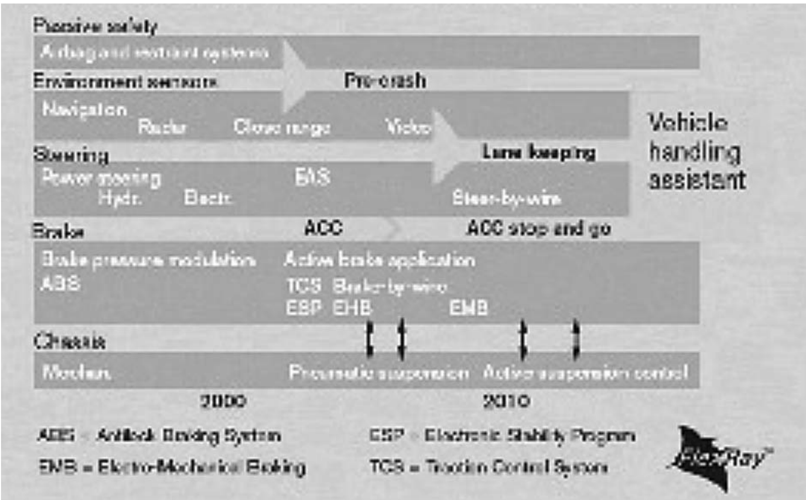

Fig. 1.39 Advanced applications: vehicle dynamics and driver assistance systems [CASE 2005].

With a gross data rate of 10 Mb/s, FlexRay delivers approximately 20 times higher net bandwidth than the CAN protocol currently used in advanced automotive control applications.

FlexRay is an open, common, scalable electronic architecture for automotive applications. It may operate in single- or dual-channel mode, providing redundancy where necessary. It allows both synchronous and asynchronous data transmissions. With the former, other nodes on the network receive time-triggered messages in a predefined latency time. With the latter, messages get to their destinations quickly or slowly, depending on their priority.

Currently, FlexRay may handle communications at 10 Mb/s -- the speed of a typical low-end, home-computing local area network. Last, FlexRay clock synchronisation mechanism aptly handles cheap clock oscillators, namely those made out of quartz. And that synchronisation, as with all of FlexRay, is faulting tolerant [GOULD 2005].

For instance, FlexRay automatically and digitally compensates for the differences in the variety of quartz clocks running on the network, as well as in their slight changes in clock frequencies. This clock synchronisation is a distributed mechanism; there is no master time-keeper here.

So if one node fails, or for some reason, is taken off the network, the other nodes may continue to operate in synchrony [GOULD 2005].

In so far as the fault tolerance of E-M motors and sensors, the normal rules of reliable systems-design apply.

For example, in an SBW AWS conversion mechatronic control system, the sensor system in the steering HW may be a redundant array, with two or three sensors providing the same signal.

A judging algorithm in the mechatronics may then determine the validity of the signals; that is, it may determine whether all three sensors are providing the same information, or at least two of the three.

Supporting the shift from mechanical to electrical in-vehicle systems, Philips is working as a FlexRay Consortium Core Partner to develop a complete RBW or XBW communications system, starting with the physical layer, capable of supporting the in-vehicle networking systems of tomorrow [PHILIPS 2004A].

A modern automotive vehicle is among the most expensive purchases a consumer may make – and safety, price and economy are often buyers' primary concerns. This impels vehicle manufacturers to find ways of making their vehicles more efficient, easier to drive, better protected in an accident, and more reliable.

In many cases, this means switching from bulky, heavy mechanical systems to light-mass electrical systems, significantly increasing the mechatronic content in the average automotive vehicle – a trend that is set to continue [PHILIPS 2004A].

The generic term *'RBW'* or *'XBW'* covers all the advanced technologies needed to interconnect automotive mechatronic control applications, from driving, braking, steering to absorbing/damping supplementing, and ultimately replacing existing mechanical and fluidic (hydraulic and/or pneumatic) solutions.

As a core technology provider to the FlexRay Consortium, Philips is working hand-in-hand with the automotive vehicle manufacturers DaimlerChrysler, BMW, GM and Volkswagen as well as many other well-known automotive OEMs such as Bosch and Motorola, to integrate the many benefits of RBW or XBW into the future vehicles [PHILIPS 2004A].

The FlexRay Consortium is developing the FlexRay communications protocol and physical layer – the core of a system supporting future in-vehicle high-speed mechatronic control applications. FlexRay addresses the demand of increased bandwidth to handle the growing number of sensors, actuators and control systems for the various safety, reliability, and comfort systems within automotive vehicles.

Providing a common, scalable communications system with the potential for expansion in the future is a key object for FlexRay™.

Alongside the protocol, software and support services in development, the FlexRay Consortium also aims to ensure the provision of tools for design, measurement, and simulation of the communications system through industry-leading tool-makers and test houses grouped in the Consortium's Development Members community. Philips is currently developing silicon solutions for the FlexRay system [PHILIPS 2004A].

Key Features

<u>*Physical layer:*</u>

- ❖ Data transfer up to 10 Mb/s;
- ❖ Deterministic data transmission, guaranteed message latency and message jitter;
- ❖ Bus guardian' ensures fault containment in the time domain;
- ❖ Flexible and extensible network layout: support for bus, star, and multiple star topologies;
- ❖ Robust network wake-up mechanism;
- ❖ Advanced power-mode handling;
- ❖ Fault separation in active star networks

<u>*Protocol:*</u>

- ❖ Fault-tolerant and time-triggered services implemented in hardware (e.g., synchronised global time base);
- ❖ Support of repetitive as well as spontaneous message scheduling;
- ❖ Dedicated online diagnosis services;
- ❖ Support of network management services and efficient message filtering mechanisms;
- ❖ Support of redundant transmission channels;
- ❖ Robust coding and bit recognition scheme.

This includes *Bus Drivers* and *Bus Guardians*, for which prototype samples have already undergone both laboratory and in-field testing, with promising results. Based on the feedback obtained, device specifications are currently being refined and future production *Bus Drivers* and *Bus Guardians* are in development, with the *TJA1080 FlexRay Bus Driver* (Fig. 1.40) being the first to be released from the roadmap [PHILIPS 2004A].

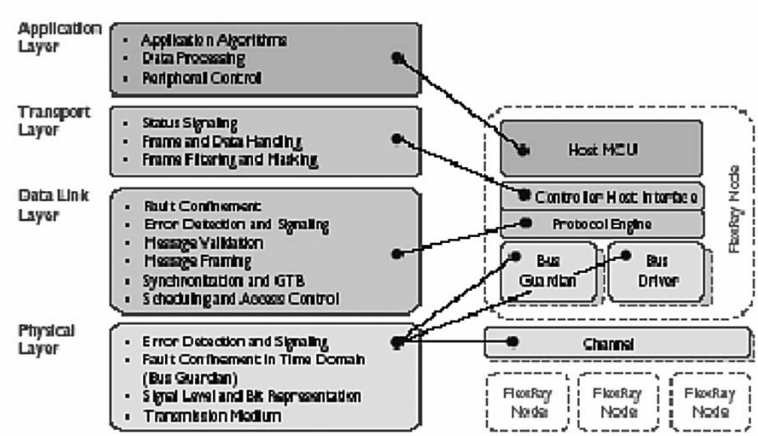

Fig. 1.40 FlexRay™ node architecture [PHILIPS 2004A].

The Consortium is driving FlexRay forward as the automotive industry standard for *'RBW'* or *'XBW'*. And as a FlexRay Core Partner, Philips could not be better positioned to develop the silicon solutions for this evolving standard – bringing drivers a safer and more comfortable ride [PHILIPS 2004A].

Summing up, FlexRay provides the flexibility and determinism necessary for high-speed communications by combining a scalable static and dynamic message transmission, incorporating the advantages of familiar synchronous and asynchronous protocols. The protocol also supports **fault-tolerant** (FT) clock synchronisation by means of a global time base, collision-free bus access, guaranteed message latency, message oriented addressing via identifiers, and scalable system fault-tolerance via the support of either single or dual channels. A physical layer incorporating an independent *Bus Guardian* provides further support for error containment. The FlexRay system is targeted to support data rates of up to 10 Mb/s, ten times the bandwidth available on a CAN-based network, with increased flexibility for easy system extension and the dynamic use of bandwidth [PHILIPS 2004B].

Philips is actively pursuing the drive towards a complete intelligent car system with FT RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems that do not require conventional backup. The company has developed silicon solutions to test and develop physical layers for these applications. This includes the first FlexRay transceiver on the market, the *TJA1080*. This high-speed, time-triggered communication system transceiver chip offers excellent EMC performance and is suitable for use in active star couplers. Combining a FlexRay transceiver and FlexRay active star device on a single chip, the *TJA1080* supports the full bandwidth of FlexRay. Other features include internal voltage and temperature monitoring, bus error detection, and a safety time-out. The first concrete FlexRay series application, using the *TJA1080* as transceiver and star device, is scheduled to go to mass production in the second half of 2006. A variety of RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems and other FlexRay applications (Fig. 1.41) at several major vehicle manufacturers are currently envisaged start of production dates in the 2010s [PHILIPS 2004B; SAUNTER ET AL. 2007].

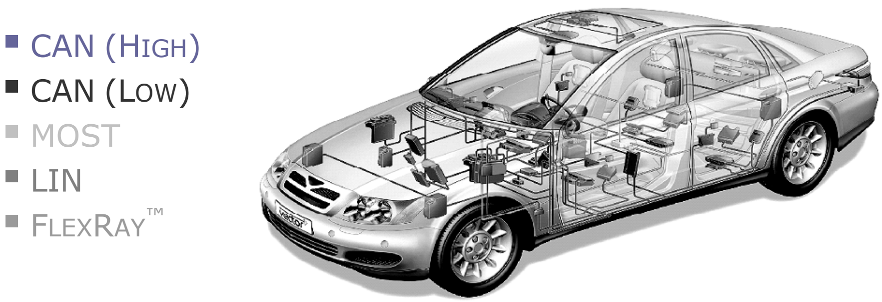

Fig. 1.41 Classic FlexRay™ applications [SAUNTER ET AL. 2007].

Freescale Semiconductor's *MFR4200* FlexRay controller is now available in production quantities. With the introduction of the first automotive-qualified FlexRay device, Freescale is helping advance the automotive industry's development of next-generation automotive mechatronic control applications (Fig. 1.42) [FREESCALE 2005; SAUTER ET AL. 2007].

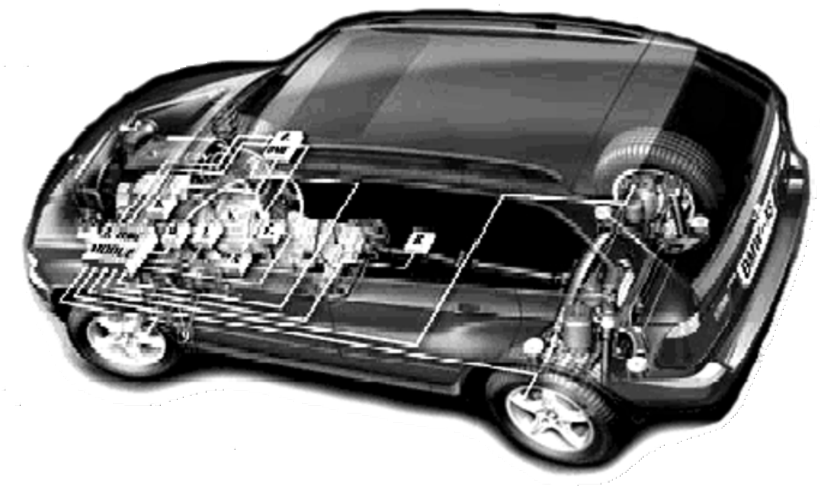

Fig. 1.42 FlexRay™ applications for *Adaptive Drive* in theBMW *X5* [SAUTER ET AL. 2007].

By standardising on the FlexRay protocol, automotive vehicle manufacturers may lower development and manufacturing costs, centralise and simplify the introduction of advanced high-speed mechatronic control systems, and increase overall vehicle stability and safety.

The *MFR4200* FlexRay is designed to help vehicle manufacturers achieve these results by delivering 10 times more throughput than current CAN solutions and providing the fault tolerance and time-deterministic performance required for RBW XBW integrated unibody or chassis motion mechatronic control hyper-systems' applications. As the number of embedded controllers for safety, reliability, and comfort systems within the automotive vehicle increases, a time-triggered communication system is critical. With major automotive industry players committed to adopting the FlexRay protocol in the near future, the *MFR4200* FlexRay may represent an important and timely investment for Freescale [FREESCALE 2005].

RBW XBW integrated unibody or chassis motion mechatronic control hyper-systems (including DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension/reaction mechatronic control systems) are expected to gradually replace most fluidical lines and mechanical cables with wire-based networks, sensors and E-M motors.

The *MFR4200* FlexRay (Fig. 1.43) is designed to serve the requirements of this market by providing a high level of communication bandwidth and deterministic, **fault-tolerant** (FT) data transmission [FREESCALE 2005].

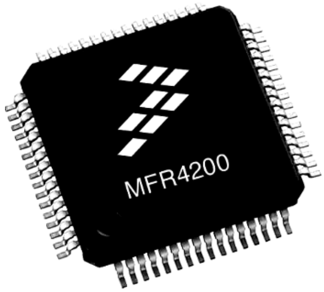

Fig. 1.43 MFR4200 FlexRay™ device [FREESCALE 2005].

This device is ideal for RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem, and powertrain applications and offers seamless integration with a wide range of macro- and microcontrollers (ASIM macrocommutators and ASIC microprocessors). In addition, FlexRay complements the major in-vehicle networking standards (CAN, LIN and MOST) by adding a high-speed protocol for the most demanding systems [FREESCALE 2005].

Some automotive scientists and engineers believe that FlexRay is destined to be the indisputable global standard for innovative high-speed control applications in the automotive vehicle. The list of vehicle manufacturers embracing the FlexRay protocol -- including Audi, BMW, DaimlerChrysler, Ford, GM, Toyota and Volkswagen -- underscores the momentum FlexRay has already achieved. As a core partner in the FlexRay Consortium, Freescale Semiconductor is working to help proliferate the standard.

MFR4200 FlexRay features [FREESCALE 2005]:

- ❖ Bit rate up to a maximum of 10 Mb/s on each of two channels;
- ❖ Two channels;
- ❖ Redundant for fault tolerance;
- ❖ Independent for 2 × bandwidth;
- ❖ 59 message buffers, each with a payload of up to 32 bytes of data;
- ❖ Each message buffer configurable as receive buffer, transmit buffer (single or double) or as part of the receive **first in-first out** (FIFO);
- ❖ 64-pin **low-profile quad flat package** (LQFP).

Fujitsu Microelectronics America, Inc. (FMA) also introduced the industry's leading Flex Ray controller, the *MB88121*, an application-specific standard product that supports Flex Ray version 2.0 [FUJITSU 2005].

Based on IP developed by Robert Bosch GmbH, the *MB88121* delivers 10 Mbit/s over two channels. It provides fault-tolerant, deterministic data transmission, which is suitable for the DBW AWD propulsion, BBW AWB dispulsion, ABW AWA suspension and SBW AWS conversion mechatronic control systems now being introduced using the FlexRay protocol.

The *MB88121* is designed to complement all of the existing standard automotive buses, including the CAN and LIN. FlexRay-based technology, which can provide approximately 10 times the throughput of CAN, is expected to gradually replace CAN as automotive vehicle manufacturers and their suppliers adopt RBW or XBW solutions in new generations of automotive vehicles.

Fujitsu has been a one of world leaders in FlexRay product development, as a member of the FlexRay Consortium, and as the first company to deliver a complete developer's kit designed to enable early-stage application development. This innovative FlexRay communication controller incorporates all the features and capabilities required to spur significant manufacture of FlexRay systems by vehicle manufacturers and automotive OEMs.

Embedding FlexRay IP into real silicon may allow early adapters to design a range of automotive mechatronic-control applications at a manufacturing grade.

The *MB88121* may be connected directly to existing CPUs, enabling the development of manufacturing systems that use a next-generation network, while simultaneously maximising the performance of equipment already in the vehicle. Internal speeds reach 80 MHz, with a 4, 5, 8, 10 MHz external oscillator, or by external clock. The chip's parallel interface affords a maximum frequency of 33 MHz [FUJITSU 2005].

Automotive scientists and engineers now may use the new *FlexRay* library for *Lab VIEW* from National Instruments (*Nasdaq: NATI*) to quickly and easily test devices on a *FlexRay* communications network. The *FlexRay* library offers a set of 28 **virtual instruments** (VI) specifically designed to work with the bus protocol defined by the *FlexRay* Consortium's System Specifications, Version 2.0 standard [BIZWIRE 2004].

FlexRay is an innovative deterministic, fault-tolerant, and high-speed bus system developed by vehicle manufacturers and leading suppliers to address the necessities of current and future in-vehicle mechatronic control applications. It delivers the error tolerance and time-determinism performance requirements for RBW or XBW applications – such as DBW AWD and BBW AWB, SBW AWS as well as ABW AWA -- and has a data frame of up to 127 words (254 bytes), which is more than 30 times the amount offered by a CAN bus.

The free, downloadable FlexRay library for *LabVIEW* makes it easy for scientists and engineers to communicate with devices on a FlexRay network. In addition, the FlexRay library for *LabVIEW* supports the *FlexCard* from TZM [BIZWIRE 2004].

National Instruments supports the development of open standards throughout the automotive industry and is a member of the FlexRay Consortium. The new library of FlexRay *LabVIEW* VIs demonstrates a commitment to supporting this advanced communications bus and empowers engineers to take advantage of *LabVIEW* graphical programming for emerging in-vehicle mechatronic control applications, including the support of RBW or XBW features and advanced control systems. New developments in the automotive industry create increased demands that existing communication protocols cannot be easily address, including the necessity for higher data rates, deterministic behaviour, and the support of fault-tolerance.

A FlexRay communications bus offers synchronous and asynchronous data transfer, increased frame length, guaranteed frame latency and jitter during synchronous transfer, and prioritisation of messages during asynchronous transfer.

The FlexRay protocol also provides multi-master clock synchronisation, dual-channel data transfer, flexible bus topology, error detection, and signalling.

Automotive customers necessitated increased functionality that requires more flexibility in both bandwidth and system extension.

The ability to create automated test applications with *LabVIEW* on a FlexRay-bus network gives us the flexibility, communications availability, reliability, and data bandwidth that we need for advanced applications in power train, chassis, and body mechatronic control [BIZWIRE 2004].

1.12 dSPACE RBW or XBW Networking

The technological concept of *'RBW or XBW'* means replacing essential mechanical components by electrical ones. It was originally used for aircraft only, but now the automotive industry is showing increased interest. As in aeronautics, this method has enormous potential for implementing new design concepts. For example, it may be possible to design the interior of an automotive vehicle with completely different mechanical connections between the steering HW or the pedals and the ECE or ICE compartment. Innovative user interfaces may also be possible – for example, a joystick instead of a steering HW. For instance, at TRW Automotive, scientist and engineers are currently designing a new RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem, using dSPACE tools to speed up the development [dSPACE 2002a].

To meet the mechatronic control design requirements of the future in applications like RBW or XBW integrated unibody or chassis motion mechatronic control systems, *MicroAutoBox* from dSPACE now offers up to 10 times more processing power. The volume of data that has to be processed is growing dramatically due to the greater bandwidths of new bus systems (for example,

FlexRay with 10 Mb/s), and the increasing number of sensors and actuators installed in automotive vehicles. *MicroAutoBox* is now equipped to handle any complexity of control functions the future may bring, without limitations and to the highest standards. Its comprehensive software supports model-based development using *Matlab/Simulink/Stateflow* [dSPACE 2004].

In addition, dSPACE offers experiment software for instrumentation tasks, the measurement of physical model variables, and calibration of control parameters, so that mechatronic control system behaviour may be analysed. *MicroAutoBox* is a compact, vehicle-proof, real-time platform for fast-function prototyping [dSPACE 2004]. Interfaces to all the major automotive bus systems -- CAN, LIN and FlexRay -- are available for different requirements in several *MicroAutoBox* variants. With its greatly enhanced processing power, *MicroAutoBox* is billed as the function prototyping solution of the future.

The new processor type has a higher CPU clock rate and an internal level 2 cache of 512 Mbyte, and reaches up to 10 times the performance of the previous 300 MHz versions, depending on the application. Software and physical models developed for the 300 MHz *MicroAutoBox* may be reused on the new platform without having to be recompiled.

MicroAutoBox's suitability for in-vehicle use has been proven in shock and vibration tests, and it is small enough to take the place of an onboard mechatronic control unit during function development. The integrated flight recorder records test data for data analysis and debugging. *MicroAutoBox* may also be coupled with a notebook and used for real-time data monitoring and parameter calibration during test-drives. Its I/O and signal conditioning features may both be adapted to any requirements a customer may have [dSPACE 2004].

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MicroAutoBox from dSPACE, a programmable prototyping control unit for function development, is now available in a new hardware version with a 300 MHz processor. Thanks to its high performance and convenient programmability, *MicroAutoBox* is already being used successfully by many vehicle manufacturers and their suppliers. The 300 MHz processor increases the speed by 10 -- 30%, depending on the application, compared with the previous 200 MHz versions. Programs and physical models developed for the earlier *Micro AutoBox* may run on the 300 MHz versions in exactly the same as on its predecessor -- without having to be recompiled [DSPACE 2002B].

MicroAutoBox's compact dimensions and shock resistance mean it may be installed practically anywhere in the vehicle. During function development, it performs the tasks that may later be done by the **electronic control unit** (ECU).

MicroAutoBox boots itself just like a production ECU. It provides real-time hardware for testing complex controller functions and automotive-specific signal conditioning, which may also be adapted to customers' requirements. For the proof-of-concept BBW AWB dispulsion development, automotive scientists and engineers are using, for example, one only **micro-auto-box** (MAB) per wheel as a wheel ECU and an **auto-box** (AB) as the central ECU, as is shown in Figure 1.44 [TRW INC. 2004].

(a)

(b)

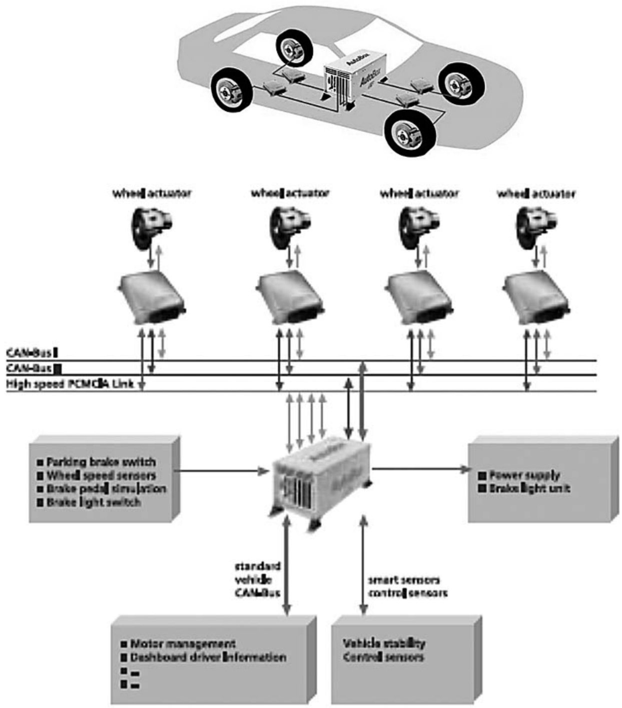

Fig. 1.44 One MAB per wheel and an AB as the central ECU (a) and the set-up in detail of the second-generation BBW AWB dispulsion mechatronic control system (EMB) – (b) [TRW Inc. – dSPACE GmbH]

Programming is done graphically from *MATLAB/Simulink*, eliminating time-consuming hand coding. *MicroAutoBox* comes in a compact aluminium housing that contains the real-time hardware with a *300 MHz* Power PC, local RAM, timer and 16 Mb Flash EPROM. The flash EPROM is used for recording measurement data on the flight recorder principle. The I/O on *MicroAutoBox* may provide A/D and D/A converters, connection to the CAN bus, digital I/O and an interface to existing ECUs. For program transfer and data evaluation, a connection may be set up to a PC or notebook on an *Ethernet*, *PCMCIA* or *ISA* basis.

In addition, dSPACE may also offer extensive software support for convenient programming of *MicroAutoBox* and for measurement data evaluation. It will also shortly be possible to control E-M motors [DSPACE 2002B].

To put BBW AWB dispulsion technology on the road, it is clear that a new hardware platform needs to be developed. The platform may have a TTA with TTP/C, FlexRay or TTCAN, and may integrate the signal conditioning and performance output stages. Because of TRW's good experience with dSPACE tools, TRW is looking forward to using *TargetLink* in this next step. This may make it very easy to reuse existing functions and minimise the overall development time [DSPACE 2002A].

1.13 DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA Intelligent Vehicles

The idea behind the intelligent vehicle is that it thinks in unison with the driver. It swings into action if drivers get into trouble. If automotive vehicles go into a skid, for instance, the intelligent vehicle immediately applies perfectly balanced brakes on each wheel to stabilise it, the accelerator instantly reduces vehicle velocity the (even if the driver's foot is on it) and the steering automatically corrects itself. Or when drivers are driving at high speeds along the motorway, the intelligent vehicle automatically senses how close the drivers are to the automotive vehicle in front, and reduces vehicle speed to avoid a collision, without interfering with the driver's handling of the steering HW.

The straightforward case for RBW or XBW advanced technology is that it massively reduces cost, being cheaper to automotive vehicle manufacturers, lowering inventory variation, and simplifying assembly. But beyond this, the removal of mechanical and fluidical linkages may act as a catalyst for other, very advanced technologies such as automated lane-keeping, stability and collision avoidance algorithms. The science fiction concept of the vehicle that drives itself isn't too far over the horizon.

The vision of intelligence has been lost in the real world of automotive vehicles, and it does not, or rather not yet, exist in actual vehicles. The demands on the performance of vehicles increases, however, as they tend to be used for more sophisticated duties than simple functions. Just a few years ago, who would have imagined that intelligent vehicles on the ground could also be driven without drivers.

Unmanned intelligent vehicle may exploit an array of sensors plus **geographic position system** (GPS) to determine its position within 5 cm. Lasers mounted on the vehicle's roof continuously scanned the on/off road surface in front of the intelligent vehicle looking for cattle gates, ditches, barbed-wire fences, or disabled vehicles on the course.

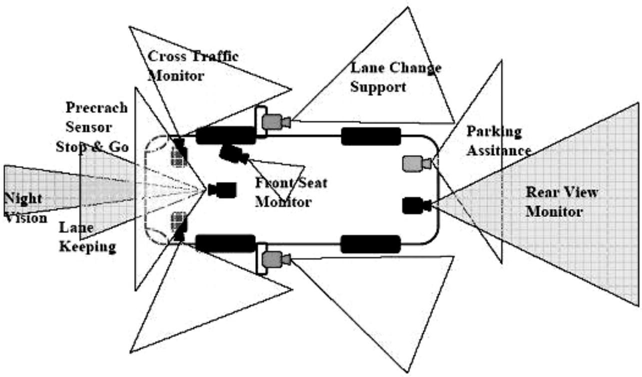

Fig. 1.45 Localisation of the day/night stereovision IR cameras [OMRON; CHEN 2003].

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While the lasers let unmanned intelligent vehicle observe only four vehicle lengths ahead, the autonomous intelligent vehicle may exploit long-range radar to scan the horizon.

Day/night stereovision IR cameras (Fig. 1.45), mounted inside the intelligent vehicle to avoid dirt spattering, may take high-resolution pictures of the course, while computer algorithms *'learned'* the terrain and mapped out an optimal driving on/off road surface [CHEN 2003].

The unmanned intelligent vehicle's brains -- for example, multi-*PentiumM* microcomputers -- may be located in the boot.

The machines ought to be shock-mounted to survive the bumps on the on/off road surface, and the E&IN mechatronic control system ought to have multiple copies of every computer program.

A thick spinal column of electrical wires connects the microcomputers to a mechatronically controlled brake, throttle, and E-M motor-driven steering column.

Figure 1.46 shows a proof-of-concept intelligent vehicle with the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem developed by Hitachi Ltd. The aim of this intelligent vehicle is to improve vehicle dynamics and layout [UEKI ET AL. 2004].

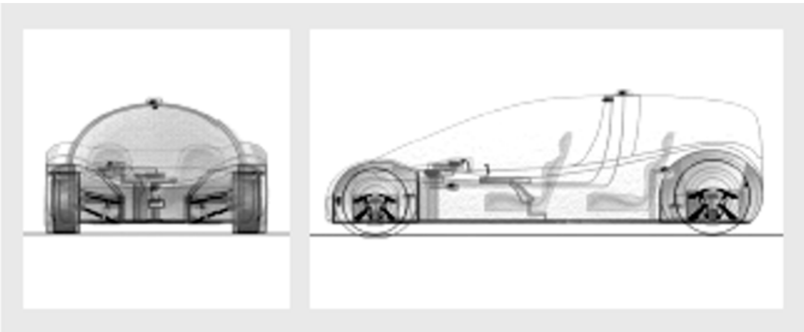

Fig. 1.46 Image of a proof-of-concept intelligent vehicle [UEKI ET AL. 2004].

Since a large proportion of traffic accidents are caused by the driver (namely, human error), adaptive driver-assistance systems -- which stop human-error accidents before they occur or alleviate damage by taking mechatronic control of the automotive vehicle just before an accident occurs -- have been actively developed, and some systems have already been implemented.

An adaptive driver-assistance system ensures safe driving by assisting the driver in the following ways: reducing driver fatigue and maintaining driver performance by supporting an driver's *'recognition'*, *'judgment'*, and *'actuation'* actions; displaying warning signs in the case that errors in certain actions are judged to be dangerous; and taking mechatronic control of the automotive vehicle in the case that the driver is unable to avoid a collision.

With environmental-recognition devices as shown in Figure 1.47, such as millimetre wave radar and vision sensors, arranged at the front, rear, as well as right and left sides of the vehicle, the circumstances of the driving environment in all directions might be detected [YOSHIDA ET AL. 2004].

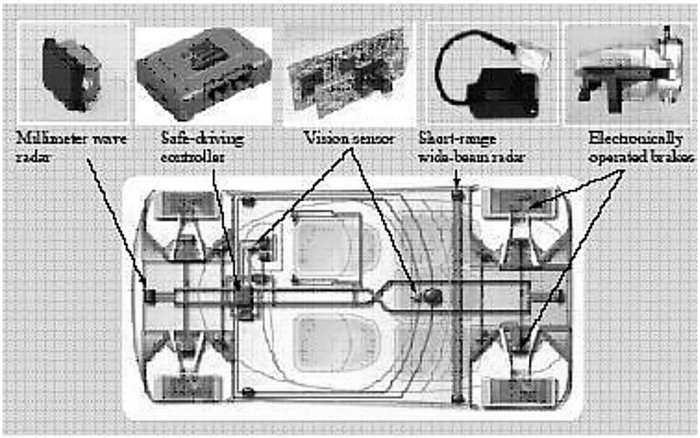

Fig. 1.47 Main components forming adaptive driver-assistance system of future [YOSHIDA ET AL. 2004].

These devices receive information from the surrounding infrastructure and a navigation system, which is then used by the safe-driving controller to mechatronically control the driving (ECE or ICE throttle), braking, and steering. This information is exchanged by means of an E&IN mounted inside the vehicle.

For intelligent vehicles, the number of functions should be greater, for instance, for electrically energised and mechatronically controlled full-time **drive-by-wire** (DBW) **four-wheel-driven** (4WD) × **brake-by-wire** (BBW) **four-wheel-braked** (4WB) × **steer-by-wire** (SBW) **four-wheel-steered** (4WS) × **absorb-by-wire** (ABW) **four-wheel-absorbed** (4WA), intelligent vehicle with extremely high mobility and steerability [FIJALKOWSKI AND TROVATO 1994; FIJALKOWSKI AND KROSNICKI 1994; FIJALKOWSKI 1995, 1997].

The DBW 4WD propulsion and BBW 4WB dispulsion, SBW AWS conversion as well as ABW 4WA suspension mechatronic control systems are designed for installation in a full-time DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA intelligent vehicle.

This brainy intelligent vehicle uses RBW or XBW advanced technology that basically eliminates the mechanical and fluidical systems that enable today's automotive vehicles to steer, brake, accelerate, and regulate suspension control. Instead, it replaces them with sophisticated and reliable mechatronic control systems. In the intelligent vehicle, electronic signals communicate the driver's intent to turn, accelerate, brake stop, and so on.

Figure 1.48 shows an overall view of the high-performance all-round energy-efficient full-time DBW 4WD × BBW 4WB × SBW 4WS ×ABW 4WA intelligent vehicle. The barycentre may be located at the centre of the vehicle's body [FIJALKOWSKI 1997].

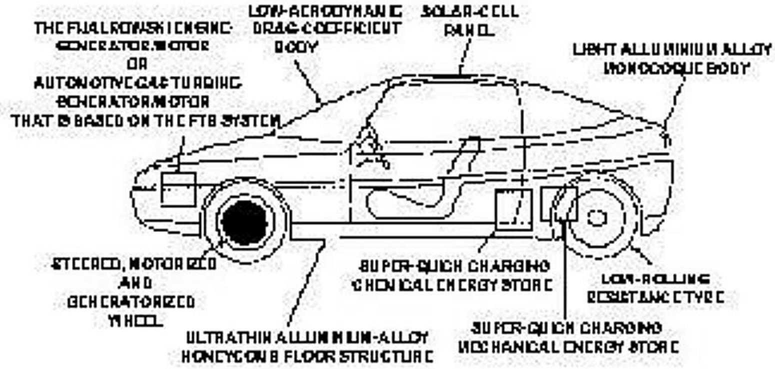

Fig. 1.48 Principle layout of a high-performance all-round energy-efficient intelligent vehicle [FIJALKOWSKI 1997]

The independent-sprung **steered, motorised and/or generatorised wheels** (SM&GW) on each side of the vehicle's body may have independent variable-damping **electro-rheological fluid** (ERF) or **giant-electro-rheological fluid (**GERF) shock absorbers' semi-active ER ABW 4WA suspensions.

The four (two front and two rear) independent-sprung SM&GWs may be driven and/or absorbed individually by four DC-AC/AC-DC macrocommutator magnetoelectrically-excited wheel-hub motors/ generators, respectively; and the angular velocity of each **front-wheel drive** (FWD) or **rear-wheel drive** (RWD) and each SM&GW may be arbitrarily controlled by a full-time RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem, incorporating DBW 4WD propulsion and BBW 4WB dispulsion, SBW AWS conversion as well as ABW 4WA suspension mechatronic control systems of the full-time DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA intelligent vehicle.

The acceleration and jerk sensor [YAMAKADA AND KADOMUKAI 1994] may be attached at the geometric centre of the intelligent vehicle. The required steering power of each FWD and/or RWD may be measured by the wheel torque gauges, which are specially designed to eliminate the bending effects of FWD and/or RWD on SM&GW bearings.

In the full-time DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA intelligent vehicle, the ECE, namely the **automotive gas turbine** (AGT) or ICE may be replaced by *'crankless'* **magneto-rheological fluid** (MRF) or **nano-magneto-rheological fluid** (NMRF) mechatronic commutator ICE, termed the **Fijalkowski engine** (FE), or AGT that is based on the **Fijalkowski turbine boosting** (FTB) system [FIJALKOWSKI 1986, 1986], and the rear or front CH-TH-F-M, DBW **two-wheel-driven** (2WD) propulsion mechatronic control system is replaced by the series hybrid **chemo-thermo-fluido-mechano-electro-mechanical** (CH-TH-F-M -E-M) or E-M DBW 4WD propulsion mechatronic control system.

The full-time DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA intelligent vehicle (Figure 1.48) has a unique type of three-mode hybrid SBW 4WS conversion mechatronic control system that incorporates adjustable torque and/or velocity **front-wheel-steering** (FWS) and **rear-wheel-steering** (RWS) gears.

When the steering **hand wheel** (HW) is turned, the power steering mechnisms are activated and push/pull the intelligent vehicle until the desired turn is made. This three-mode hybrid SBW 4WS conversion mechatronic control system has proven to be a relatively effective mobility feature because there is no power loss in braking the FWD and RWD for steering, as on a conventional FWS and or RWS automotive vehicle. When steering the full-time DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA intelligent vehicles, both FWD and RWD are still powered, providing smooth and continual power to them which allows it to achieve maximum tractive effort. The components of DBW 4WD propulsion and BBW 4WB dispulsion, SBW AWS conversion, as well as ABW 4WA suspension mechatronic control systems, are interconnected through all these heterogeneous discrete automotive functional systems [FIJALKOWSKI 1987], and the propelling (driving) and dispelling (braking) as well as suspending (absorbing/ damping) and converting (steering) power flows may be controlled by an in-vehicle RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's in-vehicle **electronic control instrument** (ECI) including in-vehicle DBW 4WD propulsion and BBW 4WB dispulsion, SBW AWS conversion, as well as an ABW 4WA suspension mechatronic control system's **electronic control units** (ECU) based on the **application specific integrated circuit** (ASIC) **neuro-fuzzy** (NF) computer or transputer **proportional integral derivative** (PID) controllers, as well as in-vehicle sensor and actuator hyposystems' **electronic control bits** (ECB), which receive commands from the **human- and/or telerobotic driver** (H&TD).

The full-time DBW 4WD × BBW 4WB × SBW 4WS × ABW 4WA intelligent vehicles may have extremely high mobility and steerability, and be driven by the same four independent-sprung SM&GWs. All four are consequently driven (motorised) and absorbed (generatorised) as well as those that are steered.

1.14 Purpose of RBW or XBW Integrated Unibody or Chassis Motion Mechatronic Control Between Individual DBW AWD, BBW AWB, SBW AWS and ABW AWA Mechatronic Controls

1.14.1 Foreword

The vertical mechatronically controlled predictive and adaptive, active E-M ABW 4WA suspension mechatronic control may make it possible to control attitude, ride comfort, stability and vehicle height and partially control the longitudinal and lateral manoeuvrability. Also, three-mode hybrid SBW 4WS conversion mechatronic control may make it possible to improve stability and controllability that may be the lateral manoeuvrability [FIJALKOWSKI 1995, 1997].

Each of these heterogeneous discrete automotive functional systems may greatly improve performances and greatly influence performances other than the intended ones.

This may be because, as shown in Figure 1.49, the basic function of an intelligent vehicle's integrated unibody motion dynamics, such as turn (lateral motion) and bounce/rebound (vertical motion), as well as drive/brake (longitudinal motion), may be closely related to each other through the on/off road-contact force of wheel tyres that may be the sole contact points between an intelligent vehicle and the on/off road surface [FIJALKOWSKI 1997].

In Figure 1.49, the heavy line shows the basic reaction, the fine line the actions against other functions, and the broken line the restrictions. As the bettering effect of more performances may be expected by increasing each automotive functional system's mechatronic control gain, the effects, other than the heavy line or the action against other automotive functional systems, cannot be ignored.

For instance, if roll is decreased by the mechatronically controlled predictive and adaptive ABW 4WA suspension mechatronic control system, the yaw response may often be weak.

Meanwhile, if yaw responses of the three-mode hybrid SBW 4WS conversion mechatronic control system may be bettered, roll convergence may also weaken. Under a steady state, the roll-understeer function cannot be used and roll-oversteer disposition may appear by eliminating the roll.

Therefore, individual control of each dynamical automotive functional mechatronic control system may often affect performances other than the intended ones. It is important for a better integrated-performance of intelligent vehicles to eliminate unwelcome actions of different forces.

Cooperative control of each dynamical automotive functional mechatronic control system may allow the whole intelligent vehicle that is the dynamical automotive vehicle mechatronic control hypersystem to provide a balanced performance.

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Intelligent Systems, Control and Automation: Science and Engineering 47,
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Moreover, performances may be improved by the aggregation of individual controls of each dynamical automotive functional mechatronic control systems.

The proposed in-vehicle RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's **electronic control instrument** (ECI) has a concentrical configuration in which all in-vehicle DBW 4WD propulsion, BBW 4WB dispulsion, ABW 4WA suspension, and SBW 4WS conversion mechatronic control systems' **electronic control units** (ECU) are centred in one place.

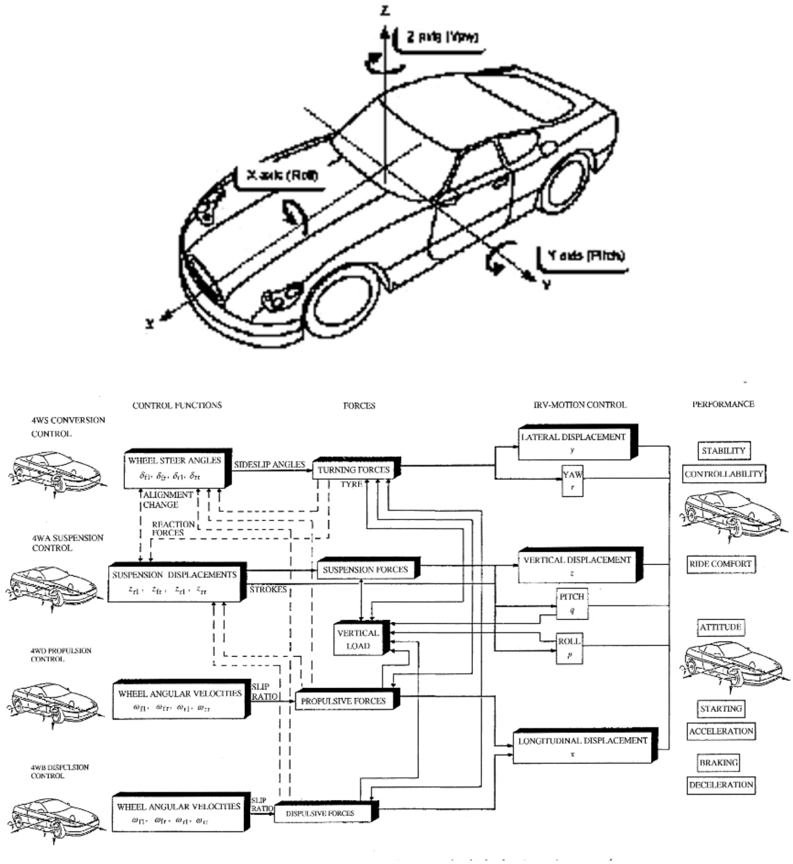

Fig. 1.49 Cooperative intelligent vehicle's integrated unibody motion mechatronic control [FIJALKOWSKI 1997].

This tends to make the electrical connections (cabling) connected to intelligent vehicles, as well as reciprocating E-M actuators and rotating E-M motors, long. It stands to reason that a hybrid (concentrical/dispersal) configuration, shown in Figure 1.50, ought to be used [FIJALKOWSKI 1997].

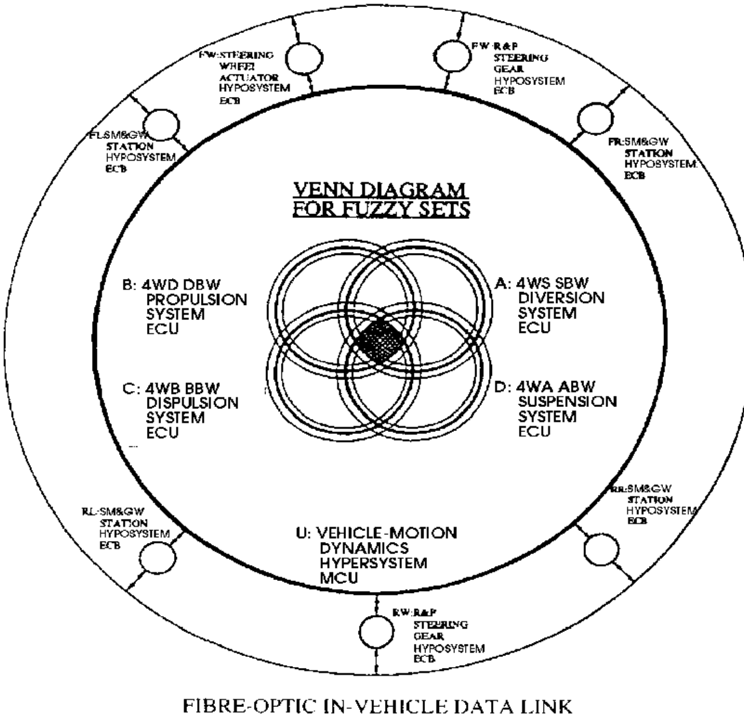

Fig. 1.50 Concept of the intelligent vehicle's integrated unibody, space-chassis or body-over-chassis motion mechatronic control between SBW 4WS, ABW 4WA, DBW 4WD and BBW 4WB mechatronic controls [FIJALKOWSKI 1997].

Exclusive **in-vehicle sensor** () and actuator hyposystems' **electronic control bit** (ECB) placed at each SM&GW station, may be combined with a bisensual - direction **fibre-optic** (FO) in-vehicle data link for information exchange.

Thus, the in-vehicle RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's ECI may be placed at the centre, which may do the calculations for the whole intelligent vehicle's integrated unibody or chassis mechatronic control. It may also exchange data between in-vehicle SBW 4WS conversion, ABW 4WA suspension, DBW 4WD propulsion and BBW 4WB dispulsion mechatronic control systems' ECUs, which may be translated to the IVS and actuator hyposystems' ECBs at the SM&GWs.

In this way, it may be possible to fit together reciprocating E-M actuators and rotating E-M/M-E motors/generators with unified ones and their IVS and actuator hyposystems' ECBs, which may seem to be a promising intelligent vehicle's unibody or chassis motion mechatronic control for the future. The distinction between randomness and imprecisions can perhaps be being made clearer by considering of crisp or fuzzy sets.

The universal set U may be an in-vehicle RBW or XBW integrated unibody, space-chassis or body-over-chassis motion mechatronic control hypersystem's ECI for the intelligent vehicle's integrated unibody or chassis motion mechatronic control and the four sets A, B, C and D may be the in-vehicle SBW 4WS conversion, ABW 4WA suspension, DBW 4WD propulsion and BBW 4WB dispulsion mechatronic control systems' ECUs for SBW 4WS, ABW 4WA, DBW 4WD and BBW 4WB mechatronic controls, respectively. The union is the crisp or fuzzy set of all the in-vehicle SBW 4WS conversion, ABW 4WA suspension, DBW 4WD propulsion, and BBW 4WB dispulsion mechatronic control systems' ECUs for SBW 4WS, ABW 4WA, DBW 4WD or BBW 4WB mechatronic controls or all, i.e. the intelligent vehicle's integrated unibody, space-chassis or body-over-chassis motion mechatronic control.

The intersection is the crisp or fuzzy set of all the in-vehicle SBW 4WS conversion, ABW 4WA suspension, DBW 4WD propulsion, and BBW 4WB dispulsion mechatronic control systems' ECUs for all individual SBW 4WS, ABW 4WA, DBW 4WD, and BBW 4WB mechatronic controls. The *Venn* diagram shown in Figure 1.50 may adequately explain the primary purpose of the intelligent vehicle's integrated unibody, space-chassis or body-over-chassis motion mechatronic control between individual dynamical automotive functional mechatronic control systems.

"SBW 4WS + ABW 4WA + DBW 4WD + BBW 4WB" in Figure 1.50 represents simple aggregation of individual SBW 4WS, ABW 4WA, DBW 4WD, and BBW 4WB mechatronic controls, while "SBW 4WS × ABW 4WA × DBW 4WD × BBW 4WB" represents the intelligent vehicle's integrated unibody, space-chassis or body-over-chassis mechatronic control between SBW 4WS, ABW 4WA, DBW 4WD, and BBW 4WB mechatronic controls which shows "SBW 4WS × ABW 4WA × DBW 4WD × BBW 4WB" improves performance more than "4WS + 4WA + 4WD + 4WB" does. This intelligent vehicle's integrated unibody or chassis motion mechatronic control between dedicated automotive functional mechatronic controls is sophisticated because it may consist of many components.

1.14.2 Three-Mode Hybrid SBW 4WS Conversion Mechatronic Control System

A conventional **rack-and-pinion** (R&P) steering gear, shown in Figure 1.51, may be used as a base [FIJALKOWSKI 1993]. The tubular linear DC-DC ASIM macro-commutator conversion-actuator E-M motor is placed concentric to the rack and drives it, which produces the necessary rack force that necessitates being in the order of 12 kN for a full-time three-mode hybrid E-M SBW 4WS conversion mechatronic control system. Hardware for the all-electric SBW 4WS conversion gear is also shown in Figure 1.51 [FIJALKOWSKI 1997].

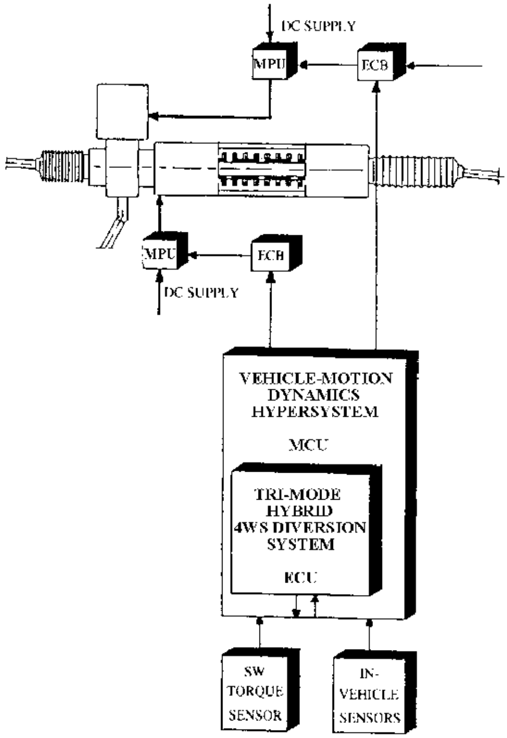

Fig. 1.51 Principle layout of an E-M R&P steering gear with the tubular linear DC-AC macrocommutator magnetoelectrically excited steering-actuator motor and its hardware (MC – macrocommutator; ECI – electronic control instrument; ECU – electronic control unit; ECB – electronic control bit) [FIJALKOWSKI 1997].

The steering converts the steering HW rotary motion into a turn motion of the SM&GWs of the full-time SBW 4WS × ABW 4WA × DBW 4WD × BBW 4WB intelligent vehicles. A perfect three-mode hybrid SBW 4WS conversion mechatronic control system should use not only a feedback control for an intelligent vehicle stability, but also a feedforward control signal for better steering response [IRIE ET AL. 1986; HOSAKA ET AL. 1989].

The three-mode hybrid E-M SBW 4WS conversion mechatronic control system may be vehicle-velocity controlled by an in-vehicle SBW 4WS conversion mechatronic control systems' ECU based on the ASIC NF PID controller, and sensor and actuator hyposystems' ECBs for each of the SM&GW stations. Tighter turning and reduced scrub may be the benefits.

The series hybrid DBW 4WD propulsion mechatronic control system mentioned may allow the omission of the conventional **front-wheel-drive** (FWD) and **rear-wheel-drive** (RWD) as well as **centre-wheel-drive** (CWD) M-M differentials.

Therefore a superimposed inter-vehicle's integrated unibody or chassis control may be necessary to co-ordinate both FWD and RWD units. Both front and rear independent-sprung SM&GWs may be controlled individually.

Obviously, the distribution of wheel torques can influence the driving behaviour very much. If both front and rear wheel torques are equal, the DBW 4WD propulsion mechatronic control system may behave like a conventional one with an M-M differentials lock. In practice, each distribution of wheel torques may be possible within the technical limits. This means, for instance, maximum positive wheel torques at the right-hand front and rear SM&GWs and maximum negative wheel torques at the left-hand ones at the same time.

Such a didtribution of the **inner-front-wheel** (IFW) and/or **inner-rear-wheel** (IRW) torques may lead to yaw torques around the vertical axis, that is, a turn of the intelligent vehicle. Consequently, the influence of the DBW 4WD propulsion mechatronic control system on the driving behaviour of the intelligent vehicle can be compared with a torque-steering mode of three-mode hybrid E-M SBW 4WS conversion mechatronic control system.

Thus, the torque steering can be used to control the yaw motion of the intelligent vehicle simultaneously with the conventional **front-wheel-steering** (FWS) and **rear-wheel-steering** (RWS) mechanisms. If a yaw angular velocity sensor is applied, it may be useful to combine an open-loop control with superimposed closed-loop control of the yaw angular velocity, as described in [INOE 1991].

One possibility to control the yaw angular velocity is the application of an in-vehicle SBW 4WS conversion mechatronic control system's ECU based on the ASIC conventional PID controller. Also, an in-vehicle SBW 4WS conversion mechatronic control system's ECU based on the ASIC NF PID controller can already give satisfactory results with little knowledge of the lateral-motion dynamics of the three-mode hybrid E-M SBW 4WS conversion mechatronic control system, which has to be controlled.

An NF reasoning-based lateral intelligent vehicle's integrated unibody or chassis motion mechatronic control may be easier to adapt.

Thus, using torque and/or velocity controls of the DBW 4WD propulsion mechatronic control system's inner SM&GWs can increase this effect especially at recuperative braking with the inner SM&GWs acting as the AC-DC macrocommutator magnetoelectrically excited in-wheel-hub M-E generators, because the front gravitational forces onto the intelligent vehicle become greater than the respective rear ones. At the same creep, this leads to greater horizontal (longitudinal and lateral) forces.

Figure 1.52 shows the three-mode hybrid E-M SBW 4WS conversion mechatronic control system configuration [FIJALKOWSKI 1997].

The rear independent-sprung SM&GWs may be steered according to the front-wheel steer angle by installing the steering mechanism to steer the rear SM&GWs at the rear suspension and electrically connecting it with the front steering mechanism by electrical connections (cabling) only.

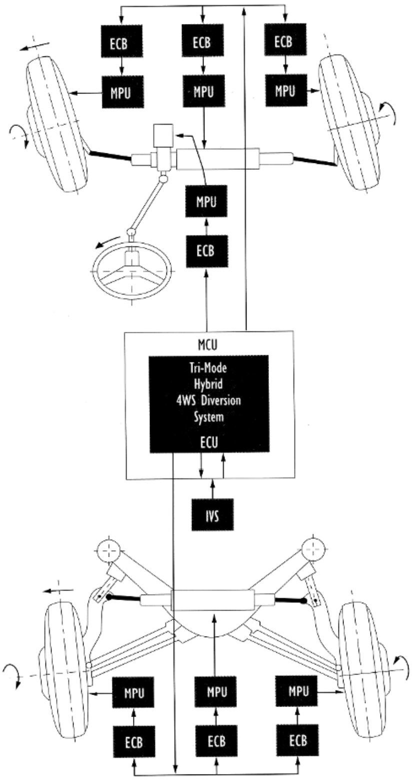

Fig. 1.52 Principle layout of a full-time three-mode hybrid E-M SBW 4WS conversion mechatronic control system with the front and rear E-M R&P steering gears, two right-side and two left-side SM&GWs, the steering HW and its hardware (MC – macrocommutator; ECI – electronic control instrument; ECU – electronic control unit; ECB – electronic control bit) [FIJALKOWSKI 1997, 2000].

The relation of steer angles between the front and rear SM&GWs may be mechatronically controlled according to the front- or backward movement of the intelligent vehicle and the vehicle velocity (speed).

1.14.3 Predictive and Adaptive, Semi-Active ABW 4WA Suspension Mechatronic Control System

In vibration control, the ABW 4WA suspension mechatronic control system's ECU based on the ASIC NF PID controller, may first obtain five system-state variables from the sensors. Then, the on/off road-surface condition, whether smooth or rough, may be judged by statistics operations of relative vertical velocities to select control gains.

From these data, the control amounts may be calculated, and the control DC voltages of the damping force **electro-rheological** (ER) fluidical valves may be decided. Furthermore, floor vibration due to other SM&GW manoeuvres, may be compensated based on the gains selected by its mode and the SM&GW system-state variables of all the SM&GWs. Vibration control may be realised with the ER fluidically-suspended intelligent vehicle. Position US sonars or linear potentiometer or electromagnetic sensors alongside the variable-damping ERF shock absorbers, may read the on/off road surfaces. The cornerstone of ERF automotive high-tech has been the ER fluidic valve and the resultant ERF shock absorber. In the ER fluidical valve, the ERF is pumped through a channel capacitor wherein the DC voltage difference between the walls may be varied to regulate the oily-fluid flow resistance up to the point where the oily-fluid solidifies and flow ceases [JORDAN AND SHAW 1989].

A schematic diagram of a force-control-based predictive and adaptive, semi-active ABW 4WA suspension mechatronic control system with the ERF shock absorber and ER fluidical valve is shown in Figure 1.53 [FIJALKOWSKI 1997].

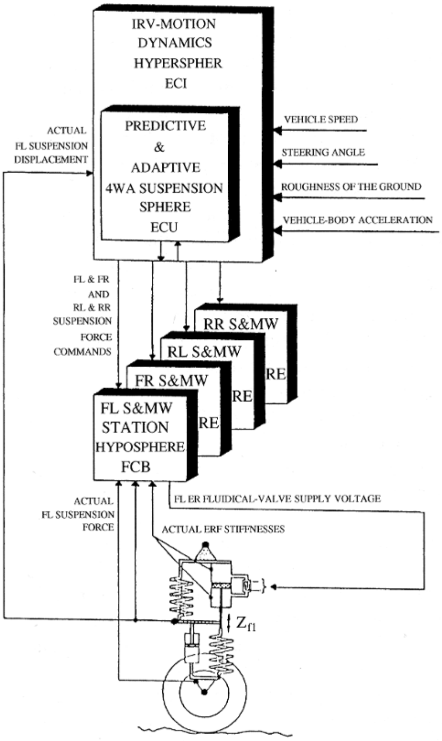

Fig. 1.53 Principle layout of a full-time force-control based predictive and adaptive, semi-active ABW 4WA suspension mechatronic control system with the ERF shock absorber, ER fluidic valve and its hardware (ECI – electronic control instrument; ECU – electronic control unit; ECB – electronic control bit) [FIJALKOWSKI 1999].

Variable-damping ERF shock absorbers exploit the property of electric-field-dependent stiffness for a virtually limitless range of damping response.

When one considers the milliseconds response time involved, and exciting automotive high-tech in position US sonars for anticipating on/off road-surface roughness, it is easy to understand what motivates competitors in the automotive industry to be the first to offer an ultra smooth, AI ASIC computer- or transputer-controlled predictive and adaptive, semi-active ABW 4WA suspension mechatronic control system for controlling stability, ride comfort, attitude, and vehicle height.

An in-vehicle ABW 4WA suspension mechatronic control system's ECU based on the ASIC NF PID controller, may be responsible for achieving commanded forces despite disturbances and non-linearities.

This force-servo approach may facilitate the design of the in-vehicle RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's ECI, but there may also be systems where the DBW 4WD propulsion mechatronic control system's ECUs for the SM&GWs may only be used for some local stabilisation, but the in-vehicle RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem's ECI may directly inject control signals into the ER fluidical valves.

In general, a large number of sensors, four ER fluidic valves, and a large number of mechanical **degrees of freedom** (DoF) of an intelligent vehicle may create a demanding multi-variable control problem. All motion interacts. Control designs must also take the non-linearities of fluidics into consideration.

In the attitude control, the reactive real (measured) displacements between the top and the bottom of the suspensions may coincide with the aimed displacements by feedback controls.

In addition, for immediate reduction in roll angles caused by steering manoeuvres, feed-forward controls based on the estimation of roll angles from steer angles, and compensation of roll angles based on changes in ABW 4WA suspension mechatronic control system's electric-field-dependent stiffnesses due to lateral acceleration will be performed. Attitude controls for roll and pitch directions decreases low-frequency vibration.

Acceleration in the horizontal (longitudinal and lateral) directions of a full-time SBW 4WS × ABW 4WA × DBW 4WD × BBW 4WB intelligent vehicle during turning, acceleration, and deceleration may be detected by the acceleration and jerk sensor [YAMAKADA AND KADOMUKAI 1994] or the other acceleration sensor, that is the so-termed *g* sensor [YOKOYA ET AL. 1990] and the control signal, may be given to the linear control ER fluidical valve of each wheel to control the shock-absorber-cylinder ERF solidification.

As a result, attitude change, including roll and pitch, may be eliminated and the intelligent vehicle's attitude may be kept constant.

To compensate for the delay of control response, roll may be controlled by foreseeing rolling with the steer angles and vehicle velocity sensors at the beginning of turning.

The predictive and adaptive, semi-active ABW 4WA suspension mechatronic control system detects the abruptness of an on/off road bump almost quickly enough to react before the shock of the impact reaches the intelligent vehicle spring.

In practice, the predictive and adaptive, semi-active ABW 4WA suspension mechatronic control system swallows high-speed undulations, prevents bottoming, and retains a smooth ride on harsh on/off road surfaces.

1.14.4 Series Hybrid-Electric DBW 4WD Propulsion Mechatronic Control System

An advantage of series hybrid-electric DBW 4WD propulsion mechatronic control system may be that a novel form of ICE can be used, designed specifically for high efficiency constant reciprocating velocity and power operation and minimum emission. Other longer-term options include future hydrogen-fuelled ICEs and fuel cells, with the prospect of the virtually **zero emission vehicles** (ZEV).

The DBW 4WD propulsion mechatronic control system using SM&GWs with the DC-AC/AC-DC macrocommutator magnetoelectrically-excited in-wheel- hub motors/generators may eliminate the necessity of axles and drive shafts, which may allow a separate suspension of each independent-sprung SM&GW (Fig. 1.54) [FIJALKOWSKI 1997].

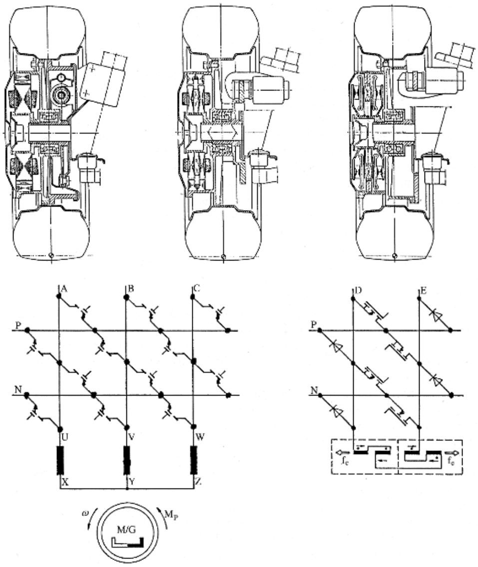

Fig. 1.54 Principle layouts of three different independent-sprung, planetary gearless, SM&GWs with rotary DC-AC/AC-DC macrocommutator (unwound outer rotor and wound inner stator) in-wheel-hub E-M/M-E motors/generators and tubular linear DC-DC macrocommutator drum-, disc- or ring-brake actuator E-M motors [FIJALKOWSKI 1997].

The rotating housing is made in the form of a wheel hub, designed to fit the standard rim sizes on the automotive market.

The DC-AC macrocommutator magnetoelectrically-excited in-wheel-hub-motors' transmission offers complete freedom in the design of the intelligent vehicle.

While the basic principles of hybrid-electric DBW 4WD intelligent vehicles remain the same for virtually all classes of intelligent vehicles, the actual arrangements vary -- for instance, some may have 2WD that is either FWD or RWD, and others 4WD.

Another requirement for the hybrid-electric DBW 4WD propulsion stems from the fact that, when the intelligent vehicle is cornering, the outer SM&GWs must roll faster than the inner ones which may be traversing circles of smaller radii, yet the mean value of the wheel velocity, and therefore both the reciprocating piston velocity of the **Fijalkowski engine** (FE) and the translational velocity of the vehicle, may be required to remain constant.

So far as effectiveness of traction is concerned, FWD is better than RWD, especially on difficult terrain, including ice or snow.

This is partly because the mass of the ICE on the front SM&GWs enables them to grip the on/off road surface better, which also applies to rear-engine RWD intelligent vehicles.

Principally, however, the advantage is gained by virtue of the fact that the propulsive force, i.e. tractive effort is always delivered along the line in which the front SM&GWs are steered.

Another factor is that front SM&GWs tend to climb out of holes or ruts, whereas rear SM&GWs tend to thrust the front undriven wheels deeper down and, in any case, not necessarily in the direction in which they are steered.

The use of full-time SBW 4WS × ABW 4WA × DBW 4WD × BBW 4WB intelligent vehicles may grow rapidly in the future. This is due to the increasing demand for intelligent vehicles with higher performance and power.

It is well known that the distribution of gross tractive effort (thrust) and slip between the front and rear SM&GWs of full-time DBW 4WD and/or SBW 4WS intelligent vehicles has considerable effect on the efficiency of operation.

Differences in theoretical values of the wheel velocity (wheel velocity when no slip or skid occurs) and the concept of cooperation between the front and rear SM&GWs generally affect the gross tractive effort and slip distribution.

Analysis and experiments indicate that the development of new-concept axleless FWD and RWD as well as CWD E-M differentials which can provide the optimum distribution of gross tractive effort and slip between front and rear SM&GWs, is of practical importance.

Typically, in FWD and RWD as well as CWD E-M differential layout, Figure 1.55, a series electrical connection (cabling) is interposed between the electrical power source, that is the FE and/or CH-E/E-CH storage battery power-outputs, as well as FWD and RWD units [FIJALKOWSKI 1997].

The function of a series electrical connection is to transfer the drive electrical energy from the electrical energy source to both the front and/or rear SM&GWs.

The CWD E-M differential in the series electrical connection is also necessary to distribute the drive equally between the front and rear SM&GWs and to allow for the fact that, when the intelligent vehicle is driven in a circle, the mean values of the wheel velocity of the front SM&GWs is different from that of the rear SM&GWs and therefore the values of the wheel velocity of the two FWD and RWD units must differ too.

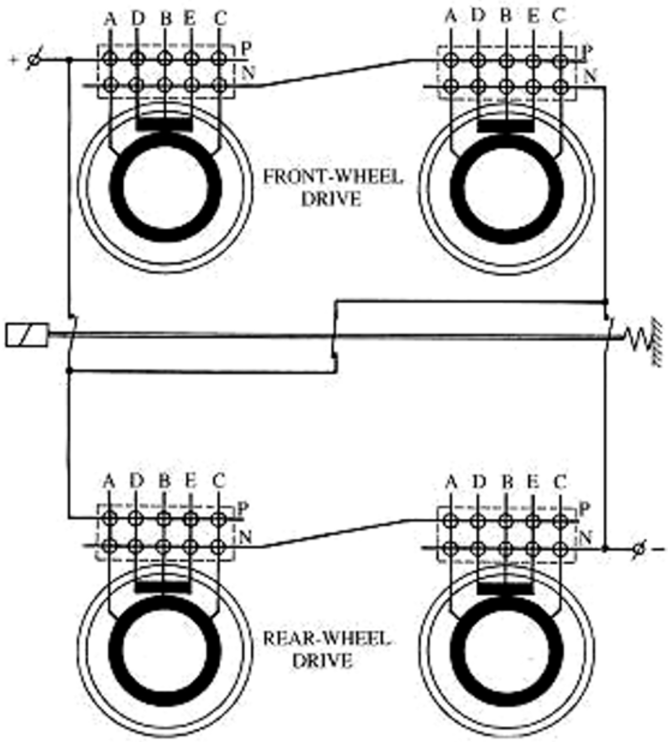

Fig. 1.55 Elementary wiring connections for hybrid-electric full-time DBW 4WD propulsion and BBW 4WB dispulsion mechatronic control systems with the torque-proportioning FWD and RWD as well as CWD E-M differentials [FIJALKOWSKI 1997].

Other factors include different rolling radii of wheel tyres owing to, for example, manufacturing tolerances, different degrees of wear and, perhaps, different wheel-tyre pressures.

Provision is usually made for locking this CWD E-M differential out of operation, to improve the performance and reliability of traction when the intelligent vehicle is driven on slippery ground.

For intelligent vehicles intended mainly for operation on soft ground, the CWD E-M differential may be omitted from the drive E-M powertrain line, but some means of disengaging 4WD, leaving only single pair of SM&GWs to do the driving, is generally provided for use if the intelligent vehicle is required to operate on metalled roads.

As is well-known from the principle of *Ackerman*'s 2WS SBW conversion mechatronic control system, the front SM&GWs always tend to roll further than the fixed-geometry rear SM&GWs, because their radius of turn is always larger, a parallel electrical connection (cabling) can be interposed between the **electrical energy source** (EES) as well as FWD and RWD units and the CWD E-M differential may be omitted from the drive E-M powertrain line (see Figure 1.55).

In practice, this usually takes the form of the two separate FWD and RWD units, single on each front or rear SM&GWs, on which there are rotary controls which can be locked by the H&TD, but they has to stop and get out to do so.

As soon as the H&TD again drives his intelligent vehicle on firm ground, however, s/he must remember to unlock the FWD and RWD units. Should the rear SM&GWs lose traction, on the other hand, and therefore tend to rotate further than the front ones, the drive may automatically be transferred to the front SM&GWs, even if they are in the freewheeling mode.

1.14.5 Anti-Wheel-Lock and Anti-Wheel-Spin BBW 4WB Dispulsion Mechatronic Control System

During unexpected conditions, for instance, without warning braking on rain-slick or icy on/off road surfaces, the wheels may lock and the intelligent vehicle may slide in a direction completely unrelated to the H&TD's steering HW operation. Under these conditions, skilled and experienced drivers release the left-foot brake pedal to recover wheel-locking, and depress the left-foot brake pedal when they obtain wheel recovery.

Such braking operations are repeated to stop the intelligent vehicle stably and efficiently. These countermeasures are acted on automatically by an in-vehicle BBW 4WB mechatronic control system's ECU based on the ASIC NF PID controller in the anti-wheel-lock and anti-wheel-spin BBW 4WB dispulsion mechatronic control system. The relationship of the wheel-slip ratio and the friction coefficient between the on/off road surfaces and wheel-tyre differs according to the on/off road surface conditions and vehicle velocity. The friction coefficient may peak at a slip ratio of 0.2 on a particular on/off road surface, but at 0.05 on another one.

Thus, how to determine the desired command signal, under the moment-to-moment on/off road-surface conditions and vehicle velocity, becomes the major aspect in stably and efficiently stopping the intelligent vehicle.

Besides, in an anti-wheel-lock and anti-wheel-spin BBW 4WB dispulsion mechatronic control system based on optimal conventional ASIC PID controller, feedback gain must be determined within certain limits so as to eliminate wheel velocity fluctuations. With this type of gain, a problem of slow responsiveness results when the on/off road-surface conditions change unexpectedly causing rapid variation in the disturbance to the conventional ASIC PID controller.

Realising that on/off road-surface conditions (on/off road friction coefficient) are unintelligible or uncertain factors, which cannot be accurately measured, MATSUMOTO ET AL. [1987] began to apply **fuzzy logic** (FL) in order to separate the two problems discussed above. A driver perceives on/off road-surface conditions by visual sensation and senses wheel slippage by bodily sensation. By comparison with past experience, the driver decides on a given amount of the braking force to be applied, that is, left-foot brake pedal pressure. While FL is applicable to qualitative approaches, it can replace perception and sense. Thus, a common in-vehicle RBW XBW integrated unibody or chassis motion mechatronic control hypersystem's ECI including BBW 4WB dispulsion mechatronic control system's ECUs based on the ASIC NF PID controllers, ought to be used.

The drum-, disc- or ring-brake actuator voltages may be measured and supplied to the BBW 4WB dispulsion mechatronic control system's ECU based on the ASIC NF PID controller as analogue voltage signals, which are then converted by high-speed high- resolution **analog-to-digital** (A/D) converters.

The conventional ASIC PID controller based on the optimal one may be applied to the part that can be modelled mathematically. On the other hand, an ASIC NF PID controller ought to be applied to the part that cannot be modelled mathematically, containing non-linear elements. It may be described by IF-THAN-ELSE rules.

Fundamentally, in case of braking the intelligent vehicle, the front SM&GWs must lock earlier than the rear ones, otherwise the intelligent vehicle's stability is dangerously lost and the intelligent vehicle would skid, because the locked wheel tyre cannot contribute to side-stability. Thus, yaw torques cannot be balanced. Consequently, in intelligent vehicles without the anti-lock and anti-spin BBW 4WB dispulsion mechatronic control system, the braking force between front and rear SM&GWs is distributed in a relation of approximately 0.7 to 0.3 [NEWTON ET AL. 1987].

If an anti-wheel-lock and anti-wheel-spin 2WB BBW dispulsion mechatronic control system is built in, it always acts on the RWD, never only on to the FWD. The co-ordination of a recuperative braking with the steering HWs acting as the AC-DC macrocommutator magnetoelectrically-excited wheel-hub generators in order to optimise recuperation of kinetic mechanical energy, is very difficult for FWD or RWD DBW propulsion mechatronic control systems, especially for RWD ones. In addition, in intelligent vehicles with a FWD or RWD DBW propulsion mechatronic control system, the kinetic mechanical energy contribution of the **specific kinetic mechanical energy** (SKME) can only be partly recuperated into the CH-E/E-CH storage battery and/or the high-density mechanical energy-storing high-speed **twin-disc ultraflywheel** (TDUF) with the AC-DC/DC-AC macrocommutator twin-disc-flywheel generator/ motor. Series hybrid-electric DBW 4WD propulsion mechatronic control systems offer the possibility of recuperative braking, that is recuperation and conversion of kinetic mechanical energy at each SM&GW until the maximum torque and/or limit of adhesion is reached. Then, the activity of drum, disc or ring **electro-mechanical brakes** (EMB) must also be controlled by an anti-wheel-lock and anti-wheel-spin BBW 4WB dispulsion mechatronic control system to avoid the locking of a single or all SM&GWs.

The optimisation of recuperation is only useful if many changes in the vehicle velocity occur and/or distance between two following stops of the intelligent vehicle is short.

Otherwise, the SKME, which can be used for recuperation, is negligible compared to the **specific basic mechanical energy** (SBME) that is necessary to overcome the rolling resistances of SM&GWs. This means, a DBW 4WD propulsion mechatronic control system that is optimised towards recuperative braking is especially interesting for intelligent vehicles which are used in urban and rural areas.

1.14.6 Conclusion

In the intelligent vehicle of the future, full-time RBW or XBW integrated integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hyper-system, including full-time AWD BBW propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems and in-vehicle route guidance navigation and collision avoidance systems, might not only do much of the work, they might also monitor themselves, respond adaptability to changing demands and emergencies, and have the intelligence to keep the heterogeneous discrete automotive functional systems operating smoothly and efficiently. Such is the hope of the author of this book who is working towards this goal using several AI techniques.

Telerobotic-driven unmanned intelligent vehicles may never become a reality in on/off road transport, since there may always be situations in which decisions must be left to the driver. Because of this, automotive high-tech may continue to give the driver the final responsibility for the decisions.

The foregoing is a brief and very personal selection of some aspects of intelligent automotive systems tackled in a systems approach. A full and complete point of view can be achieved from a study of the increasing literature on this subject. The author has little doubt that much of the material presented herein may have been subsumed by more general ones, or perhaps by an alternative of more evident utility, even before the book is published.

1.15 Discussion and Conclusions

Automotive mechatronics escalation today is necessary thanks to [HENNING 2006]:

- ❖ Provisions for automotive vehicle manufacturers for downgraded fuel consumption, low pollutant emission standards, advanced safety and progressive comfort can only be realised through even smarter full-time RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems;
- ❖ 90% of actual innovations (relative to characteristic enhancements) of automotive vehicles emerge in the domain of automotive mechatronics;
- ❖ For first-class automotive vehicles 35% of the expenses are full-time RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems – this trend is escalating.

Challenges of automotive mechatronics escalation are as follow [HENNING 2006]:

- ❖ Sophistication of DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, is still increasing:
  - ➢ Available existing DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, are getting more and more complex;
  - ➢ Advanced emerging DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, are added;
  - ➢ Gradually DBW AWD propulsion and BBW AWB dispulsion, ASBW AWS conversion, as well ABW AWA suspension mechatronic control systems, are networked together into the full-time RBW or XBW integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hypersystem;
  - ➢ Bus systems are integrated with each other;
  - ➢ Sensors and ASIC microcontroller signals are shared;
  - ➢ Functions are distributed over several ASIC microcontrollers.
- ❖ Challenge: Establish the sophistication of automotive mechatronics in the automotive vehicle as controllable, relating to quality and reliability as well as security.
- ❖ Sophisticated DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion, as well as ABW AWA suspension mechatronic control systems, can only be managed by a development process using seamless integrated simulation tools for *'virtual test driving'*:
  - ➢ Software in the Loop (SIL) – Simulation:
    - o Architecture development;
    - o System integration;
    - o Parameter optimisation.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_15,

- Hardware in the Loop (HIL) – Simulation:
  - Diagnostics;
  - Fail-safe:
  - Performance.
- Virtual Test Driving (VTD):
  - System tuning;
  - Random testing;
  - Validation.

RBW or XBW integrated unibody or chassis motion mechatronic control advanced technology has been under development for a number of years. Using the hypersystem, automotive vehicle manufacturers intend to replace the mechanical linkages within the automotive vehicle with mechatronic connections.

The advantages of such a hypersystem are obvious from a design standpoint, explicitly:

- ❖ More efficient propulsion (driving) and dispulsion (braking), conversion (steering) as well as suspension (absorbing/damping);
- ❖ Automotive industry standardisation;
- ❖ Less fuel consumption;
- ❖ Safety, comfort and reliability;
- ❖ Design freedom.

Mechatronic design may be physically and mathematically modelled on a computer and tested prior to creating a prototype.

RBW or XBW is the generic term used when clunky and inaccurate mechanical systems are replaced with precise mechatronic sensors and E-M actuators.

Many of the advancements to come as a result of the 42 V_{DC} bus, may be lumped into the category of RBW or XBW. This RBW or XBW trend has been evident in the automotive industry for years.

The trend may be seen in the implementation of fuel injectors to replace their bulky counterpart, the carburettor, and in the development of mechatronically controlled brakes, known as ABS.

RBW or XBW is not a new program to implement, but a term capturing the existing trend of development and pointing in the direction of future advancements. Many are hesitant to move to RBW or XBW for reliability and safety concerns. Conventional mechanical systems have stood the test of time and have proven to be reliable.

More than a decade ago, the U.S. Air Force went through a similar struggle in the change-over from mechanical and fluidic linkages to electrical connections in aircraft. The now indispensable FBW endured much scrutiny at its conception. An electrical failure could be catastrophic to any RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem.

In military applications, such a failure would be totally unacceptable. Military craft are required to function in some of the most extreme conditions in the world with unacceptable consequences of failure. Redundant electrical systems were developed and have been implemented in both military and commercial aircraft over the past decade.

FBW has allowed improvements to the military that would have otherwise been impossible. New standards being met by military aircraft could only be achieved using RBW or XBW.

The latest U.S. Air Force development, the *F-22 Raptor*, is fully FBW, enabling it to perform manoeuvres once thought impossible. RBW or XBW integrated unibody or chassis motion mechatronic control systems are now being incorporated into military land units as well.

The innovative *Grizzly Tank*, the U.S. Army's high-tech ground-assault vehicle, uses RBW or XBW. The military has proven that RBW or XBW may be both reliable and highly effective [BRAUER 2001; TREVETT 2002].

For instance, the recent launch of Citroen's ambitious *C5-by-Wire* hatchback, with its mechatronically controlled brake, throttle, and radical steering system, marks yet another high-profile advance for so-termed RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems that replace traditional mechanical linkages with mechatronic ones. The humble parking brake may be the most likely part of modern automotive vehicles to reap the benefits of RBW or XBW.

Electronic parking brakes (EPB) engage automatically to prevent, for example, a vehicle stopped at a traffic light on a hill, from rolling backwards when the accelerator is released.

The workhorse RBW or XBW application, unlike **electrical power steering,** (EPS), that simply replaces a mechanical system with a mechatronic equivalent, EPB actually adds new functionality to the automotive vehicle, and may be installed in automotive vehicles of any size and power.

EPB may prove more popular in Europe than in the USA or Asia, some automotive scientist and engineers believe; because of the prevalence, they're of **manual transmission** (MT) automotive vehicles with their greater risk of rolling back on hills. Europe's frequently hilly environments and its technological lead in active safety systems should also lead to earlier adoption.

RBW or XBW braking adds a measure of safety to the automotive vehicle, since it may also form part of pre-crash systems that reduce vehicle speed when sensors detect an impending collision.

For instance, ABI Research's study, *"X-by-Wire: Market Strategies for Electronic Power Steering, Brake-by-Wire and Electronic Parking Brake Systems"* presents regional forecasts for the period 2004 -- 2012, and discusses legislative and implementation issues, as well as the implications of rising fuel costs and **hybrid-electric vehicles** (HEV).

The study also offers detailed profiles of all the major industry players [ABIRESEARCH 2005].

RBW or XBW Revolution

- ❖ RBW or XBW applications are coming up;
- ❖ The TTP/C vs. FlexRay™ battle is still on-going and dependability is a key aspect;
- ❖ RBW or XBW deployment may push the automotive vehicle in the safety critical systems area.

In the next years, RBW or XBW technology may emerge that intends to replace mechanical or fluidical control systems by mechatronic control systems, especially for critical functions such as driving, braking, steering, and absorbing/damping. This requires stringent proof that these innovative vehicles may ensure the safety of driver, passengers, vehicle, and environment.

A key point for the dependability of an embedded system is the communication architecture. For instance, within the Research Team for Technology, CARAMELS, a comparative study between networks (TTP/C, FlexRay™, and TTCAN) that are candidates to support RBW or XBW application has been done.

The result is a clear and fair classification of their functions and of the services that they provide to ensure dependability properties.

To reach this goal, automotive scientists and engineers have developed a physical model that allows identifying, at each layer (according to the OSI physical model of ISO), faulting tolerant services that are relevant for satisfying the application requirements [WILWERT ET AL. 2003B, 2003C].

WILWERT ET AL. [2003B, 2003C] stress the importance of a clear visioning process to identify and develop innovative products that consumers may actually want to buy. They also share Delphi Automotive Systems' list of *'next century winners'* such as an RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem, collision avoidance, and advanced energy systems.

- ❖ An RBW or XBW integrated unibody or chassis motion mechatronic control system may help eliminate the necessity for excessive maintenance over the life of a vehicle; an RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem that can control driving, braking, steering, and absorbing/damping, eliminate mechanical links from the driver's control to the control actuator; by eliminating mechanical links, an RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem reduces raw material and labour costs in the manufacturing process; they may also help improve fuel efficiency because automotive vehicles can be made lighter.
- ❖ Collision avoidance systems inform drivers of impending danger such as a possible crash or a dangerous out-of-control situation; consisting of radar and vision sensors, warning displays, DBW AWD propulsion and BBW AWB dispulsion, SBW AWS conversion as well as ABW AWA suspension mechatronic control systems (RBW or XBW), and processors and software, collision avoidance systems could eventually control the vehicle, making corrective action to advert danger.
- ❖ Advanced energy systems provide power and range required by the highly automated vehicles of the future; to power new options such as in-vehicle computing, new energy generation/storage and control systems are necessitated; in addition, as ECEs or ICEs move toward hybrid and all electric designs, new E-M/M-E motors/generators, ASIM macrocommutators (inverters/rectifiers), respectively, and CH-E/E-CH storage batteries must be developed.

RBW or XBW is the generic term used to describe mechatronic control hypersystems that depend on a real-time communications network to connect different mechatronic components. Historically, these mechatronic control hypersystems relied on mechanical or fluidic linkages, and the goal of by-wire is to replace nearly every automotive mechanical or fluidic system with mechatronics.

The introduction of RBW or XBW signifies a quantum leap in automotive vehicle design and the amount of mechatronic components used in an automotive vehicle. RBW or XBW is a mechatronic system in automotive vehicles without mechanical backup.

The *'R'* or *'X'* may stand for different safety related applications such as DBW, BBW, SBW and ABW. The purpose of a RBW or an XBW integrated unibody or chassis motion mechatronic control hypersystem is to assist the driver in different situations and to make it safer for all on/off road-users. This increases the overall automotive vehicle safety, as the driver does not have to be concerned of the routine tasks anymore.

Computerised RBW or XBW integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hyper-systems have already been introduced in commercial vehicle systems.

Another advantage is the lower cost for manufacture of this type of hypersystem. The hypersystem is also simpler, easier to diagnose and maintain. Finally, the consumers' demand of safer, fuel-efficient, environment friendly, comfortable and easy to drive automotive vehicles may become a reality [GARBENFELDT 2005].

RBW or XBW refers to hypersystems under development that would assist or replace traditional mechanical or fluidical (hydraulical and/or pneumatical) systems with a mechatronically-controlled connection between parts of the RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem.

An RBW or XBW integrated unibody or chassis motion mechatronic control hypersystem has been establishing the technological basis that is opening opportunities for the development of new driver assistance and safety systems, making it possible for even a computer to drive or park an automotive vehicle.

Driving a vehicle by using just electronic signals also opens possibilities for the development of new **human-machine interfaces** (HMI) that can eventually substitute the current steering HW and pedals structure.

For some physically handicapped people, however, this signifies the possibility of driving the family's automotive vehicle by just attaching the appropriate HMI onto it, which could be, for example, a joystick.

The use of a joystick as an HMI and its relation to the automotive vehicle dynamics may be analysed, and overcoming possible *'fishtailing movements'* an active steering unit with integrated ACC feature, incorporated into the joystick, may be proposed in the not-too-distant future [KELBER ET AL. 2004].

Although the automotive market is slowly moving towards E-M RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems for small automotive vehicles there is still a significant necessity for E-F-M RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems in high-power braking and steering applications.

Therefore ongoing development in the trend of more precise, reliable, and cost effective RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems is taking place.

Consequently, the performances of the respective sensorial systems have to be enhanced. That is why the development effort for innovative concepts for **micro-electro-mechanical system** (MEMS) pressure sensors is justified.

Moreover, many of the servo-assisted E-F-M applications operate in two pressure ranges: a low range, where high precision is necessary, and a high-pressure one, where stability is a primary requirement. Normally, these characteristics may be well fulfilled only by two pressure sensor types, one for each range.

In TOMASI ET AL. [2002], a silicon pressure sensor with a two-level sensitivity that aims to meet the described specifications in one sensor design, is presented.

Moreover, self-test and recalibration is conceived in the design in order to enhance reliability and precision in a cost-effective way. While it is true that increasing the operating voltage of current automotive vehicles may improve efficiency and increase fuel kilometreage (mileage), exploring the new electrical applications the 42 V_{DC} bus may allow, can only see the true potential of this endeavour. Automotive vehicles, at their onset, were almost entirely mechanical.

Throughout a century of development, more and more systems have come to be controlled mechatronically. Mechatronic components provide increased control and are not as prone to wear as mechanical devices. By eliminating frictional losses associated with mechanical members, electronic controls offer higher efficiencies.

In summary, **energy-and-information network** (E&IN) and communication technologies are set to become a standard in automotive vehicles in the not-too-distant future. However, it must be remembered that these are still emerging technologies where possibilities of improvement are still large.

These technologies may have the following attributes [FUHRMAN 2002]:

- ❖ Embedded software does have an important and growing role in the automotive industry;
- ❖ Embedded software is the origin of much of the novelty in the automotive industry;
- ❖ Automotive vehicle information systems (infotainment and telematics);
- ❖ Automotive vehicle's integrated unibody or chassis motion mechatronic control (RBW or XBW);
- ❖ The automotive industry is undergoing a change from a mechanical-based industry to a computer-based industry;
- ❖ There are many interesting career possibilities for mechatronic (computer and software) scientists and engineers in the automotive industry of the 21st century.

Even in its nascent stages, implementation of these technologies would require the passing of stringent and complete tests certified by the automotive industry to demonstrate their safety. In areas that are very safety-critical, the performance of these technologies and devices should be flawless in tough environments. It has yet to be seen whether they can live up to the standards expected.

Summing up, requirements for automotive manufacturers for downgraded fuel consumption, low exhaust emission standards, excellent safety and extensive comfort may only be put into practice through intelligent RBW or XBW integrated unibody or chassis motion mechatronic control hypersystems. More than 90% of real innovations (relative to feature enhancements) of automotive vehicles take place in the domain of automotive mechatronics. At this time, for first-class automotive vehicles 45% of the costs are mechatronic control systems – this inclination is escalating.

Sophistication of intelligent RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control hypersystems is still escalating:

- ❖ Extant automotive mechatronic control systems are getting more and more complex;
- ❖ Novel automotive mechatronic control systems are introduced;
- ❖ More and more automotive mechatronic control systems are networked together;
- ❖ Bus systems are integrated with each other;
- ❖ Sensors and single-chip microcontroller signals are shared;
- ❖ Functions are dispersed over numerous single-chip microcontrollers.

Challenge:

- ❖ Create the sophistication of automotive mechatronics in automotive vehicle control, relating to quality, reliability and security;
- ❖ Complex automotive mechatronic control systems ought to be developed by a process using seamless integrated simulation tools for *'virtual test driving'* [HENNING 2006].

Glossary

Anti-lock braking system (ABS) is a system on automotive vehicles which prevents the wheels from locking while braking; the purpose of this is to allow the driver to maintain steering control under heavy braking and, in some situations, to shorten braking distances (by allowing the driver to hit the brake fully without the fear of skidding or loss of control); disadvantages of the system include increased braking distances under certain circumstances and the creation of a *'false sense of security'* among drivers who do not understand the operation and limitations of ABS.

AC-DC commutator -- The commutator is a mechanical AC-DC rectifier; for a rotary DC-AC commutator generators, the commutator mechanically switches the armature windings so that the resultant induced source AC armature voltages always act with the same sense of voltage polarisation; this requires a reversal of the armature winding connection every π rad; the induced source AC armature voltages are mechanically rectified to the induced source DC armature voltage via commutator segments that contact the carbon brushes.

AC-DC macrocommutator -- The macrocommutator is an ASIM AC-DC rectifier; for a rotary DC-AC commutator generator, the macrocommutator electronically switches the armature windings so that the resultant induced source AC armature voltages always act with the same sense of voltage polarisation; this requires a reversal of the armature winding connection every π rad; the induced source AC armature voltages are electronically rectified to induced source DC armature voltage via inputs of the ASIM that contact the output of the ASIM via bipolar electrical valves.

Actuator -- The component of an open-loop or closed-loop mechatronic control system that connects the electronic control unit (ECU) with the process; the actuator consists of a commutator and a final-control element; positioning electrical signals are converted to mechanical output.

Algorithm - A set of software instructions causing a computer to go through a prescribed routine; because embedded computer ECE or ICE controls have become so common, algorithms have become essentially synonymous with control law for automotive scientists and engineers.

Analog input -- Sensors usually generate electrical signals that are directly proportional to the mechanism being sensed; the signal is, therefore, analog signal or may vary from a minimum to a maximum limit.

Analog signal -- A signal in which the information of interest is communicated in the form of a continuous signal; the magnitude of this signal is proportional (or analogous) to the actual quantity of interest.

Analog-to-digital (A/D) converter -- An electronic device that produces a digital result that is proportional to the analog input voltage.

Architecture -- The organisational structure of an automotive-vehicle multiplex network, mainly referring to the application structure and communication protocol.

ASIC -- Application-specific integrated circuit, an IC designed for a custom requirement, frequently a gate array, single-chip microprocessor or programmable logic device.

ASIM -- Application-specific integrated matrixer, an IM designed for a custom requirement, frequently a gate array or single-chip macrocommutator.

Bus -- Topology of a communications network where all nodes are reached by links that allow transmission in both senses of direction.

Capacity -- Energy storage capability of the CH-E/E-CH storage battery, ultracapacitor, ultra-inductor or ultraflywheel.

Central processing unit (CPU) -- The portion of a computer system or microcontroller that controls the interpretation and execution of instructions and includes arithmetic capability.

CH-E/E-CH storage battery -- Self-contained CH-E/E-CH cell/cells or system that converts chemical energy to electrical energy in a reversible process.

Class A system -- A multiplex system whereby automotive-vehicle wiring is reduced by the transmission and reception of multiple signals over the same signal bus between nodes replacing the conventional wiring in automotive vehicles; the nodes used to accomplish multiplexed vehicle-body wiring typically did not exist in the same or similar form in totally conventionally wired vehicles.

Class B system -- A multiplex system whereby data, for example, parametric data values) is transferred between nodes to eliminate redundant sensors and other system elements; the nodes in this form of a multiplex system typically already existed as stand-alone modules in conventionally wired vehicles.

Class C system -- A multiplex system whereby high data rate signals typically associated with real-time mechatronic control systems, such as ECE or ICE controls and ABS, are sent over a signal bus to facilitate distributed control and to further reduce vehicle wiring.

Closed-loop mechatronic control -- A process by which a variable is continuously measured, compared with a reference variable, and changes as a result of this comparison in such a manner that the deviation from the reference variable is reduced; the purpose of closed-loop mechatronic control is to bring the value of the output variable as close as possible to the value specified by the reference variable in spite of disturbances; in contrast to open-loop mechatronic control, a closed-loop mechatronic control system acts to offset the effect of all disturbances.

Command mode -- A mode of operation of a master-slave system in which the master node takes prompt control of the network to achieve the input and/or output function.

Control mode -- Control mode and command mode are used interchangeably and refer to a mode of operation of a master-slave system in which the master node takes prompt control of the network to perform the input and/or output function.

Data collision -- A state of the bus in which two or more transmitters are turned on simultaneously to conflicting states.

Data consistency -- A feature of communications in some multiplex wiring systems whereby it is determined and ensured that all required recipients of a message have received the message accurately before acting upon it simultaneously; this feature is desirable in, for example, ensuring that all four vehicle brakes are energised simultaneously or four vehicle lamps are turned on at once.

D controller - A controller with the derivative characteristics.

DC-AC commutator -- The commutator is a mechanical DC-AC inverter; for a rotary DC-AC commutator motors or actuators, the commutator mechanically switches the armature windings so that the resultant force always acts with the same sense of rotary direction; this requires a reversal of the armature winding connection every π rad; the DC supply to the armature is via carbon brushes that contact the commutator segments.

DC-AC macrocommutator - The macrocommutator is an ASIM DC-AC inverter; for a rotary DC-AC commutator motors or actuators, the macrocommutator electronically switches the armature windings so that the resultant force always acts the same sense of rotary direction; this requires a reversal of the armature winding connection every π rad; the DC supply to the armature is via an input of the ASIM that contacts via the bipolar electrical valves' output of the ASIM.

Defuzzification -- The process of translating output grades to analogue output values.

Depth of discharge (DoD) -- Percentage of capacity [Ah] that has been removed from the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel.

Digital signal -- A signal in which the information of interest is communicated in the form of a number; the magnitude of this number is proportional to (within the limitations of the resolution of the number) the actual quantity of interest.

***Digital signal processor (DSP)* --** A monolithic integrated circuit (IC) optimised for digital signal-processing applications; portions of device are similar to a conventional microprocessor; the architecture is highly optimised for the rapid, repeated additions and multiplications required for digital signal processing; digital signal processors may be implemented as programmable devices or may be realised as dedicated high-speed logic.

Driver -- A solid state device used to transfer electrical energy to the next stage that may be another driver, an electrical load (power driver), a wire or cable (line driver), a display (display driver), etc.

Fault tolerance -- Ability of a system to survive a certain number of failures while performing its required functions, but possibly with some degraded characteristics.

Final-control element -- The second or last stage of an actuator to control mechanical output.

Fuzzification -- The process of translating analog input variables to input memberships or labels.

Fuzzy logic (FL) -- Software design based upon a reasoning model rather than fixed mathematical algorithms; a FL design allows the automotive system engineer to participate in the software design because the fuzzy language is linguistic and built upon easy-to-comprehend fundamentals.

Global time base -- A clock or timing device relating to, or involving, the entire automotive vehicle network and providing the time base for the time-triggered protocol (TTP).

Inference engine -- The internal software program that produces output values through fuzzy rules for given input values; the inference process involves three steps: fuzzification, rule evaluation, and defuzzification.

Input memberships -- The input signal or sensor range is divided into degrees of membership, i.e., low, medium, high or cold, cool, comfortable, warm, hot; each of these member-ship levels is assigned numerical values or grades.

Local area network (LAN) -- A local multiplex that can serve a variety of devices; typically in integrated unibody, space-chassis or body-over-chassis motion mechatronic control hypersystems, it is used for collecting data from sensors and controlling actuators for one host module.

Master (node or module) -- The master node and master module are used interchangeably and are defined as the device that controls the transfer of information on a multiplex network.

Master-slave -- A type of system whereby one node, a module, acts as a master or central unit and controls the actions of the other nodes designated as slaves or remote units.

Microcontroller unit (MCU) -- A semiconductor device that has a CPU, memory, and I/O capability on the same chip.

Multiplexing -- The process of combining several messages for transmission over the signal path; there are two widely used methods of multiplexing: time division and frequency division.

Open-loop mechatronic control -- A process within a mechatronic control system in which one or more input variables act on output variables based on the inherent characteristics of the mechatronic control system; an open loop is a series of elements that act on one another as links in a chain; in an open loop, only disturbances that are measured by the control unit can be addressed; the open loop has no effect on other disturbances.

Output memberships -- The output signal is divided into grades such as off, slow, medium, fast, and full-on; numerical values are assigned to each grade; grades can be either singleton (one value) or *Mandani* (a range of values per grade).

PI controller -- A controller with the proportional and integral characteristics.

PID controller -- A controller with the proportional, integral and derivative characteristics.

Protocol -- A formal set of conventions or rules governing the exchange of information (data) between nodes (networked elements), including the procedures for establishing and controlling transmission on the multiplex signal bus (message administration|) and the organisation, meaning, and timing associated with the bits of data (message transfer).

Pulse-width modulation (PWM) -- The precise and timely creation of negative and positive waveform edges to achieve a waveform with a specific frequency and duty cycle.

Rule evaluation -- Output values are computed per the input memberships and their relationship to the output memberships; the number of rules is usually set by the total number of input memberships and the total number of output memberships; the rules consist of *IF inputvarA* is *x*, *AND inputvarB* is *y*, *THEN outvar* is *z*.

Semicustom MCU -- A microcontroller unit (MCU) that incorporates normal MCU elements plus application-specified peripheral devices such as higher-power port outputs, special timer units, etc.

Time division multiple access (TDMA) -- A general classification of multiplexing that uses time division multiplex protocol.

Time triggered protocol (TTP) -- A real-time mechatronic control system architecture where all system activities are triggered by the progression of real-time; this distributed time triggered architecture requires clock synchronisation by a global time base.

Transceiver -- An electrical circuit which both transmits (line driver portion and receives (line receiver portion).

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PART 2

DBW AWD Propulsion Mechatronic Control Systems

2.1 Introduction

In this chapter, interested readers may consider the longitudinal motion in the x-axis of an automotive vehicle. By longitudinal motion of the automotive vehicle, we mean how the vehicle responds to a driving input.

For over 100 years, the majority of automotive mechatronic control systems concerned with the direct mechatronic control of a vehicle by a **human driver** (HD) have been under direct actuation by **mechano-mechanical** (M-M) and/or **fluido-mechanical** (F-M), that is, **hydro-mechanical** (H-M) and/or **pneumo-mechanical** (P-M) means. If such a system fails and the driver is unable to continue to control the automotive vehicle, the consequences could affect the safety of the vehicle or other road users.

Such systems are now recognised as *'safety-critical'*. The automotive mechatronic control systems in a vehicle are safety-critical systems that must continue to operate without endangering the driver as well as passengers' lives, in the event of a fault. The risk must be minimised, achieving at least the high safety and reliability of current automotive mechatronic control systems, whilst achieving a sensible and cost effective solution.

Safety has always been a high priority for vehicle designers and traditional engineering processes have served the industry well in ensuring that safe products are produced. M-M, F-M, or P-M components are designed and tested to ensure they have the correct characteristics, and the more critical systems are often designed with a degree of redundancy.

An example is the attachment of dual-circuit propulsion (driving) mechatronic control systems to automotive vehicles. If one circuit breaks down, the other gives the driver an extent of mechatronic control authority over driving. There is well-known consciousness in escalating functionality and safety by developing **drive-by-wire** (DBW) **all-wheel-driven** (AWD) propulsion mechatronic control systems where the controls are used to enhance the driver controls or even give **full authority** (FA) over a vehicle's functions [WARD AND WOODGATE, 2004].

In a FA DBW AWD propulsion mechatronic control system, the driver controls are principally inputs to a computerised system rather than directly commanding the automotive vehicle functions. There is substantial advantage in setting up supplementary advanced driving support systems such as lane-keeping assistance, collision avoidance, and, in due course, fully autonomous convoys or '*road trains*'.

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For most advantageous performance, these may necessitate vehicles to be equipped with full mechatronic control of propulsion (driving), dispulsion (braking), suspension (absorption), and conversion (steering).

In the aerospace industry, development of **fly-by-wire** (FBW) integrated aircraft mechatronic control hypersystems has been devoted to similar trends in vehicle mechatronic controls [WARD & WOOD GATE, 2004].

Modern FBW integrated aircraft mechatronic control surfaces are actuated using fluidical (hydraulical) systems with a high degree of redundancy (triple or quadruple circuits are ordinary) including multiple energy sources and multiple actuators. Aircraft have been built with **full-authority digital engine control** (FADEC) for some time. More lately, full mechatronic control of flight surfaces has been initiated. These critical aircraft mechatronic control systems have high levels of redundancy and back-up built in, including the requirement of multiple mechatronic control computers, energy sources, as well as sensors and actuators.

In one well-known aircraft approach, the **human pilot**'s (HP) inputs are evaluated as commands for the aircraft to manoeuvre within the constraints of the safe flight envelope. Mechatronics move the aircraft mechatronic control surfaces appropriately.

In the second well-known approach, which is similar, maintains the pilot in full aircraft mechatronic control, permitting control demands that may cause flight outside the envelope. This is an imperative dissimilarity, and it has not been evident until now that the approach is foremost. The first approach causes that most flight accidents are initiated by pilot error, and their system reduces this. The second approach's designer claims that pilots should be skilled to use a verdict when faced with extreme situations. Aircraft also have *'stick shakers'*, intended to simulate the result of approaching an aerodynamic stall -- a very dangerous loss of mechatronic control. The stick shaker vibrates the control column to give the pilot feedback of the impending stall, but before it really arises. Such a device gives sensory feedback to the pilot that -- due to the fluidical (hydraulical) assistance or FBW integrated aircraft mechatronic control hypersystem -- is no longer accessible from the *'feel'* of the flying controls. Principally, there are various similarities between FBW integrated aircraft mechatronic control systems and those included in, or projected for, automotive vehicles (Table 2.1).

Table 2.1 Comparison of automotive and aerospace mechatronic control systems [WARD AND WOODGATE 2004].

Aircraft system	Equivalent vehicle systems	Automotive market status
FADEC	Drive-by-wire engine control Cruise control	Mass market
Fly-by-wire	Brake-by-wire	Limited fitment
	Steer-by-wire	Limited fitment of partial authority systems
Stick shaker	No equivalent	–
TCAS	Collision warning	Limited fitment
	Collision avoidance	Concept
Glide-slope	Lane departure warning	Limited fitment
Automatic landing	Cruise control	Mass market
	Adaptive cruise control	Limited fitment
	Lane keeping support	Concept
UAV	Convoy ('road train')	Concept

Maybe, predictably, the automotive industry is not moving towards a different approach being developed and used effectively in aerospace systems. But there are challenges for the automotive industry:

- ❖ Realising analogous levels of authority (equability) in DBW as the aerospace industry has for FBW, but within the covering, mass, and cost constraints of automotive vehicles;
- ❖ Determining how much authority mechatronic systems should have over automotive vehicle functions; some believe the driver must endure in final control (e.g. the second approach) whilst others believe it is preferable to reduce or remove the scope for human error altogether (e.g. the first approach);
- ❖ Implementing sensory feedback systems in full-authority DBW AWD propulsion mechatronic control systems; for example, should some form of feedback force be applied in a DBW AWD to the acceleration (gas) pedal, communicating road conditions to the driver?

The above paragraphs have summarized potential advantages and functions for DBW AWD mechatronic control systems controlled largely by computers, usually eradicating the constraints imposed by M-M or F-M systems. However, this introduces new issues for the DBW AWD mechatronic control system developer:

- ❖ In an DBW AWD performance, the relationships between inputs and outputs are not derivable from the physical performance; this means that an alteration to any input can alter one or more outputs; besides, a minor alteration in an input may well result in large, multiple output alterations -- there is no linearity;
- ❖ The number of fusions of inputs is too large to be able to verify exactly the correctness of the system by testing alone.

This point to the perception that it is indispensable to guarantee that the development process, as well as the product, is acceptable. So to put DBW AWD propulsion mechatronic control systems into practice, a number of specific additional activities are necessary in the product lifecycle compared to conventional engineering processes. To terminate what level of safety properties it should have, primarily, the system requirements should be considered. Conventionally, the automotive industry classified systems as being safety-related or non-safety-related. Most other industries now use a four-level classification of safety requirements, commonly known as the **safety integrity level** (SIL) of a system. The automotive industry has adopted a similar scheme.

SILs are appropriate to automotive vehicle systems and functions by surveilling a safety analysis process. The safety integrity requirements are then used to choose the perfect development process. During design and performance safety analysis is used to certify that the product is being developed consistent with its safety integrity requests. Safety analysis should be carried out using a multidisciplinary team including application domain experts. This guarantees that the effects of the safety analysis take account of automotive-specific issues and requirements. For example, a safety analysis on a DBW AWD propulsion mechatronic control system should include experts in automotive propulsion systems and vehicle dynamics.

The SIL of an automotive vehicle system guides the requirements for the degree of rigour indispensable in the specification, design, performance, and legalisation of the system. This rigour escalates across the hardware, software and system architecture, and becomes more intense as the safety integrity request of the system enhances.

In practical terms, an escalated safety integrity requirement may necessitate taking measures in the system such as:

- ❖ Redundancy in energy supplies, sensors, actuators, processing, and multiplex communications;
- ❖ Terms for error checking in all of the above;
- ❖ Terms for fault management strategies -- definition of safe states and fail-safe versus fault tolerant architectures;
- ❖ Enhanced software development processes such as the application of formal specification, programming language subsets, and code verification tools.

DBW AWD propulsion mechatronic control systems may play an important role in future RBW, also known as XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control hypersystems.

The main idea of DBW AWD is to substitute M-M, F-M and/ or P-M driveline (engine/transmission) mechatronic control systems by mechatronic components that allow for higher performance and enhanced functionality.

An entire variety of new functions such as collision avoidance, autonomous driving, **adaptive cruise control** (ACC), and anti-skid, **adaptive traction control** (ATC) approaches rely on DBW AWD propulsion mechatronic control systems. The major stimulus for setting up such a mechatronic control system is to enhance vehicle safety.

In the case of the DBW AWD propulsion mechatronic control system, the evident primary criterion is that in eradicating the conventional ECE or ICE **throttle valve control** (TVC) and/or **gear-shifting transmission control** (GTC), a well-known and robust M-M system, one must substitute it with a DBW AWD propulsion mechatronic control system that is no less robust or safe.

The M-M or F-M system's easiness, to some measure, creates its reliability but the character of the mechatronic control systems is such that, to achieve the same or better reliability, a *'fault-tolerant'* approach must be adopted necessitating multiple redundancies in the system.

In nearly all other systems within the automotive vehicle, loss of propulsion (driving) at optimum may lead to an inoperative automotive vehicle (if it was immobile at the time), but in all probability, an accident.

For that reason there should be no single point of failure in the system, necessitating redundancy for all the components implicated, as well as sensors, actuators, control and energy sources. Away from this, in a sequence to detect a failure and maintain safe operation it may be necessary that particular system has dual or triple redundancy.

For such systems, it is worth looking towards aerospace and military approaches. Such approaches, using *Markov* modelling, have been assumed to resemble the desired dependability of 10^{-9}.
Only dual-dual and triplex systems can give the necessary level of failure detection and recovery performance [HAMMETT AND BABCOCK 2003].

In putting a safety-critical system into practice, not only should the architecture be reliable but the design and development process should also precede exceptional practise to realise very similar dependability as a conventional propulsion system [PITECHOLOGY 2004].

Particular processes and guidelines should be come first, including software guidelines [MISRA, 1998]. These are used to give guidance to the automotive industry in the construction and application of safe, reliable software within an automotive vehicle system, and receive from the more universal IEC61508 standard. A scale is used to detect the level of dependability necessary, the SIL. Level 0 is the lowest while level 4 is the highest. It may be argued that for prototype automotive vehicle systems with restricted running, (that is, not on public roads, maximum value of the vehicle velocity limits, and so on), that the automotive vehicle system could be classed at a lower SIL, and appropriate processes that follow, but for a production program, the level is likely to be 4.

However, setting-up redundancy can downgrade the SIL of individual automotive vehicle systems. Other process and standards should also be looked into when designing a production DBW AWD propulsion mechatronic control system.

The *United Nations Economic Commission for Europe* is responsible for setting worldwide regulations for automotive vehicle systems that afterwards become encompassed in the national legislation of the member countries. Their regulation on approval of automotive vehicles with reference to propulsion (driving) equipment [UN ECE R79.00], above all Annex 6 – "*Safety aspects of complex vehicle control systems*", must be executed.

Moreover, it is worth looking at aerospace and military processes for regulation in the development of an automotive vehicle system, as well as other industry standards such as *SAE* and *IEC* [US DOD 1990; DO-178B 1992; US DOD 1993; UK MOD 1996; UK MOD 1997; IEC 1997; UK MOD 1999; SAE 1999; US DOD 2000].

Why DBW AWD propulsion?

- ❖ Stimulus is to eradicate M-M, F-M, or P-M linkages with computer controllers as well as position sensors and actuators;
- ❖ Provides larger design freedom;
- ❖ Easier integration with different mechatronic control systems (for example, ABS);
- ❖ Elimination of M-M, F-M, or P-M links can release mass;
- ❖ Indispensable networks are already necessary and are being built-up;
- ❖ Not a novel concept; civil and military aircrafts have used FBW integrated aircraft mechatronic control systems for a number of years (an evenly safety-critical function) [SCHOFIELD 2004].

A futuristic feature that did not fare well in the study is *'DBW AWD'* technology. The DBW AWD propulsion mechatronic control systems that are similar to the technology used in the latest military fighter aircraft, would substitute many of the M-M, F-M or P-M connections with wire systems linking the gear shift and accelerator (gas) pedal to the automotive vehicle's transmission and throttle.

Each year the automotive vehicle gets considerably more sophisticated new technology is introduced. It began with '*extravagances*' like electrical **external combustion engines** (ECE) or **internal combustion engines** (ICE) start (crank) and **fluido-mechanical brakes** (FMB), that is, **hydro-mechanical brakes** (HMB) or **pneumo-mechanical brakes** (PMB) and continues with **direct-injection** (DI) ICEs, yaw mechatronic control, and DBW AWD propulsion mechatronic control systems. Those first two items may be the subject of other chapters, but DBW AWD propulsion has yet to appear in this chapter. Until recent times, the ECE or ICE has generally been installed towards the front of the vehicle, with a long central shaft taking mechanical energy to the driving rear axle. Lighter and more compact arrangements with the ECE or ICE at the same end as the driving wheels have now become common-place, though – either a rear ECE or ICE driving the front wheels. These three layouts are illustrated in Figs 2.1 – 2.3 [OLDHAMS LTD 1977; DUFFY 2008].

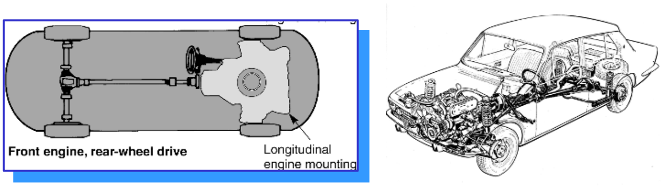


Fig. 2.1 Basic mechanical layout of the front ICEs driving the rear wheels [Triumph –*Dolomite*; DUFFY 2008].

As a generalisation, the rear ECE or ICE layout, that is, **rear-wheel-drive** (RWD) tends to make an automotive vehicle light and inexpensive but unstable in side winds, whereas the **front-wheel-drive** (FWD) arrangement gives more inherent stability, but transmitting mechanical energy to steered and driving wheels adds mass and cost.

All kinds of DBW AWD propulsion mechatronic control systems have been use on automotive vehicles, including **thermo-mechanical** (TH-M) steam engines, as well as **fluido-mechanical** (F-M), that is **hydro-mechanical** (H-M) or **pneumo-mechanical** (P-M) or **electro-mechanica**l (E-M) motors. These latter run from ECE- or ICE-driven **mechano-fluidical** (M-F) pumps, **mechano-pneumatical** (M-P) compressors, or **mechano-electrical generators** or even **chemo-electrical/electro-chemical** (CH-E/E-CH) storage batteries or **fuel cells** (FC), respectively.

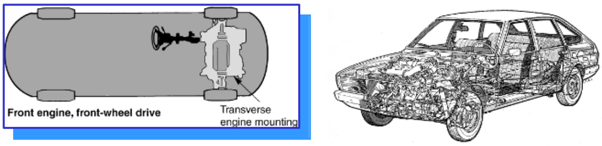


Fig. 2.2 Basic mechanical layout of the front ICE driving the front wheels [Chrysler – *Alpine;* DUFFY 2008].

Due to many factors such as cost to buy and to run, ease of driving, reliability, quick availability, quietness, freedom from smell, and good power-to-mass ratio, the four-stroke petrol ICE has come to dominate the scene.

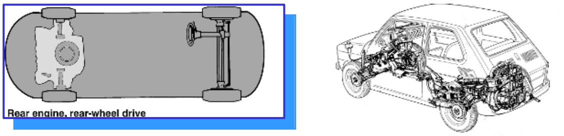


Fig. 2.3 Basic mechanical layout of the rear ICEs driving the rear wheels [Polski Fiat – *126p*; DUFFY 2008].

It is an ICE that has a wide but not unlimited crankshaft angular-velocity range, having a minimum as well as a maximum useful rotational velocity that results in it needing some sort of gradually-engaged M-M clutch to be able to start an automotive vehicle from rest, and change – velocity gearing to suit various values of the vehicle velocity and gradients while running. Like so many technologies nowadays, DBW AWD propulsion mechatronic control systems are primarily a response to tightening emission standards. As with fuel injection and integrated **engine management controllers** (EMC), these systems improve ECE or ICE energy efficiency while cutting exhaust emissions. They do this by replacing clunky and inaccurate M-M, F-M or P-M systems with highly advanced and precise electronic sensors. Currently, DBW AWD propulsion applications are being used to replace the throttle-cable system on newly developed vehicles. These systems work by replacing conventional **throttle valve control** (TVC) systems. Instead of relying on a mechanical cable that winds from the back of the accelerator pedal, through the automotive vehicle firewall, and onto the throttle body, a DBW AWD propulsion mechatronic control system consists of a sophisticated **pedal-position sensor** (PPS) that closely tracks the position of the accelerator pedal and sends this information to the EMC. This is superior to a cable-operated throttle system for the following reasons:

- ❖ By eliminating the M-M elements and transmitting an automotive vehicle's throttle position mechatronically, DBW AWD propulsion greatly reduces the number of moving parts in the throttle system; this means greater accuracy, reduced mass, and, theoretically, no service requirements (like oiling and adjusting the throttle cable).

- ❖ The greater accuracy not only improves the driving experience (increased responsiveness and consistent pedal feel regardless of outside temperature or pedal position), but it allows the throttle position to be tied closely into EMC information like fuel pressure, engine temperature, and **exhaust gas recirculation** (EGR); this means improved fuel economy and power delivery as well as lower exhaust emissions.
- ❖ With the pedal inputs reduced to a series of electronic signals, it becomes a simple matter to integrate a vehicle's throttle with non-engine specific items like ABS, gear selection and traction control; this increases the effectiveness of these systems while further reducing the amount of moving parts, service requirements, and vehicle mass.

But what may occur if the '*wire*' in the DBW AWD propulsion mechatronic control system, breaks? In other words, what if a mechatronic malfunction disrupts the flow of information between the TPSs and the EMC? It could give a whole new meaning to the term *'sticking throttle'*, couldn't it?

The reality is that, just like fuel injection and an **anti-lock braking system** (ABS), a DBW AWD propulsion mechatronic control system is only as good as its programmers and manufacturers.

While the first generation of fuel-injected ICEs had its share of technical gremlins, the fuel system of the average 2005 model is far more accurate, and dependable, than any carburettor-equipped vehicle from *25* years ago.

Because DBW technology was first used on civil and military aircraft over 20 years ago (except it was termed **fly-by-wire** (FBW) back then), consumers can be assured that its reliability under less-than-ideal circumstances has been tested.

It is now used on everything from industrial equipment (like heavy-duty machines) to cutting-edge ground-assault vehicles (like the future *Grizzly* tank).

Speaking of aircraft (air-plane), many of modern jets use FBW technology for turning and braking, in addition to throttle mechatronic control.

Could the same thing sooner or later be subjected to automotive vehicles? Could an unsophisticated joystick in the future substitute a vehicle's steering hand wheel, accelerator pedal, and brake pedal? That would be like suggesting that sooner or later vehicles may be able to drive themselves without any driver input [BRAUER 2004].

To achieve an overall improvement in vehicle safety, a fully-controlled powertrain is necessary. For instance, the technical objective of a **powertrain equipped with intelligent technologies** (PEIT) project [PEIT 2004] might be thus to build up an integrated self-stabilising powertrain that provides an interface to add all accident prevention and driver assistance functions of the vehicle.

The powertrain interface may make it possible to integrate DBW AWD propulsion, BBW AWB dispulsion, ABW AWA suspension, and SBW AWS conversion mechatronic control systems and fail operative energy management into the RBW or XBW integrated unibody or chassis motion mechatronic control system, for example as shown in Figure 2.4 [PEIT 2004]

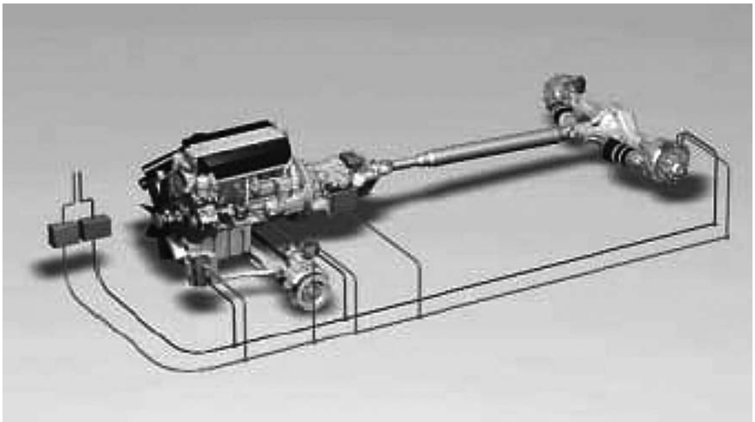


Fig. 2.4 Principle layout of the RBW or XBW integrated unibody or chassis motion mechatronic control system, integrating DBW AWD propulsion, BBW AWB dispulsion, SBW AWS conversion and ABW AWA suspension mechatronic control systems [PEIT 2004].

To connect the functionalities and their mechatronically controlled devices, a failure tolerant system architecture is developed with two or even three central **electronic control units** (ECU) derived from the avionics industry co-ordinating the powertrain functions. Thus, only a single input, the motion vector providing the information of vector length and vector angle for acceleration/deceleration and yaw angle, respectively, vehicle body sideslip angle, may be necessary to control the whole motion task.

The integrated **engine-transmission management control** (E-TMC) system is responsible for the coordination of safety and redundancy functionality. This key technology function may serve as a new standard in the automotive industry to coordinate a powertrain's automotive mechatronics.

DBW AWD propulsion mechatronic control systems could eventually use joy-stick-like mechatronic controls that would eradicate the necessity for a steering wheel as well as accelerator and brake pedals, freeing up room in the interior for other potential innovative advancements.

Besides, DBW AWD propulsion mechatronic control systems allow faster, more accurate interfacing with **vehicle stability control** (VSC) systems, as well as *'smart'* ACC and ATC, and they also leave room for future active safety measures like collision-avoidance systems and park-assist gadgets.

DBW AWD propulsion mechatronic control systems allow a level of integration not possible with M-M systems. For instance, a vehicle's airbag system could take into account the throttle position at the time of impact (or release the throttle on impact), an automatic suspension system could stiffen in response to a punch of the gas, or the steering system could take the throttle position into account when deciding how much boost to give [HALVORSON, 2004].

There are many advantages in replacing a vehicle's M-M, F-M and/or P-M hyposystems with mechatronic ones (for example, sidebar, *'DBW AWD'*, and so on**)**.

Mechatronic control systems are inherently more reliable, more efficient, add less mass to an automotive vehicle, and can offer more functionality than M-M systems can.

Lighter mass and more efficiency equate to better fuel economy -- an average of 5% improvement over traditional systems, a factor on everyone's mind in recent times of skyrocketing fuel prices.

However, the mechanical-to-electrical shift is hampered by several factors, including the inertia of the automotive industry and a vehicle's available power source [LIPMAN 2004].

In not-too-distant automotive vehicles, in place of the steering **hand wheel** (HW) and floor acceleration and brake pedals mechatronic control systems may be used.

The accelerator, gear shifting, and clutch actuator, as well as brakes and steering may be mechatronically controlled by DBW AWD technology.

DBW AWD propulsion mechatronic control systems may be mechatronically controlled by the proof-of-concept driver interface shown in Figure 1.5 [SAE INTERNATIONAL, 2004; CITROËN 2005].

(a) **(b)**

Fig. 2.5 Principle layout of the driver's mechatronic control system, consists of left and right steering control yokes for mechatronic controlling throttling (acceleration), gear shifting, and clutch actuation, as well as braking (deceleration) and steering [SKF and Bertone -- *Guida-Filo* (a); CITROËN 2005 (b)].

Gearshift and clutch operation are so closely coupled that the systems may be considered together. The gearbox for the automotive vehicle may be based on an existing production unit employing a conventional H-pattern manual shift configuration.

However, to accomplish the second-third and fourth-fifth movements of the selector mechanism inside the gearbox, more precise linear and rotational movements may be required.

Up and down shifts are handled via the *'+'* and *'-'* buttons on the right-side side of the driver interface, with neutral being a logical '0'.

Reverse is selected via a dedicated button and is protected from inappropriate application by algorithms in the actuator control unit.

Both clutch and gearshift-actuating units may be on a conventional 14 V_{DC} or future 42 V_{DC} **energy-and-information network** (E&IN).

For the BBW AWB dispulsion mechatronic control systems, compact E-M actuating units may be coupled with brake calliper and braking design. At its current, interim stage of development, the braking system is said to rival conventional F-M arrangements in performance.

Significant progress has been made in mass and size reductions during development, with the complete mechatronic brake calliper assembly now being a compact unit with a mass comparable to that of the conventional F-M design it replaces.

Control of the braking mechatronic control system is duplicated on both the left and right driver interface yokes and is enabled by squeezing the handgrips.

The M-M design incorporates a progressive resistance and a small, discernible free-play at the beginning of the movement to provide the driver with a tactile indication when the brakes begin to operate.

The system controls each brake as an individual subsystem under an umbrella control for the complete vehicle braking system.

The driver interface's left and right steering control yokes are linked mechanically and have a full movement of just 20 deg.

Movement of the vehicle's front wheels is aided by full logic mechatronic control, with feedback to the driver being provided by a high-torque motor. driver *'feel'* is programmable, as is the relationship between yoke and front-wheel movement.

A next-generation steering actuator fits easily into the front subframe assembly of the future production automotive vehicle.

The vehicle of the future gives the impression of being just similar to this: it has no ECE or ICE, no steering column, and no brake pedal. It needs no petrol (gasoline), emits no pollution (only a little water vapour) and hitherto handles similarly to a high-performance vehicle.

It might seem not unlike an ecologist's imagination, in place of an ICE, for example, the vehicle of the future may be energised by **fuel cells** (FC) similar to those used in the orbiting space station [HM-MILTON, 2002].

Electrical energy is generated by an **electro-chemical** (E-CH) reaction of hydrogen and oxygen that submits only thermal energy (heat) and water (H_2O) as its side-effect. No smelly exhaust, no smog, no greenhouse gases.

Misplaced too are the cables and mechanical links that have held together automotive vehicles since the beginning of the automobile age a century ago.

As a substitute, the steering and braking are fully mechatronically controlled; using techniques originated in FBW aircraft cockpits.

Instead of a steering column there is a miniature colour screen and two handgrips, as shown in Figure 2.6 [THIESEN 2003, SCHMIDT 2004].

Fig. 2.6 Miniature colour screen and two handgrips
[GM Opel's ***Hy***-*Wire* FCEV; THIESEN 2003; SCHMIDT 2004]

To accelerate, drivers twist the grips. To have an effect on the brakes, drivers squeeze them. To turn left or right, drivers reposition the grips up or down. In place of a rear-view mirror, there is a video camera that visualises an image of the road travelled, along with such driving data as vehicle velocity and hydrogen-fuel levels. For the reason that the automotive vehicle is properly programmable, drivers can adjust their performance preferences. (Brakes ought to be soft or hard? ECE or ICE sporty or fuel saving?) Eradicating all the mechanical controls frees up the space where an ECE or ICE would normally dwell; for example, in the automotive vehicle of the future, drivers can watch straight through the front of the vehicle.

Without a steering column, vehicle designers can locate the mechatronic controls anywhere in the vehicle for maximum comfort and safety, even in the backseat. The core of the vehicle of the future, however, is an aluminium, skateboard-like chassis that runs the length of the automotive vehicle. Incorporated within it are the FCs, an **electro-mechanical** (E-M) motor, tanks of compressed hydrogen and all the mechatronics.

Since the fibreglass body is principally a shell, different models can be exchanged similar to cell-phone covers. Consequently drivers could in theory drive a sports car on the weekends and alter it into a minivan to take the children to school. For one thing, the roadside infrastructure that fuels and services nowadays *'gas guzzlers'* would have to be modified to distribute hydrogen and reprogram out-of-order mechatronic control systems.

However, if the effect may be a fleet of safe, fuel-efficient, non-polluting vehicles that downgraded or eradicated the world's dependence on fossil fuel, it would be worth the effort.

Automotive engineers and scientists seek future enhancements to the automotive vehicles of the future to principally approach from systems engineering efficiencies prior to breakthroughs in specific components. For example, separated wheel E-M motors are likely may be made possible by fully integrating the brake, suspension, and wheel into an optimised corner module.

Although part of the concept platform was unveiled some time ago, such technology is not on the driveable automotive vehicle of the future that features a central electrical system to power the wheels. But the automotive vehicle manufacturers maintain their goal remains to put an in-wheel-hub E-M motor at each wheel -- if it can find a way to fit them into the skateboard-chassis along with the FC system, drivetrain, storage tanks, and various mechatronics.

Some vehicle manufacturers are working on a solid-state system that uses sodium alienate hydride material to store hydrogen. The system can store a relatively large amount of hydrogen but it currently takes too long to infuse the hydride and release the hydrogen. Another challenge is reducing the amount of expensive precious metals from the FC stack and costly carbon fibre in the fuel tank. It is estimated that three-quarters of the cost of the tank may be attributed to the carbon fibre shell [AUTOTECH 2003].

All of the emerging automotive vehicle's working parts may reside in a skateboard-chassis of less than a foot thick. The chassis may contain, for example, the FC, hydrogen tanks and E-M motors to drive the front and rear wheels. What appears to be a kind of video game to a conventional driver is actually a unique innovation based on a revolutionary concept known as *'DBW AWD'*. This new system not only offers improved safety, comfort, and ergonomics, but also provides extra advantages in terms of vehicle design and production. It's all made possible by a mechatronic control system that replaces the mechanical and fluidical connections linking the steering wheel and pedals with the steering, drive, and brakes. Designed so that it can only be moved to the left or right, a unique sidestick (see Fig. 2.7) enables drivers to steer with high precision.

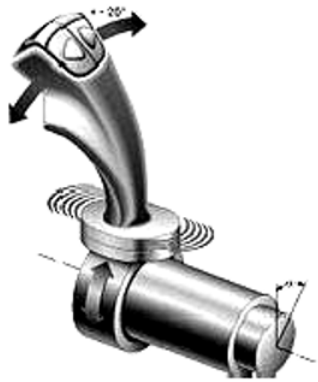


Fig. 2.7 Principle layout of a unique sidestick (joystick) [DaimlerChrysler].

At the same time, an integrated E-M motor gives them a more realistic feeling of steering resistance. A two-dimensional force-measuring sensor that reacts to forward or backward hand pressure, registers commands to accelerate or brake.

The DBW AWD propulsion mechatronic control system takes over control of the ECE or ICE plus the braking and steering functions. In this manner, it can control the automotive vehicle as the driver would wish, even in a situation where the driver might not be able to react in time.

Today, there are in normal driving operations *'DBW AWD'* automotive vehicles of the future without steering hand wheels, acceleration or brake pedals that are steered only by sidesticks, as shown in Figure 2.8.

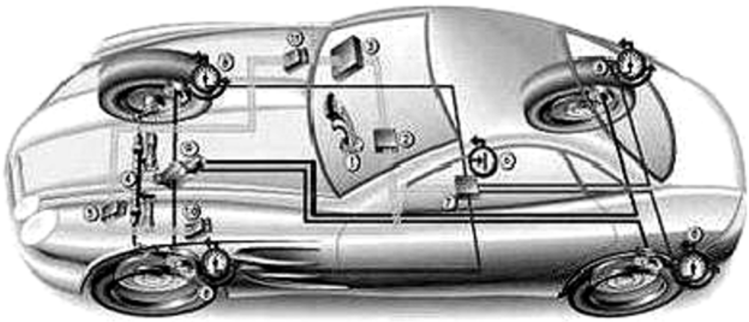


Fig. 2.8 Principle layout of the proof-of-concept automotive vehicle [DailmlerChrysler].

Appearances can be deceiving: The easy-to-use sidestick is based on a complex mechatronic system with redundant safeguards. A DBW AWD propulsion mechatronic control system consists of sensors and control elements connected by a redundant data bus (black). The driving dynamics controller plays an important role here, actively taking over when the driver loses control of the vehicle. All mechatronic components have a backup system to ensure maximum safety. To achieve this ambitious objective, automotive scientists and engineers disconnected the fluidical and mechanical connections and replaced them with E-M servomotors and electronic switching elements. Both types of mechatronic components are controlled by a fault-tolerant microcomputer system. The latter receives its data not only from the driver, who issues commands to the system, but also from sensors that continually monitor the vehicle's status.
'DBW AWD' automotive vehicles of the future may offer numerous benefits:

- Their safety systems react automatically to potentially dangerous driving situations within fractions of a second;
- The push of a button on a sidestick (side-mounted joystick) may be sufficient to make parking and other difficult manoeuvres child's play;
- The advanced concept may also enable designers to completely revamp automobile interiors.

High values of the vehicle velocity, tight curves, and wet cobblestones -- even experienced race car drivers would struggle with the steering under such conditions.

As far as automotive scientists and engineers are concerned, two fingers are sufficient to control the vehicle; the driver is driving with a hand-sized sidestick, or side-mounted joystick. The driver's left elbow may be supported against the centrifugal force by the arm console in the door and the right elbow may rest on the centre console. The driver literally has a handle on the automotive vehicle.

The most important driving operations -- accelerating, braking, steering, signalling, and honking the horn -- are integrated, for instance, in two sidesticks in the vehicle's armrests, as shown in Figure 2.9.

Fig. 2.9 View of two sidesticks in the automotive vehicle's armrests [DaimlerChrysler].

Much like a modern jet fighter, the automotive vehicle can be accelerated by lightly pushing forward the compact joysticks that are linked electronically.

Once the vehicle is on its way, the integrated ACC automatically maintains vehicle velocity. When the driver wants to brake, he or she simply pulls back the side-stick (see Fig. 2.10).

Fig. 2.10 The *'DBW AWD'* automotive vehicle can be accelerated by lightly pushing forward the compact joysticks that are linked electronically [DaimlerChrysler].

A significant safety feature of DBW AWD is that, unlike the **electronic stability program** (ESP) currently in use, it can be extended to act on the steering as well as on the brakes (see Fig. 2.11), even sceptical drivers end up delighted by the system. While the sidestick is held comfortably in the hand that sets the course, the wheels dance over wet, slippery cobblestones, controlled by microcomputers that automatically compensate for every bump with a corrective steering adjustment.

Fig. 2.11 View of sidestick's comfortable location [DaimlerChrysler].

A test procedure in which strong winds are directed at the side of a vehicle also demonstrates the effectiveness of the stabilising algorithms.

When the wind corridor is reached, a conventional vehicle immediately swerves off course and the driver must steer accordingly to counteract its effect. With DBW AWD, drivers hardly notice the wind at all. This is because the sensors immediately register the deviation it causes, while the computer already *'knows'* the direction that the driver wants to take due to the position of the sidestick.

As a result, the wheels are automatically turned in the right direction to offset the effect of the side wind. With the stabilising algorithm of DBW AWD, however, sensors, computers, and actuators react so quickly that the vehicle neither skids nor swerves out of the lane. Instead, it maintains the desired course.

Passive Safety - Integrating driving functions into a sidestick offers additional passive safety benefits, too. It is well known that, if there is no steering column, then there is also no danger of the chest injuries often caused in an accident and if the driver's foot can no longer get caught in one of the pedals during a collision, then the number of foot injuries may also be reduced.

Braking Speed - But the sidestick concept's ace in the hole is braking speed. In order to brake, drivers of conventional vehicles require an average of 0.2 s to move their feet from the acceleration to the brake pedal. At a speed of circa 50 km/h (30 mph), this translates into an additional braking distance of roughly 2.9 m (9.5 feet). The quicker reaction time of the sidestick system could therefore prevent many collisions [DAIMLERCHRYSLER 1998-2004].

Automatic Vehicle Velocity Adjustion - DBW AWD -- whether by means of sidestick or mechatronic steering wheel -- also offers a general advantage. Because there is no longer a direct mechanical or fluidic (hydraulic) connection between the driver and the wheel, the steering ratio can be automatically adjusted to the vehicle's velocity.

2.1.1 Engine Management Control

Why Throttle Valve Control? The development of engine management controls (EMC) shows how mechatronics have been gradually introduced to the point where the majority of automotive vehicles sold on the world market now have full-authority EMC [WARD AND WOODGATE .2004].

Early ECEs or ICEs were controlled by the driver regulating induced air with an accelerator pedal (see Fig. 2.12).

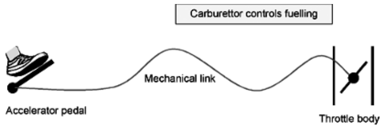


Fig. 2.12 Original engine management control (EMC) concept (simplified) [WARD AND WOODGATE 2004].

Subsequently, electronic ignition was introduced, followed by closed-loop EMC [WARD AND WOODGATE, 2004].

In the latter systems, the driver still controlled the throttle directly, but the EMC system regulated the fuelling and the spark timing (Fig. 2.13).

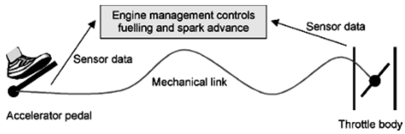


Fig. 2.13 Advanced engine management control (EMC) concept [WARD AND WOODGATE 2004].

In modern ECEs or ICEs, the accelerator is simply an input to the EMC micro-computer and there is no direct M-M link to the ECE or ICE (Fig. 2.14).

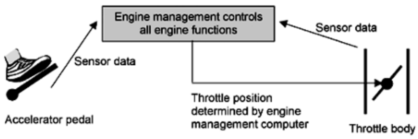


Fig. 2.14 Very advanced closed-loop engine management control (EMC) concept [WARD AND WOODGATE 2004].

As a consequence, it has changed from being the driver's instrument to vary ECE shaft or ICE crankshaft angular velocity to being the instrument to generate torque -- an automotive vehicle *'objective'*. The driver's command may be overridden or modified in pursuit of other vehicle objectives. Most EMC systems are designed to *'failsafe'*. If faults occur from that, the mechatronic control system cannot recover and, the systems enter a designated *'safe state'*, usually with the ECE or ICE operating at limited power or shutdown. Failsafe design commonly incorporates redundancy in sensors and processing so that a first fault does not immobilise the automotive vehicle.

Most new automotive vehicles have been updated with TVC systems that make conventional throttle cables and linkages a thing of the past. With these systems, there is actually no continuous mechanical connection between the accelerator pedal and the fuel system, just a set of sensors, wiring harnesses, and connectors. A throttle cable can not have too many twists and kinks, but with only wiring harnesses, it doesn't matter and helps reduce general clutter underhood [HALVORSON 2004].

Mechatronic throttles allow a full communication loop between the EMC microcomputer, accelerator pedal, and fuel injection system, meaning that the vehicle can respond faster and more efficiently to changes in the driver's right foot or functioning circumstances. They can even anticipate how hard drivers are going to press into the throttle based on past driving habits, and work together with the transmission to give the best performance and efficiency.

DBW AWD propulsion mechatronic control systems have fewer moving parts and can be better isolated from vibration and the elements. Failure is safer, too: while throttle cables might wear, break, or snag, **artificial intelligence** (AI) operation may keep the throttle valve from ever *'sticking'* open, and if the throttle system fails it is linked to the vehicle's diagnostic system [HALVORSON, 2004].

The TVC performs an imperative role in the advance of DBW AWD propulsion mechatronic control systems. The position mechatronic control of the throttle valve is practically an intricate dilemma, due to assumed constraints and system features.

TVC already implemented by many vehicle manufacturers, has the following advantages [SCHOFIELD, 2004]:

- ❖ Eliminates a number of M-M, F-M or P-M components;
- ❖ Superior precision and permanence realisable;
- ❖ Much larger freedom for integration with different mechatronic control; systems, for example, emission control, vehicle traction/stability systems;
- ❖ Enhanced design flexibility: throttle does not have to be an accelerator pedal; could be, for example, a joystick (sidestick) controller.

A cascaded mechatronic control structure, including a non-linear trajectory generator filter, is implemented, permitting each different mechatronic control dilemma to be elucidated with the right and proper mechatronic control algorithm and implementation technology. Regarding the application of variable structure mechatronic control techniques is the indispensable aspect to finding the solution.

Comprehensive simulation tests are reported in ROSSI ET AL. [2000] to show the performance of the proposed control algorithm. A prototype controller is presented there. The investigational implementation of the controller for an amount from 2.5 deg to 85.5 deg indicates a very flat position trajectory with a maximum value of the dynamic position error of 7 deg. Appliance requirements are absolutely fulfilled both in terms of control performance and controller cost. For instance, one of the well-known TVC systems [MCKAY ET AL., 2000] uses a minimum of two accelerator-pedal sensor potentiometers and two throttle sensor potentiometers (see Fig. 2.15).

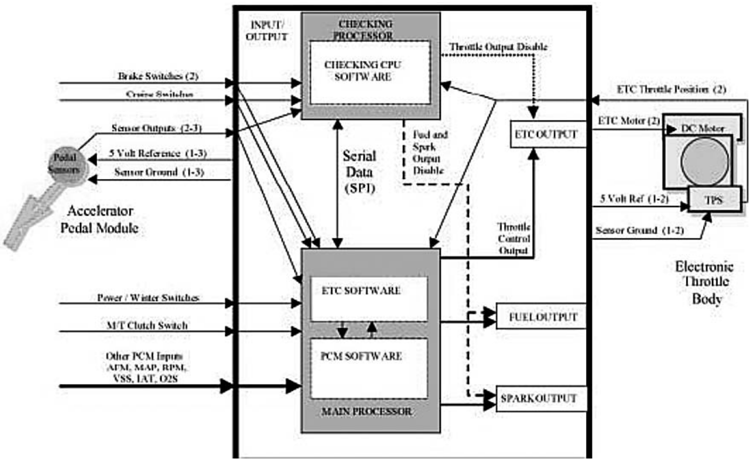


Fig. 2.15 TVC structural and functional block diagram
[Delphi; MCKAY ET AL. 2000].

Additional voltage references, sensor grounds, or a third accelerator pedal sensor are available to increase the overall accelerator pedal position sensing reliability depending upon the customer requirements (see Fig. 2.16).

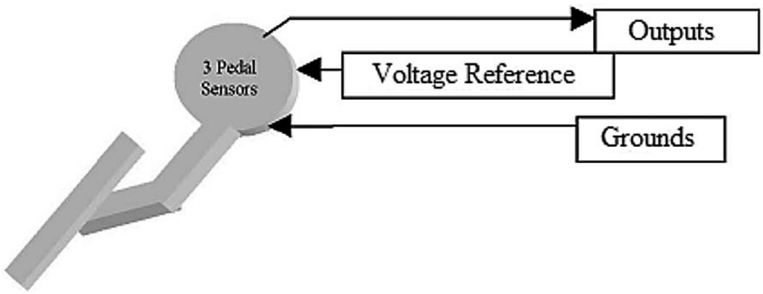


Fig. 2.16 Accelerator pedal module [MCKAY ET AL. 2000].

Electrically isolated voltage references and grounds may be used so that a single-point electrical short/open condition does not invalidate all pedal/throttle position sensors.

The sensor-output characteristics are diversified to improve the detectability of common mode failures using correlation rationality diagnostics (see Figs 2.17 and 2.18).

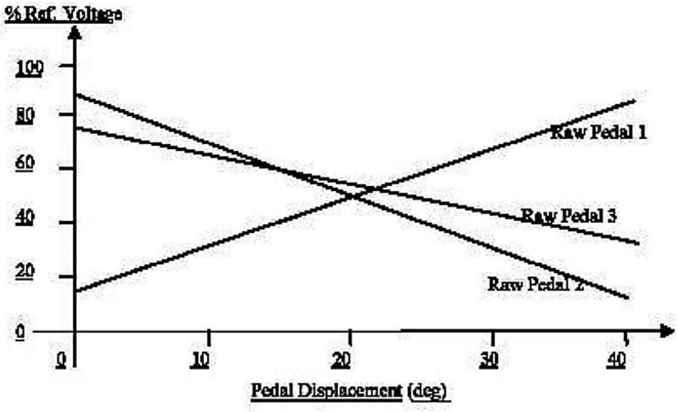


Fig. 2.17 Accelerator pedal position sensor characteristics [McKAY ET AL. 2000].

The TVC system also uses redundant brake switches that are logically opposed, one normally open and one normally closed. As with the throttle and pedal sensors, brake switch redundancy and diversity facilitates reliable braking signals and rationality diagnostics.

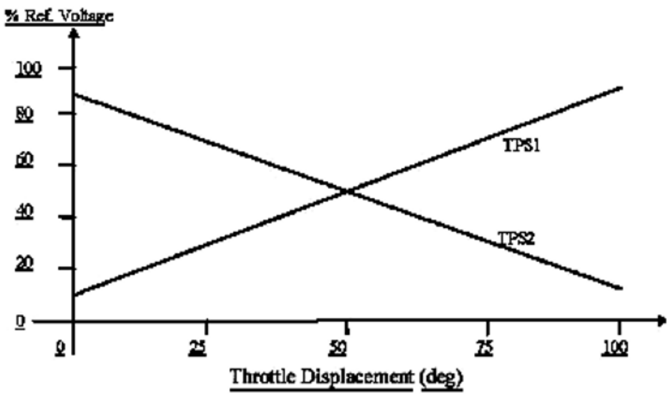


Fig. 2.18 Throttle position sensor characteristics [McKAY ET AL. 2000].

A pedal-sensor position determination method based upon the fault status of the sensors is used to convert the multiple sensor readings into a single, highly reliable value of accelerator pedal position [Nichols and Vergerlehner 1997].

Real-time programming based on schedule carrying code may be also used for TVC system with *Giotto*: a time-triggered programming language that supports the development of an embedded control system for the DBW AWD propulsion mechatronic control system, as shown in Figure 2.19 [Henzinger et al. 2003; Kirsch 2003].

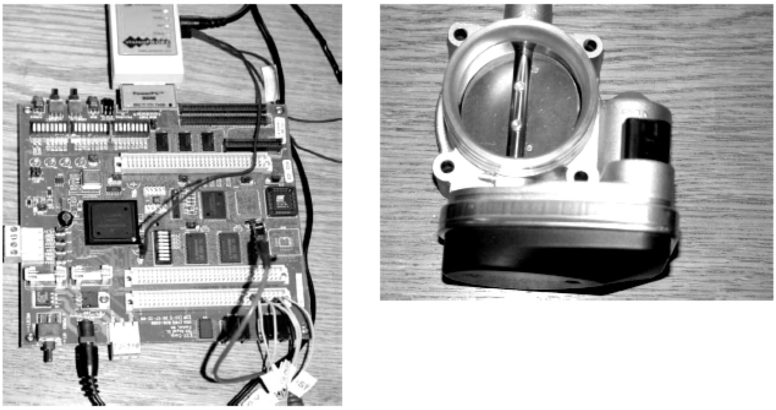


Fig. 2.19 Giotto for BMW's *TVMC* (Part of the DARPA *MoBIES* Project continued at Universität Salzburg) available for OSEKWorks *RTOS*, 1 processor: Motorola *MPC 555* 40 MHz [Kirsch 2003].

Time-safe *Giotto* program is:

- ❖ Predictable – *deterministic* real-time code;
- ❖ Platform-independent – runs on *distributed* systems;
- ❖ Multi-modal – supports *mode switching*;
- ❖ Composable – supports *modular* compilation.

Giotto is available for:

- ➢ Windows, Linux, OSEKWorks, HelyOS;
- ➢ Java.

An automotive vehicle **chemo-thermo-fluido-mechanical** (CH-TH-F-M) ICE's logic (Fig. 2.20) still consists mainly of primitive linkages, rocker arms, contacts, valves, and gears [Huber and Mills 2000, 2005].

Much of the mass of the conventional ICE, most of its cost, and all the logical sophistication, are located in the peripherals that surround the pistons and cylinder at the core.

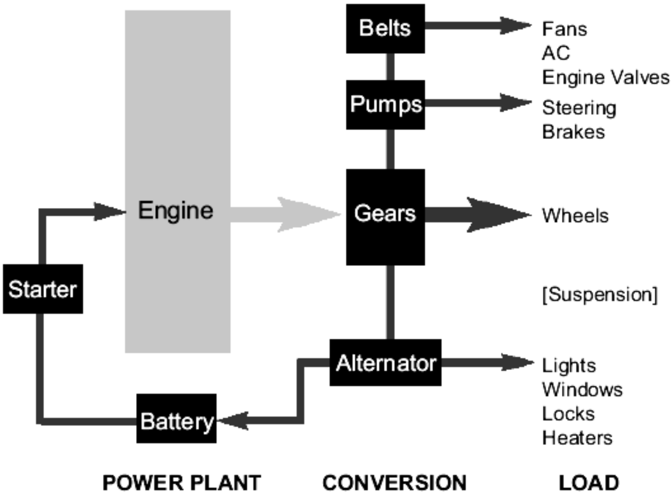


Fig. 2.20 Chemo-thermo-fluido-mechanical (CH-TH-F-M) powerplant and mechano-mechanical (M-M) drivetrain [HUBER AND MILLS 2000, 2005].

The vehicle's **mechano-mechanical** (M-M) powertrain is being transformed from mechanical to digital **electro-mechanical** (E-M) because of low-cost high-power macroelectronics and low-power microelectronics may now control high-power faster, more precisely, more reliably, and in less space, than M-M substitutes (Fig. 2.21) [HUBER AND MILLS 2000, 2005].

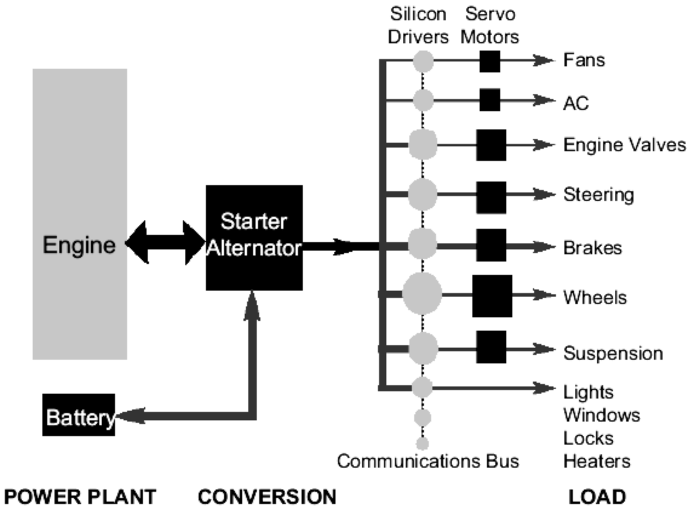


Fig. 2.21 Chemo-thermo-fluido-mechano-electrical (CH-TH-F-M-E) powerplant and electro-mechanical (E-M) drivetrain [HUBER AND MILLS 2000; 2005].

Vehicle manufacturers already spend more on etched silicon and/or other amorphous semiconductor macrocommutators, microprocessors, and drivers than on steel. When automotive scientists and engineers consider future transmissions, they must undertake to forecast how the global sharing of **semi-automatic transmissions** (SAT), **fully-automatic transmissions** (FAT) and **continuously variable transmissions** (CVT) may alter after novel innovations, for example, such as mechatronically-controlled multi-velocity SATs, FATs and CVTs have had a opportunity to offer solutions to the practical uncertainties they have nowadays.

Moreover, they must enquire the problem of whether entirely recent EMC ECUs are realistic with this current era's M-M DBW AWD propulsion mechatronic control systems. Such recent EMCs should comprise less complicated automatic shift means that would be less expensive to produce. Figure 2.22 exemplarily illustrates one of the conventional EMCs [SEIFFERT AND WALZER 1991].

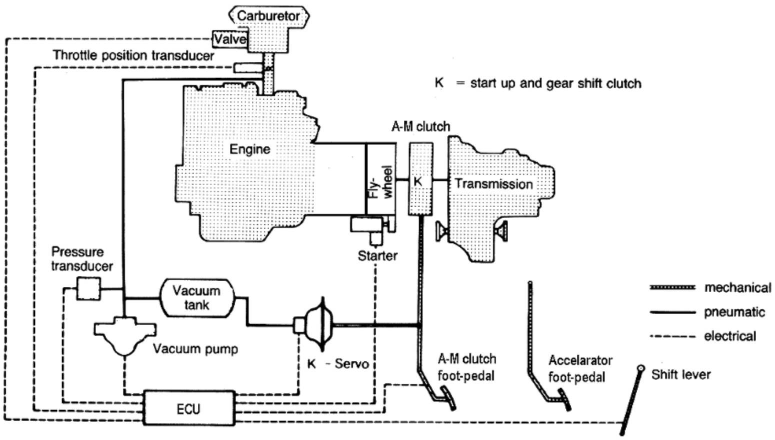


Fig. 2.22 Conventional EMC [VW; SEIFFERT AND WALZER 1991].

A start-up and gear-shift drive M-M clutch is, on the one hand, between the ICE and MT, it is, on the other hand, actuated by a servomechanism actuator so that it is reasonable to start the vehicle automatically, that is, without the M-M clutch foot-pedal.

Flexibility and reliability in M-M DBW AWD propulsion, decreased SFC as well as noise, necessitate a high number of gear steps, and if they further provide this idea, they enter the hypothesis of an SAT or FAT or CVT.

Due to its extensive range between **bottom-to-top** (BTT) ratio, such an SAT or FAT or CVT would be perfectly compatible for all the automotive vehicles.

Regarding the potential limits of low SFC, a variety of categories of **start-stop** (SS) EMC occurs. Several of these systems function just when the vehicle is at standstill; others work properly, when the vehicle is in motion.

To comprehend the course of action of transmission ratios on a vehicle's SFC, lines for rolling resistance, constant power, and SFC are shown and compared in Figure 2.23 that consequently depicts an exemplary ICE performance map [SEIFFERT AND WALZER 1991].

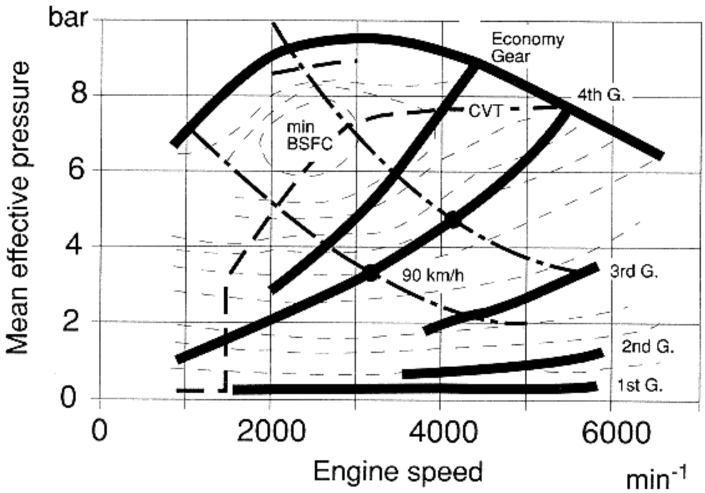


Fig. 2.23 Internal combustion engine (ICE) performance map showing lines for rolling resistance, constant power and SFC; heavy lines: five-speed MT; heavy dashed line: CVT; dash-dotted lines: constant power; thin dashed lines: CVT [VW; SEIFFERT AND WALZER 1991].

Shown on the ICE performance map is a mean value of the input-manifold effective air-pressure that is proportional to ICE crankshaft torque against ICE crankshaft rotational velocity.

The rolling resistance lines for constant, level driving for the first four gears illustrate that the vehicle's functional points are normally distant from the vicinity of optimum ICE efficiency that is exposed on the left side of the ICE performance map as an atoll signed **min best SFC** (min BSFC).

In other words, an ICE can generate a given value of the ICE crankshaft output power most economically at a high value of the ICE crankshaft torque and low value of the ICE crankshaft rotational velocity. These superlative ICE-functional points may be comprehended through supplementary '*long*' transmission ratios, for example the so-termed E-MTs (E for economy) or by means of SATs or FATs or CVTs that allow the ECE or ICE to operate autonomous of vehicle velocity at optimal ICE functional points.

One more means to decrease SFC may be established by a SS EMC ECU that switches the ECE or ICE off exclusively when no ECE or ICE crankshaft output power is indispensable. This means ECE or ICE idle is prevented, and with it the detrimental SFC and exhaust-emission circumstances that are related with idling.

Figure 2.24 illustrates one of the potential SS EMCs [SEIFFERT AND WALZER 1991].

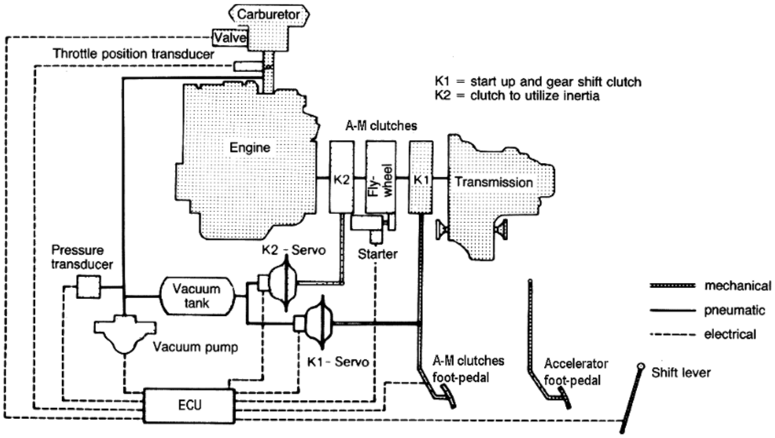


Fig. 2.24 **SS** EMC that uses inertia [VW; SEIFFERT AND WALZER 1991].

A start-up and gear-shift drive M-M clutch is the normal M-M clutch between the ICE and MT, it is, on the other hand, actuated by a servomechanism actuator so that it is reasonable to start the automotive vehicle automatically, that is, without the M-M clutch foot-pedal.

An M-M clutch, to make use of inertias is a supplementary M-M clutch that disconnects the flywheel from the ICE crankshaft.

Another servomechanism actuator also actuates this M-M clutch, if the driver releases the accelerator foot-pedal, both M-M clutches are released concurrently, at the same time the fossil fuel supply to the ICE is disconnected and, without the flywheel mass, the ICE immediately stops.

The flywheel, on the other hand, remains spinning and once the driver actuates the accelerator foot-pedal for a second time, the still-rotating flywheel is disconnected from the ICE crankshaft and the flywheel's kinetic mechanical energy cranks up the ICE without emitting contaminants.

Once the ICE has cranked up, the servomechanism actuator sets up an interaction with the automotive vehicle through the drive M-M clutch; this is performed so precisely that the driver and passengers do not sense any jerking.

After a full stop, starting the automotive vehicle is realised in an analogous manner. Should the rotating mechanical energy stored in the flywheel not be sufficient to crank up the ICE, an E-M motor may cause the flywheel to spin up to angular velocity.

This E-M motor can be much lower than current starter E-M motors for the reason that it does not strongly affect the ICE's compression.

A SS EMC ensures that the ICE is engaged in operation when the **starting, lighting, and ignition** (SLI) CH-E/E-CH storage battery charge is low, while the servomechanism actuator's vacuum pressures are not enough, or after downhill ICE is necessary.

Experiments in the European urban driving cycle have produced 20% fuel savings with this SS EMC; in reasonable driving circumstances 30% fuel savings can be attained.

What stands against it is the substantial complication of mechanisms and the sophistication of the mechatronic control.

In view of current fossil fuel costs, this mechatronic control system is not visibly cost efficient.

This basis, on the other hand, includes adequate opportunities for designing soon-to-be SS EMCs that could ultimately be attractive for mass manufacture.

Summing up, the term *'DBW AWD'* refers to the replacement of a vehicle's M-M, F-M and/or P-M subsystems by mechatronic controls.

An example of a subsystem where a DBW AWD propulsion mechatronic control development is occurring includes TC.

Interfacing the driver and subsystem with a microprocessor-controlled DBW AWD propulsion mechatronic control system may result in less mass, more design flexibility, decreased manufacturing complexity, and higher reliability.

TVC puts an electrical connection between the throttle valve and accelerator pedal in place of a traditional cable. It is more efficient than traditional throttle systems and has the added benefit of enhancing some of a vehicle's safety systems, such as electronic stability and traction control.

Vehicle manufacturers primarily introduced the TVC on its luxury vehicles as an efficient way of both synchronizing the EMC microcomputers (two microcomputers were necessary for the combustion for all 12-cylinders on a day when CPUs were sluggish been.

Through the years, mechatronic throttles have gradually phased in for more expensive luxury models, and during the past couple of years, been introduced into mainstream and low-cost automotive vehicles.

Why Variable Valve-Timing Control?

Development of a non-throttled ICE torque mechatronic control based on both intake and exhaust valves fully **variable valve-timing control** (VVC), may be used in EMC systems. Major results of an application of the VVC may be [UNIVERSITA' DI BOLOGNA 2004]:

- Significant reduction of the SFC at partial and low ICE loads;
- Internal exhaust gas mechatronic control by means of the variable valves overlapping.

In Figure 2.25 is displayed the SFC reduction in percents versus the ICE's crankshaft angular velocity (rotational speed) in percents and load in percents [UNIVERSITA' DI BOLOGNA 2004].

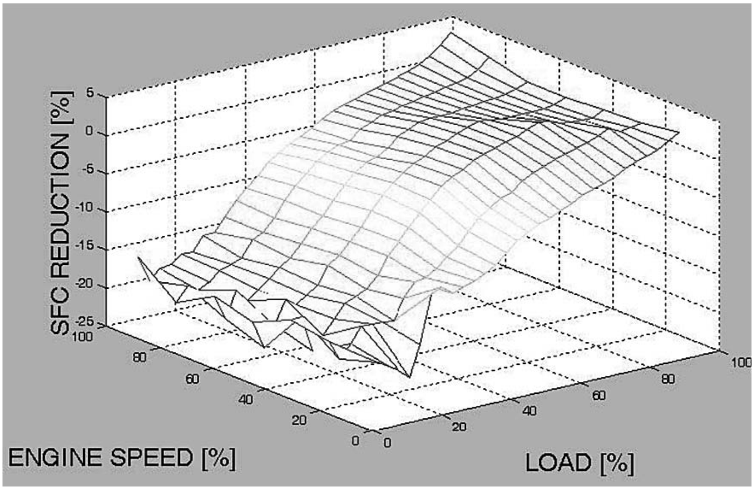


Fig. 2.25 SFC reduction in percent versus the ICE's crankshaft angular velocity in percents and load in percents [MagnetiMarelli].

Optimised intake and exhaust valve-timing angular position in degrees versus ICE load in percents, at ICE crankshaft angular velocity 524 rad/s (5,000 rpm) is shown in Figure 2.26 [UNIVERSITA' DI BOLOGNA 2004].

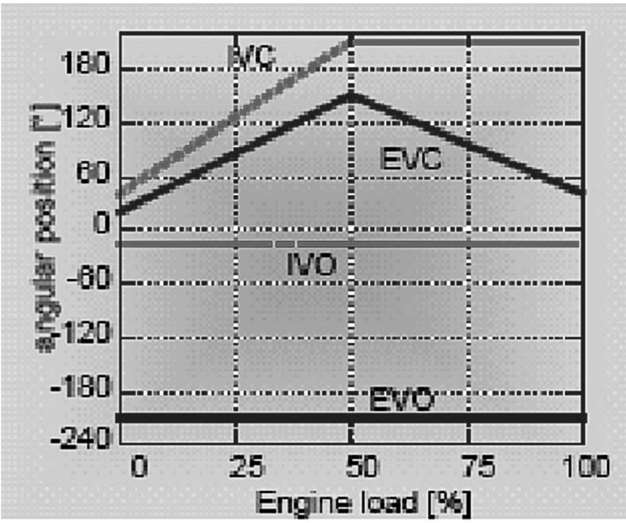


Fig. 2.26 Optimised intake and exhaust valve timing angular position in degrees versus ICE load in percents [MagnetiMarelli].

Figure 2.27 illustrates ICE efficiency trends for different kinds of ICE load mechatronic control systems [UNIVERSITA' DI BOLOGNA 2004], also well known as EMC systems.

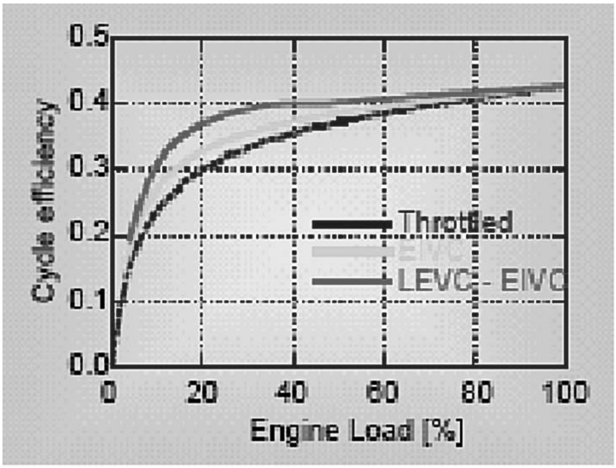


Fig. 2.27 ICE cycle efficiency versus ICE load in percents for different kinds of the EMC systems [MagnetiMarelli].

A non-throttled ICE torque mechatronic control based on both intake and exhaust valves' fully variable timing mechatronic control, is in fact an **air-fuel-ratio** (AFR) mechatronic control and it is one of the well-known problems in EMC systems design [CHANG ET AL. 1995, JONES ET AL. 1995, POWELL ET AL. 1998, KING AND GRIZZLE 1999, MIANZO AND PENG 1999, MIANZO ET AL. 2001].

It is also one of the most critical emission mechatronic control systems. For instance, *US Federal Emission Regulations* put severe limitations on the emission rates of certain exhaust gas components. These regulations in turn motivate the automotive industry to deliver better and more cost-effective emissions mechatronic control technologies.

Application of **three-way-catalytic** (TWC) converters provides simultaneous efficient conversion of the ICE exhaust gases to less harmful substances over a narrow band around stoichiometry. In this setting, the primary objective of the AFR mechatronic control can be stated as the regulation of the air-fuel-ratio to stoichiometry to realise the maximum performance of a TWC.

In most production air-fuel controllers, feedforward is an important part of the mechatronic control structure. This is due to the presence of pure delays in the system that places a limitation on the system's bandwidth and therefore on the transient response of the system.

It is common in a production system to use a measurement or estimation of the air charge and to supply a proportional amount of fuel to achieve the desired stoichiometric air/fuel ratio.

AFR mechatronic control in DBW AWD propulsion mechatronic control systems presents additional challenges and opportunities [MIANZO ET AL. 2001].

DBW propulsion is a term commonly used to describe the EMC systems where the driver does not have a mechanical linkage to the throttle and therefore does not directly control the amount of air charge into the cylinder.

In such cases, a powertrain mechatronic control computer interprets pedal input from the driver and calculates a driver's demand, typically in terms of demanded torque, air charge, or acceleration.

The computer then schedules the amount of charge into the ICE cylinder to deliver the driver's demand. This is typically done by using a non-linear static mapping between accelerator pedal position and the demanded variable (for example, torque or air charge).

The mapping that is used is conceived by expert calibration during the automotive vehicle's development stage and is assumed to be available. Examples of DBW applications are throttle control and variable valve timing ICEs where the air charge into the ICE cylinder is mechatronically controlled by the valve timing instead of a throttle [MIANZO ET AL. 2001].

One of the primary advantages to DBW AWD propulsion mechatronic control systems is the ability to smoothly schedule what might otherwise be inefficient driver transient pedal inputs.

A four-induction event delay may be inserted after the demand map. The delay (40 ms at 1500 rpm and approximately 17 ms at 3500 rpm) sacrifices, for practical purposes, an imperceptible deterioration in acceleration performance for improved AFR control. The delay allows a *'lookahead'* or preview mechatronic control approach on what the *'future'* air charge demand request may be. The current air charge estimate or measurement would be used for the current sample in the preview mechatronic control.

In this chapter, a H_∞ preview control algorithm may be used to take advantage of this *'future'* information [MIANZO ET AL. 2001].

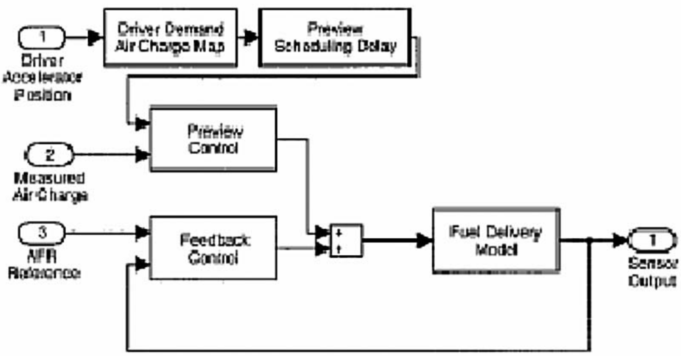


Fig. 2.28 Transient air fuel ratio (AFR) H_∞ preview control structure. [MIANZO ET AL. 2001].

The preview may be used to improve performance over limitations due to any delay in the powertrain. Feedback may be used to provide robustness to modelling errors and disturbances. The H_{∞} preview mechatronic control structure is shown in Figure 2.28.

2.1.2 Active Engine Management Control

In Figure 2.29 a structural and functional block diagram of the **active engine management control** (AEMC) system is shown with the **throttle valve control** (TVC), **adaptive cruise control** (ACC), ASR, MSR, and acceleration pedal, as well as the driver [MAGNETIMARRELLI 2001].

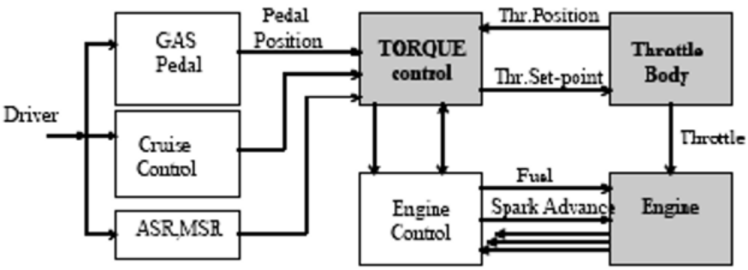


Fig. 2.29 Structural and functional block diagram of the active engine management control (AEMC) system with the throttle valve control (TVC), adaptive cruise control (ACC), ASR, MSR and acceleration pedal, as well as the driver [MAGNETIMARRELLI 2001].

A vehicle velocity mechatronic control system can range from a simple throttle-latching device to a sophisticated digital mechatronic controller that constantly maintains a set vehicle velocity under varying driving conditions.

The contemporary generation of the vehicle velocity mechatronic control systems may still use a separate module but may share data from the ECE or ICE, ABS, and transmission mechatronic control systems.

Modern ACC systems that include millimetre-wave radar sensors to measure the rate of closure to other automotive vehicles and adjust the vehicle velocity to maintain a constant distance, may be possible but need significant cost reductions for widespread private automotive vehicle usage [VALENTINE 1995].

The objective of an ACC is to sustain a steady vehicle velocity under varying road conditions, thus allowing the vehicle driver's to relax from constant foot throttle manipulation. In some cases, the ACC system may actually improve the vehicle's SFC value by limiting throttle excursions to small steps. By using the power and speed of an ECU and **fuzzy-logic** (FL) software design, an excellent ACC system can be designed [BANNATYNE 1992].

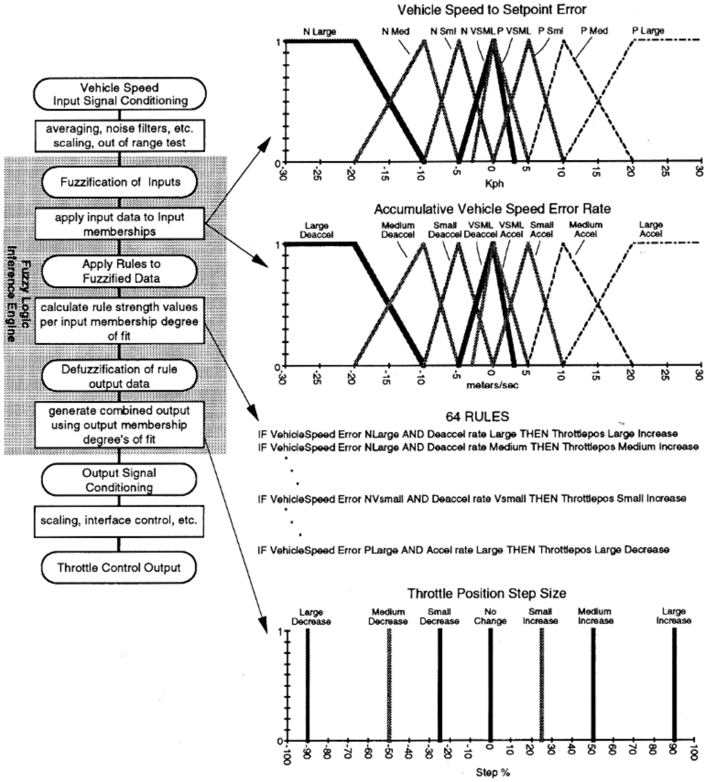


Fig. 2.30 Fuzzy logic (FL) vehicle velocity (speed) program flow [VALENTINE, 1995].

Fuzzy logic (FL) allows somewhat easier implementation of the vehicle-velocity error calculation because its design syntax uses simple linguistics. For instance, *IF* vehicle-velocity difference negative and small, *THEN* increase throttle slightly. The output is then adjusted to slightly increase the throttle.

The throttle position update rule is determined by another FL program that looks for the driver's cruise performance request (slow, medium, or fast reaction), the application type (small, medium, or large ECE or ICE size), and other ACC system factory-preset parameters.

Figure 2.30 shows one part of a FL design for computing normal throttle position. Other parts would compute the effects of other inputs, such as resume driver habits, ECE or ICE type, and the like [VALENTINE 1995; FIJALKOWSKI 1997A].

Other program design requirements include verification that the input signals fall within expected boundaries. For instance, a broken or intermittent vehicle-velocity sensor could be detected.

A FL design can limit the acceleration upon resumption, using simple rules such as *IF* resume and big vehicle-velocity error, *THEN* increase throttle slightly [VALENTINE 1995].

When a practical vehicular distance sensor is available, the ACC can be programmed to maintain either a constant value of the vehicle velocity or constant value of the distance from another vehicle.

Other methods of ACC should include receiving a roadside signal that gives an optimum value of the vehicle velocity for the vehicle when travelling within certain traffic control areas.

ACC, within the AEMC with the **preview distance control** (PDC), as well as the **brake-by-wire** (BBW) **all-wheel-braked** (AWB) conversion mechatronic control for co-operation with the DBW AWD propulsion mechatronic control, can also be integrated, with road-speed governing, and a manual ECE or ICE TMC is accessible for a power take-off (see Fig. 2.31) [TŐRNGREN 2002].

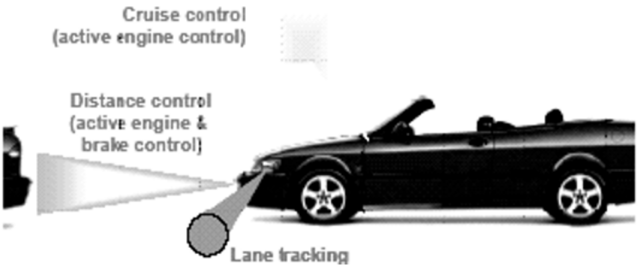


Fig. 2.31 Principle layout of the adaptive cruise control (ACC) and preview distance control (DC) [TŐRNGREN 2002].

Consider a DC maintaining desired values of the vehicle velocity and distance from other vehicles, safety implies:

- ❖ Reliable operation, for example, achieving the desired distance;
- ❖ Ensuring, for example, that a fault somewhere does not cause an undesired ECE or ICE command.

Compared also with a **steer-by-wire** (SBW) **all-wheel-steered** (AWS) conversion mechatronic control system, here reliability of the steering function is directly related to safety.

<u>*Radar Cruise Control (RCC)*</u> (Low-velocity following mode included) - At values of vehicle velocity lower than 30 km/h, if the preceding vehicle stops, a warning through display and alarm is given to stimulate the driver to press on the brake, as well as in the incident where the driver is late in pressing the brakes, stops the automotive vehicle (see Fig. 2.32) [AMEMIYA 2004].

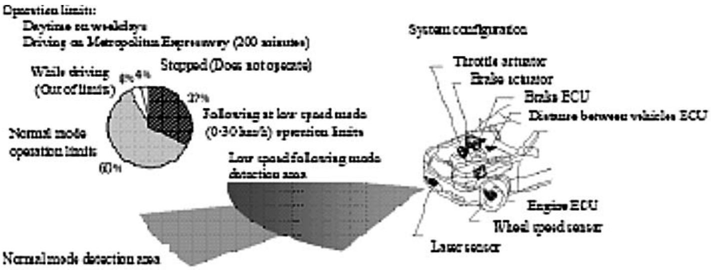


Fig. 2.32 Principle layout of the radar cruise mechatronic control
[Toyota; AMEMIYA 2004].

Radar Cruise Control (RCC) (Brake mechatronic control built-in) - Because of the information from the laser radar sensor located inside the bumper and so on, thus preserving a distance proportional to the vehicle velocity, within the cruise vehicle velocity set by the vehicle in front, uses the brake for deceleration (see Fig. 2.33) [AMEMIYA 2004].

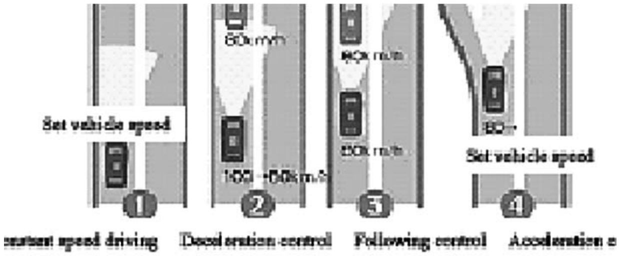


Fig. 2.33 Principle layout of the radar cruise control (RCC)
[Toyota; AMEMIYA 2004].

Lane Monitoring Control (LMC) - When driving on a highway, the distance between the vehicle and the white (yellow) lines on the roads is continuously measured using a colour CCD camera for guidance monitoring to the rear (see Fig. 2.34).

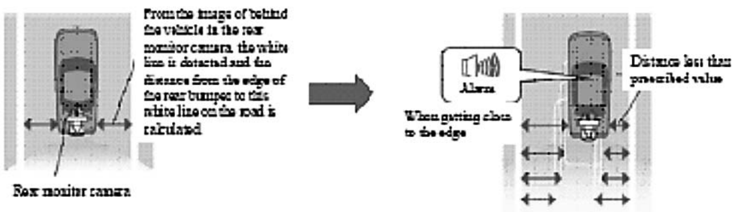


Fig. 2.34 Principle layout of the lane monitoring control
[Toyota; AMEMIYA 2004].

When the distance set by the driver is attained, an alarm sounds. This alarm does not sound when the turn signal is being used [AMEMIYA 2004].

Night Vision - It illustrates road circumstances, obstacles, as well as other vehicles and pedestrians, that are not easy to observe and are within or beyond the range of headlights during night driving and makes available a wider field of visibility (see Fig. 2.35).

Fig. 2.35 Principle layout of the night vision [Toyota; AMEMIYA 2004].

The system uses near-**infrared** (IR) light to make a possible display of the road surface and shape, fallen objects on the road, and virtually all information on the subject of the road surface [AMEMIYA 2004].

Back Guide Monitor with Voice (Comprising night vision capability) -- using the signal from a steering sensor, the automotive vehicle's predicted course is evaluated and displayed on the monitor (see Fig. 2.36). This assists drivers who have difficulty with backing up, such as into a driveway or parallel parking.

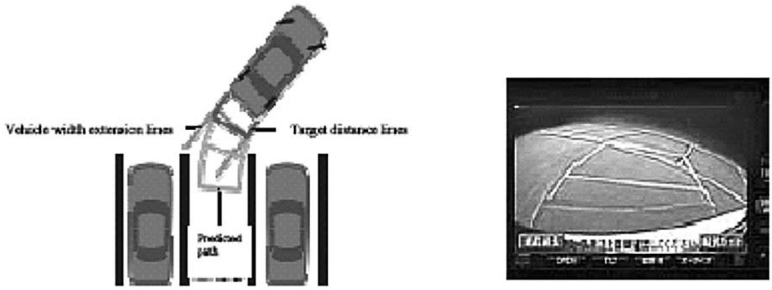


Fig. 2.36 Principle layout of the back guide monitor with voice [Toyota; AMEMIYA 2004].

Because of a colour guidance-monitoring camera at the rear, using near-IR radiation transmission, visibility at night is improved [AMEMIYA 2004].

Intelligent Parking Assist Control (PAC) -- The world's first mechatronic steering, assisting the mechatronic control system when backing up to when parking such as backing into a driveway or parallel parking (see Fig. 2.37). The driver can park the vehicle by just estimating the surroundings and operating the brake, steering is not necessary.

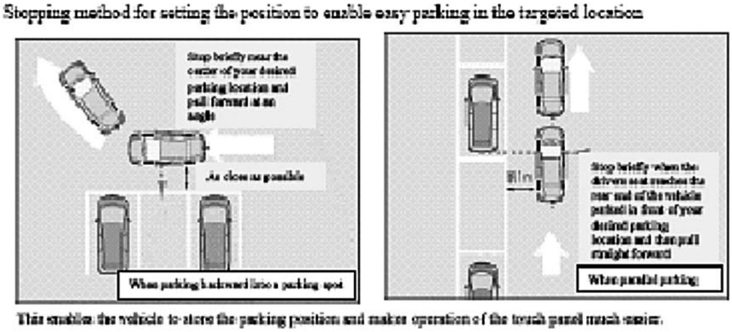


Fig. 2.37 Principle layout of the intelligent parking assist mechatronic control [Toyota; AMEMIYA 2004].

This function is very valuable to new drivers and those who have difficulty with parking (incorporated in a vehicle manufacturer's option set of DVD voice navigation systems, TV tuner, and colour rear guidance monitor with night vision) [AMEMIYA 2004].

Intelligent Brake Assist Control (BAC) - Stimulates driver to proceed by sounding an alarm when quick avoidance action is necessary so as to prevent a rear-end collision (see Fig. 2.38).

Fig. 2.38 Principle layout of the intelligent brake assist control (BAC) [Nissan; AMEMIYTA 2004].

If it is decided that a driver's action may not prevent a rear-end collision, the mechatronic control system uses the brakes to decelerate [AMEMIYA 2004].

Brake Assist (With preview function) - When the system decides that emergency braking is necessary, because of detection of the distance and relative vehicle velocity between itself and the vehicle in front, using millimetre-wave radar, it preuses fluidic pressure or electric voltage to the brakes prior to the driver using the brakes and because a reduction of the play in the system enhances the responsiveness and effectiveness of the brakes [AMEMIYA, 2004].

Lane-keeping Support Control (LSC) -- Gives slight torque to steering so as to continue driving inside a lane on a straight road supports the driver by using sound and display if the chance for deviation from the lane exists. Does not use any torque around a curve.

The function is temporarily suspended when the steering **hand wheel** (HW) or sidestick is turned for changing of lanes or a turning signal is turned on. The function is re-allowed after finishing the lane change and so on, and the camera is again capable of detecting the lane [AMEMIYA 2004].

<u>Adaptive Cruise Control (ACC)</u> (Laser radar type) - Because of setting the driver's desired value of the vehicle velocity (roughly 40 – 100 km/h), the constant value of the vehicle velocity driving is restricted. While travelling at a constant vehicle velocity, when coming up to a vehicle in the same lane, the vehicle velocity is gradually reduced and a predetermined distance between the vehicle in rear and the vehicle in front is maintained. When the vehicle in front of the vehicle in the rear moves away, the vehicle velocity gradually accelerates to the set value of the vehicle velocity leading to a constant value of the vehicle velocity driving. During a constant value of the vehicle velocity or constant value of the distance driving, if another vehicle moves into lane the mechatronic control system decelerates the automotive vehicle and informs the driver with an alarm if driver intervention is necessary [AMEMIYA 2004].

<u>Active Driving Assist (ADA)</u> - Through a stereo camera and millimetre-wave radar, expansive confirmation of the traffic environment in front of the vehicle is made possible. Because of cooperative mechatronic control of the throttle, brake, and **vehicle dynamics control** (VDC), the necessary mechatronic control and alarms are executed. Information with reference to vehicles in front and vehicles travelling in the opposite sense of direction is provided by sensor integration technology and given to the driver using the centre display, the metre display and an alarm. As a consequence of adding millimetre-wave radar as a sensor, the range of application is extended (see Fig. 2.35). The response of the sensor for distant objects has been enhanced and its capability has been verified during severe weather such as into the sun and snowy circumstances [AMEMIYA 2004].

<u>Adaptive Cruise Control</u> (Segment of ADA) - Verifies vehicles in front using a camera and radar. When there is no vehicle in front in the same lane, the constant value of the vehicle velocity set by the driver is continued (see Fig. 2.39).

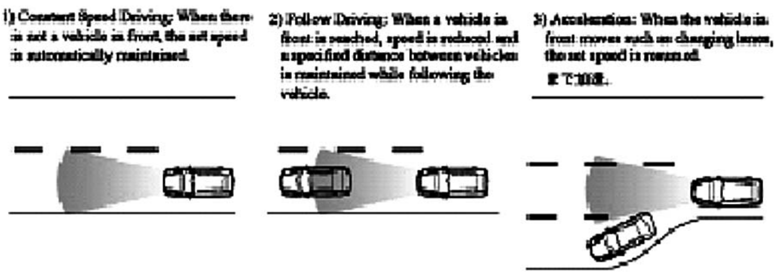


Fig. 2.39 Principle layout of the adaptive cruise control (Portion of ADA) [Subaru; AMEMIYA 2004].

When there is a vehicle in front, the vehicle velocity is automatically controlled to match that of the vehicle in front using throttle and brakes. When the front vehicle moves, the vehicle velocity recommences to that set by the driver [AMEMIYA 2004].

Vehicle Dynamics Control (VDC) - Comparison between actual performance of a vehicle and prediction of performance using driver operations and vehicle velocity. System for stabilising a vehicle’s performance through collaborative mechatronic control of the DBW AWD propulsion mechatronic control system, the ECE or ICE, transmission, and brakes so as to reduce the differentity between the performances of the two vehicles (see Fig. 2.40).

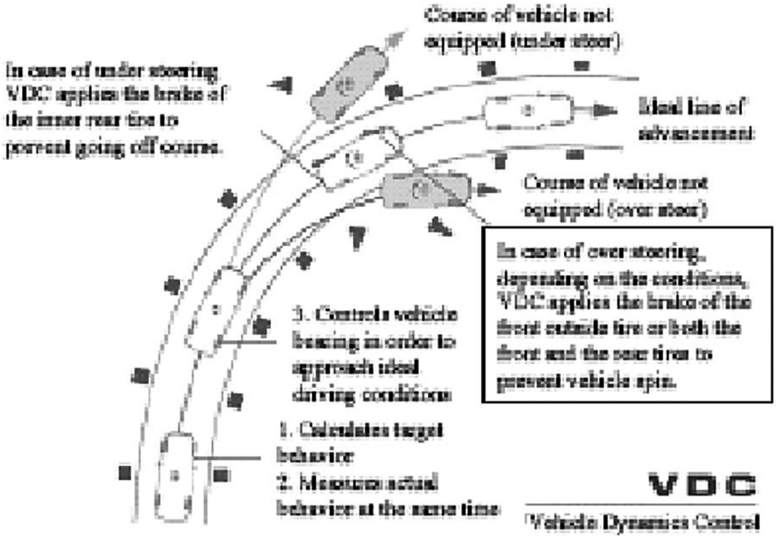


Fig. 2.40 Principle layout of the vehicle dynamics control (VDC) [Subaru; AMEMIYA 2004].

This system stimulates only when there is a prediction of hazards. Besides, there is a switch that permits the driver to turn the system off when this is shown to be necessary for the driving circumstances [AMEMIYA 2004].

Lane-keeping Assist Control (LAC) - The LAC confirms the lane using the image captured by the C-MOS camera located on the inside near the top of the windscreen. Applies suitable torque using the **electrical power steering** (EPS) and assists in holding the lane at values of vehicle velocity greater than 65 km/h, on straight roads and curves with a minimum radius of 230 m, allowing use on nearly all highways (see Fig. 2.41).

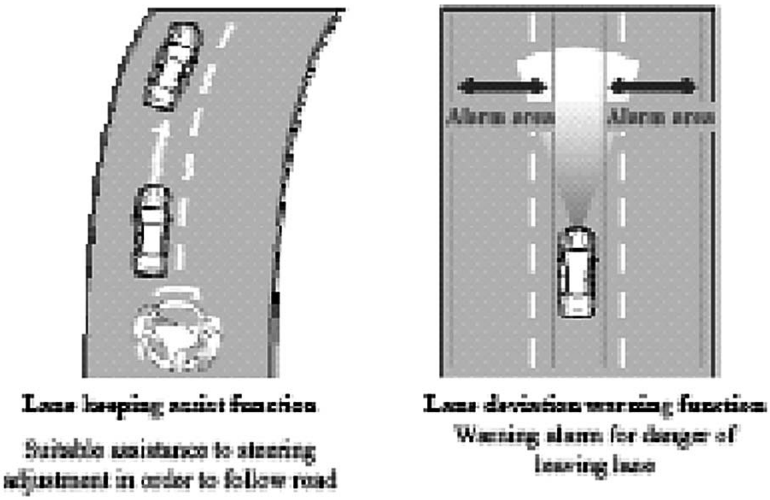


Fig. 2.41 Principle layout of the lane keeping-assist control (LAC) [Honda; AMEMIYA 2004].

Besides, if an incident deviation from the lane is feasible, the driver is predisposed to use an alarm. This moves the driver conscious of maintaining in the lane and that through light operation of the steering HW or sidestick; the driver's intention can be communicated allowing stability in remaining in the right lane [AMEMIYA 2004].

<u>*Lane-departure Warning Control (LWC)*</u> - The most common causes of unintentional lane departures are poor driver concentration, and statistics show that inatten-tion can be a factor in more than 30% of accidents in Europe and the United States [VALEO 2004A].

For that reason, some vehicle manufacturers have introduced a revolutionary solution that warns drivers of unintentional lane departure that can potentially reduce the number of accidents.

The LWC system is based on a high technology video-processing system. It integrates advanced signal processing in a single unit that can identify the road ahead. During unintentional lane departures -- detected when the driver fails to apply the indicator -- the driver is alerted by an audio or tactile system.

High processing speeds provide drivers with accurate and timely warnings to ensure immediate correction of the deviation. With the LWC system, customers can drive more safely, knowing that as soon as they change lanes without using an indicator, the system may immediately alert them, limiting the possibility of an accident. A miniature windscreen-mounted electronic video sensor warns the driver as soon as he or she departs from the lane. This high-tech video processing mechatronic control system warns drivers as soon as their vehicles unintentionally depart from the right lane.

The LWC system has the following features [VALEO 2004A]:

- ❖ The electronic video sensor is mounted behind the windscreen or built into the bumper;
- ❖ High picture processing speed permits warning the driver when necessary;
- ❖ An alarm or a vibration in the driver's seat gives the warning.

Intelligent Lighting Control (ILC) - An **intelligent lighting control** (ILC) system that improves visibility on curves by up to 90% may be applied. In vehicles with conventional headlamps, at nighttime, drivers have to rely on reduced visibility. The light beam points straight ahead regardless of the environment. On winding roads, these lights give drivers little forward visibility. Some vehicle manufacturers [VALEO 2004B] have therefore developed two-directional lighting solutions that can be installed separately or together in order to ensure optimum visibility in all conditions, as shown in Figure 2.42.

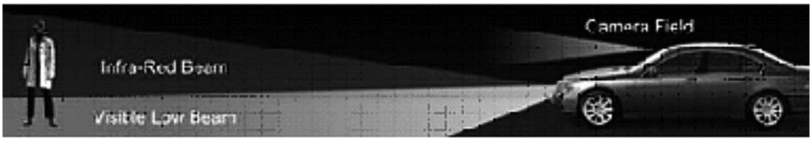


Fig. 2.42 Night-vision intelligent lighting control (ILC) system [Valeo; VALEO 2004B].

Dynamic bending light (DBL) enhances vision in wide curves at medium to high speeds. A motorised *Xenon* bi-function projector rotates the light beam according to the direction taken by the automotive vehicle whether in high or low beam.

Fixed bending light (FBL) enhances visibility and safety in sharp curves at low to medium speeds and at intersections. An additional light source is integrated into the headlamp to light up an area of 45 deg on either side of the vehicle. With bending light, the light beam follows the road ahead and illuminates where the driver needs light most. Based on vehicle information, such as vehicle velocity or steering wheel angle, the beam is automatically adapted to the road ahead, thus offering twice as much visibility in curves.

A technology driver may enjoy every time he or she drives at night:

- ❖ Better road visibility;
- ❖ Increased safety;
- ❖ Less fatigue;
- ❖ Less stress.

Bending Light - A state-of-the-art technology offers not only a high-tech image but also increased road safety.

Dynamic Bending Light (DBL) – With DBL, the low beam is rotated to illuminate the curves.

Fixed Bending Light (FBL) – Some vehicle manufacturers [VALEO 2004B] developed FBL technology to adapt the light to sharp curves, corners, and intersections. An additional fixed-light source is oriented towards the vehicle exterior and switched on progressively as a function of steering angle.

An Efficient Windscreen Washer Control (WWC) - Nobody would ever think of washing his or her dirty dishes without using hot water, so why shouldn't the same principle apply to cleaning vehicle windscreens? That was the question that led some automotive vehicle manufacturers [VALEO 2004C] to develop this innovative washer fluid heating system that effectively cleans and defrosts windscreens. Installed between the E-M-F pump and the washer nozzles, the WWC system is activated as soon as the ignition is switched on and remains available on demand. What is the result? Driver comfort and safety are ensured! An efficient WWC system enhances windscreen cleaning by heating the washer fluid. Windscreen smudges and ice are therefore removed more easily. This system is easy to install and fits all vehicle types.

Autonomous and automatic washer fluid heating systems have the following features [VALEO 2004C]:

- ❖ The fluid is hot and ready for use, 1 min after automotive vehicle ignition;
- ❖ It reaches the jets at about 65 deg C.

An efficient WWC system heats the washer fluid to ensure better visibility in all driving conditions.

Adaptive traction control (ATC) intended to avoid the drive wheels from spinning in response to submission of surplus throttle have been used since 1987. Automotive vehicles with powerful ECEs or ICEs are particularly susceptible to drive-wheel slip under acceleration from immobile and/or on low-traction on/off road surfaces. The effects moderated steering response on DBW FWD vehicles, reduced vehicle stability on DBW RWD vehicles, and failure of effective accelerative force [CZINCZEL 1995].

Great reciprocal differentities in left- and right-side traction levels cause premature driving-wheel slipping on slick on/off road surfaces. In these circumstances, the effective accelerative forces at both drive wheels may be moderated to a level proportionate to the adhesion available at the low-traction side. The ATC system brings wheel spin under mechatronic control, permitting the wheel on the high-traction on/off road surface to use the maximum value of the accelerative force to the on/off road surface.

The indispensable prerequisite for systems intended to optimise vehicle stability (with RWD) and steering mechatronic control (with FWD) is to continue acceptable lateral traction. The simplest arrangements realise this purpose by controlling an ECE or ICE torque. Both driving wheels transmit the same level of motive force, evaluated in proportion to the adhesion available at the low-traction wheel and, by this means, presenting exceptionally extensive lateral-traction reserves at the wheel with greater adhesion. When the traction levels are approximately equal at both driving wheels, the ATC system upgrades vehicle stability (steering mechatronic control) while enhancing accessible effective accelerative force beyond that available on an uncontrolled automotive vehicle with slipping wheels [CZINCZEL 1995].

The optimisation of traction creates a highest ascendancy when the tractive effort (motive force) must be transmitted to on/off road surfaces on which the adhesion changes considerably.

The conventional passenger DBW AWD automotive vehicle includes an M-M differential unit at the drive axle; this unit permits virtually failure-free differentities in wheel angular velocity (for instance, in corners) in conjunction with homogeneous torque sharing to the drive wheels.

This arrangement normally gives the appropriate dynamic vehicle response, as the equal sharing of a drive torque restrains vehicle yaw. On the other hand, differentity in the force-transmission potentials at the driving wheels can bring together requests from maximum traction to disclosure indispensable dependabilities in the design principle.

The development of ATC in automotive vehicles came about in the 1980s. During this era, mechatronics were giving new life to modern vehicles, allowing for great improvements in the mechatronic control systems.

ATC was developed from advances in the technology of ABS. These advances in ABS technology allowed the mechatronic control system to prevent wheel spin on vehicle and improve handling around corners. ATC was first developed for high-performance racing cars.

The performance, velocity (speed) and manoeuvrability that were required of these vehicles meant that superior mechatronic control was necessary.

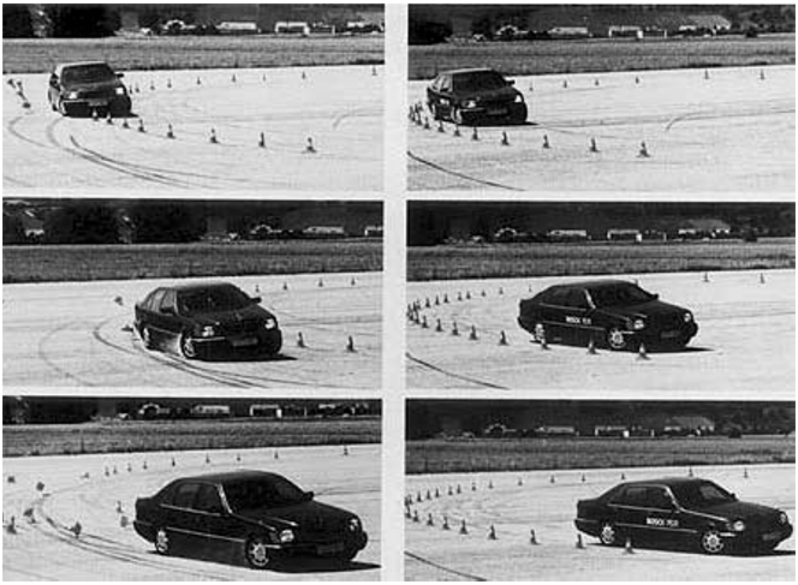
Formulae One racing first adopted ATC technology as teams searched for an edge over their opponents. It was developed in *Formula 1* racing to control wheel spin as racing cars travelled through tight turns and on slick surfaces at high values of vehicle velocity, allowing consistent application of power and maintenance of mechatronic control.

During the 2010s **vehicle stability-and-handling** (VS&H) became a major issue with normal on-road vehicles. People began looking for vehicles that would provide safe and efficient driving, while DBW 4WD enthusiasts were also looking for superior handling in their off-road vehicles.

As ATC technology became more familiar, the technology became cheaper to develop and more practical to apply to day-to-day vehicles. These days, ATC systems are combined with other vehicle mechatronic control systems such as ABS, SBW 4WS conversion and mechatronically controlled DBW 4WD propulsion to provide superior mechatronic control systems.

An ATC system is a closed loop feedback mechatronic control system used in most new automotive vehicles to stop them losing traction when cornering or accelerating rapidly. Basically, ATC systems are an enhancement of an ABS that stops wheels spinning while accelerating, cornering, or on wet or slick surfaces, as well as when off-roading.

The system has sensors and detects values of the angular velocity of all four wheels. It then processes this information and determines if any of the wheels are going faster than the others. The ATC system then drops the torque to the slipping drive wheel in a number of ways. Some ATC system strategies to stop wheel spinning include: braking, fuel cuts, spark cuts, throttle position, and altering the transmission (see Fig. 2.43) [MEMMER 2001].



Without ATC **With ATC**

Fig. 2.43 Bosch test track with an automotive vehicle testing adaptive traction control (ATC) [Robert Bosch Corporation; MEMMER 2001].

Mechatronic control aim is to maintain traction between the wheels and the road. This is to be done such that any loss in traction due to too great an acceleration, slippery roads, or cornering is corrected and traction quickly regained. A loss of traction during driving can be very dangerous.

When ABS is fitted to vehicles it can help deal with a loss of traction when decelerating. In other words, if you needed to stop rapidly while driving (for example, if someone has not seen you coming and pulls out dangerously in front of you), ABS is just the thing you need. It may prevent you skidding when *'slamming'* on the brakes. This is beneficial as the maximum grip between your tyres and the road occurs when the wheels are still rotating and therefore able to apply a larger deceleration. This is similar to how ATC works [GODFREY AND YATES 2002].

Although the term *'adaptive traction control'* implies that the driver may have control over the traction between vehicle's tyres and the road at all times, this is not the case. ATC in automotive vehicles deals specifically with controlling any loss in traction during acceleration only. This can be helpful in avoiding some dangerous situations. For example, if an driver is turning onto a busy road and is going to try and pick a small gap between vehicles to pull out into, then the driver wants the maximum acceleration that the vehicle can deliver.

If the road is a bit wet and the driver pulls out, the wheel-tyres may slip, this could have disastrous consequences. As with ABS, it is known that the maximum friction that wheel-tyres can obtain occurs just before they start significant slipping. Therefore, the ATC system aims to give the vehicle's wheel-tyres the maximum grip on the road that is possible while accelerating. It may do this by reducing the power delivered to any slipping tyres until they achieve the desired grip. A graph showing the friction experienced between a tyre and the road versus how much it is slipping for various wheel-tyre conditions is shown in Figure 2.44 [THOMAS 1998].

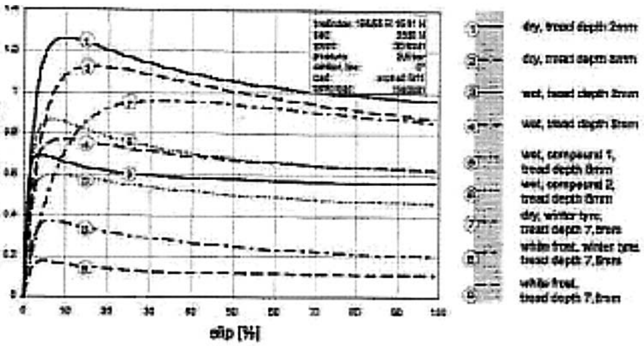


Fig. 2.44 Friction versus percentage slip.[*RACE*LOGIC; THOMAS 1998].

Achieving quick and accurate responses is essential in maintaining safe vehicle operation. In order to obtain the optimal system response, it is important to take into account the system's rise time, percentage overshoot, settling time, and the steady-state errors that are explained below. All of these factors should be reduced to a minimum for the system to be effective, and are influenced by all the components contained within the system. The faster -- the components, the faster -- the response of the system. A typical system response is shown in Figure 2.45 [GODFREY AND YATES 2002; THOMAS 1998].

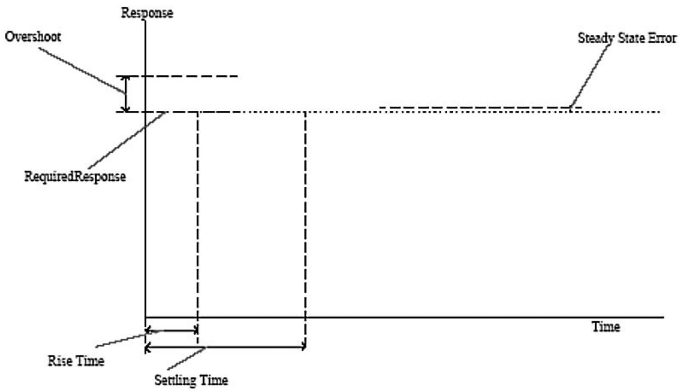


Fig. 2.45 A typical system response physical model [*RACE*LOGIC].

At any point in time, the system is trying to achieve the required response. There will be a delay in the system reacting to a new requirement and achieving it. This is referred to as the rise time. The system then wants to stay at this point for maximum benefit; however, this is not physically possible and results in an amount of overshoot. The system must then settle itself at the required position. Any difference between the given response and the required result as time approaches infinity is called the steady-state error. The essence of ATC is to prevent undesired slipping of the tyres. These can be dangerous situations and a quick response is paramount. Likewise, the amount of system overshoot can cause inefficient mechatronic control of the vehicle if the brakes are applied more than is necessary, and the ability of the vehicle to rapidly accelerate is hindered. The mechatronic control system reduces these factors in a number of ways, including using compensators and fast-acting electrical equipment [GODFREY AND YATES, 2002].

The ATC system is a feedback mechatronic control system. The controller is the part that makes the decision as to whether or not any action needs to be taken. The controller constantly receives a signal from the sensors and sends out its own signal to the actuators. It then receives feedback from the sensors and the cycle is repeated many times a second. These sensors are continually measuring the angular velocity at which the wheel-tyres are rotating. The controller then compares the angular velocity of the tyres. Should the angular velocity of any of the tyres be determined to be too great relative to the others, the controller than sends a signal to the actuators (for example, the spark plugs and the brakes). This signal tells the spark plugs to ignite at a later timing in the ICE, and/or the brakes to apply themselves to the offending wheel-tyre. This reduces the effective power output to the tyre and therefore the angular velocity at which it is rotating. This power reduction is sustained until the controller determines that the signal received from the sensors indicates that the tyres are now all rotating at a sufficiently close angular velocity to each other (this means that a larger amount of friction is being retained between the road and the tyre). The controller then sends a signal to the actuators telling them to resume their normal operation. The ATC system can combine with existing EM^{2}C systems to provide a more efficient operating system. A basic interpretation of the complete system is shown in Figure 2.46 [GODFREY AND YATES 2002; THOMAS 1998].

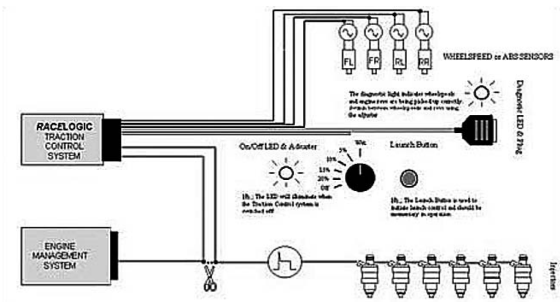


Fig. 2.46 Combined *RACE*LOGIC automotive vehicle's ATC system [THOMAS1998].

The yaw rate is a measure of an automotive vehicle's behaviour to do with the wheel’s movement on its vertical *z* axis, in other words, tilting.

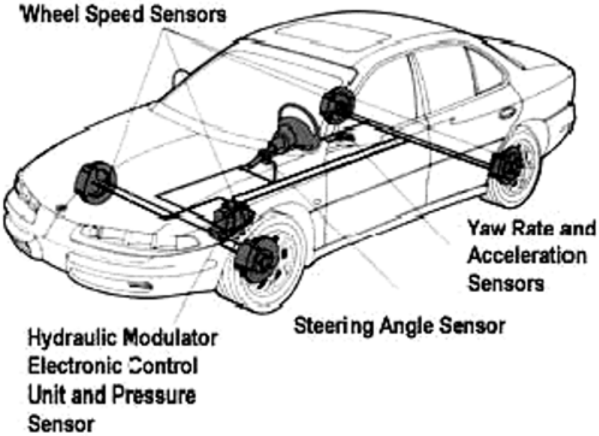


Fig. 2.47 The positioning of a traction control system’s sensors [MEMMER 2001].

It is important to measure the yaw rate for calculating the wheels’ actual values of angular velocity, because when cornering, if the tilting of the wheels is not monitored, the angular velocity (speed) sensors may report incorrect data that could lead to a change in traction by the actuator when it is already satisfactory. Overall, an ATC system relies on three different sorts of sensors: angular velocity (speed) sensors, steering angle sensors, and yaw rate sensors (see Figure 2.47). When used together, they are quite effective in delivering the information required by the controller for effective ATC.

Figure 2.48 exemplifies the system dynamics of a M-M drive shaft, differential, and drive wheels on on/off road surfaces affording differing levels of traction with adhesion coefficients μ_H and μ_L (high wheel and low wheel) [CZINCZEL 1995].

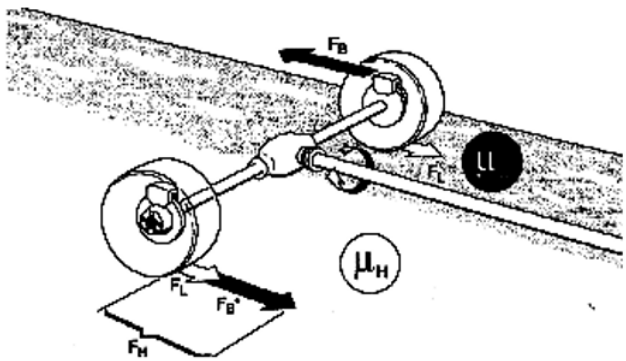


Fig. 2.48 Braking intervention to limit M-M differential slip [CZINCZEL 1995].

The torque activating from the driveshaft is disseminated equally between the wheels. The low wheel acts in response to imperfect adhesion potential by spinning during concise wheel acceleration. The acceleration force transmitted because of the high wheel, then corresponds to the sum of the accelerative force at low wheel added to its inertia. When the low wheel attains its determined angular velocity, the accelerative force accessible at both wheels is restricted to the maximum at the low wheel. The simply means to intensify the acceleration force at the wheel is to prevent the low wheel from spinning.

The first variety, action of the wheel brake, is shown in Figure 2.48. The action of braking force F_B at low wheel prevents it from spinning. This creates the supplementary acceleration force F_B^* (the product of F_B multiplied by the ratio of effective braking radius to wheel radius) accessible at high wheel. The second variety for maximum use of traction potential is characterised by the action of fix-ed, variable, or controlled M-M differential-slip limitation mechanisms. These give a fixed coupling to guarantee the same slippage rates at the drive wheels, by this means permitting them to multiply the maximum accelerative force. During cornering at high rates of lateral acceleration, lateral differentities in drive-wheel load take place, again creating dissimilarity in acceleration potential. Brakes and limited-slip differential actions can also be relevant to assist in guaranteeing maximum traction under these circumstances. ATC implanting EMC and supplementary braking intervention (or controlled M-M differentials), can be used concurrently to guarantee reliable vehicle stability (steering mechatronic control) and optimal acceleration within the restrictions necessitated by physical limitations. EMC is the principal mode on/off road surfaces giving uniform adhesion, while the action of braking force (or M-M differential mechatronic control) gives optimal acceleration at both drive wheels for dealing with on/off road surfaces presenting lateral differentities in traction. For instance, the four values of the wheel angular velocity used for the ABS, supply the following closed-loop mechatronic control parameters for the ASR ATC system: acceleration slip from lateral variation in values of the wheel angular velocity of driven and undriven wheels, and the angular acceleration of driven wheels.

The following secondary mechatronic control parameters are also calculated: Vehicle velocity and acceleration based on values of the undriven wheel angular velocity, and curve recognition, derived from comparison of values of the undriven wheel angular velocity. The target value for acceleration slip is defined as the mean value of the undriven wheel angular velocity plus a specified value of the wheel angular velocity difference known as the slip threshold setpoint. The main goal of regulating acceleration slip can thus be divided into two subsidiary objectives: closed-loop mechatronic control of acceleration slip to maintain slip rates at the specified levels with maximum precision, and calculation of optimal slip set-points for different operating conditions and their implementation as mechatronic control objectives.

Depending on the final-control strategy being used, various mechatronic control concepts can be employed to meet the first objective. With TVC, a setpoint calculated from a number of signals is adopted for regulation as soon as the closed-loop mechatronic control comes into operation.

The subsequent mechatronic control process basically corresponds to that of a **proportional-integral** (PI) controller. When the brakes are used, arrangements are necessary to compensate for the non-linear fluidic pressure-volume curve that governs the response in the brake callipers. The first stage of the closed-loop mechatronic control program thus employs a sensing pulse corresponding to a relatively large volume; this compensates for compliance in the brake callipers. In the next stage, the system responds to positive deviations from the setpoint with graduated fluidic pressure increases; the rate of increase corresponds to the degree of divergence. A subsequent drop below the mechatronic control setpoint initiates a pressure-relief stage (sequence of defined pressure-relief and holding phases). This pulse series, in which the length of the pressure-relief phases continually increases, is followed by termination of braking intervention. Ignition and fuel-injection intervention essentially conform to the **derivate** (D) controller closed-loop mechatronic control concept. The difficulty associated with determining satisfactory setpoint values results from the fact that optimal acceleration and lateral forces cannot be achieved simultaneously. The ASR mechatronic control algorithm must therefore meet varying driver demands for linear traction and lateral adhesion by using priority-control strategies and adaptive response patterns. High values of vehicle velocity are accompanied by lower driver requirements for traction, especially with low coefficients of adhesion. At the same time, reductions in vehicle stability and steering response are not acceptable. The mechatronic control strategy is thus designed to provide progressively lower slip threshold setpoints as the vehicle velocity increases with priority being shifted from linear traction to lateral adhesion.

The automotive vehicle's acceleration rate and the regulated level of ECE or ICE output provide the basis for reliable conclusions regarding the coefficient of friction. Thus, another important strategy takes into account the coefficient of friction at the on/off road surface. The slip threshold setpoint is raised in response to higher values of the friction coefficient. This ensures that an ASR system designed for optimum performance on low-friction on/off road surfaces may not intervene prematurely on high-traction on/off road surfaces. Yet another important mechatronic control strategy is based on the cornering detection mentioned previously. This system employs the difference in the values of the wheel angular velocity of the undriven wheels as a basis for reductions in the slip setpoint to enhance stability in curves. This wheel angular-velocity differential can be used to calculate the automotive vehicle's rate of lateral acceleration. A large discrepancy indicates a high rate of lateral acceleration, meaning that a high coefficient of friction may also be assumed. In this case, the slip setpoint should not be reduced, but rather increased. A variety of mechatronic control intervention procedures such as modulation of ICE torque may be working, either extremely or in arrangement, to adjust ICE torque:

- ❖ Throttle valve control (TVC) with the assistance of the performance mechatronic control or an automatic throttle actuator;
- ❖ Adjustment of the ignition-advance angle;
- ❖ Selective ignition cut-out, integrated with suppression of fuel injection;
- ❖ Fuel injection suppression alone.

Slippage at the vehicle's drive wheels normally arises in response to an immoderation of ICE torque in relation to the coefficient of friction accessible at the on/off road surface. Mechatronically controlled attenuation of the ICE torque is thus a logical step. It is always the most appropriate mode in situations where virtually the same adhesion is caused at both drive wheels. Simultaneously, the response times for the ICE separate mechatronic controls must be assumed if reasonable vehicle stability is to be guaranteed (see Fig. 2.49).

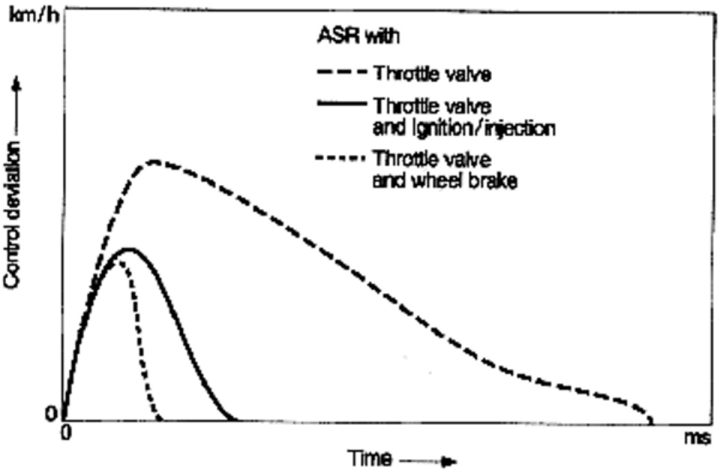


Fig. 2.49 Deviation of the controlled variable during the first control cycle with different actuators [CZINCZEL 1995].

If mechatronic control is restricted to the throttle position alone, the throttle valve's response time, response delays within the intake track, inertial forces in the ICE, and drivetrain compliance, may all result in palpable wheel slippage continuing for a relatively long period of time. TMC alone cannot ensure adequate vehicle stability on RWD automotive vehicles.

The qualification is particularly applicable to automotive vehicles with a high power-to-mass ratio. On FWD and DBW 4WD vehicles, TMC alone can be sufficiently effective if response delays are minimised. Arrangements combining TVC with interruption of the fuel injection, produce substantial reduction in the amplitude and duration of wheel slip. Thus, this concept can be used to guarantee good vehicle stability regardless of which axles are driven. In principle, it is also possible to design an ASR system based solely on mechatronic control of the ignition and injection systems. This concept employs a system with sequential fuel injection. It alternately cuts out individual ICE cylinders, while the ignition is also adjusted for the duration of the mechatronic control process. Although this concept can be employed to ensure adequate vehicle stability regardless of drive configuration, certain sacrifices in comfort are necessary, especially during operation on ice and during the warm-up phase. Also, miscellaneous mechatronic control intervention procedures such as brake torque control may be employed for ABS/ASR systems to regulate brake torque:

- ❖ Brake torque mechatronic control system with stored fluidic energy;
- ❖ Brake torque mechatronic control system without stored fluidic energy.

The brakes at the drive wheels are capable of converting large amounts of kinetic mechanical energy into thermal energy (heat), at least for limited periods of time. In addition, the response times can be extremely short, making it possible to limit slippage increases to very low levels.

ABS/ASR systems relying exclusively on braking intervention, appear suitable for regulating spin at the drive wheels. Traction enhancements during starting and under acceleration on/off road surfaces affording varying levels of adhesion at the left and right sides are especially significant with this system.

The ASR F-M unit used to generate the braking forces employs components that are already present in the ABS. Cost considerations make it important that ASR F-M systems require an absolute minimum in additional components beyond those already available for the ABS. The F-M concepts can be classified in two categories, according to whether stored fluidic energy is employed or not. A dual-strategy system, including rapid braking intervention with stored fluidical energy, is always to be recommended where the ICE torque mechatronic control is based entirely on TVC adjustments with their relatively long response times.

In a brake torque mechatronic control system with stored fluidic energy, designed for DBW RWD vehicles in the upper price range, the ICE torque is regulated exclusively by the **engine performance control** (EPC) unit.

Rapid braking intervention is required for enhanced regulation of vehicle stability; this also ensures optimal traction at both drive wheels, especially with lateral variations in adhesion potential. This system offers optimal vehicle stability and traction control combined with a high level of comfort [CZINCZEL 1995].

In a brake torque mechatronic control system without stored fluidical energy, it is known that each of the ASR F-M units used requires a high-pressure fluidical accumulator to ensure that the braking fluidic energy can be provided quickly enough. This means additional design complications with attendant expenditure.

Another system differs from those well known by using the supply fluidical circuit of the ABS return M-F pump exclusively to regulate the braking force at the drive wheels. The return M-F pump forms part of a self-priming fluidical circuit, thus employing the ABS return M-F pump as an inexpensive source of fluidical energy for braking. The ASR braking function can thus be achieved with a minimum of additional design complications.

The principle of braking intervention without stored fluidic energy has been developed further for a new generation of ASR systems that entered production in 1993 [CZINCZEL 1995].

Besides, other mechatronic control intervention procedures such as M-M differential slip modulation, may be employed for ABS/ASR systems to regulate the differential's lateral slip to improve traction for starting off and for simultaneous acceleration and cornering on/off road surfaces, affording different levels of traction from left to right (the slip-limitation mode remains active until a specific vehicle velocity is attained, and is deactivated at higher values of the vehicle velocity), namely:

- ❖ ABS/ASR system regulating differential slip on DBW RWD vehicles;
- ❖ ABS/ASR system for controlling rear-axle and interaxle differential slip rates on passenger DBW 4WD vehicles.

Passenger DBW 4WD vehicles employ a specific fixed front-to-rear distribution of ECE or ICE output to provide optimum vehicle characteristics within a stable range, that is, with limited amounts of acceleration slip. One or both wheels at either axle can respond to TVC application on low-traction on/off road surfaces with immoderate wheel spin. This is where the interaxle slip limiter is activated to adapt the distribution of ECE or ICE torque to the traction available at the respective axles, thereby improving traction while also enhancing vehicle stability and steering response.

Fuel injection and ignition mechatronic control reduces ICE output by suppressing the fuel injection process. Complete suppression would lead to a total loss of ICE output – a smooth, graduated response would be impossible with this kind of arrangement. In contrast, selective suppression of the injection process at individual ICE cylinders can be employed to achieve a good compromise between quick response and a graduated reduction of ICE power. This is the design principle behind the new concept.

With suppression according to individual ICE cylinders, the number of mechatronic control increments is the same as the number of ICE cylinders.

Because this limited number of mechatronic control stages is still inadequate, for instance, for a four-cylinder ICE, a supplementary strategy is employed: this is referred to as alternating injection suppression. It consists of varying the number of active ICE cylinders by one after every two ICE crankshaft rotations to produce a mean torque lying between the torques produced at the two ICE cylinder stages. This method doubles the number of mechatronic control stages to achieve an acceptable level of driving comfort, while complementary reduction in ignition advance can be employed to provide additional incremental adjustments. In cases where the excess torque is substantial, injection suppression can be supplemented by short-term ignition cut-out to provide extremely rapid ICE output reductions.

In addition to the modest expense, this system also offers vehicle manufacturers additional advantages in the form of space savings (no additional space required) and simplicity (limited amount of extra wiring).

In principle, the ABS/ASR installed on vehicles employs two mechatronic control strategies: ICE output mechatronic control and braking intervention. Ensuring driving stability is the most important task of ABS/ASR with RWD DBW automotive vehicles. A fast ICE torque mechatronic control or a combination of TMC and a fast brake mechatronic control can achieve this task.

ASR systems with a fast ICE torque mechatronic control (ignition and injection intervention) and brake mechatronic control without stored energy, may be widely used. Although the application of controllable differential locks also offers efficient ASR mechatronic control, the higher costs of this system may prevent wide usage.

The predominant demand on ASR systems for FWD DBW automotive vehicles is that of traction optimisation. Therefore, an ASR system with a brake torque mechatronic control is needed.

The combination of brake torque mechatronic control and ICE torque mechatronic control does result in a complex, efficient system.

In the future, only ASR systems with brake torque mechatronic controls may be widely used with FWD DBW vehicles. Especially, the combination of a brake torque mechatronic control and ICE torque mechatronic control with ignition and injection intervention may be widely used.

Why Gear-shifting Transmission Control?

Gear-shifting transmission control (GTC) enhancements are very much related to torque estimations. Ability to handle ECE or ICE torque in a mechatronically controlled and predicted mode leads to possible development in avoiding longitudinal vibrations due to poor gear-shift quality.

Another factor to deal with is judder that is influenced by the frictional characteristics of the M-M clutch. For that reason, a robust controller, using torque estimation and feedback mechatronic control, is recommended [BANSBACH 1998, HAHN AND LEE 2002].

Two kinds of observers are suggested: conventional full state and neural-network-based open loop F-M actuator observer. The objective is to improve the accuracy of the ECE torque estimation.

A non-linear robust measurement feedback controller for a **torque converter** (TC) clutch slip system may be used. *Lyaponov* control theory is applied to diminish the unwanted driveline dynamics by letting the lock-up clutch slip in a mechatronically-controlled mode.

A physical model of the gear shifting mechatronic control system where one uncertainty is the friction coefficient of torque converter's clutch is shown in Figure 2.50 [HAHN AND LEE 2002].

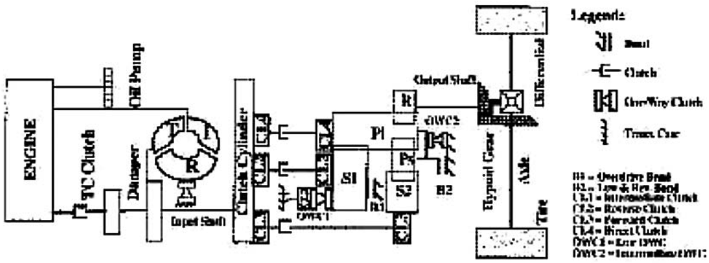


Fig. 2.50 Physical model of a rear-wheel drive (RWD) powertrain arrangement including: ECE or ICE, transmission and driveline, where the latter includes a driveshaft, a hypoid gear, a differential, two axles and two wheel-tyres [HWANG ET AL. 1998].

Other unknown elements may be

- ECE or ICE torque estimate is obtained using their steady-state performance characteristics obtained from automotive engine manufacturers' charts;
- Torque converter's impeller torque is assumed equal to ECE or ICE torque;
- ECE or ICE torque is the result of driveshaft or crankshaft angular velocity, temperature and fluid friction factor of the rotating components in the torque converter;
- *Driving load torque* is obtained from observer-based estimation algorithm based on rotational ECE or ICE dynamics.

Manual transmission (MT) can be automated by changing gear without engaging the clutch [PETERSON AND NIELSEN 2000]. The objective is to reduce the time indispensable for a gearshift; a shift process may also induce driveline resonance. Internal driveline torque control that lessens the time and improves gearshift quality may be the solution. EMC ECU may be obtained by estimating transmitted torque. If the transmitted torque is zero, this may lead to minimised driver disturbance and faster angular velocity synchronisation when disengaging the previous gear. Field trials have shown fast shift to neutral gear, despite disturbance and driveline oscillations at the start of the gearshift [PETTERSSON AND NIELSEN 2000]. A mechatronic control scheme may be used for different gears.

In order to eradicate driveline resonance, an observer is used in combination with a **proportional integral derivate** (PID) feedback structure, namely:

- *P* - tuning the proportional parameter such that the negative peak values of the engine are possible to generate;
- *I* - adjust low enough not to interfere with the dynamics;
- *D* - tuned until the drive-shaft torsion is well damped.

A physical model of the powertrain arrangement, where the control signal is transmitted torque from the ECE or ICE may be built [PETTERSSON AND NIELSEN 2000].

A physical model is capable of explaining the oscillation in the transmission angular velocity after disengaging gear. It is not able to measure ECE or ICE torque; instead, an indication of this is the amplitude of the oscillations in the trans-missions angular velocity and time delay during gearshift. Also, 1-2 up shift for **automatic power-shift transmission** (APT) is also studied [YANG ET AL. 2001].

Since the APT has become more common, there is an increased interest in reducing the shock during gearshifts and avoiding excessive slip that may cause unnecessary wear.

Two mechatronic control objectives may be

- Minimise the acceleration and jerk levels to enhance ride comfort;
- Minimise the clutch energy dissipation to enhance the durability of frictional elements.

A physical model of the powertrain arrangement that includes ECE or ICE, torque converter, APT, propulsion shaft, M-M differential, and two axle shafts, is presented in Figure 2.51.

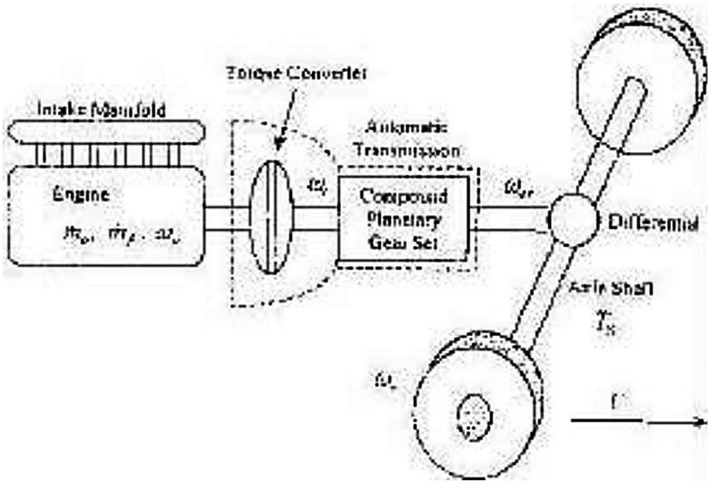


Fig. 2.51 Physical model of the powertrain that includes: ICE, torque converter, automatic power-shift transmission (APT), driveshaft, M-M differential and two axle shafts [YANG ET AL. 1999].

The mechatronic control system is very complex and non-linear; automotive scientists and engineers may use a robust shift control strategy for an integrated engine-transmission system to overcome the non-modelled dynamics. It may be possible to incorporate modelling uncertainties directly into the mechatronic control law. Control variables for the integrated **engine-transmission management controller** (E-TMC) are throttle angle; spark advance and second clutch torque [YANG ET AL. 2001].

This controller may enhance shift smoothness and improve clutch endurance, with much better results than the open loop controller. Control variables used for determine enhancements may be time for gearshift and energy dissipation. The innovative controller may work, even when there are large uncertainties, and it provides acceptable performance levels [YANG ET AL. 2001].

A smooth gearshift mechatronic control technology for clutch-to-clutch shifting on an FAT without on-way clutch, is also developed [MINOWA ET AL. 1999].

Clutch-to-clutch shifting involves two engaged and disengaged clutches. Knowledge about ECE or ICE output torque fluctuations is vital, and automotive scientists and engineers propose two different modes of detecting ECE or ICE torque; one is using **torque converter** (TC) characteristics and the existing angular-velocity sensor, the other uses shaft angular velocity, also by means of existing angular velocity sensors.

When the target value of ECE or ICE torque is reached, a smooth clutch-to-clutch shifting may be possible. This is possible for upshifts and downshifts and for oil temperatures of the transmissions M-Mid 303 – 393 K (30 -- 120 ^{0}C) [MINOWA ET AL. 1999].

A mode description method with the modular structure of an APT, consists of a **torque converter** (TC) module, gear-train module, AF system module, and modules of clutches and bands [ZHANG ET AL. 2002].

The purpose of the physical model may be to simulate transient dynamics of gear changes, and the study is performed for a 1-2 shift, 100% throttle condition and at an engine speed of 503 rad/s (4800 r/min). Simulations may be performed where the effects of a dynamic friction coefficient of the band material, as well as band pressure. ECE or ICE torque control and optimum clutch pressure coordination is the topic of a study by HAN AND YI [2003].

Mathematical modelling of the ECE or ICE, the TC, the planetary gear system, clutches, and band brakes may be followed by dynamic equations of the *Ravigneaux*-type APT.

In order to define shift quality, four sub-cost functions may be presented that are based on torque drop during the torque phase, duration of the torque phase, torque rise during the inertia phase, and the duration of the inertia phase. Overshoots and undershoots in the clutch slips during the shift may be also considered, and the result may be a shift quality index. Simulations show that ECE or ICE torque reduction mechatronic control during shifting reduces the shift shock, and the application of optimum pressure and ECE or ICE torque reduction results in enhanced shift transient performance. Other automotive scientists and engineers have studied an **automatic manual transmission** (AMT) and they propose a nonlinear filter for the generation of enhanced shift quality [MORSEL ET AL. 2002].

They may present a head-neck dynamic physical model since enhancements may be measured in terms of passenger's head oscillation. The proposed solution is suitable for gear-shift operations where the dead settling time is similar to the gearshift duration. Vibrations when the AMT is in neutral state can be also investigated [ZHENG ET AL. 2001].

A **linear quadratic regulator** (LQR) with **explicit model following** (EMF) may be proposed, where the purpose is to allow the system's dynamic response to track two desired trajectories for ECE driveshaft and ICE crankshaft angular velocity. A dynamic band brake physical model may be presented too [FUJII ET AL. 2002].

With the aid of the physical model, it is possible to predict the upshift behaviour of a four-velocity AMT system under various operating circumstances. A powertrain physical model with the purpose of simulation of servo-actuated synchromesh transmission may also be used [ERCOLE ET AL. 1999].

Parameters that may be varied in the physical model are, for instance, clutch characteristics and damper spring stiffness. Different control strategies may also be tested. The physical model considers six rigid bodies connected by spring damper systems or by friction transmission. Springs simulate clutch damper spring and tier stiffness, while friction transmission simulates the clutch, the synchromesh, and the wheel-tyre-ground contract. Shaft springiness is neglected.

Simulations show that optimal performance may be achieved only through synchronised clutch, throttle valve, and synchromesh actuator drive. For standing starts and upshifts, optimal parameters differ.

A **fuzzy-logic** (FL) controller may be proposed where input signals are ECE or ICE torque, driveshaft or crankshaft angular-velocity derivative, clutch slip velocity and its derivative, and clutch position derivative [ERCOLE ET AL. 1999].

Outputs are a throttle valve opening derivative and clutch position derivative. Judder is a longitudinal vibration in the vehicle influenced by the frictional characteristics of the clutch.

The clutch engagement process that is influenced by the driver. also induces the vibrations. Two elastic half-spaces slide against each other in the clutch, where there is a relationship between the coefficient of friction and relative velocity. Some automotive scientists and engineers find that self-exited vibrations can be decreased and even eradicated by the choice of friction materials in the clutch [CENTEA ET AL. 1999]. Others [BOSTWICK AND SZADKOWSKI 1998] investigate self-excited vibrations due to clutch engagement. The result of different friction coefficients for ceramic and organic facings may be studied.

A physical model may be proposed where a dynamometer is introduced in order to model actual vehicle applications.

The physical model may be a **two-degrees of freedom** (2DoF) system with two lumped inertias.

Physical models for ceramics material as well as organic, may also be presented. Simulations were performed which showed that the physical models might be accurate.

It was also shown that clutch-facing materials having a negative rate of change of friction coefficient with sliding velocity, generate self-excited vibrations.

If the friction coefficient takes lower values at a higher sliding velocity, this may be interpreted as '*negative damping*' that is a well-known result [BOSTWICK AND SZADKOWSKI, 1998].

This chapter gives an overview of some important DBW AWD propulsion mechatronic control systems and related applications. Customer requirements regarding vehicle performance are becoming increasingly demanding and complex.

Legal regulations concern environmental aspects, but the expectations of the customer are strongly characterised by the desire for individuality, quality of mobility, and practicality [SCHOEGGL ET AL. 2001].

In order to meet customer demands, an approach involving the classical integrated M-M powertrain may be suggested where the aim might be to gain advantages by treating the M-M powertrain as a whole.

Figure 2.52 shows the parts of the M-M powertrain: ECE or ICE, M-M clutch, M-M transmission, **universal-joints** (UJ), M-M propeller shaft (driveshaft), M-M differential and rear wheels.

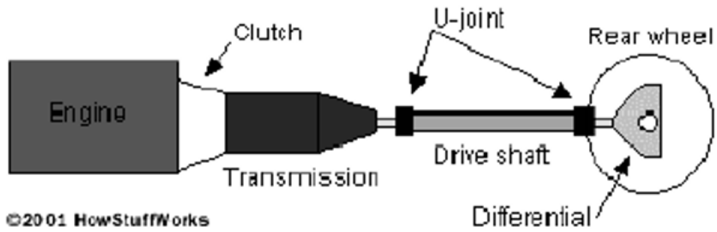


Fig. 2.52 Basic mechanical layout of the classical integrated M-M powertrain that includes the ECE or ICE, M-M clutch, M-M transmission, universal-joints (UJ), M-M propeller shaft (drive-shaft), M-M differential and rear wheels [HOWSTUFFWORKS.COM 2001].

At present there is a general consensus that an M-M powertrain is an M-M driveline with an ECE or ICE.

Integrated powertrain control (IPC), deals with all elements of a vehicle's M-M powertrain as parts in an integrated system, thus being the opposite of treating each part as an individual component.

Problems that occur in modern vehicles involving the M-M powertrain are phenomena referred to as shunt and shuffle. Shunt, also known as clonk or clunk, is a high frequency, metallic noise, occurring when a backlash causes components to thrash against each other. Shuffle is a longitudinal vibration of the entire automotive vehicle excited by the oscillation of the flywheel against the wheels [BIERMANN ET AL. 2000].

When shunt and shuffle occur, this is experienced as a sharp jerk followed by a longitudinal oscillation. The human body accepts some oscillations, for example vertical oscillation coinciding with walking oscillation is well tolerated. Horizontal oscillation is much less accepted.

The passenger experiences great discomfort that may cause motion sickness. The problem with shunt and shuffle is therefore of great interest because of the severe impact on passenger comfort [PERSSON 2004].

Increasingly intense international competition among vehicle manufacturers leads to a situation where the customer demands *'top-of-the-line'* products. Several areas are of importance, such as technical development, brand image, cost, but also driveability.

The term driveability includes several aspects of driver perception that are highly subjective reflections. Technical development and brand image are two different areas where vehicle manufactures compete, but lately difference in technical development has lessened. One way that has become more important in order to attract customers is to present certain driving qualities.

Currently, the *IPC* projects at some automotive R&D institutions began involving mechatronic control engineering and vehicle dynamics.

The aim of *IPC* projects is to find innovative and very advanced concepts for *IPC*. The projects are motivated by the potential benefits in using computerisation in combination with modern mechatronic control techniques.

The goal is to improve drivability, driving comfort, and economy, as well as to reduce the environmental impact of driving. The area is approached by a combination of modelling, control design, simulation, and experimental verification [IPC WEBSITE 2002-09-09].

The integrated approach towards controlling the M-M powertrain is a fairly new way to investigate problems with shunt and shuffle. The *IPC* projects are on the verge of deciding future assignments that are also a reason for wishing to update the international status of *IPC* research.

This section will review studied areas and where emphasis is put in automotive R&D institutions around the world.

The objective of automotive vehicle product development is real or expected customer demands. For instance, future customers may insist on faster gearshifts, decreased risk of motion sickness, and reduced fuel consumption. Many of these future challenges involve the M-M powertrain and, in some cases, also increase the risk of shunt and shuffle.

The customer's final purchase decision is based on several aspects, where driveability is one of the most important. Another aspect to consider is the wish for decreased impact on the environment that has become a mandatory area of interest due to present and future legal regulations.

The automotive industry acts in a mature market where actors are large and powerful. If the vehicle manufacturers wish to maintain or increase their market shares, they are forced to spend immense amounts on product development. To keep old or attract new customers, the product must fulfil as many customer demands as possible.

The customers' demands for constant improvement and new models have lead to a shortened product life cycle that is another challenge in product development. The release of a new car or truck model is but a short breathing space before a new one must be presented. Because of the short lifetime of a product, new strategies must be presented in order to stay a competitive participant in the automotive industry.

The newest generation of E-TMCs has overcome the former disadvantage regarding fuel efficiency. Adaptive functions in cooperation with carefully designed TC clutch control [NEUFFER ET AL. 1992, 1995] that may allow the clutch to be closed even at low gears, have improved SFC significantly.

Based upon the driver's behaviour, together with an adaptive shift strategy, part of the E-TMC's adaptive programme software may select an economy or even super-economy shift strategy whenever possible. There is, however, still more potential for fuel economy by optimisation of the driveline. The exemplary concept [STREIB AND LEONHARD 1992] is shown in Figure 2.53.

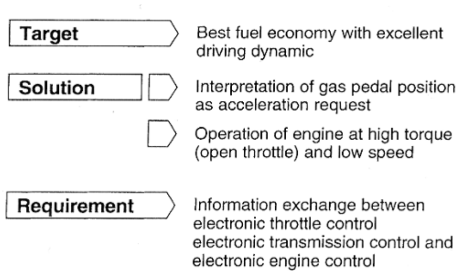


Fig. 2.53 Layout of the concept for driveline optimisation [STREIB AND LEONHARD 1992].

The basic idea is to interpret the accelerator (gas) pedal position as an acceleration request. The acceleration request, or a request for wheel torque, has to be converted by operating the ECE or ICE at high torque, that is, open throttle and low values of the driveshaft or crankshaft angular velocity. In order to realise this, it is necessary to use a TVC system.

The communication between the throttle, the ECE or ICE, and transmission is shown in Figure 2.54 [STREIB AND LEONHARD 1992].

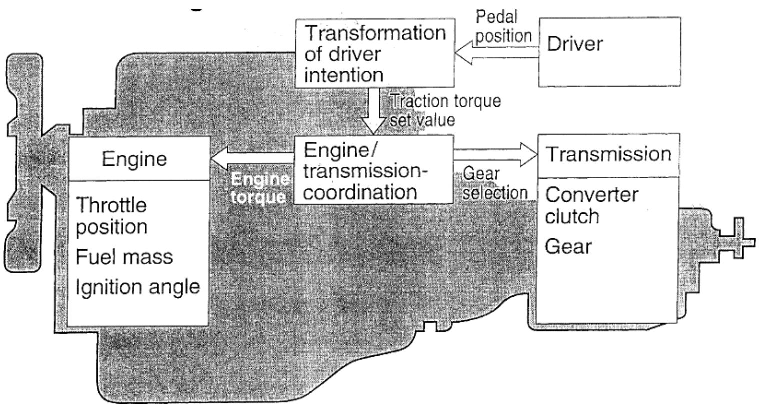


Fig. 2.54 Layout of the logical structure and communication between different mechatronic control systems [STREIB AND LEONHARD 1992].

In such a system, well-defined coordination between the ECE or ICE torque, mainly given by throttle position (air mass), fuel mass, and ignition angle (if any) on the one side and selection of the appropriate gear including TC clutch on the other side, is imperative. Depending on the kind of ECE or ICE, SFC can be reduced further by 5 – 10% with this optimised exemplary concept.

Because the average ECE or ICE operation is at higher torque levels compared to standard systems, a greater number of gearshifts may occur. This is important to guarantee optimal shift control.

Figure 2.55 shows how that can be accomplished by using the additional DoF given by TVC.

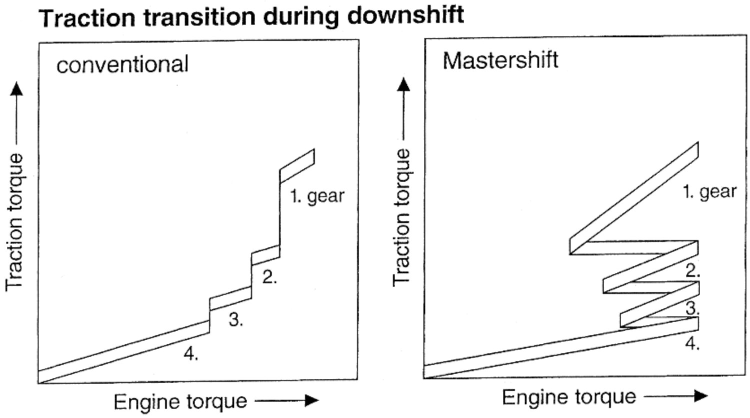


Fig. 2.55 Constant traction torque by operation of throttle opening during gearshift [STREIB AND LEONHARD 1992].

It is possible to operate the throttle angle during the gearshift in such a way so as to achieve constant wheel torque before and after downshifts.

In future years, R&D work may be concentrated on redesigning hardware components for cost reduction, improvement of yield to reduce SFC, and improvement of driveability. A good approach to meet cost targets on the electronic hardware side would be to integrate two or more individual control modules into a common housing. Regarding the mechatronic components, one could continue using two separate microcontrollers. This would have the advantage that the software development and application could be done individually for two dissimilar systems, for example ECE or ICE and transmission controllers. Another approach could be to mount the E-TMC on the transmission housing itself. This could lead to a significant reduction in the expense for the wiring harness. Here however, the problem of hostile values of the ambient temperature on electronic components has to be solved. Today's stand-alone actuators could be integrated into a common housing in a vehicle's transmission. The improvement of the yield is a main topic for designers of APTs. M-F pumps and TCs are a major source of energy loss. A significant improvement of yield may be possible as soon as TC clutches are available with the capability for continuous slip operation. The TC clutch can then be operated in low gears and at low values of the ECE's shaft or ICE's crankshaft angular velocity without facing problems from driveline oscillations and/or noise emission.

The driveability is the most important feature for drivers' acceptance of APTs. In addition to the self-adaptive functions described, the implementation of shift strategies benefiting from algorithms using FL theory, may further improve driveability.

Preview Distance Control (Adaptive cruise control system) - This is the world's first distance control system, and was introduced in 1995. When the laser radar sensor installed in the front bumper detects a vehicle in front in the same lane, the system controls the throttle and gear shifting to follow behind the vehicle in front at a safe distance (see Fig. 2.56). The driver is alerted by an alarm and a warning light if the two vehicles get too close together.

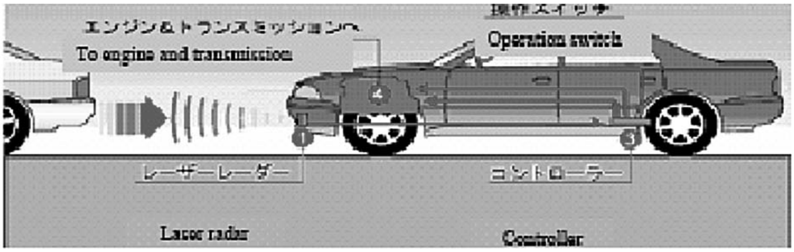


Fig. 2.56 Principle layout of the preview distance control (PDC) [Mitsubishi].

The vehicle returns to the initially set vehicle velocity when the forward automotive vehicle moves out of the lane or increases its vehicle velocity [AMEMIYA 2004].

Intelligent Highway Cruise Control (HCC) - Through a device situated inside the front grille, which generates millimetre-wave radar that does well in various types of weather, the distance from a vehicle in front, up to 100 m and with an angle of 16 deg, is measured. Automotive vehicle travel circumstances are sensed through a yaw rate sensor and a vehicle velocity sensor (see Fig. 2.57).

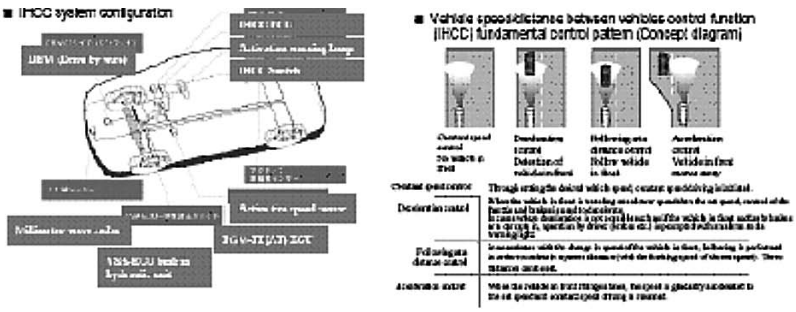


Fig. 2.57 Principle layout of the intelligent highway cruise control (HCC) [Honda].

Comparable to normal cruise mechatronic control, as well as the ability to preserve a set vehicle velocity, conditional on whether or not there is an automotive vehicle in front that is in the same lane, this system can provide vehicle velocity or distance between vehicles by mechatronic control [AMEMIYA 2004].
<u>*Navigation – AI Gear-shifting Control System*</u> - Using curve shapes from navigation and the inclination information from the automotive vehicle, the road circumstances are estimated in three dimensions and an appropriate gear out of the range fifth to third is chosen (see Fig. 2.58).

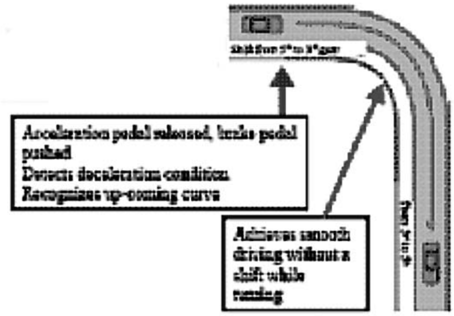


Fig. 2.58 **Principle** layout of the navigation – AI gear shifting [Toyota].

Using information from navigation, an upcoming curve is recognised and when the driver releases the acceleration pedal when coming up to the curve, the vehicle automatically shifts gear down from fifth gear to third gear, and third gear is continued even when driving through the curve. After the curve, this mechatronic control is terminated [AMEMIYA 2004].

With the existence of mechatronic control units for various applications in automotive vehicles, many opportunities exist to link these ECUs and to establish communication between them.

The main partner of the ATC is the E-TMC system. Due to the coupling of ECE or ICE and transmission within the vehicle's powertrain, it is necessary to have an interface between these ECUs for a functional coupling and the interchange of signals.

It is essential for the pressure mechatronic control inside the transmission mechatronic control to sense the ECE or ICE load, the ECE shaft or ICE crankshaft angular velocity, and the throttle position.

The ECE or ICE torque reduction during shifting is also important to establish shift comfort and a satisfactory lifetime for the clutches. By handing over certain signals like position lever state, lockup condition, or shift commands, to the E-TMC system, the driving comfort of the automotive vehicle can be improved significantly. An interface to ABS and ATC is useful for some self-learning functions in the transmission mechatronic control when using the values of the wheel angular velocity.

It is possible to implement certain shift strategies in the transmission mechatronic control as an active support for ABS and ATC. A link to the TC or ACC makes it possible to optimise certain functions for the total automotive vehicle. By interfaces between the ECUs, a reduction of the sensor expense results from a multiple use via communications.

Suitable links especially include, **pulse-width modulation** (PWM) or bus configurations for trouble-free communication. Bus systems in particular have the advantage of the link-up of additional ECUs without changing their existing hardware. Additional coupling requires only a software change. The interchange of required supplementary signals for new functions is possible without any problems. An example of E-TMC, by coupling the powertrain ECUs to achieve lower SFC, simultaneously improving the driveability, is described in technical literature [NEUFFER ET AL. 1995].

Why Parallel Hybrid-Electric Powertrain Mechatronic Control?

One of the major reasons for parallel **hybrid-electric** (HE) powertrains may be to get radically better fuel economy that may also lead to decreased exhaust pollution [JACOVIDES 1980; UNNEWEHR AND NASAR 1982].

A problem of **hybrid-electric vehicles** (HEV) has been range. In order to be a convincing competitor, a range similar to conventional automotive vehicles has to be offered [DELPRAT ET AL. 2001]. Different mechatronic control methods may be suggested [PAGANELLI ET AL. 2000].

A mechatronic control strategy based on **specific fuel consumption** (SFC) criteria and an instantaneous minimisation of the equivalent fuel flow, may be proposed. A comparison between an optimal solution set-up for a specified driving schedule and a mechatronic control strategy, may be proposed too [SEILER AND SCHRÖDER 1998].

These are right and proper to evaluate because both use an instantaneous minimisation criteria [PAGANELLI ET AL. 2000]. A powertrain operating point is selected so that the total efficiency loss is minimised. The global optimisation based on simulated annealing is a guideline even if it cannot be used for real-time mechatronic control. Simulation results demonstrate that SFC for the proof-of-concept vehicle during the normal European driving cycle, is as follows:

- Loss minimising mechatronic control strategy: 7.0 l/100 km;
- Equivalent consumption minimising mechatronic control strategy 6.6 l/100 km;
- Global optimisation based on simulated annealing 6.3 l/100km [PAGANELLI ET AL. 2000].

Two standardized driving cycles may be used during experiments: city and extra urban driving [KLEIMAIER AND SCHRÖDER 2000].

An optimal mechatronic control vector used on the ECE or ICE, the **electro-mechanical/mechano-electrical** (E-M/M-E) machine (motor/generator), and the CVT of the proof-of-concept automotive vehicle may be proposed. The optimal mechatronic control vector is computed with the assistance of the program *DIRCOL* that may be of assistance when searching for a numerical solution of optimal mechatronic control problems [STRYK 1994].

Calculating and then using the optimal mechatronic control vector results in reduced fuel consumption during a city cycle, for example, from 6.2 l/100 km to 5.0 l/100 km using the original ICE, a TD 1.7 l [KLEIMAIER AND SCHRÖDER 2000]. A logical state machine with corresponding dynamic mechatronic control outputs for each state may be also used [PHILLIPS ET AL. 2000].

Possible automotive vehicle operating states may be identified, for example, ECE or ICE '*On*', ECE or ICE '*Off*'. In possible transitions between these states, for example, alteration in driver demand may be the preferred. The last step may be to decide the priorities that may be the result of driver demands.

An automotive vehicle DBW AWD propulsion mechatronic control system may be responsible for output command to each part of the powertrain and dynamic mechatronic control algorithms may be used to provide smooth transitions between states. Simulations for testing the controller are presented, but results regarding fuel savings are missing [PHILLIPS ET AL. 2000].

A global optimisation algorithm based on optimal mechatronic control theory may be also proposed [DEPART ET AL. 2001].

The proof-of-concept automotive vehicle may be the same. When the proposed algorithm is used, the SFC may be, for example, 6.3 l/100 km compared to 8 l/100 km [PAGANELLI ET AL. 2000].

Some advantages and disadvantages of a parallel HE powertrain include:

- ❖ Increase performance over ECE or ICE alone as it optimises operating efficiency by choosing the best energy source for the vehicle velocity/torque requirement;
- ❖ Most parallel HEVs do not need an M-E generator to generate electrical energy for the energy storage unit as an ECE or ICE standard onboard M-E generator can be used;
- ❖ The mechanical energy is directly coupled to the on/off road surface, thus, it can be more efficient;
- ❖ Full size ECE or ICE and transmission produce no mass or size savings;
- ❖ This proof-of-concept vehicle offers no improvement with respect to overall maintenance of the HEV.

The advantages and disadvantages of a series HE powertrain include:

- ❖ The ECE or ICE never idles so reduces vehicle emissions;
- ❖ The ECE or ICE drives an M-E generator to run at optimum performance thereby achieving better fuel economy;
- ❖ Allows a variety of options when mounting the ECE and vehicle components;
- ❖ Some series HE powertrains do not necessitate an M-M transmission;
- ❖ The ECE or ICE is used to generate electrical energy for its supply to the energy storage unit and thus can remain fairly small in comparison to those used in the parallel HE powertrain;
- ❖ Depending on energy storage unit capacity, the ECE or ICE and M-E generator may be working frequently to ensure the energy storage units are maintained at an adequate level; this diminishes the life of the ECE or ICE and M-E generator, as well as increasing SFC.

2.2 Automotive Vehicle Driving Performance

2.2.1 Foreword

The automotive vehicle dynamics is related to the movements of automotive vehicles - automobiles, vans, trucks, buses, coaches, and special-purpose vehicles – on on/off-road surfaces. The movements of relevance are ride and turning as well as acceleration (driving) and deceleration (braking). The forces affecting on the vehicle from the tyres, gravity, and aerodynamics, resolve dynamic behaviour.

The automotive vehicle and its components are examined to resolve what forces may be created by each of these sources to a particular manoeuvre and trim circumstance, and how the vehicle may react to these forces. For that reason, it is necessary to create a perfect approach to physical and mathematical modelling the systems and conventions that may be used to emphasize motions.

2.2.2 Lumped Mass

An automotive vehicle is manufactured with various components dispersed within its peripheral enclosed space. However, for several of the more basic analyses related to it, all components move as one. For instance, under acceleration (driving), the entire vehicle speeds up as a unit; thus it can be symbolised as one lumped mass positioned at its centre of gravity (barycentre) with relevant mass and inertia properties. For acceleration (driving), one mass is adequate.

For ride analysis, it is normally indispensable to consider the wheels as discrete lumped masses. In that instance, the lumped mass symbolising the body is the *'sprung mass'*, and the road wheels are symbolised as *'unsprung masses'*.

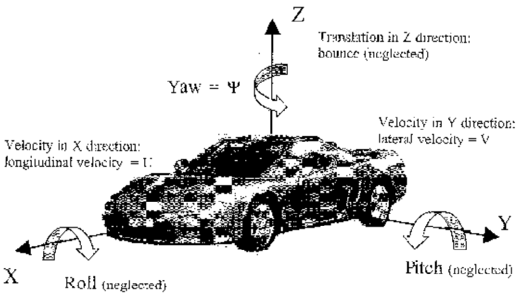


Fig. 2.59 Automotive vehicle states associated with the single-track half-vehicle (bicycle) physical model [LYNCH 2000].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
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For single mass depiction, the vehicle is considered as a mass focused at its centre of gravity as shown in Figure 2.59 [LYNCH 2000].

The point mass at the centre of gravity, with relevant rotational moments of inertia, is dynamically comparable to the automotive vehicle itself for all motions in which it is sensible to presume the vehicle to be of rigid body.

2.2.3 Euler Angles

The relationship of the automotive vehicle's fixed coordinate system to the earth-fixed co-ordinate system is recognised by *Euler* angles. These are created by a series of three angular rotations. Beginning at the earth fixed system, the axis system is first rotated in yaw ψ (around the z axis), then in pitch θ (around the y axis), and then in roll ϕ (around the x axis) to line up with the vehicle's fixed coordinate system. The three angles acquired are the *Euler* angles. It is necessary to remain exactly at the distinct series of rotations, for the reason that the resultant attitude may change with the sequence of rotations.

2.2.4 Forces and Rotational Moments of Inertia

Forces and rotational moments of inertia are usually described as they function on the automotive vehicle. Thus, a positive force in the longitudinal (x axis) sense of direction on the vehicle is forward.

The force in relation to the load on a wheel-tyre functions in the upward sense of direction and is therefore negative in magnitude (in the negative sense of z-axis direction).

As a consequence of the inconvenience of this convention, the *SAE* J670e, *"Vehicle Dynamics Terminology"*, provides the term *'normal force'* as that acting downward, and '*vertical force*' as the negative of the normal force.

Thus the vertical force is the same as wheel-tyre load with a positive *SAE* convention in the upward sense of direction.

In some countries, different conventions may be used. Given these definitions of co-ordinate systems and forces, it is physically possible to initiate formulating *Euler-Lagrange* equations of the second order by which to analyse and represent the behaviour of the vehicle.

2.2.5 Automotive Vehicle Fixed Coordinate System

Onboard, the automotive vehicle motions are defined with reference to a left-hand orthogonal coordinate system (the automotive vehicle fixed coordinate system) that originates at the centre of gravity and travels with the vehicle.

By *SAE* convention [*SAE J670e*], the coordinates are as follows:

x – forward and on the longitudinal plane of symmetry;
y – lateral out the left side of the automotive vehicle;
z – upward with respect to the automotive vehicle;
$\dot{\phi} = p$ – roll velocity about the x axis;
$\dot{\theta} = q$ – pitch velocity about the y axis;
$\dot{\psi} = r$ – yaw velocity about the z axis.

2.2.6 Motion Variables

Automotive vehicle motion is usually described by the velocities (forward -- $U = v_x$, lateral – $V = v_y$, vertical – $W = v_z$, roll -- $\dot{\phi} = p$, pitch -- $\dot{\theta} = q$ and yaw -- $\dot{\psi} = r$) with respect to the automotive vehicle fixed coordinate system.

2.2.7 On/Off-Road Surface Fixed Coordinate System

Automotive vehicle attitude and trajectory through the course of a manoeuvre are defined with respect to a left-hand orthogonal axis system fixed on the on/off-road surface. It is normally selected to coincide with the vehicle's fixed coordinate system at the point where the manoeuvre is started.

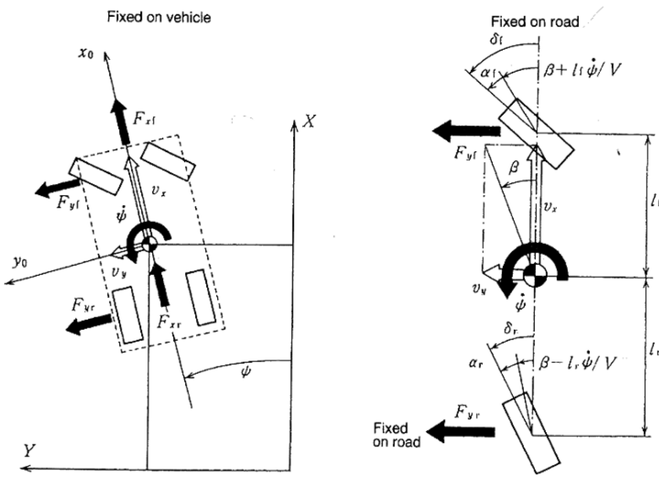

Fig. 2.60 Double-track, full vehicle physical model fixed on the vehicle and single-track, half vehicle (bicycle) physical model fixed on the road [MAKATO 1995].

The coordinates (see Fig. 2.60) are as follows:

X – forward travel;
Y – travel to the left;
Z – vertical travel (positive upward);
Ψ – heading angle (angle between x and X in the ground plane);
v – course angle (angle between the vehicle's velocity vector and X axis);
β – sideslip angle (angle between x axis and the vehicle's velocity vector).

2.2.8 Newton's Second Law

The fundamental law from where most automotive vehicle dynamics analyses begin is the second law formulated by *Sir Isaac Newton* (1642--1727). The law applies to both translational and rotational systems [DEN HARTOG 1948; GILLESPIE 1992].

Translational Systems – The sum of the external forces acting on the body in a given direction is equal to the product of its mass and the acceleration in that direction (assuming the mass is fixed), namely

$$\Sigma F_x = m\ a_x \ , \tag{2.1}$$

where F_x - forces in the x-axis direction;
m - mass of the body;
a_x - acceleration in the x-axis direction.

Rotational Systems – The sum of the torques acting on a body about a given axis is equal to the product of its rotational moment of inertia and the rotational acceleration about that axis, namely:

$$\Sigma T_x = J_{xx}\ \alpha_x \ , \tag{2.2}$$

where T_x – torques about the x-axis;
J_{xx}-- moment of inertia about the x-axis;
α_x -- rotational acceleration about the x-axis.

***Newton*'s second law** (NSL) is applied by visualising a boundary around the body of interest. The appropriate forces and/or torques are substituted at each point of contact with the outside world, along with any gravitational forces. This forms a free-body diagram. A NSL *Euler–Lagrange* equation of the second order can than be written for each of the three independent axis-directions (normally the auto-motive vehicle fixed axes).

2.2.9 Dynamic Axle Loads

Determining the axle loading on an automotive vehicle under arbitrary circumstances is the first simple application of NSL. It is an important first step in analysis of driving (acceleration) performance because the axle load determines the tractive effort obtainable at each axle, affecting the acceleration, gradeability, maximum value of the vehicle velocity, and drawbar effort. Consider the vehicle shown in Figure 2.61, in which most of the significant forces on it are shown.

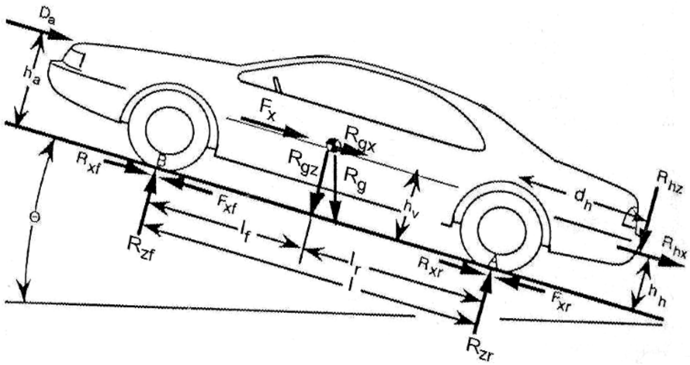

Fig. 2.61 Arbitrary forces acting on an automotive vehicle [GILLESPIE 1992].

The loads carried on each axle may consist of a static component, plus the load transferred from front to rear (or vice versa) due to the other forces acting on the vehicle. The load on the front axle can be found by summing torques about the point A under the rear wheel-tyres. Presuming that the vehicle is not accelerating in pitch, the sum of the torques at point A must be zero. By the *SAE* convention, a clockwise torque about point A is positive, then

$$F_{zf}\, l + D_a\, h_a + F_x\, h_v + R_{hx}\, h_h + R_{hz}\, d_h + R_g \sin\theta\, h_v - R_g \cos\theta\, l_r = 0 \qquad (2.3)$$

or

$$m_{vf}\, g\, l + D_a h_a + m_v a_x h_v + R_{hx} h_h + R_{hz} d_h + m_v g \sin\theta\; h_v - m_v g \cos\theta\; l_r = 0\ , \qquad (2.4)$$

By the *SAE* convention, a clockwise torque about point B is also positive, then:

$$F_{zr}\, l - D_a h_a - F_x h_v - R_{hx} h_h - R_{hz} (d_h + l) - R_g \sin\theta\, h_v - R_g \cos\theta\, l_r = 0 \qquad (2.5)$$

or

$$m_{vr} g\, l - D_a h_a - m_v a_x h_v - R_{hx} h_h - R_{hz}(d_h + l) - m_v g \sin\Theta\, h_v - m_v g \cos\Theta\, l_f = 0\,, \qquad (2.6)$$

where

R_g = $m_v\ g$ – gravitational force, known as the weight of the automotive vehicle with which the earth attracts the vehicle's body, acting at its centre of gravity (barycentre); on a grade it may have two components, a cosine component that is perpendicular to the on/off-road surface R_{gz} and a sine component parallel to the on/off-road surface R_{gx} arising from grade [N];

m_v - mass of the automotive vehicle acting at its centre of gravity (barycentre) [kg];

g - acceleration of gravity (gravity vector) [m/s^2];

R_{gx} = R_g sin Θ - additional force on the automotive vehicle arising from grade in the x-axis direction [N];

R_{gz} = R_g cos Θ - additional force on the automotive vehicle arising from grade in the z-axis direction [N];

θ -- Uphill/downhill grade [rad];

F_{zf} = m_{vf} g - dynamic force normal to the on/off-road surface acting in the z-axis direction on the front wheel-tyres [N];

m_{vf} – mass carried on the front wheel-tyres [kg];

F_{zr} = m_{vr} g - dynamic force normal to the on/off-road surface acting in the z-axis direction on the rear wheel-tyres [N];

m_{vr} – mass carried on the rear wheel-tyres [kg];

F_x = m_v a_x - equivalent inertial force known as the '*d'Alambert force*' acting if the automotive vehicle is accelerating along the on/off road surface at the centre of gravity (barycentre) opposite to the sense of direction of the acceleration [N];

F_{xf} = m_{vf} a_x - tractive force (tractive effort) acting in the ground plane in the front wheel-tyres contact patch [N];

F_{xr} = m_{vr} a_x - ractive force (tractive effort) acting in the ground plane in the rear wheel-tyres contact patch [N];

a_x - acceleration in the x-axis direction [m/s^2];

R_{xf} - rolling resistance force acting in the ground plane in the front wheel-tyres contact patch [N];

R_{xr} - rolling resistance force acting in the ground plane in the rear wheel-tyres contact patch [N];

D_a - aerodynamic force acting on the vehicle's body; it may be represented as acting at a point above the ground indicated by the height h_a [m], or by a longitudinal force of the same magnitude in the ground plane with the associated aerodynamic pitching moment (equivalent to D_a times h_a) [N];

R_{hx} - longitudinal force acting at the hitch point when the vehicle is towing a trailer [N];

R_{hz} - vertical force acting at the hitch point when the vehicle is towing a trailer [N].

Note that an uphill attitude corresponds to a positive angle Θ, such that the sine term is positive; a downhill attitude produces a negative value for this term.

From Eqs (2.3) – (3.6), it may be solved for F_{zf} and F_{zr} as well as for m_{vf} and m_{vr}.

The axle load expressions then become, respectively

$$F_{zf} = (R_g \cos\theta \, l_r - D_a h_a - F_x h_v - R_{hx} h_h - R_{hz} d_h - R_g \sin\theta \, h_v)/l \qquad (2.7)$$

and

$$F_{zr} = (R_g \cos\theta \, l_f + D_a h_a + F_x h_v + R_{hx} h_h + R_{hz}(d_h + l) + R_g \sin\theta \, h_v)/l \qquad (2.8)$$

or

$$m_{vf} = (m_v g \cos\theta \frac{l_r}{l} - D_a \frac{h_a}{l} + m_v a_x \frac{h_v}{l} h_v + R_{hx} \frac{h_h}{l} + R_{hz} \frac{d_h}{l} + m_v g \sin\theta \frac{h_v}{l})/g \qquad (2.9)$$

and

$$m_{vr} = (m_v g \cos\theta \frac{l_f}{l} + D_a \frac{h_a}{l} + m_v a_x \frac{h_v}{l} + R_{hx} \frac{h_h}{l} + R_{hz} \frac{d_h + l}{l} + m_v g \sin\theta \frac{h_v}{l})/g \, . \qquad (2.10)$$

2.2.10 Forces Affecting Wheel Traction

The dynamic forces that define the wheel-tyres' braking response on straights and during cornering are already familiar from the technical literature. The transmission of accelerative force in straight-line operation and in curves is subject to the same qualitative principles that apply during braking [CZINCZEL 1995].

The slip ratio that applies for braking:

$$\lambda_B = \frac{V_F - \theta_R R}{V_F}$$

is replaced by the ratio

$$\lambda_A = \frac{\theta_R\, r - V_F}{V_F} \ ,$$

with $\theta_R\, r \geq V_F$.

Acceleration slip rates can range all the way from zero to the very high numbers used to describe the conditions that can occur when the drive wheels spin freely during attempts to accelerate from rest.

Figures 2.62 to 2.64 show acceleration and side-force coefficients as a function of the acceleration slip [CZINCZEL 1995].

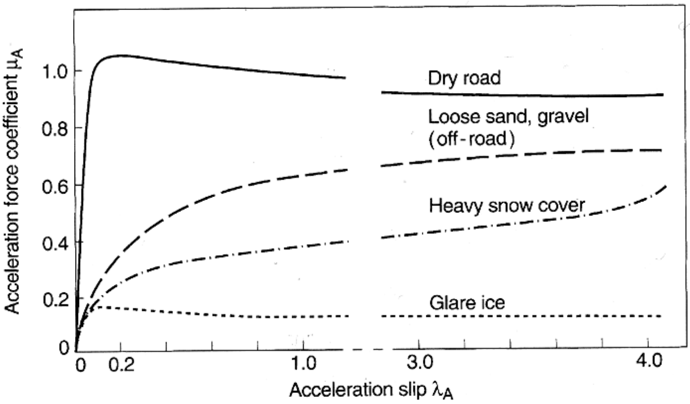

Fig. 2.62: Adhesion coefficients for acceleration μA as a function of acceleration slip λ_A [CZINCZEL 1995].

Figure 2.62 shows acceleration during straight-line operation. The demand for reserves in lateral adhesion is fairly diminutive under these conditions (including, for instance, compensation for side winds); thus traction remains the salient factor.

On dry on/off road surfaces, maximum accelerative force is available at slip rates of 10 to 30%, with traction enhancement of 5 to 10% possible relative to spinning drive wheels.

On glare ice, maximum traction is achieved at extremely diminutive acceleration slip levels (2 to 5%).

On loose sand and gravel and in deep snow (especially in combination with snow chains), the coefficient of acceleration force may increase continually along with the slip rate, with the respective maxima only being reached somewhere beyond 60%.

Thus, the slip rates of 2 to 20% found within the ASR's operating range may not provide adequate traction under all operating conditions. For this reason, all known ASR systems incorporate slip-threshold switches or ASR deactivation switches that allow the driver to either reset the ASR slip-control threshold to substantially higher levels or to switch the system off entirely should the need arise.

Figures 2.63 and 2.64 apply to acceleration during cornering; under these conditions, the drive wheels are subject to various degrees of lateral force as a function of the vehicle's rate of lateral acceleration.

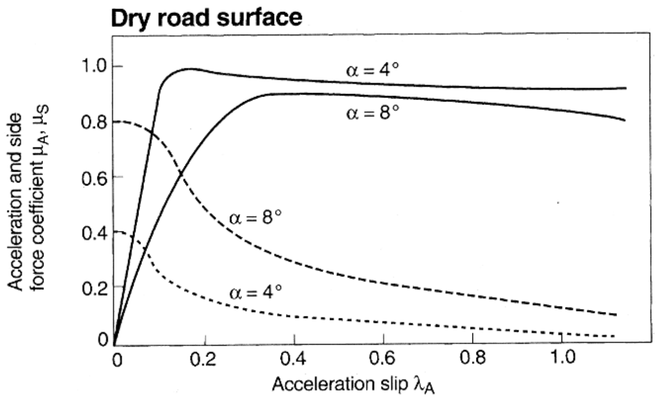

Fig. 2.63 Acceleration and lateral traction coefficients at different slip angles α [CZINCZEL 1995].

Increasing acceleration slip (and increasing accelerative forces) cause a drop in lateral forces that then respond to still higher slip rates by collapsing to small residual levels.

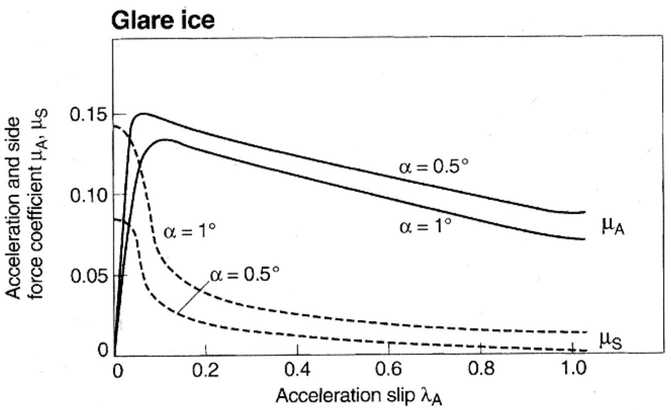

Fig. 2.64 Acceleration and side-force coefficients at different slip angles α [CZINCZEL 1995].

Figure 2.63 represents the response pattern on a dry on/off road surface. The curve starts at a rate of acceleration slip of zero. Initially, the side-force coefficient displays a moderate downward trend. However, continuing increases in the coefficient of acceleration force induce a substantial fall in the side-force coefficient.

Figure 2.63 also shows that the accelerative force must be limited to a fraction of its ultimate potential if sufficient lateral forces are to be maintained.

On glare ice (Fig. 2.64), the extremely limited friction potential means that vehicle stability under acceleration remains available only at relatively small slip angles (circa ≤ 2 deg).

Relatively diminutive slip angles (≤ 5 deg) may be sufficient to induce a radical drop in the side-force coefficient. This makes it clear that an extremely precise and sensitive slip control is required on glare ice (and other low-friction on/off road surfaces).

The ATC system must thus exhibit a high degree of monitoring accuracy, while signal processing and actuation of the final-control elements must be rapid and precise.

2.3 M-M DBW AWD Propulsion Mechatronic Control Systems for Conventional Automotive Vehicles

2.3.1 Classical Mechano-Mechanical (M-M) Powertrains for M-M DBW AWD Propulsion Mechatronic Control Systems

A conventional M-M powertrain is the part of an automotive vehicle connecting the ECE or ICE to the propeller or driven axles, may include drive shaft, M-M clutch, transmission, and differentials. Everything that is involved in the process of moving the vehicle forward is included in the definition of the classical M-M powertrain, namely, ECE or ICE, M-M clutch, transmission, shafts, differentials, and road-driven wheels. For instance, a vehicle's driveline consists of the parts of the powertrain excluding the ECE or ICE, M-M clutch and transmission.

Figure 2.65 shows a physical model of a **front-wheel drive** (FWD) powertrain for DBW AWD propulsion mechatronic control including ICE, flywheel plus M-M clutch, transmission, differential, axle shaft, coupling, wheel-hub, and wheel-tyres [CAPITANI ET AL. 2000, 2001].

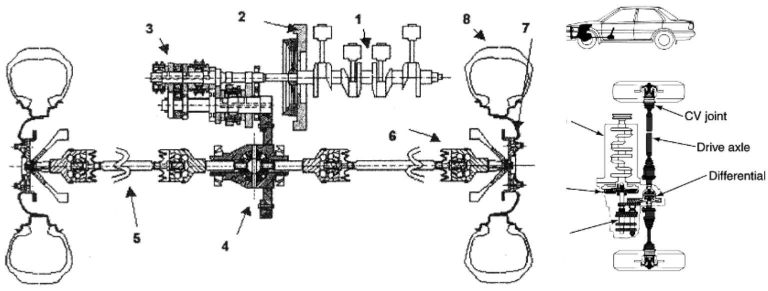

Fig. 2.65 Front-wheel-drive (FWD) powertrain physical model: 1 – internal combustion engine (ICE), 2 – flywheel plus M-M clutch, 3 – M-M transmission, 4 – M-M differential, 5 – axle M-M shaft, 6 – coupling, 7 – wheel-hub, 8 –wheel-tyre [CAPITANI ET AL. 2000, 2001 – Left image].

In Figure 2.66 is shown a physical model of a 2WD and/or 4WD powertrain for DBW AWD propulsion mechatronic control including: ICE, ICE, front axle M-M differential with or without **viscous coupling** (VC), permanent 4WD centre M-M differential with VC, part-time 4WD manual lock, **viscous transmission** (VT) and driveline, where the latter includes a driveshaft, a rear-axle M-M differential with VC, four axles, and four wheel-tyres [NEWTON ET AL. 1989].

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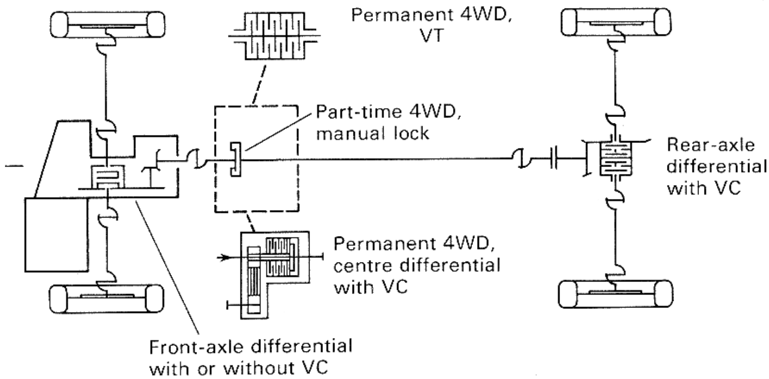

Fig. 2.66 Physical model of the 2WD and/or 4WD powertrain including ICE, front axle M-M differential with or without viscous coupling (VC), permanent 4WD centre M-M differential with viscous coupling (VC), part-time 4WD manual lock, viscous transmission (VT) and driveline, where the latter includes a driveshaft, a rear-axle differential with viscous coupling (VC), four axles, and four wheel-tyres [NEWTON ET AL. 1989].

In the following sections, a brief description of the indispensable components of the DBW AWD mechatronic control systems for different categories of automotive vehicles is presented. The purpose is to give sufficient knowledge and thus bring a better understanding of the rest of the chapter.

Chemo-thermo-fluido-mechanical (CH-TH-F-M) External Combustion Engines (ECE) and/or Internal Combustion Engines (ICE) **-** Provide the mechanical energy to propel the vehicle and operate the other automotive systems. As a rule, most ECEs or ICEs burn liquid fuel (e.g. gasoline or diesel oil) or gas fuel (e.g. hydrogen or biogas).The liquid or gas fuel (chemical energy) burns to produce thermal energy (heat) The heat causes gas expansion (fluidical energy), creating pressure. The pressure moves the ECE or ICE parts to produce mechanical energy (power). The developmental trends for ECEs and ICEs are set up, on the one hand, by the viewpoints that legislators, ecologist, and economists have concerning future automotive vehicles and, on the other hand, by up-and-coming technologies that contribute to new possibilities in ECE or ICE design [SEIFFERT AND WALZER 1991].

It is to be accepted that environmental topics and the resultant legislative measures may have the prevalent effect on future ECE or ICE advances. New technological advances in mechatronics and the employment of other materials can be accepted to cause essential contributions toward further advancement of ECEs and ICEs. To realise supplementary enhancements in **engine management control** (EMC), it may no longer be adequate to control ECEs or ICEs consistent with reference performance data or maps that may be resolved during the R&D period of a standard ECE or ICE.

It may be necessary to estimate the requirements of each specific ECE or ICE as regards mechatronic control details. The modification from conventional electronic EMC without feedback to EMC with not only feedback but also feedforward is much easier with a mechatronic control system. Finally, the EMC system has the advantage that an adaptation to different and often short-time objectives can be accomplished more quickly than with M-M components. This is imperative, for instance, for regulations necessary to fulfil with emission rules that show a discrepancy from country to country and also regularly change. Contemporary materials for ECEs and/or ICEs have been built up in the form of ceramics and fibre-reinforced plastics. Their components revealed to thermal energy (heat) can be better insulated and are more stable under load when prepared from ceramics. Fibre-reinforced materials are light that is why their major advantage may recline in use for oscillating components. Almost all modern vehicles use ECE or ICE. Some of the advantages of the ECE with four-stroke thermodynamic cycle ICE (also known as the Otto cycle, from the inventor *Nikolaus Otto*) are [PERSSON 2004]:

- ❖ Efficient, compared to the ECE, that is, automotive steam engine;
- ❖ Inexpensive, compared to the ECE, that is, automotive gas turbine;
- ❖ Easy to refuel, compared to the AEV (all-electric vehicle).

The primary method to control the ICE, for example, the Otto engine (Fig. 2.67) is the throttle valve that varies the influx of air-fuel mix.

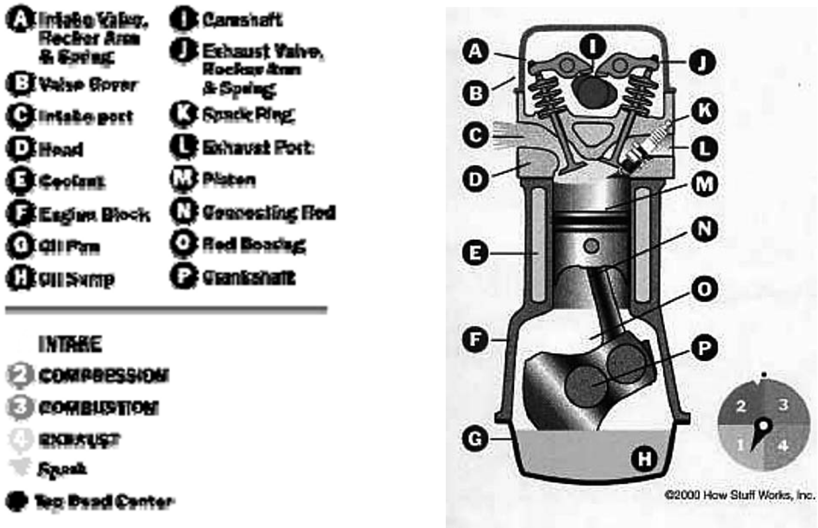

Fig. 2.67 The Otto engine's cylinder [HOWSTUFFWORKS.COM 2000].

Another method to control the M-M driveshaft torque and angular velocity is to control the timing of the ignition. The ratio between air, fuel, and compression are other parameters that can be used [HOWSTUFFWORKS.COM 2003].

The diesel engines works in a similar way, with the difference being that fuel is injected directly into the cylinder and self-ignites when heat is generated from the higher compression caused by the piston. The method of controlling the Otto engines and diesel engines also differ.

The diesel engines are primary mechatronically controlled by the amount of injected fuel.

In Figure 2.68 is shown a cut-away section of a diesel engine [SEIFFERT AND WALZER 1991]. Its major features are EMC, high-pressure injection and dual-spring injectors with five-hole injector nozzles. The function of the dual-spring injectors is to inject the diesel-oil fuel in two stages.

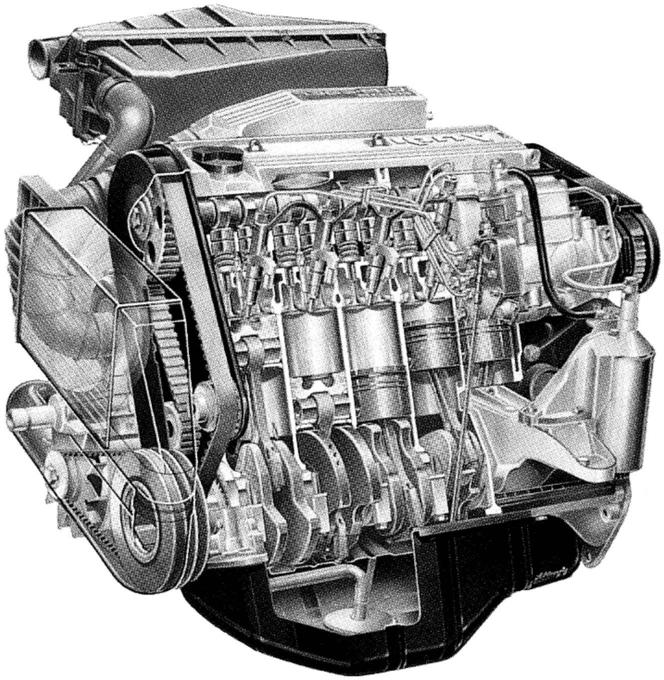

Fig. 2.68 Cut-away section of a diesel engine – 2.5 l, 5-cylinders, turbocharged mechatronically controlled [Audi; SEIFFERT AND WALZER 1991].

The supplementary progressing pressure boost in the cylinder has as a consequence a '*quieter*' combustion process that is softer. Injection rate and timing are controlled and monitored mechatronically. This makes it possible for the diesel engine to provide high power and good economy with low exhaust emissions under all functioning circumstances and throughout its service life.

In multi-cylinder diesel engines, 2, 3, 4, 5, 6, 8, or 10 cylinders may be used. Additional cylinders smooth the diesel engine operation and increase power output because there is less time between power strokes.

M-M Transmissions - In the design of an automotive vehicle, one consideration is the need of torque and angular velocity. These two states work opposite to each other; what is gained in torque T is loosen in angular velocity ω, summarised in power $P = T\,\omega$.

In Figure 2.69, the optimum curve of the ICE is combined with the optimum curve of the different four-gears [LECHNER AND NAUNHEIMER 1999].

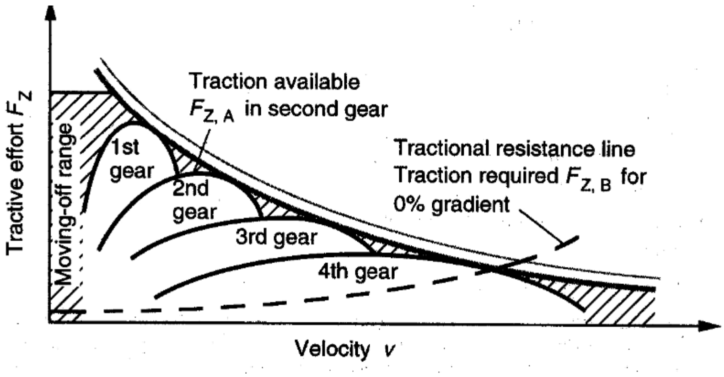

Fig. 2.69 Traction curve for an automotive vehicle with four gears [LECHNER AND NAUNHEIMER 1999].

Small automotive vehicles normally use five-gears and large vehicles (trucks) are equipped with up to twenty-gears. To efficiently use the ICE, different gears must be applied in order to obtain the required angular velocity and torque.

Gear shifting makes the vehicle capable of following the optimum curve during the whole vehicle velocity range [LECHNER AND NAUNHEIMER 1999].

The prime target of the M-M transmission is to allow the ICE to operate in its narrow range of crankshaft angular velocity while providing a wide range of wheel angular velocities.

M-M transmissions compensate the weakness of the ICE at low values of the crankshaft angular velocity. For example, a 75 kW (100 hp) ICE gives only 10 h at idling and without low gears this is not enough to overcome the start inertia of a vehicle of 1.5 Mg.

Automotive vehicle M-M transmissions are classified into different categories:

- Classical 4-6 velocity **manual transmissions** (MT) that in turn can be divided into:
  - Unsynchronised, **constant-mesh manual transmission** (CMT);
  - Synchronised, **synchronised manual transmission** (SMT);
  - **Semi-automatic transmissions** (SAT).

- ❖ **Fully automatic transmission** (FAT) that, in turn, can be divided into
  - ➢ **Automatic power-shift transmissions** (APS);
  - ➢ **Automatic manual transmission** (AMT);
- ❖ **Mechano-mechanical** (M-M) **continuously variable transmission** (CVT).

Manual Transmissions (MT) - The manual gearbox consists of different gear-wheels that are engaged and disengaged (Fig. 2.70). In conventional MTs, the driver is involved in the process of changing gears. The driver changes gears and performs the process of engaging and disengaging the master clutch. The MT is synchromesh and fitted with helical gears that result in easy gear shifting and avoidance of wear and unpleasant noise.

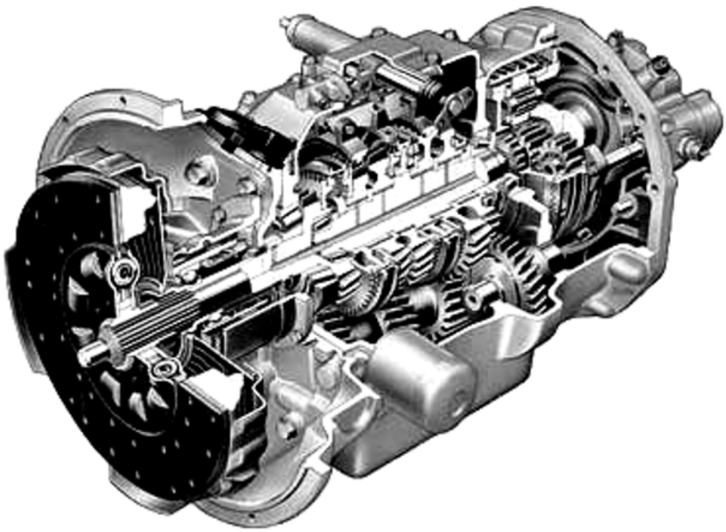

Fig. 2.70 Eight-velocity range-change manual transmission (MT) [Scania's MT - GR801-8].

Semi-Automatic Transmissions (SAT) -- In SATs, one of the operations of engaging the clutch and changing gear is automatic, for example, the driver chooses the gear and the transmission performs the clutch manoeuvre. Another kind of SAT is when the driver is pre-selecting the gear or follows a recommendation and engages the clutch when the driver wants to change gear. For instance, the latter may be Scania's MT -- *Opticruise*.

Fully-Automatic Transmissions (FAT) - In FATs, the M-M clutch manoeuvre and gear performance are automatic. The key difference between a manual and an automatic transmission is that the MT locks and unlocks different sets of cylindrical gear pairs to the output shaft by means of dog M-M clutches to achieve the various gear ratios, while in automatic transmission, the planetary sets of gears produce all the different gear ratios by engagement and release of multi-discs M-M clutches. At present, a computer controls the transmissions; the automotive vehicle can agree with the driver's agility and change gear. The system can also be tuned for economic, sporty, or winter characteristics. In some automotive vehicles, a choice can be made between manual and automatic transmissions. When driving with manual shift, the transmission's computer betters the driver if she/he tries to shift in a less suitable situation. The computer may make the shift as soon as the situation is considered suitable.

In Figure 2.71, as an example of this development, a mechatronically controlled four-speed automatic transmission with driver-selected operating modes is shown. This automatic transmission uses a **torque converter** (TC) that allows the ECE or ICE to spin somewhat independently of the transmission.

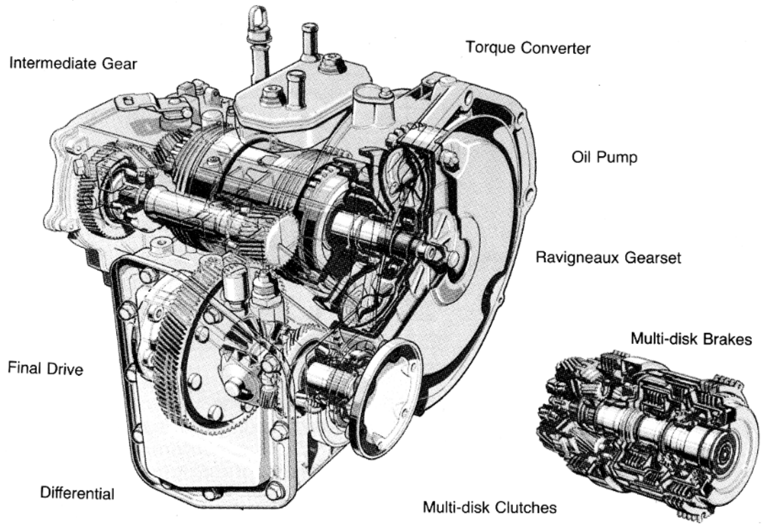

Fig. 2.71 Contemporary four-velocity automatic transmission with fluidodynamical M-M torque converter (CT) and human driver-selected operating modes [Renault and Volkswagen ; SEIFFERT AND WALZER 1991].

The **torque converter** (TC) with its connections to the ECE or ICE and the transmission is shown in Figure 2.72. The M-F pump inside a TC is a type of centrifugal M-F pump. As fluid is flung to the outside, a vacuum is created that draws more fluid in at the centre. The fluid then enters the blades of the turbine, which is connected to the transmission. The fluid exits the turbine at the centre, moving in a different direction than when it entered.

If the fluid was allowed to hit the M-F pump, it would slow the ECE or ICE down, wasting power which is the reason for the stator.

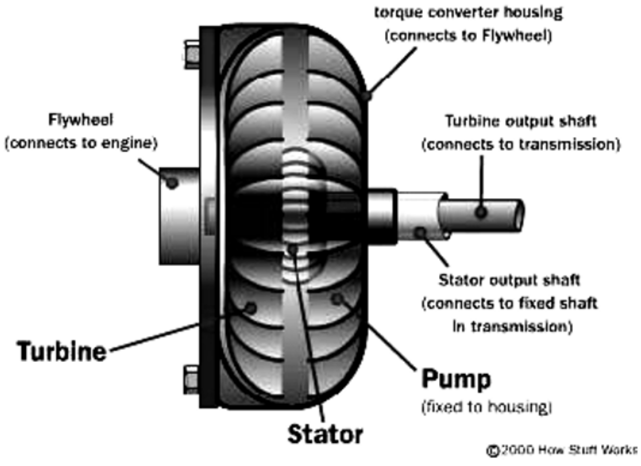

Fig. 2.72 Torque converter (TC) [HOWSTUFFWORKS.COM 2003].

The stator resides at the very centre of the torque converter. Its job is to redirect the fluid returning from the turbine before it hits the pump again which dramatically increases the efficiency of the torque converter. The disadvantage with an automatic transmission is that it does not transfer all power. To counter this effect, some automotive vehicles have a **torque converter** (TC) with a lockup F-M clutch. When the two halves of the TC get up to speed, this clutch locks them together, eliminating the slippage and improving efficiency. The combination of SAT and fully automated gearshift is termed AMTs and the result is the same as from FATs but the design is identical with SATs. Instead of a having the driver managing the engaging and disengaging of the M-M clutch and choosing gear, a controller performs the whole process.

Continuously Variable Transmissions (CVT) - CVTs are torque and speed converters whose ratio can continuously vary without interaction. They can therefore, together with an intelligent ECE or ICE system, follow the optimum curve of the engine. The problem with a CVT is that the efficiency is significantly worse than in an ordinary geared transmission [LECHNER AND NAUNHEIMER 1999]. Various ratio-altering transmissions may be used. These take the form of friction drives, selective sliding gearboxes and progressive sliding gearboxes with clutches, planetary gears with brake bands, and belt systems with loose pulleys. The friction disc transmission had a large future.

A simplest, early 1900s automotive vehicle's CVT is the *'driving-disc and driven disc'* design, in which a friction driving disc rides upon the surface of a friction-driven disc (see Fig. 2.73). The simplest form had the driven disc set on a shaft at right angles to the driving disc.

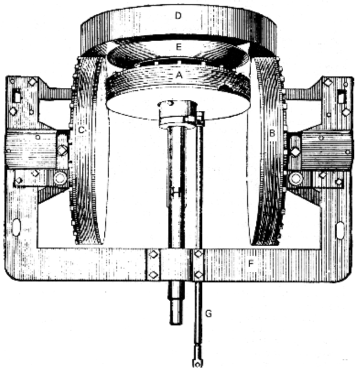

Fig. 2.73 Basic mechanical layout of a simplest, early 1900s automotive vehicle's CVT [Bobbs-Merrill Co. Indianopolis, Ind.; HOMANS 1910].

The driving disc may be slid along its splinted axle to contact the driven friction discs at different distances from its centre [HOMANS 1910]. The speed ratio of such a design is simply the radius of the driving disc divided by the distance from the contact point to the centre of the driven discs. Many of the automotive vehicle manufacturers still perform research in this area. From Figure 2.74 it can be seen that a contemporary CVT is particularly suitable for FWD vehicles.

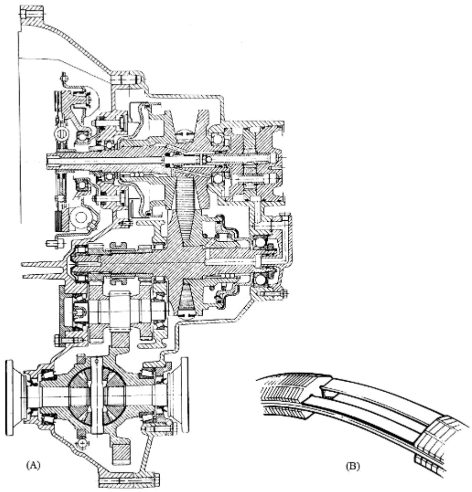

Fig. 2.74 Schematic diagram of a contemporary CVT (A) and its single segmented metal drive-belt (B) [Van Doorne Transmissie BV; NEWTON ET AL. 1989].

A centrifugal clutch, top left, transmits the drive to the primary pulley and, through a quill drive, to a M-F pump, top right, the adjustable flanges of both the primary and secondary – driving and driven – pulleys slide axially on linear ball-bearing splines, that of the primary one being controlled by fluidical pressure in the cylinder to the left of it, while the secondary one is closed by the coil spring plus fluidical pressure in the smaller diameter cylinder on its right.

A splined muff coupling between the two gears to the left of the secondary pulley is disengaged in its central position, engages forward drive if moved to the right. The whole unit is totally enclosed in cast housing and the belt-pulley interface is lubricated by oil passing from the primary pulley actuation cylinder through ducts into the base of *V*-groove [NEWTON ET AL. 1989].

One of the intriguing possibilities offered by wide-range CVTs and hybrid powertrains is that the velocity range and torque envelope of the ECE or ICE can be reduced, leading to savings in rotation inertia, friction, and better optimised ECE or ICE processes [BRACE 2000].

The passenger automotive vehicle with CVT, shown in Figure 2.75, may satisfy **low-emission vehicle** (LEV) standards, reducing major pollutants by 25% from current requirements [YAMAGUCHI 2000].

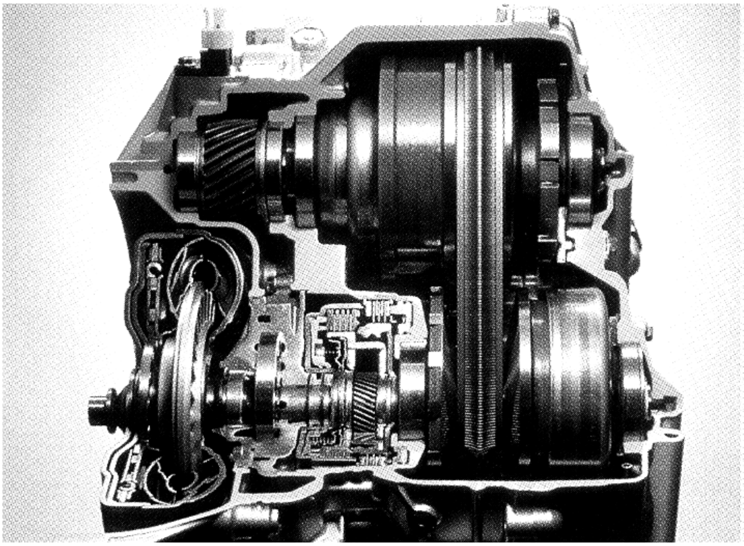

Fig. 2.75 Continuously variable transmission (CVT)
that satisfies low emission vehicle (LEV) standards [Toyota; YAMAGUCHI 2000].

The passenger vehicle's ICE computer and automatic air-conditioning amplifier are coordinated to save fuel. The compressor kicks in at peak efficiency whenever the throttle valve is closed, as on deceleration and braking that cuts the fuel supply to the ICE, or when the ICE is accelerating hard, at which time the ICE is producing more than enough power to spare to drive the compressor.

The mechatronically controlled CVT employs a TC with lockup clutch for the start-up unit. The transmission may operate in a manual selection range with steering-wheel-mounted push buttons, allowing selection of six virtual ratios ranging from 2.396 through 0.428 : 1. The CVT is combined with a final drive ratio of 5.182 : 1. The transmission can, of course, be left alone to select ratios automatically. It features hill-grade logic to provide ample ICE braking downhill [YAMAGUCHI 2000].

Differential -- The differential has three main objectives:

- ❖ To aim the ECE or ICE power at the wheels;
- ❖ To act as the final gear reduction in the automotive vehicle, slowing the rotational speed of the drive shaft one final time before the rotation reaches the wheels;
- ❖ To transmit the power to the wheels while allowing them to rotate at dissimilar angular velocity.

Otherwise it would be impossible for the automotive vehicle to turn, since the inside wheels travel a shorter distance than the outside wheels.

Hybrid Powertrains - There is an increasing interest in **hybrid-electric vehicles** (HEV) today. For instance, some automotive vehicle manufacturers have developed and produced HEVs for the customer market. An example of an HEV is the combination of a petrol (gasoline) or diesel oil ECE or ICE powered and electrically driven automotive vehicle. The ECE or ICE is generally used to maintain the state of charge of the CH-E/E-CH storage battery. In some cases, the CH-E/E-CH storage battery is only charged from a wall socket and by regenerative braking but never from the ECE or ICE which leads to a continuous decrease of the CH-E/E-CH storage battery's state of charge. In a standard solution, the CH-E/E-CH storage battery can be charged from the ECE's or ICE's onboard M-E generator. The benefits of using both an E-M motor and an ECE or ICE arise from three fundamentals:

- ❖ The ECE or ICE can be downsized because the EM motor can be used to provide the extra power under high performance conditions. This allows the ECE or ICE to work closer to its optimum during average conditions;
- ❖ The ECE or ICE can be turned off on special occasions. The E-M motor could be used as a mechanical energy source or as a help to quickly restart the ECE or ICE;
- ❖ The E-M motor could be used as an M-E generator to recover kinetic mechanical energy through regenerative braking.

Now another revolution could be sparked by automotive technology, one fuelled by hydrogen rather than petroleum. **Fuel cells** (FC) – that cleave hydrogen atoms into protons and electrons that drive E-M motors while emitting nothing worse than water vapour – could make the automotive vehicle much more environmentally friendly. Not only could vehicles become cleaner, they could also be become safer, more comfortable, more personalised, and even perhaps less expensive. Further, these FCEVs could be instrumental in motivating a shift toward a *'greener'* energy economy based on hydrogen.

As that occurs, energy application and production could change significantly. Thus, hydrogen FCEVs could help ensure a future in which personal mobility – the freedom to travel independently – could be sustained indefinitely, without compromising the environment or depleting the Earth's natural resources. A confluence of factors makes the big change seem increasingly likely. For one, the petroleum-fuelled ICE, as highly refined, reliable, and economical as it is, is finally reaching its limits.

Despite steady improvements, today's ICE automotive vehicles are only 20--25% efficient in converting the energy content of fuels into drive-wheel power. And although the automotive industry has cut exhaust emissions substantially since the unregulated 1960s – hydrocarbon dropped by 99%, carbon monoxide by 96%, and nitrogen oxides by 95% -- the continued production of carbon dioxide causes concern because of its potential to change the planet's climate.

Even with application of new technologies, the efficiency of the petroleum-fuelled ICE is expected to plateau around 30% -- and whatever happens, it may still discharge carbon dioxide.

In comparison, the hydrogen FCEV is nearly twice as efficient as an ICE, so it may require only half the fuel energy, as shown in Figure 2.76 below [BURNS ET AL. 2002].

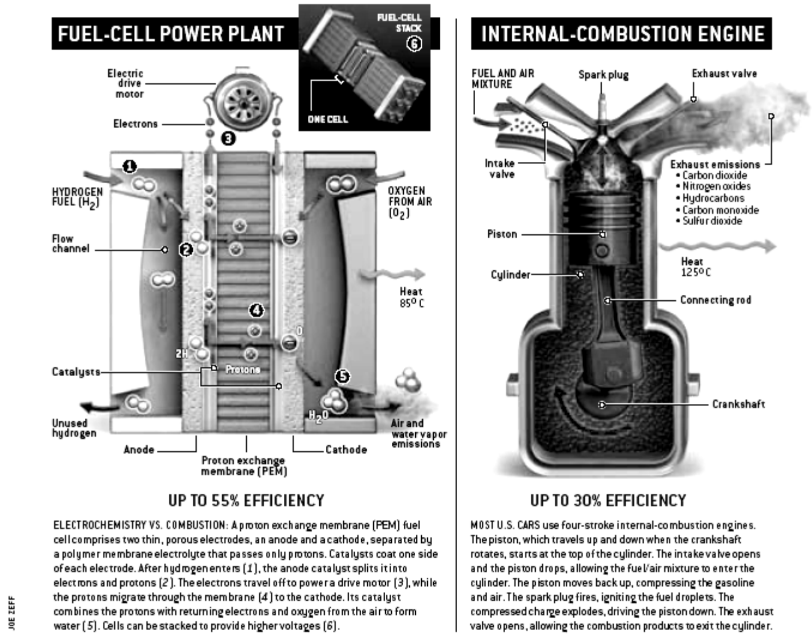

Fig. 2.76 Electrochemistry versus combustion [Scientific American, Inc.; BURNS ET AL. 2002].

Of even more significance, FCs emit only chemical energy (water) and thermal energy (heat) as by-products. Finally, hydrogen gas can be extracted from various fuels and energy sources, such as natural gas, ethanol, water (by means of electrolysis using electrical energy) and, eventually, renewable energy systems. Realising this potential, an impressive roster of automotive vehicle manufacturers is making a sustained effort to develop FCEVs. To understand why H-E DBW AWD propulsion technology could be so revolutionary, consider the operation of a FCEV that at base is an automotive vehicle with a traction E-M drive. Instead of a CH-E/E-CH storage battery, gets electrical energy from a FC unit through the E-M motor(s). Electrical energy is produced when electrons are stripped from hydrogen fuel travelling through a membrane in the cell. The resulting current runs the E-M motor that turns the wheel.

The hydrogen protons then combine with oxygen and electrons to form water. When using pure hydrogen, a FCEV is a **zero-emission vehicle** (ZEV). Although it takes energy to extracts hydrogen from substances, by either reforming hydrocarbon molecules with catalysts or splitting water with electrical energy, the FC's high efficiency more than compensates for the energy required to accomplish these processes. Of course, this energy has to come from somewhere.

Some generation sources, such as natural gas, oil and coal-burning power facilities, produce carbon dioxide and other greenhouse gases. Others, including nuclear plants, do not. An optimal goal would be to produce electrical energy from renewable sources such as biomass, hydroelectric, solar, wind, or geothermal energy.

By adopting hydrogen as an automotive fuel, the automotive industry could begin the transition from near-total reliance on petroleum to a mix of fuel sources.

Today 98% of the energy used to power automotive vehicles is derived from petroleum. FCEVs have the following advantages:

- ❖ FCs convert chemical energy (hydrogen gas) into electrical energy (electricity) making possible non-polluting automotive vehicles powered by traction E-M motors; when combined with compact throttling, braking and steering mechatronic controls, FC technology allows automotive scientists and engineers to split a vehicle into a rolling chassis and a potentially unchangeable body with an expansive interior;
- ❖ The prospect of clean hydrogen FCEVs could also augur an altered energy economy and a sustainable environment without compromising personal mobility;
- ❖ The *'chicken-and egg'* problem: large numbers of FCEVs require adequate fuel availability to support them, but the required infrastructure is hard to build unless there are significant numbers of FCEV on the roads.

All the HEVs can be divided in series, parallel and series/parallel as well as split hybrids. In the bibliographical references, the majority of mechatronic control studies that have been found are performed on parallel HEVs.

Parallel Hybrid - Both the ECE or ICE and the E-M motor can turn the transmission at the same time.

In comparison with series hybrids, parallel hybrids provide a shorter energy chain that ensures a higher energy efficiency and low production cost. The drawback is the sophistication of the powertrain mechanical transmission system. The wheel torque is the sum of the ECE or ICE and the E-M motor torques. The problem is that the optimal distribution for these two is normally unknown. This means that the mechatronic control of the powertrain requirements needs to be defined in order to use the electrical energy in the best way.

Series Hybrid - The petrol or diesel fuelled ECE or ICE turns an M-E generator, and the M-E generator can either charge the CH-E/E-CH storage batteries or run an E-M motor.

Through-The-Road Hybrid - A through-the-road hybrid consists of separated power trains that are connected to each other by means of the road or ground surface and, normally, they can operate collectively and simultaneously.

Conclusion - The ECE or ICE may be the most dominant propulsion system and may survive due to hybrid solutions, decreased fuel consumption, reduced emissions, and other improved technologies [BIRCH 2002]. If hydrogen can be used as the chemical energy source, it may possibly be tested in an ECE or ICE since the technology is well known. Though **fuel cells** (FC) have a great promise for the future, focus may be on improving the ECE or ICE [BIRCH 2002]. There may probably be a transition period where hybrids and FCs are used in combination with the ECE or ICE. Major challenges are the system sophistication, as well as the infrastructure, according to some automotive scientists and engineers [BIRCH, 2002]. CVT versus six-gear transmission may be another interesting question where the answer lies in the near future.

2.4 M-M Transmission Arrangement Requirements for Conventional Automotive Vehicles

2.4.1 Foreword

An automotive vehicle's transmission arrangement comprises the whole of the components concerned with transmitting ECE or ICE power as well as F-M, P-M or E-M motor power to the road wheels, that is, the M-M clutch and **manual transmission** (MT), termed the '*gearbox*', **semi-automatic transmission** (SAT), **fully-automatic transmission** (FAT) or **continuously-variable transmission** (CVT), the propeller shaft (driveshaft), and final drive gearing, and the axles and bearings for the driving wheels [HOLMES 1977].

Classical M-M transmission arrangements with the **rear-wheel-drive** (RWD) and **front-wheel-drive** (FWD) for the M-M DBW 2WD propulsion mechatronic control system is shown in Figure 2.77 [DUFFY 2008].

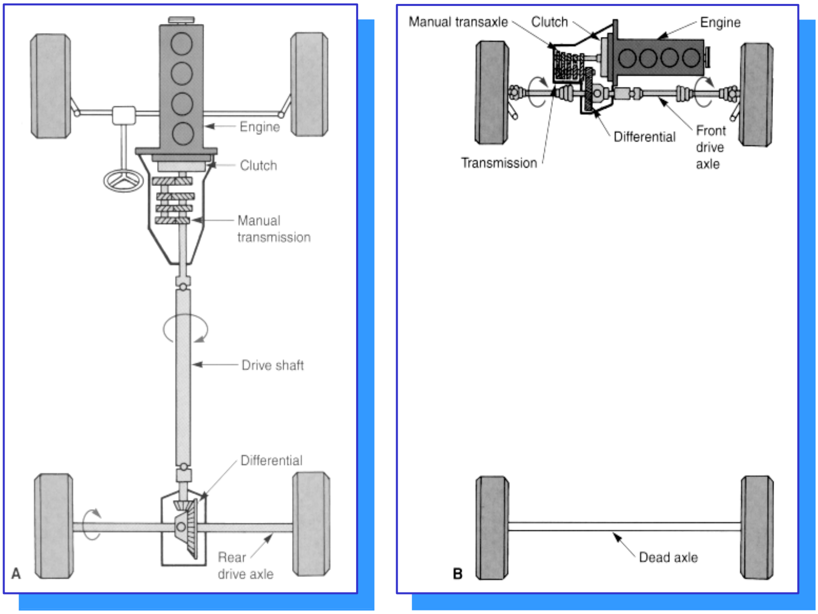

Fig. 2.77 Classical M-M transmission arrangements with the rear-wheel-drive (RWD) and front-wheel-drive (FWD) for the M-M DBW 2WD propulsion mechatronic control system [DUFFY 2008].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_19,

As a rule in a classical M-M transmission arrangement for the DBW AWD propulsion mechatronic control system, a '*transfer box*' is interposed between the MT, called the '*gearbox*' or SAT or FAT or CVT, and other axle units (see Fig. 2.78) [NEWTON ET AL. 1989].

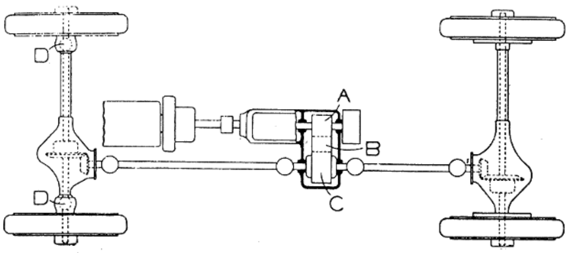

Fig. 2.78 Classical M-M transmission arrangement for the M-M DBW 4WD propulsion mechatronic control system [NEWTON ET AL., 1989].

The function of the transfer box is to transmit the drive from the major MT (gearbox) or SAT or FAT or CVT to the comprehensive front, middle, and rear axles. In this transfer box is a pinion A, driven by a coupling from the MT or SAT or FAT or CVT output shaft. The pinion, through an intermediary gear B, drives a supplementary gear C, installed in the cage of a power-splitting **inter-axle** (IA) M-M differential assembly. From the power-splitting IA M-M differential, one shaft is taken forward to the front axle and the other rearwards to the rear axles. Both axles contain their own axle M-M differentials and final drive gears, but that at the front takes the **flexible joints** (FJ), **universal joints** (UJ), or **constant-velocity joints** (CVJ) at D its outer ends. Those are indispensable in permitting the front wheels to be steered.

For DBW **four-wheel driven** (4WD) × SBW **four-wheel steered** (4WS) automotive vehicles, all the axles contain FJs or UJs or CVJ at their ends that are indispensable to allow the front and rear wheels to be steered (see Fig. 2.78).

The power-splitting IA M-M differential at C in the transfer box is the mechanism that shares the input value of torque from the *'propeller shaft'* or *'Cardan shaft'* uniformly between the two output drive shafts to the wheels, irrespective of the reality that they may be revolving at different values of wheel angular velocity, for instance on taking a corner. Thus, the power-splitting IA M-M differential at C is indispensable for sharing out the drive uniformly between the front, middle, and rear axles and to allow for the fact that, when the automotive vehicle is driven around, the mean values of the angular velocity of the front wheels are different from those of the middle and rear wheels and therefore the values of the angular velocity of all the propeller shafts must be at variance too.

Other features include different rolling radii of wheel tyres due to, for example, manufacturing tolerances, different degrees of wear and, imaginably, different values of the wheel-tyre pressure.

It is normally necessary to lock these power-splitting IA M-M differentials out of operation to enhance the performance and reliability of traction when the automotive vehicle is driven on soft ground.

For automotive vehicles that will be mainly used on soft ground, the mid-power-splitting IA M-M differential may be disconnected from the driveline, but various means of uncoupling DBW AWD, taking away only one or more axle(s) to perform the driving, is normally made available if the vehicle is to be driven on metalled roads.

In view of the fact that the steered front wheels are perpetually predisposed to turn further than the wheels on the fixed-geometry middle or rear axle, for the reason that the radius of turn is perpetually the larger, a one-way M-M clutch, or freewheel can be substituted for the power-splitting IA M-M differential. In reality, this normally takes the form of two free wheels, one on each front hub, where there are rotary mechatronic controls through which they can be locked by the driver, but, naturally, the driver has to stop to prevent such an act. As soon as the driver continues to drive the vehicle on solid ground, on the other hand, the driver must remember to unlock the hubs. Should the rear wheels lose traction, on the other hand, and therefore have a tendency to turn further than the front ones, the drive may automatically be transmitted to the front wheels, even if they are in the freewheeling '*modus operandi*'.

A similar, classical M-M transmission arrangement with a power-splitting IA M-M differential for the M-M DBW 4WD propulsion mechatronic control system is shown in Figure 2.79 [FIJALKOWSKI 1985B].

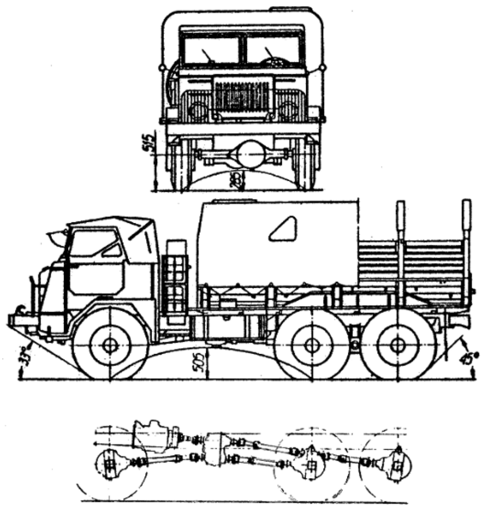

Fig. 2.79 Classical M-M transmission arrangement with the power-splitting inter-axle (IA) M-M differential for the M-M DBW 4WD propulsion mechatronic control system [Star - *Truck Factory Starachowice, PL*; FIJALKOWSKI 1985B].

Along with the high-tech found in modern automotive vehicles comes a sophisticated three-mode M-M DBW 4WD propulsion mechatronic control system, as shown in Figure 2.80 [NISSAN 2002B]. This system has been developed to allow secure and relaxed driving under virtually all circumstances, with automotive mechatronics ensuring that optimum drive is instantaneously delivered to each wheel [NISSAN 2002B].

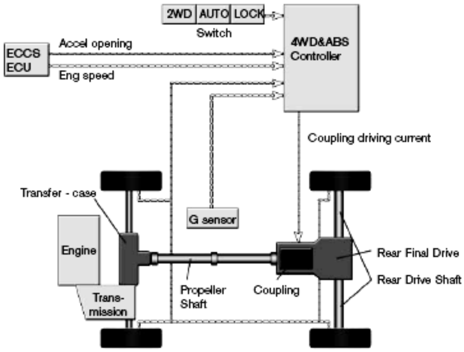

Fig. 2.80 A three-mode M-M transmission arrangement with the centre M-M clutch for the M-M DBW 4WD propulsion mechatronic control system [Nissan 's- *X-Trial*; NISSAN 2002B].

Where automatic 4WD is used, this is often applied by means of all-mechanically based systems that require one pair of wheels to slip in order to bring in the other pair. Naturally, there is a delay of several wheel rotations until this occurs, but the M-M DBW 4WD propulsion mechatronic control system anticipates loss of traction through the throttle control and transmits torque to the rear wheels according to the driver's accelerator operation and the type of on/ off-road surface. Under normal circumstances, the M-M DBW 4WD propulsion mechatronic control system is a **front-wheel drive** (FWD), saving on energy losses and on fuel. By pushing the buttons on the fascia, 2WD, *'AUTO'* or *'LOCK'* mode can be selected, according to the driving circumstances. In '*AUTO*' mode, the M-M DBW 4WD propulsion mechatronic control system may automatically apportion torque to each side as on/off-road surface circumstances demand. The M-M DBW 4WD propulsion mechatronic control system reacts to either a loss of traction or a potential loss of traction through the 4WD controller that then transmits an electrical current signal to the mechatronically controlled E-M coupling in the final RWD. E-M coupling torque is transmitted to the rear axle in varying degrees to allow the M-M DBW 4WD propulsion mechatronic control system to ensure that the most suitable percentage of propulsive force is applied to each axle. If the *'LOCK'* button is pressed then propulsive force is delivered to each axle due to the locked centre M-M clutch in the torque-distributing ratio between front and rear axle of 57 : 43. This is used for serious off-road functions or for extreme circumstances, such as when starting off on a snow-covered incline or driving through deep mud [NISSAN 2002B].

The M-M DBW 4WD propulsion mechatronic control system brings peace of mind under difficult circumstances, and may automatically default to *'AUTO'* mode once the velocity builds up and the problem recedes.

The three-mode M-M DBW 4WD propulsion mechatronic control system offers instant and increased security when starting on snow or ice, when driving on side slopes, or under a whole range of what would normally be difficult circumstances, such as encountered on icy roads or maybe on outings to ski slopes or rural areas. In three-mode M-M 4WS DBW propulsion mechatronic control systems, there are not many torque-distributing ratios of propulsive torque from single to two axes, as shown in Figure 2.81 [SZ. 1986].

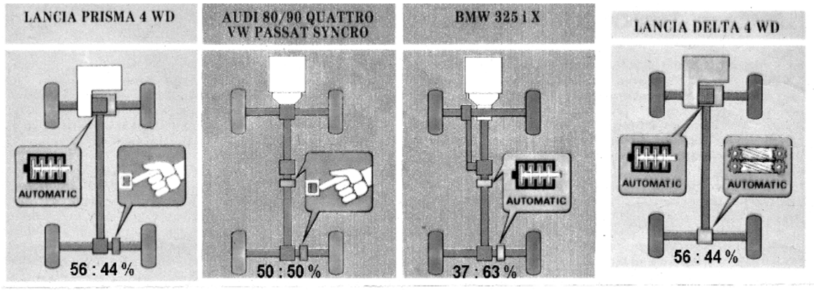

Fig. 2.81 Torque-distributing ratio between front and rear axles of a three-mode M-M DBW 4WD propulsion mechatronic control system [SZ 1986].

The three-mode M-M 4WS DBW propulsion mechatronic control system described above is integrated into the **electronic stability program** (ESP), which isoptional on ECE, and ICE, as shown in Figure 2.82 [NISSAN 2002B].

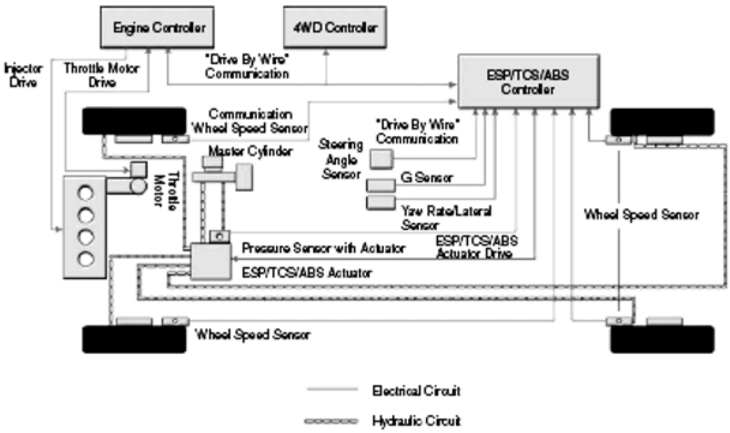

Fig. 2.82 A three-mode M-M DBW 4WD propulsion mechatronic control system with ESP, TCS, and ABS controller [Nissan's *X-Trial*; NISSAN 2002B].

Offering more than conventional ESP systems, a recent version uses sensors and other detectors to control a variety of situations both on and off roads.

The yaw rate sensor, the *G*-sensor, **anti-lock braking system** (ABS) sensor three-mode 4WD controller and throttle control are all mechatronic and communicate with each other to detect a potential loss of traction or grip on any given wheel and then react accordingly.

Depending upon the situation, the ESP **microprocessor control unit** (MCU) can contact the ABS actuator and apply the brake to any given wheel, engage the 4WD unit, or activate the **traction control system** (TCS).

The **active-brake limited-slip differential** (ALD), available in combination with ESP and controlled again by the ABS sensors, applies the brake to any wheel that has lost traction and, in doing so, directs drive to the opposite wheel on the axle.

The result of this integrated approach is that EPS can either apply the brake or apportion torque to any individual wheel independently; negating understeering or oversteering on roads and ensuring maximum traction is maintained off road or during slippery conditions.

Another key to producing a truly revolutionary automotive vehicle is the integration of the FC with HE DBW AWD propulsion technology, replacing throttling, braking, steering, and other functions with mechatronically controlled units.

This frees up space because mechatronic control systems tend to be less bulky than those of M-M. The DBW AWD propulsion mechatronic control system performance can be programmed using software.

In addition, with no conventional drivetrain to limit structural and styling choices, automotive vehicle manufacturers may be free to create dramatically different designs to satisfy customer needs.

Replacing conventional ICEs with FCs enables the application of a flat chassis that gives vehicle designers great freedom in creating unique body styles.

HE DBW AWD propulsion technology similarly liberates the interior because the driving mechatronic controls can be radically altered and can be operated from different seating positions. Recognising this design opportunity, some vehicle manufacturers came up with a concept that will be introduced in the early 2020s.

The flat chassis concept and the automotive vehicle prototype may be created, literally, from the wheels up.

The foundation for both is a thin, skateboard-chassis containing the FC, traction E-M motor(s), hydrogen storage tanks, mechatronic controls and heat exchangers, as well as throttling, braking, and steering mechatronic control systems.

There are no ECE or ICE, transmission, drivetrain, axles, or mechanical linkages, as shown in Figure 2.83 [BURNS ET AL. 2002].

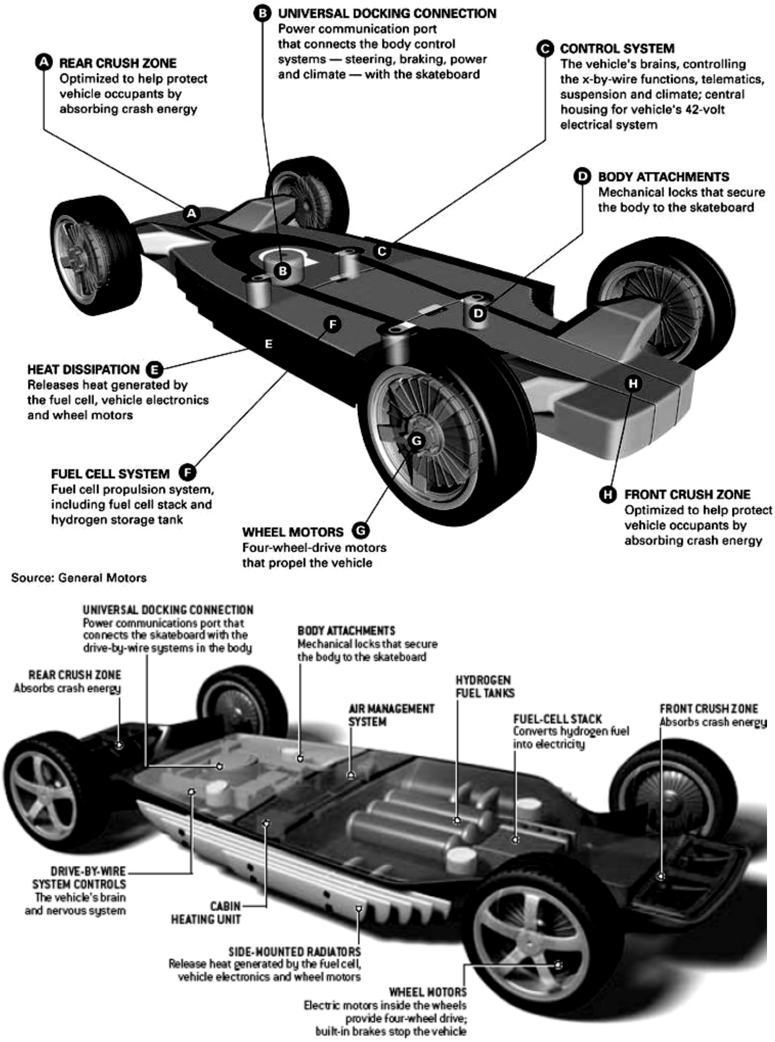

Fig. 2.83 Principle layout of the flat skateboard-chassis concept [Scientific American, Inc.; General Motors; BURNS ET AL. 2002].

In a fully developed automotive vehicle, HE DBW AWD propulsion technology would require only one simple electrical connection and a set of mechanical links to unite chassis and body. The body could plug into the chassis much like a laptop connects to a docking station.

The single-electrical-port concept creates a quick and easy way to link all the body mechatronic control systems – controls, power and heating – to the skateboard. This simple separation of body and chassis can help keep the vehicle's body light and uncomplicated. It also makes the body easily replaceable.

Shoehorning functional automotive systems into a flat, skateboard-chassis is the key to some vehicle manufacturers' chassis concepts for the future hydrogen FCEV. That and the application of compact HE DBW AWD propulsion technology for throttling, braking, and steering permits vehicle designers much greater freedom in configuring the upper bodies.

It means no more bulky ECE or ICE compartments, awkward centre cabin hump or conventional steering wheel to work around. The novel approach also allows bodies to be interchangeable. Customers could have new, personalised bodies *'plugged in'* to their used chassis at the dealership, or do it themselves – turning, say, a family sedan into a minivan or a luxury automotive vehicle.

In principle, simply by having the dealer or vehicle owner *'pop on'* an interchangeable body module, the vehicle could become a luxury vehicle today, a family sedan next week, or a minivan next year [BURNS ET AL. 2002].

Much like a computer, automotive vehicle mechatronic control systems would be upgradeable through software. As a result, service personnel could download a programme as desired to improve automotive vehicle performance or to tailor particular **ride and handling** (R&H) characteristics to suit a particular vehicle brand, body style, or customer preference. With DBW AWD propulsion mechatronic controls, the driver needs no foot pedals, gear shifter, or steering hand wheel.

The automotive vehicle of the future is equipped with a steering guidance mechatronic control system, termed the guidancer. The guidancer easily moves from side to side across the width of the vehicle to accommodate left- or right-hand driving positions. The guidancer operates something like a motorcyclist grips the driver accelerates by twisting the handgrips and brakes by squeezing them. Steering involves a turning action similar to today's steering hand wheel.

The driver also has the option to accelerate or decelerate (brake) with either the right or left hand, with braking taking priority in the case of mixed signals. drivers start the automotive vehicle by pushing a single power bottom and then selecting one of three settings: neutral, drive, or reverse.

The guidancer also eliminates the conventional instrument panel and steering column. This frees up the automotive vehicle interior and allows novel placement of seats and storage area. For example, because there is no ECE or ICE compartment, the driver and all passengers have more visibility and much greater legroom than in a conventional vehicle of the same length. By lowering the vehicle's barycentre and eliminating the rigid ECE or ICE block in front of the passengers, a flat chassis-like skateboard chassis can improve **ride handling and stability** (RH&S) characteristics beyond what is possible with conventional automotive vehicle architecture [BURNS ET AL. 2002].

The simplified design of an advanced FCEV, as suggested by the flat chassis concept and the automotive vehicle of the future, could have a profound effect on automotive vehicle manufacturing and so excess production capacity in the automotive industry is driving down automotive vehicle prices.

At the same time, the regulatory standards-driven content of automotive vehicles continues to grow, pushing up costs. Taken together, lower prices and higher costs are threatening profit margins.

A concept such as the flat chassis, however, could significantly change the current business model. It could conceivably lower vehicle development costs because, with modules able to be produced independently, design changes to the body and chassis modules could be made more easily and cheaply.

As with today's truck platform derivatives, it may be possible to design the chassis only once to accommodate various body styles. These derivatives could easily have different front ends, interior layouts, and chassis tuning. With perhaps only three chassis needed -- compact, midsize, and large – production volumes could be much larger than those now, bringing greater economies of scale. Having far fewer components and part types may further reduce costs. The FC stack, for example, is created from a series of identical individual cells, each comprising a flat cathode sheet and similar anode component separated by a polymer-electrolyte membrane. Depending on the power requirements of a particular vehicle, the number of cells in the FC stack can be scaled up or down. The flat chassis concept also makes it possible to decouple body and chassis manufacture.

An automotive vehicle manufacturer could build and ship the chassis (an ideal scenario, given its thin profile), and local firms could build the bodies and assemble the complete vehicle. The chassis could be very economical because it would be mass-produced.

In high-end automotive markets, this kind of arrangement might mean that new chassis might debut every three or four years – when software upgrades could no longer match performance desires – but that customers could purchase a new body module annually or lease one even more frequently.

In addition, if chassis hardware is developed appropriately, then new hardware and software upgrades could become practical. Alternatively, consumers who wish to keep their vehicle body but want a higher performance chassis could buy one. In less affluent automotive markets, the chassis would comprise durable hardware and could be financed for much longer periods, perhaps decades [BURNS ET AL. 2002].

2.4.2 Classical M-M Transmission Arrangement Requirements for the M-M DBW AWD Propulsion Mechatronic Control System

The conventional ECE or ICE, as used in automotive vehicles, has intermittently the following conditions and characteristics:

- ❖ To start it, certain forms of external mechanical energy must be used;
- ❖ Its maximum value of torque is small compared with that of a steam engine, gas turbine, or traction E-M motor of the same maximum value of power;
- ❖ Its maximum value of power is developed at a relatively high value of the ICE crankshaft's angular velocity -- ranging from about 157 rad/s (1,500 rpm) for heavy commercial vehicles to 1257 rad/s (12,000 rpm) and more in racing cars.

In consequence, it must be applied together with an M-M DBW AWD propulsion mechatronic control system that deviates in several differences from those of steam engine, gas turbine, or traction-E-M motor-propelled automotive vehicles.

A variety of means have been used for starting ECEs or ICEs -- for instance, from mechanical energy stored in a spring or flywheel, or chemical energy in a cartridge -- but the entire principle naturally is to apply a CH-E/E-CH storage battery-powered brushed DC-AC mechanocommutator electromagnetically-excited starter E-M motor.

To produce the starting (cranking) mechatronic control system as compact -- and therefore as economical -- as possible, it must be stipulated how to disengage the ECE or ICE from the driveline for the duration of the starting operation. Engaging it once more to the driveline, for propelling the vehicle, must be realised as fluently as possible, both for the sake of passengers and to preclude breaking the vehicle mechanisms. In passing down the driveline, the torque of the ECE or ICE is adapted, stage-by-stage, until it may be converted into the propulsive force, or *'traction effort'*, at the interface between the wheel tyres or caterpillar tracks and the on- and/or off-road, respectively.

If fast acceleration is necessitated, either when starting from rest or in any other circumstances -- for passing, for example -- that propulsive force must be greater than before. This is achieved in part by amplifying the ECE or ICE torque output but, since this alone may not be adequate, the mechanic gear ratios may normally have to be altered too. Under this circumstance, gear alteration can be compared to changing the leverage between the ECE or ICE and the driving wheels, as a result of the comparatively minor value of torque accessibility can being converted into a major value of propulsive force. A major leverage may also be necessary for climbing hills or traversing very soft or uneven ground.

In view of the fact that a major leverage entails a decreased motion at the output end, this involves a large decrease in the angular-velocity value between the ECE or ICE and the driving wheels. As a result, the leverage must be decreased as the value of the vehicle velocity increases, or else the value of the ECE driveshaft or ICE crankshaft angular velocity would be become too high and the potential maximum value of the vehicle velocity would be inaccessible.

Besides, the relationship between ECE driveshaft and ICE crankshaft's physical values of power, torque, and the angular velocity is such that the value of torque decreases as the value of the angular velocity increases.

As a result too, certain simple means of altering the leverage -- variable gear -- is indispensable.

Whereas the indispensable principles of classical M-M transmission arrangement for the M-M DBW AWD propulsion mechatronic control system have remained similar for nearly all categories of automotive vehicle, the explicit arrangements differ -- for instance, some may have DBW AWD -- for example, DBW 4WD and the others DBW 2WD either **front-wheel drive** (FWD) or **rear-wheel drive** (RWD).

Where the ECE or ICE is mounted at the front and the axis of its crankshaft is parallel to, or coincident with, the longitudinal axis of the vehicle, the driveline must eventually be twisted through $\pi/2$ rad in a sequence so that it may be transmitted out to the road-wheels, the axes of which are naturally perpendicular to that of longitudinal axis. Such a twist, however, is not indispensable if the ECE or ICE is mounted transversely, while other technical hitches, for instance a stipulation for dipping the driveline to a level underneath that of the ECE driveshaft or ICE crankshaft while twisting it through 2π rad, may take place.

One more requirement for a classical M-M transmission arrangement for the M-M DBW AWD propulsion mechatronic control system stems from the fact that, when the vehicle is cornering, the outer road-wheels must turn faster than the inner ones that may be traversing circles of smaller values of radius, so the mean value of the wheel angular velocity and, consequently, both the value of the ECE driveshaft or ICE crankshaft angular velocity and the value of the translational vehicle velocity, may need to remain constant.

Subsequently, once more, to decrease the transmission of vibrations to the chassis frame, the ECE or ICE is universally mounted on it, while the driving wheels, fastened to the chassis frame by the road springs, also have a **degree-of-freedom** (DoF) of motion in relation to it. Both these motions must be contained by the M-M DBW AWD propulsion mechatronic control system.

In conclusion, the requirements for a classical M-M transmission arrangement for the M-M DBW AWD propulsion mechatronic control system are as follows:

- ❖ To provide for disengaging the ECE or ICE from the driving wheels;
- ❖ When the ECE or ICE is operating, to allow the linkage to the driving wheels to be done fluently and without shock;
- ❖ To allow the leverage between the ECE or ICE and driving wheels to be at variance;
- ❖ It must decrease the driveline angular velocity from that of the ECE or ICE to that of the driving wheels in a ratio of somewhere between about 3 : 1 and 10 : 1, or more in relation to the comparative size and mass of ECE or ICE and comprehensive mass of the automotive vehicle;
- ❖ Twist the driveline, if indispensable, through π rad or if not, re-align it;
- ❖ Allow the driving wheels to rotate at different values of the wheel angular velocity;
- ❖ Make available for comparative motion between the ECE or ICE and driving wheels.

There are various means in which these requirements may be encounter, and classical M-M transmission arrangements for DBW AWD propulsion mechatronic control systems are put into four categories:

- M-M (Mechano-mechanical);
- E-M (Electro-Mechanical);
- P-M (Pneumo-Mechanical);
- F-M (Fluido-Mechanical):
  - Fluido-static (FS),
  - Fluido-dynamic (FD),
  - Electro-rheological fluid (ERF),
  - Giant-electro-rheological (GERF),
  - Magneto-rheological fluid (MRF),
  - Nano-magneto-rheological fluid (NMRF).

Whereas the first of these is widespread, combined M-M and E-M, P-M or F-M DBW AWD propulsion mechatronic control systems are becoming prevalent, even on certain categories of heavy commercial vehicles.

Contemporary automotive vehicles with **electro-mechanical** (E-M), **pneumo-mechanical** (P-M) or **fluido-mechanical** (F-M) transmission arrangements for DBW AWD propulsion mechatronic control systems have been built but have not gone into large-scale production.

On the other hand, such transmission arrangements for DBW AWD propulsion mechatronic control systems are not at all uncommon in tractors for agricultural and, more especially, construction and related industrial equipment, such as diggers, in which alteration from idling to full load may be, of necessity, effected unexpectedly and cyclically. With a **mechano-fluidical** (M-F) pump, **mechano-pneumatical** (M-P) compressor, or **mechano-electrical** (M-E) generator driving individual in-wheel-hub F-M, P-M or E-M motors, respectively, on each pair of wheels, there is no stipulation for an M-M differential gear. E-M transmission arrangements for DBW AWD propulsion mechatronic control systems may be used in **main battle tanks** (MBT) and various civil and military all-terrain automotive vehicles in the not-too-distant future and are still extensively employed in diesel-electric buses and locomotives. With the current renaissance of concern in **all-electric vehicles** (AEV), which are **battery-electric vehicles** (BEV) and **fuel-cell-electric vehicles** (FCEV), as well as **hybrid electric vehicles** (HEV), they are being reconsidered for more extensive application. With an M-E generator or CH-E/E-CH storage battery or fuel cell, M-P compressor or M-F pump driving individual E-M, P-M or F-M motors on each pair of wheels, there is no stipulation for an M-M differential gear because an E-M, P-M or F-M differential unit may be very easily realised, respectively.

Predominantly, however, E-M, P-M and F-M transmission arrangements for DBW AWD propulsion mechatronic control systems have various mechanical components in common. For instance, these components normally substitute the M-M clutch, and MT (gearbox) or SAT or FAT or CVT of an M-M DBW AWD propulsion system.

Most conventional M-M transmission arrangements for M-M DBW AWD propulsion systems fall into one of the following three categories, each of which has three main components:

- ❖ M-M clutch, M-MT or SAT or FAT or CVT and live-axle driveline;
- ❖ M-M clutch, M-MT or SAT or FAT or CVT and dead-axle driveline;
- ❖ M-M clutch, M-MT or SAT or FAT or CVT and axleless driveline.

2.4.3 M-M Clutches

If the ECE or ICE were in permanent linkage with the driving wheels, it would, evidently, be at rest and the tractive effort would be zero. A M-M clutch, on the other hand, permits the ECE or ICE to be run at a value of the ECE shaft or ICE crankshaft angular velocity in that a value of torque giving a greater tractive effort than ECE or ICE is developed and allows the torque to be transmitted to the driving wheels, despite the fact that at the start the latter are at rest.

The M-M clutch is a releasable coupling connecting the adjoining ends of two coaxial shafts. It is presumed to be *'engaged'* or, *'in'*, when the shafts are coupled, and *'disengaged'*, or *'out'*, when they are released. M-M clutches fall into two main categories:

- ❖ Positive engagement;
- ❖ Progressive engagement.

The previous is positively disengaged so that no torque can be transmitted from the driving to the driven shaft, or positively engaged, in which case the shafts rotate together, linked by some M-M devices such as splints, keys, or dogs.

Differently, the progressive one is steadily engaged so that the value of the driving-shaft angular velocity decreases while, simultaneously, which of the driven shaft increases from its initial stationary state until both are rotating at equal values of the angular velocity. Positive engagement M-M clutches are inadequate for linking the ICE to the MT or SAT or FAT or CVT, despite the fact that they are used inside MTs.

For automotive vehicles, a progressive engagement M-M clutch of the '*friction*' form is inserted between the ECE or ICE and the MT or SAT or FAT or CVT. It can be either in a completely individual housing, with a short shaft in front linking it to the ECE or ICE, and another behind to link it to the MT or SAT or FAT or CVT. Instead, it can be integral with either unit or definitely with both. In the previous case, it is in either a single ECE or ICE and MT unit. The housing for the M-M clutch can be one of the pieces or, otherwise, it can be integral with either the ECE shaftcase, ICE crankcase, or the MT housing.

In automotive vehicles, the uncomplicated friction form M-M clutch consists of two discs, the major of which is, as a rule, the ECE or ICE flywheel and the other, normally called the *'presser'* or *'pressure plate'*, is lighter. The ECE or ICE flywheel is fastened to a flange on the end of the ECE shaft or ICE crankshaft, while the other plate slides axially on the output shaft, except in as far as a spring or springs have a tendency to press it against the ECE or ICE flywheel.

Such an M-M clutch is engaged by its spring or springs, and disengaged by a left-foot pedal-actuated linkage under the mechatronic control of the driver.

For the reason that the ECE shaft or ICE crankshaft torque has to be transmitted from the ECE or ICE flywheel to the presser plate by the friction between their two adjoining faces, one may be opposite with a specifically prepared material having a high coefficient of friction, together with good wearing properties.

On the other hand, a significantly enhanced arrangement and one that is quite common, is inserted between the driving plates of the third, much lighter disc, lined on both faces with high friction material.

This disc is free to float coaxially between the other two, and it is contained in a hub splinted on the shaft linking the M-M clutch to the MT.

To differentiate it from the presser, or pressure plates, it is termed the *'centre plate'* or *'friction disc'*. It has the advantages of, in fact, doubling the torque capacity of the M-M clutch and sharing equally the speed of rubbing during progressive engagement, thus increasing the life of the friction material.

There is a maximum value of torque above which a simple foot-pedal-actuated M-M clutch of this form cannot be applied. Without doubt, for heavy commercial vehicles and various others comprising of very powerful ECEs or ICEs, certain means of gaining a higher value of torque capacity are indispensable.
Any of the following three means may be relevant:

- ❖ The application of a cone M-M clutch;
- ❖ Doubling or trebling the number of intermediate friction plates;
- ❖ The application of a multiple-plate M-M clutch.

The cone M-M clutch, although sometimes applied initially, is not now regarded to be appropriate as a dry M-M clutch for this use due to its inclination concerning sticking, harshness, and randomness in function. It is, on the other hand, used in M-M DBW AWD propulsion mechatronic control systems, normally in fluid, and principally in synchromesh mechanisms. Various efforts have been made to manufacture automotive vehicles that can be mechatronically controlled by the right-foot accelerator pedal and left-foot brake pedal only. A centrifugal M-M clutch that automatically disengages it when the value of the angular velocity decreases beneath and re-engages when the value of the angular velocity increases over certain preset values, may be applied. Instead, a fluid coupling, a **fluido-mechanical** (F-M) **torque converter** (TC) or certain specific form of **electro-mechanical** (E-M) clutch may be used.

2.4.4 M-M Transmissions

Mechatronic control over ECE shaft or ICE crankshaft output power, through the accelerator (throttle pneumatic valve) foot pedal, mechatronically controls the rate at which the ECE or ICE is operating; at very high values of the ECE shaft or ICE crankshaft angular velocity, the value of the ECE or ICE crankshaft output power may be high but the value of the ECE shaft or ICE crankshaft output torque can simultaneously be considerably less than at significantly lower values of the ECE shaft or ICE crankshaft's angular velocity.

In other verbal skills, the maximum value of the ECE shaft or ICE crankshaft output torque may be accessible only over a very restricted ECE shaft or ICE-crankshaft-angular-velocity range.

Thus, a driver needs to be able to alter both the ICE output power and the ECE shaft or ICE-crankshaft-angular-velocity range in relation to the range of values of the vehicle velocity which the automotive vehicle is at, whatever prearranged probable time is necessary. Just in this means can the values of torque at the wheels be maintained in equilibrium against demands for either an investigation speed up or downhill, or on the level, or for acceleration or deceleration.

For that reason, MT (gearbox) or SAT or FAT or CVT is indispensable so that the driver can alter torque by choosing the appropriate vehicle velocity range or, in other verbal skills, the vehicle velocity at that maximum value of torque is accessible.

While an automotive vehicle is moving at a homogeneous value of vehicle velocity, the value of the propulsive, or *'tractive effort'*, at the wheels must be such as to exactly maintain equilibrium the sum of three classes of alterable forces acting to resist the motion. If it is greater, the vehicle may accelerate and, if it is smaller, it may decelerate until equilibrium is attained. Such equilibrium may be set up ultimately, because two of the forces alter with changes in the vehicle velocity.

The three forces are as follows:

- ❖ Aerodynanic, or air resistance;
- ❖ Gradient resistance that can be either positive or negative;
- ❖ Rolling resistance.

In view of the fact that the ECE or ICE is geared to the driving wheels, an explicit value of the ICE crankshaft angular velocity relates to an explicit value of the vehicle velocity, and as the tractive effort is relative to the ECE shaft or ICE crankshaft output torque, the alteration of the tractive effort with the alteration of the vehicle velocity may rely upon the alteration of the ICE crankshaft output torque when the ECE shaft or ICE crankshaft angular velocity is changed.

The procedure of selecting the gear ratios for a conventional vehicle with a MT is being tested, but a skilled driver may derive approximate values that may serve as a starting point. The top gear ratio is then completed such that the value of the vehicle velocity relates to the value of the ECE shaft or ICE crankshaft angular velocity so that the maximum value of the ICE crankshaft output power is attained. Next, the maximum value of the gradient to be acceptable must be presumed and the resultant value of the gradient resistance set up. This provides the maximum value of the tractive effort necessary and the maximum value of the ECE shaft or ICE crankshaft output torque being accepted, the gear ratio is indispensable for allowing this value of tractive effort to be attained. The top and bottom gear ratios are thus set up and the residual ratios may be fixed so that they form a geometric progression.

The ECE or ICE has a particular range of ECE driveshaft or ICE crankshaft angular velocity within which the values of the ECE or ICE output power developed, is not very much less than the maximum value, and the gear ratios should be such that the ECE driveshaft or ICE crankshaft angular velocity can be held within that range.

The number of gears necessary, on the other hand, relies also on the duty for which the automotive vehicle is to be employed, e.g. an on and/or off-road vehicle may need higher numerical gear ratios (lower gearing) than a comparable vehicle employed only on the road. If the on and/ or off-road automotive vehicle is also to be employed on the road, and a high top value of vehicle velocity is necessary, five or more steps of the vehicle velocity may be desirable in relation to, e.g. four steps for the analogous on-road-only vehicle.

In the heavy range, the circumstances alter even more extensively in relation to not only the terrain -- gradients, altitudes, and so on -- but also the range of loading to be accepted. A lightly laden or empty vehicle, may need only four to six gears, while an identical vehicle fully laden, may need eight to twelve gears.

To come upon these stipulations, automotive scientists and engineers have designed range-alteration and splitter MTs. Conditions also rely on the road traffic that, if intense, may necessitate the driver of a heavy vehicle to change gear continuously.

The driver may also require more gear ratios so that she/he can keep up with other traffic without moving the ECE or ICE beyond its economical ECE-shaft or ICE-crankshaft-angular-velocity range and thus critically enhancing the rate of **specific fuel consumption** (SFC). With very heavy vehicles -- 40 Mg and over -- as many as 16 or even 24 gear ratios may be necessary.

The MTs that are, or have been, employed in automotive vehicles may be split into those where the drive in each ratio is transmitted circuitously through gear teeth that mesh together, and those where a direct shaft-drive is provided for one of the ratios, while for the others the drive has to be transmitted through gear teeth.

MTs may also be categorised into the following types:

- ❖ Sliding mesh;
- ❖ Constant mesh;
- ❖ Epicyclical.

Combinations of two of these categories are not extraordinary. Spur gearing is applied in all three categories, the differences between them lie in the means by which the gears are caused to work. The sliding-mesh category is the simplest and traditionally the oldest; it may easily be used while the constant-mesh is now the most extensively applied category.

The feature of the sliding or constant-mesh category *'ordinary gearing'* MTs is that the axes of the some gears are installed and the motion of all the gears are easily rotated around their own axes.

The feature of *'epicyclical gearing'* is that at least one gear not only rotates about its own axis but also rotates physically around some other axis.

Semi-automatic operation of the SAT has been attained, including E-M, P-M or F-M servo-mechanism on the shift-bar housing.

The M-M clutch and ECE or ICE throttle pneumatic valve are both controlled by a microcomputer or microprocessor, and are activated automatically while the drive provides the proper signal by means of a switch on the console. This switch is stimulated forwards to point to an up-shift or rearwards for a downshift, and an indicator on the instrument panel lets the driver see that the gear is engaged.

Skip shifting is made either by manifold actions of the switch or automatically, depending on the load and road circumstances. Clutch pedal operation of the M-M clutch is indispensable when starting and stopping the vehicle.

A fully automatic form of the FAT allows for even better potential for economy. Its **electronic control unit** (ECU) has forward, reverse, and hold positions.

Therefore, the driver can hold any gear in anticipation of the road circumstances, excluding that prerequisite that either under- or over-speeding the ECE or ICE is prevented.

The major advantage of the overall MT hypothesis is that it is founded on a mechatronic control system that is unsophisticated and has not only been demonstrated to be powerful and simple to preserve, but also that service automotive engineers are well-acquainted with it.

The majority of the mechanisms of all the transmissions, namely MTs, SATs, FATs, of any one of the dimensions common in that it is accessible are overall the range. Just the add-on parts, such as the E-M, P-M or F-M servomechanism and self-diagnostic microcomputers (microprocessors), are peculiar parts.

2.4.5 Front ECE or ICE, M-M Clutch, MT or SAT or FAT or CVT and Live-Axle M-M Transmission Arrangement for the M-M DBW 2WD Propulsion Mechatronic Control System

In the front ECE or ICE, M-M clutch, MT or SAT or FAT or CVT or AT and live-axle transmission arrangement for the DBW 2WD propulsion mechatronic control system, the ECE or ICE is at the front with its shaft or crankshaft, respectively, parallel to the axis of the vehicle. From the ECE or ICE, the drive is transferred through a M-M clutch and a short shaft to the M-M MT or SAT or FAT or CVT.

In automotive vehicles, this short shaft is in effect often connected with the primary gear in the MT (gearbox) but, in various commercial vehicles, it is an independent part, normally with FJs, UJs or CVJs at each end and, in several examples, with a sliding joint at one end. From the MT, a *'propeller shaft'* or *'Cardan shaft'* – also with a sliding joint at one end and FJs, UJs, or CVJs at both ends carries the drive to a live rear axle.

A live axle is one by which the drive is transferred, whereas a dead axle is one that does not transfer the drive. Bevel or worm gearing within the axle turns the drive through π rad, and *'differentials'* share out it uniformly between the two *'drive shafts'*, or *'halfshafts'* that distributes it to the wheels.

The roles of the mechanisms are as follows: An M-M clutch is applied for disengaging the ECE or ICE from the driving wheels and it must also allow the driver to link the ECE or ICE when it is operating, without shock to the driving wheels. In view of the fact that the M-M clutch is engaged by a spring-loading mechanism and is disengaged by pressure of the foot on a clutch pedal, it cannot be disengaged when the driver is in the vehicle. Thus, when the driver would like to leave the vehicle with the ECE or ICE operating – and if possible starting the

ECE or ICE, too – the ECE or ICE has to be disengaged from the driving wheels has to be disengaged by applying of the gear-shift lever that the driver puts in a '*neutral*', or gears-disengaged position.

The major duty of the MT (gearbox) is to al-low the driver to alter the leverage between the ECE or ICE and driving wheels to match the fundamental circumstances – gradient, load, necessary vehicle velocity, and so on. As the propeller shaft transfers the drive on to the rear axle, the FJs, UJs or CVJs allocate either the ECE-and-MT or ICE-and-MT (gearbox) assembly and the rear axle to remove in relation to one another, as their spring elements rebound. The sliding joint, as a rule-connected with one of the FJs, UJs or CVJs, contains differences in length of the propeller shaft as its rear end goes up and goes down vertically with the rear axle and its front end pivots about the FJ, UJ or CVJ exactly at the rear of the MT. The mechanism, in what is termed the '*final drive*' unit, twists the drive through /2 rad and decreases the angular velocity in a ratio of about 4 : 1, in view of the fact that the driving wheels must revolve much more slowly than the ECE or ICE. Within the final drive unit too, is the M-M differential that distributes the driving torque uniformly between the two road-wheels while allowing them, on the other hand, to revolve concurrently at different angular velocities while the vehicle is turning.

In Figure 2.84, the MT (gearbox) is exposed as an independent unit, but the other conversions of this front ECE or ICE RWD M-M transmission arrangement are in operation [NEWTON ET AL. 1989].

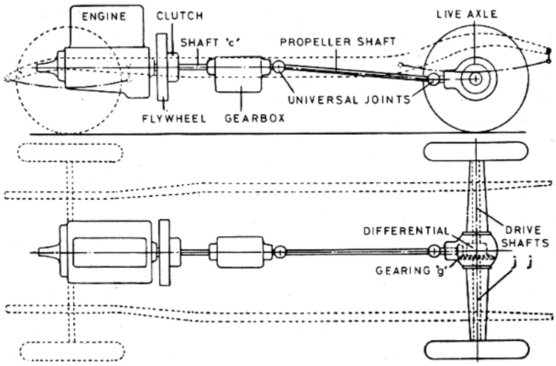

Fig. 2.84 Front ICE, M-M clutch, MT and live axle M-M transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

One is a *'unit construction'* – common on automotive vehicles – in that the MT (gearbox) casing is either connected with or fastened inflexibly to the M-M clutch *'bellhousing'* that is also protected to the ECE shaftcase or ICE crankcase. This has the advantages of limpidness, lighter mass, tidiness of form, and lower manufacturing expenses. Its major disadvantage is relative separation of the M-M clutch.

In an addendum to the accessibility of both the M-M clutch and MT (gearbox), the layout in Figure 2.84 allows a shorter, and then lighter, final drive propeller shaft to be applied, thus avoiding potential inconveniences related with whirling and other vibrations.

The second option necessitates integration of the MT into the rear axle, to create what is commonly called a *'transaxle'* unit. This arrangement is applied only seldom for the following three major causes; first, it is inclined to be considerably more expensive than the others; secondly, it necessitates the application of either a dead axle or an axleless transmission; thirdly, it is particularly complicated to install a heavy transaxle in such a way as to assist the motions, torques, and forces of the input and output drive shafts in so far as to separate it to avoid the transmission of noise and vibration to the vehicle's construction.

With particular categories of MT – conspicuously epicyclical – the M-M clutch function is carried out within the MT itself, to that the drive from the ECE or ICE is consequently transferred either directly by a shaft or through an F-M coupling or torque converter. The shaft can be either independent or linked with the MT (gearbox) mechanism. Live axles are constructing in a variety of shapes. That in Figure 2.84 is termed a *'single-reduction axle'*, because a decrease in angular velocity between the propeller shaft and final drive is realised in a single step, in the final drive at the differential.

In several heavy automotive vehicles, because the reduction ratio may have to be much higher, this reduction is performed in two or even three steps, a *'double-reduction axle'* or even *'triple-reduction axle'* being applied.

2.4.6 Front ECE or ICE, M-M Clutch, MT or SAT or FAT or CVT and Live-Axle M-M Transmission Arrangement for the M-M DBW 4WD Propulsion Mechatronic Control System

In M-M DBW **four-wheel drive** (4WD) propulsion, the overall frictional resistance of a classical M-M transmission arrangement for the M-M DBW 4WD propulsion mechatronic control system is higher than in the M-M DBW **two-wheel drive** (2WD) propulsion, and naturally the propeller shafts and gearing will increasingly wind-up and become highly emphasised so long as the wheels on the two axles are rotating differently.

On soft ground, when this wind-up turns out to be too high, the wheels can skid and thus reduce the stresses, but this may not be feasible on firm roads, and a splintered shaft may be the outcome. With autonomously sprung wheels, a classical M-M transmission arrangement for the M-M DBW AWD propulsion mechatronic control system is identical, excluding because the final drive units are contain on the frame, or structure, of the vehicle. As a result, FJs or UJs or CVJs have to be operated on all ends of the drive shafts to the road wheels, for example, as with the *de Dion* axle layout.

A classical M-M transmission arrangement for the M-M DBW AWD propulsion mechatronic control system presents two major advantages:

- ❖ There is enhanced traction available from all driven wheels that is particularly convenient on soft or slippery ground;
- ❖ If the front wheels fall into a ditch, they have a tendency to climb out, while with **rear-wheel-drive** (RWD), they have a tendency to be forced downwards, except when the vehicle is driven in contrarily, because in that situation, naturally, the disadvantage of the lower traction of 2WD is maintained.

The major disadvantages are escalated mass, dimension, and expense. If the on and/or off-road surface is slippery, even the superlative M-M DBW 2WD propulsion mechatronic control system cannot avoid the driven wheels from spinning unless drive torque is decreased.

Transmitting more torque onto the on and/or off-road can only be realized by the M-M DBW 4WD propulsion mechatronic control system.

The uncomplicated manually activated *'part-time'* M-M DBW 4WD propulsion mechatronic control system was intended to be of assistance in firm terrain and also on flat roads; it should, in spite of this, only be operated at low vehicle velocity.

An arrangement with the conventional **anti-locking brake system** (ABS) is basically impracticable due to the predetermined gear ratio between front and rear axle.

If part-time M-M DBW 4WD propulsion is not disengaged while passing round bends, particularly on firm ground and at higher values of vehicle velocity, a definite amount of tension or torque preload arises between the front and rear axles that affects wheel slip.

For the reason that the two axles are also firmly joined during braking, maximum deceleration of the vehicle can be achieved, but directional stability simply can be mislaid as both axles are concurrently braked with identical wheel slip. This breaks the principle that during braking the slip of the rear wheels should be less than that of the front wheels.

These disadvantages can be avoided with a mechatronically activated *'full-time'* M-M DBW 4WD propulsion mechatronic control system equipped with a third torque proportioning M-M differential. This presents the option of disseminating the drive torque between the front and rear axles in a prearranged ratio. To make this hypothesis real, on the other hand, a substantial mechatronic endeavour is indispensable. A full-time M-M DBW 4WD propulsion mechatronic control system is the means to circumvent the disadvantages of the manually activated part-time M-M DBW 4WD propulsion.

Two full-time M-M DBW 4WD propulsion mechatronic control systems are feasible:

- ❖ A full-time M-M DBW 4WD propulsion with a predetermined torque ratio between front and rear axles;
- ❖ A full-time M-M DBW 4WD propulsion with an adjustable torque ratio between front and rear axles.

A full-time M-M DBW 4WD propulsion mechatronic control system with a predetermined torque ratio between front and rear axles permanently has a torque-disseminating differential.

The amount of tractive effort that can be transferred to each wheel is restricted to the value of the tractive effort that is on the wheel with the lowest frictional contact.

This denotes that if adhesion is left on one wheel, the tractive effort on all other wheels is also decreased. This complication can be resolved, on the other hand, using a locking differential.

A full-time M-M DBW 4WD propulsion mechatronic control system with an adjustable, that is, slip-dependent, torque-distributing ratio between front and rear axles as a rule does not necessitate a torque-distributing differential.

As an alternative, only one axle (in the common case, it is the front axle) is driven directly, whereas the other axle is propelled only when the driven axle slips. This means any disapproving torque pretension of the driveline can be avoided under routine driving circumstances.

Rapidly gaining ground is the viscous F-M coupling, initiated as a reasonable transmission part [NEWTON ET AL. 1989]. Its foremost advantages are unsophisticated and a general lack of restrictions from wear and tear as well as preservation.

A disadvantage of its being incompetent in transferring a M-M differential torque without a M-M differential angular velocity is that there is a tendency towards a substantial time delay before it goes into action as a restricted slip mechanism. A silicon fluid is used because its viscosity descends linearly, but only insufficiently with escalation of temperature.

The functioning of this category of F-M coupling is foremost reliant on the amount of fluid used, which is the major cause why improvement from its original idea in the 1920s to its well-known recognition in the early 1980s, has taken such a long time.

While viscous F-M couplings have been used for test automotive vehicles, they are more proper for other categories and, because they can be intended for soft performance, they can be mounted on front axles.

In view of the fact that their torque transmission ability becomes more intense with angular velocity, they have a tendency to be less suitable for a drive-axle than for IA M-M differential arrangements, that is, before the angular velocity has been decreased by the crown wheel and pinion, despite the fact that they are used for both. There are two means of mounting this mechanism in a driveline. In Figure 2.85, one is shown in series, as a **viscous transmission** (VT), and the other in parallel, as a **viscous coupling** (VC) [NEWTON ET AL., 1989].

Besides, in a M-M differential there are, yet again, two means of mounting it and these are in shaft-to-carrier and shaft-to-shaft arrangements. Potential M-M DBW 4WD propulsion mechatronic control systems are exemplified in Figure 2.86 [NEWTON ET AL., 1989].

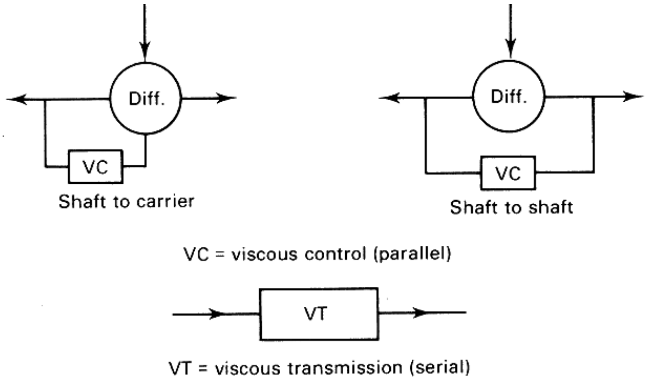

Fig. 2.85 Schematic torque distribution of shaft-to-carrier and shaft-to-shaft axle M-M differentials [NEWTON ET AL., 1989].

In a shaft-to-carrier arrangement, one set of discs is splinted to the M-M differential carrier, whereas the other set, the alternate discs, is splinted to its shaft. In contrast, with a shaft-to-shaft arrangement, the discs are linked alternately, one set to each M-M differential.

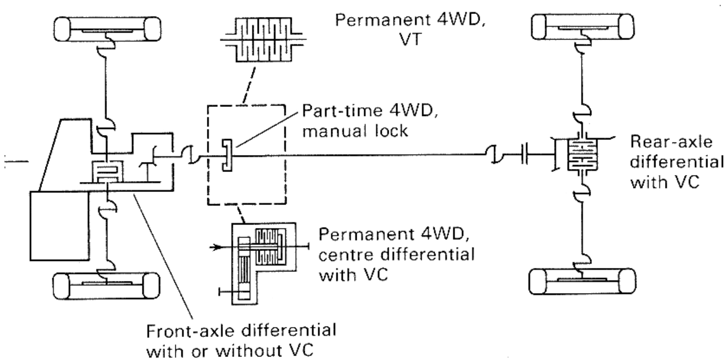

Fig. 2.86 Front ICE, M-M clutch, MT and live-axle M-M transmission arrangement for the M-M DBW 4WD propulsion mechatronic control systems [NEWTON ET AL., 1989].

With the previous M-M transmission arrangement, as the viscous F-M coupling is linked, in reality, in series between the ends of the two halfshafts, the M-M differential is never the less still in parallel with it.

Either arrangement departs from the M-M differential carrier and pinions to reliably operate with the exception of when there is a considerable angular-velocity difference between the halfshafts, in that case the viscous F-M coupling, turns up automatically to function at a restricted rate of slip, thus really decreasing the capability for powerful rotation.

For any particular angular-velocity difference, on the other hand, the shaft-to-shaft arrangement has about three times the locking torque of the shaft-to-carrier arrangement. It is thus the ideal arrangement for functions because the space accessible is limited and high values of torque are to be transferred.

A front ICE, M-M clutch, MT and live-axle M-M transmission arrangement for the M-M DBW 4WD propulsion mechatronic control systems with different mechatronically controlled **torque management devices** (TMD), provide progressive torque distribution based on vehicle velocity as well as M-M couplings tuned to optimise vehicle handling and developing innovative generation M-M couplings compatible with **vehicle stability control** (VSC) systems, as shown in Figure 2.87 [CARE AND STONE 2004].

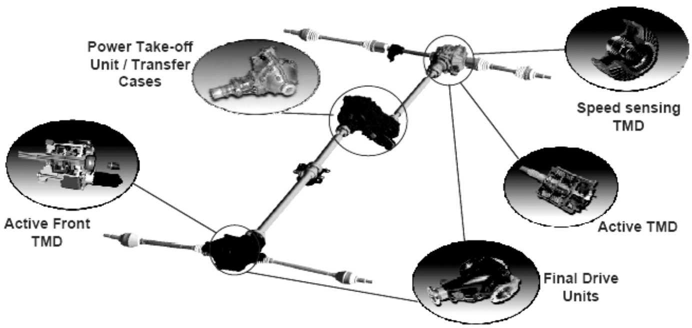

Fig. 2.87 Front ICE, M-M clutch, MT and live-axle M-M transmission arrangement for the M-M DBW 4WD propulsion mechatronic control systems with different mechatronically controlled torque management devices (TMD) [CARRE AND STONE 2004].

Advantages of the mechatronically controlled TMDs may be as follows [CARRE AND STONE 2004]:

- ❖ Actively mechatronically controlled M-M coupling for on-demand and full-time DBW AWD propulsion mechatronic control systems as well as in-axle applications;
- ❖ Market grows from 3.9 m units in 2004 to 7.4m in 2009;
- ❖ Growth driven by vehicle safety and stability coupled with VSC and brake intervention systems;
- ❖ Reduction of fuel consumption from tank to wheel;
- ❖ Important market for automotive technology.

Another technology that the automotive scientists and engineers have developed through these original layout concepts is a symmetrical M-M DBW 4WD propulsion mechatronic control system. This unique element of the automotive technology combines a horizontally-opposed piston-type ICE or ECE with a longitudinally configured drivetrain or powertrain (see Fig. 2.88) [FUJI 2004].

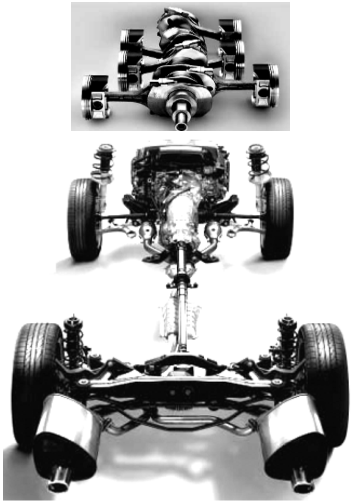

Fig. 2.88 Subaru has constantly triumphed without changing its basic mechanism; it draws upon the benefits of both its horizontally-opposed piston ICE and its longitudinally configured drivetrain [FUJI 2004].

With its low **centre of gravity** (CoG), the horizontally-opposed piston ICE or ECE delivers lower rolling forces to the automotive vehicle in cornering and stable surface traction. At the same time, the longitudinally configured drivetrain delivers superior manoeuvrability by placing the heavy transmission between the wheelbases, thereby making the yaw moment of inertia smaller.

Although M-M DBW AWD propulsion is becoming a standard vehicle powertrain configuration, this trend will in no way detract from the technological advantages held by vehicle manufacturers which they have built up in the ultimate development arena of the **World Rally Championships** (WRC). Based on this symmetrical DBW 4WD propulsion mechatronic control system, vehicle manufacturers will aim to enhance its environmental performance in the future while retaining a unique driving performance, and it is taking the advanced step of developing a horizontally-opposed piston ICE or ECE and researching new **hybrid-electric** (HE) DBW 4WD propulsion mechatronic control systems [FUJI 2004].

The advantages of symmetrical M-M DBW 4WD propulsion -- Through incorporating the same core technologies in their production models as used in WRC automotive vehicles, manufacturers have created excellent drivability with unprecedented balance and linear steering response when cornering. The laterally symmetrical design allows the horizontally-opposed piston ICE or ECE to be mounted much lower in the chassis, adding unparalleled stability and balance. Encompassing a multitude of features, the horizontally-opposed ICE is an engineering triumph that makes the symmetrical M-M DBW 4WD propulsion possible.

2.4.7 Rear ECE or ICE, M-M Clutch, MT or SAT or FAT or CVT and Live-Axle M-M Transmission Arrangements for the M-M DBW 2WD Propulsion Mechatronic Control System

The rear ECE or ICE and live axle M-M transmission arrangement has advantages for buses and coaches, primarily because it allows the floor to be put at a low level and be flat and clear right through practically the entire length of the chassis.

In Figure 2.89, the ECE or ICE and MT (gearbox) are constructing as a single unit that is fixed transversely behind the rear axle.

The M-M clutch is inserted between the ECE or ICE and MT, while at the other end of this box is a bevel gear pair termed the *'transfer drive'* [NEWTON ET AL. 1989].

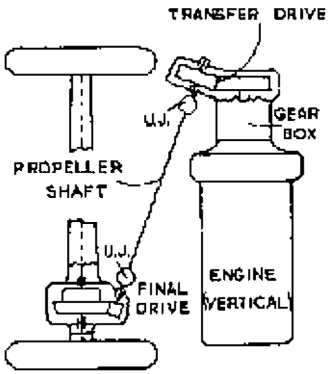

Fig. 2.89 Rear ICE, M-M clutch, MT and live-axle transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL., 1989].

To transfer the drive to the rear axle, the driven gear of the bevel gear pair is joined by a FJ, UJ or CVJ to a reasonably short propeller shaft that is also joined at its other end to the pinion shaft of the final drive unit.

Evidently, the shorter the propeller shaft, the greater is the angle through which it has to oscillate to assist adequate movements of either the ECE or ICE on its mountings and the axle on its springs. For that reason, the final drive unit is included at one side of the axle instead of near its centre.

The drive is twisted through much less than $\pi/2$ rad from the propeller shaft at both its final drive and transfer drive ends that returns to the first principles of design of both pairs of gears.

A problem with this arrangement is the housing of the long ECE or ICE, MT (gearbox) and transfer drive within the comprehensive width of the vehicle. That is why some vehicle manufacturers have mounted their ECEs or ICEs longitudinally behind the rear axle.

This arrangement is shown in Figure 2.90, where the MT (gearbox) is installed independently in front of the axle [NEWTON ET AL. 1989].

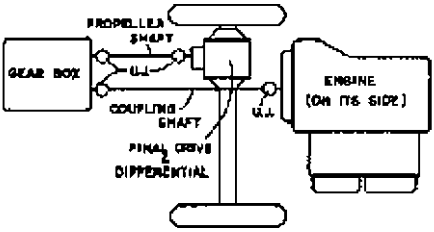

Fig. 2.90 Rear ICE, M-M clutch, MT and live-axle M-M transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL.1989].

As the FJs, UJs or CVJs on the coupling shaft between the ECE or ICE and MT (gearbox) have to assist only comparative movements due to deflections of the mountings and vehicle frame or construction – instead of movements of the axles – they can be of a basic design. CVJs are indispensable, however, on the short propeller shaft. In Figure 2.91 again, independently mounted transverse ECE or ICE and MT units are used, but the M-M differential can be closer to the centre of the axle [NEWTON ET AL. 1989].

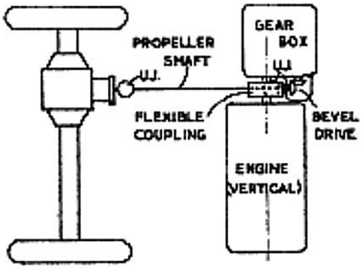

Fig. 2.91 Rear ICE, M-M clutch, MT and live-axle transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

Disadvantages of all rear ECE or ICE arrangements incorporate the lengths of the mechatronic control runs from the driving position and the reality that the driver may not be experienced enough to perceive the sound of the ECE or ICE and estimate its angular velocity, to change gear, if automatic transmission is used.

Transverse rear ECE or ICE engine M-M transmission arrangements evidently necessitate an angle drive, and some manufacturers produce such a unit. It normally comprises a bevel gear pair in a casing that can be fastened onto the MT or ECE/ICE and M-M clutch or **torque converter** (TC) assembly.

In Figure 2.92, a retarder – transmission brake – is built-in the MT (gearbox) that is fastened to the angle-drive casing [NEWTON ET AL. 1989]. A coupling joins the angle drive shaft to the ECE or ICE and M-M clutch assembly in this arrangement.

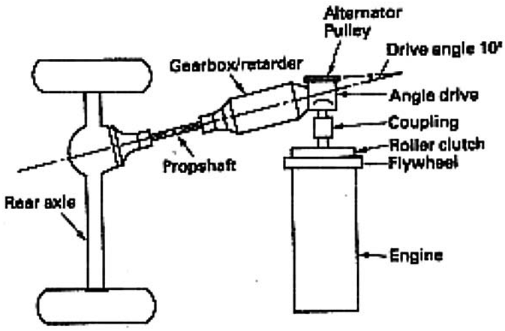

Fig. 2.92 Rear ICE, M-M clutch, MT and live-axle M-M transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

2.4.8 Dead Axle and Axleless M-M Transmission Arrangements for the M-M DBW 2WD Propulsion Mechatronic Control System

An advantage of the dead-axle M-M transmission arrangement is a substantial attenuation in the unsprung mass that gives both better driving and road holding.

Parenthetically, the insinuation that an everlasting inflexible axle restrains its wheels at a $\pi/2$ rad angle to the road is evidently a fantasy: the result of a bump under one wheel is to predispose both wheels uniformly in relation to the on and/or off-road.

The chain drive, Figure 2.93, currently seldom used, is one form of dead-axle M-M transmission. The layouts of vehicles with chain drives are usually like those with transaxles, in that the MT and final drive unit are in a single casing [NEWTON ET AL. 1989].

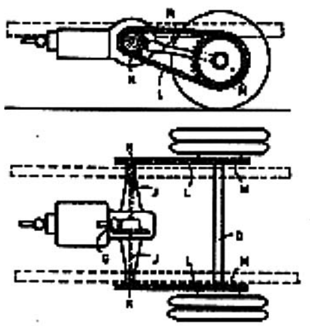

Fig. 2.93 Dead axle and axleless transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

As a result, the drive is engaged by a propeller shaft from the ECE or ICE and M-M clutch to the MT and eventually, in the final drive, is twisted through $\pi/2$ rad and uniformly separated between the two shafts. At the outer ends of these shafts are chain sprockets, around which are the driving chains for the chain wheels that are inflexibly available to the road wheels on the ends of the dead axle. Because there is an attenuation in the angular velocities of the road wheels due to the different dimensions of the chain sprocket and chain wheel, either a smaller attenuation is necessary in the final drive gear or, for example, in heavy-duty automotive vehicles, a particularly large complete attenuation can be attain-ed. Comparative movement between the axle and the frame, as the road springs bend, is assisted by the rotary motion of the loops of the chains about the axes of the chain wheels and sprockets. One more, and normally employed, dead-axle M-M transmission arrangement is that used by the *de Dion* automotive vehicles, as shown in Figure 2.94 [NEWTON ET AL. 1989].

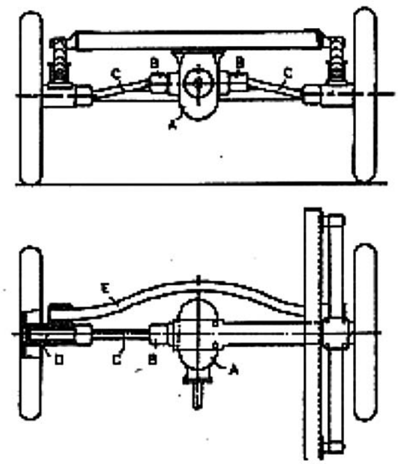

Fig. 2.94 Dead axle and axleless transmission arrangement for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

As a rule, it is accepted for low automotive vehicles with unalterable suspension, and thus is preferred by some racing car manufacturers. This is partially due to its intrinsic suspension features and practically for the reason that it is more acceptable for restricted manufacture than admittedly enhanced, separate rear suspension systems. The transmission arrangements for the *de Dion* axle layout and for the axleless systems with separate suspension are analogous. From the ECE or ICE, M-M clutch, and MT, the drive is engaged through a propeller shaft to a final drive unit that is mounted during the construction of the vehicle, instead of being within the axle. Having been twisted through $\pi/2$ rad and uniformly separated between two short drive shafts, it is then transferred out to the wheels that revolve on bearings contained in brackets fastened to the outer ends of the dead axle, or to the suspension mechanism if an autonomous suspension system is used.

Movements of the road wheels in relation to the vehicle construction are assisted by FJs, UJs or CVJs at both ends of the drive shafts, and the analogous differentities in lengths – or telescoping – of the shafts are attained by producing them in two parts connected by certain forms of splinted or sliding couplings. The springs inserted between the dead axle and the construction of the vehicle, seat on the ends of the dead axle, normally on an identical bracket that accommodates the wheel bearings.

A *de Dion* axle layout can also be used with a so-called '*transaxle*', the only differentity being the inter-location of the propeller shaft between the M-M clutch and transaxle unit instead of between the MT and final drive unit. The major advantages of the *de Dion* axle layout correlated with a live axle, are that it reduces in importance the axle of the mass of differential and final drive unit and the wheels linger in a permanent correlation to each other – either parallel or with a minor within a tendency towards the top, to oppose rear-end drift when the automotive vehicle is performed upon by centrifugal force on turning.

Simultaneously, the problems concerned in the application of chains are prevented. One disadvantage is the shortness of the drive shafts, and as a result, large angles through which they alter, necessitates the application of reasonably expensive FJs, UJs or CVJs. Another is that, while one wheel alone ascends, the contact points between the two wheel tyres and the road move sideways which, for a short time, creates a minor but evident rear-end steering effect and, as a result, incorrectly alters stability and handling. When there is no axle, the road wheel links to the vehicle frame and the springing arrangements are completed in a variety of ways. Using certain of these M-M transmission arrangements, it is feasible to dispense with the outer FJs, UJs or CVJs and with the sliding coupling on the shafts.

A front ECE or ICE and RWD M-M transmission arrangement with autonomous suspension is shown in Figure 2.95 [NEWTON ET AL. 1989].

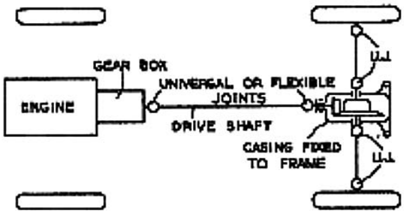

Fig. 2.95 Dead axle and axleless transmission arrangement
for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

Even if the ECE or ICE, M-M clutch, and M-M MT unit and the independent final drive unit are all contained on the frame, or fundamental construction, of the vehicle, FJs, UJs or CVJs are still used at the ends of the propeller shaft. This is to assist the minor M-M differential movement that can take place between these two units because of deflections of both of their adaptable mountings and the construction of the automotive vehicle.

The forces on the mountings for the final drive unit are definitely the biggest dilemma, due to the reaction from the final drive torque. Loading become available with vibration separation and suspending the mass of the unit under dynamic circumstances is far from being complicated and, for that reason, requires softer mountings.

An axleless M-M transmission arrangement for a FWD automotive vehicle is exposed in Figure 2.96 [NEWTON ET AL. 1989]. This illustrates a transmission arrangement in a vehicle where the ECE or ICE is mounted longitudinally forward of the front wheels and the MT to the rear of them, the final drive being inserted between the two. The MT in this instance is of the all-indirect type.

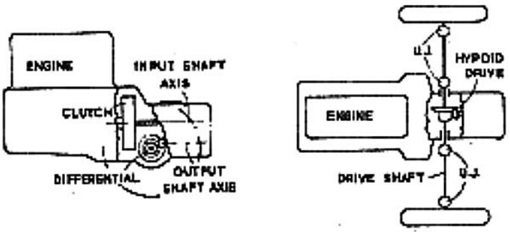

Fig. 2.96 Dead axle and axleless M-M transmission arrangement
for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

As a result, its output shaft is beneath its input shaft, instead of the more prevalent arrangement in that the two are in line. The pinion of the hypoid final drive unit is on the end of the MT output shaft and interlocks with the crown wheel that is fastened to the cage containing the M-M differentials.

Each of the M-M differential and crown-wheel assemblies have bearings in casings that house the ECE or ICE, M-M clutch and MT (gearbox) unit.

The very short shafts holding the M-M differentials and projecting from this casing are joined to the road wheels by universal-jointed drive shafts and sliding joints. The M-M transmission arrangement designed by Sir *Alec Issigonis* is shown in Figure 2.97 [NEWTON ET AL. 1989].

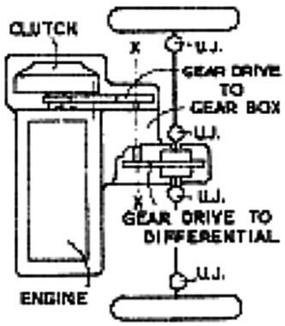

Fig. 2.97 Dead axle and axleless M-M transmission arrangement
for the M-M DBW 2WD propulsion mechatronic control system [NEWTON ET AL. 1989].

In the ECE or ICE and MT (gearbox), the axes of all the shafts are transverse in relation to the longitudinal axis of the automotive vehicle, thus spur gears transfer the drive from the driven member of the M-M clutch, downwards to the input shaft of the MT.

In the same way, spur gears receive the drive from the shaft at the output end of the MT to the final drive unit that is located almost on the longitudinal axis of the vehicle.

The MT is generally in the ECE or ICE sump, and the final drive unit behind it, but in identical casing. All three units distribute identical lubricants. Both these FWD M-M arrangements are suitable for small vehicles because the entire space behind the final drive unit is accessible for unrestricted accommodation of the occupants.

A disadvantage, in addition to the shortness, and the possible wide angles swept by the drive shafts, is the inherently high stiffness of such a short drive line between the M-M clutch and the final drive. This may necessitate the integration of additional softness in the hub of the driven plate of the M-M clutch, to prevent shock and hardness from taking up the drive as the M-M clutch is connected.

One more disadvantage is that the final drive torque, which is that of an ECE or ICE, amplified by the MT and final drive ratios, has to be counteracted by the ECE or ICE mountings or actions must be taken to counteract it by other means.

Rear ECE or ICE M-M transmission arrangements, behind or above the rear axle, have been rebuffed. This is because of the related instability due to disadvantaged mass sharing joined with a rear suspension that is almost predictably adverse as a result of the little space accessible for it on each side of the ECE or ICE. A mid ECE or ICE arrangement is acceptable for racing cars, because it has a tendency to provide an almost identical mass sharing between all four wheels, thus enhancing stability and, in the instance of DBW 4WD, traction too. It necessitates the application of either of the FWD M-M transmission arrangements but with the ECE or ICE in front of, and driving, the rear axle.

Prime disadvantages are interior noise problem of allowing the preservation, and infringement of the ECE or ICE into space that would then be accessible for passengers at the rear.

For buses and coaches, the ECE or ICE is, in certain circumstances, mid-mounted either vertically or horizontally below the floor, again for enhanced mass sharing. In such vehicles, on the other hand, owing to their high floors, access is not such a dilemma, particularly in horizontal diesel ICEs, where the rocker covers and other moving parts are simply accessible from one side.

Admittance to the top of a vertically mounted ECE or ICE, through a hatch in the floor, inclines to be difficult but can be done. As much as the efficacy of traction is affected, FWD is better than RWD, particularly on rough terrain comprising ice or snow. This is partially because the mass of the ECE or ICE on the front wheels allows them to grip the surface better and, naturally, also affects to rear ECE or ICE RWD automotive vehicles.

Essentially, on the other hand, the advantage is enhanced by the asset that the tractive effort is in all events distributed along the line where the front wheels are steered.

One more issue is that front driven wheels have a tendency to climb out of holes or ruts, while rear driven wheels have a tendency to thrust the front wheels deeper down and, sometimes in the direction that they are steered.

2.5 F-M DBW AWD Propulsion Mechatronic Control Systems for All-Fluidic Vehicles

2.5.1 Foreword

An alternative extraordinary **fluido-mechanical** (F-M) concept is the a**ll-fluidic vehicle** (AFV) being developed by some automotive manufacturers. Fluidics is the technology of using the flow characteristics of liquid or gas to operate a mechatronic control system. One of the newest of the mechatronic control technologies, fluidics has recently come to compete with M-M and E-M DBW AWD propulsion mechatronic control systems.

Fluidics have potential benefits in circumstances of higher power density, higher regenerative braking recovery, and lower cost, and potential drawbacks in circumstances of lower energy density, higher noise, and packaging issues. Until further advances appear with these alternative technologies, they seem to be long-term, low probability replacements for **chemo-electrical/electro-chemical** (CH-E/E-CH) storage batteries.

Although F-M DBW AWD propulsion mechatronic control systems have been used in automotive industry for many years, recent developments have considerably widened the range of applications for such systems. With improved product design and manufacture, cost has been considerably reduced whilst maintaining extremely good power to mass ratio as well as the inherent installation versatility of these systems.

It has long been the practice of automotive designers to use fluidics to transfer power and also lubricate the moving parts of the driveline. The fluido-static approach evolution has created well-balanced units having a low noise level and high efficiency. It is now quite usual for fluidostatic-approach M-F pumps and F-M motors to function continuously at fluid pressures in excess of 27.5 MPa (4,000 psi) and angular speeds of 366 rad /s (3,500 rpm) depending upon size. Field and rig testing of fluidostatic F-M drives using heavy duty earth-moving vehicles has been invaluable in helping to finalise the design of components. The effects of sudden alterations in applied load and of harsh deceleration give rise to extremely high transient fluid pressures and powers in the F-M transmission. Regeneration within the FM transmission takes place and all the components of the F-M drive are subjected to operating conditions many times in excess of the steady-state design loads. There has also been continuous development of the rotating parts and piston sub-assemblies and these components that, when manufactured to good tolerance mechatronic control, provide precise constant angular velocity F-M drives to the cylinder barrel while relieving the pistons of most of the fluidic loads in the F-M transmission. This enables components to work at optimum clearance and higher fluid pressures and velocity; thus the overall power to mass ratio of the F-M transmission is increased and cost per kilowatt is reduced.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_20,

Current mass to power ratios are of the order 1.8 kg/kW (3 lb/hp). For many years, applications requiring critical mechatronic control of all types have made use of the excellent response characteristics of F-M drives. The F-M DBW AWD propulsion mechatronic control system is one of low inertia and high stiffness and well suited to servo control. Output characteristics of the F-M drives are determined by adjustment of fluid pressure and flow in the fluidic circuit, usually by means of a servo control changing the M-F pump or F-M motor displacement. The servo jack provides enough power to '*on stroke*' the head or swash plate and is mechatronically controlled by a full follow-up spool fluidic valve that requires only small loads to actuate it. Flow changes from zero to maximum in 500 ms can be obtained with standard servos and special actuators are available for faster response applications.

Various mechatronic control modes can be provided as extensions to the basic servo control. Construction is of the module type and the mechatronic control elements are arranged to be *'add on'* features to the basic servo control.

The five types of mechatronic control that cover most applications are as follows:

- M-M mechatronic control;
- Remote E-M mechatronic control;
- Remote F-M mechatronic control;
- Constant output power mechatronic control;
- Constant fluid pressure mechatronic control.

M-M mechatronic control is achieved by the use of conventional cable or rod systems usually installed with spring boxes having neutral adjustment and dash pots to monitor the servo response and avoid '*creep*'.

Remote E-M mechatronic control can be of the open or closed loop type depending upon application. Solenoid fluidical valves indexing the head by means of a simple base fluid pressure-operated actuator achieve simple, open loop E-M mechatronic control of the swash plate or tilting.

Output velocity is usually indicated by a tachogenerator and push-button switches at the control console may increase velocity, decrease velocity or emergency stop.

Various override and alarm features such as low base fluid pressure, electrical failure, low oil level, high temperature, can be built into the fluidical circuit.

The closed loop E-M mechatronic control makes use of an **electro-fluidical** (E-F) proportional control fluidical valve and is used when accuracies of less than 1% are required for the position or velocity. This system usually requires a separate high-fluid pressure feed to the servo actuator and a high degree of filtration through the fluidic valve, usually to 5 μ.

In a remote F-M controller, it is usual to use the base oily-fluid pressure of the F-M mechatronic control system to give positive control over large distances without sponginess or creep being introduced into it.

The main control fluidical valve is arranged to be proportional with respect to the fluid pressure drop across it and so accurately determines the position of the tilting head against the position of the fluidic valve. This accuracy is usually within 3 – 5%.

Should the mechatronic control lines be excessively long, amplifier fluidic valves can be used to maintain fluid pressure at the servo actuator and overcome line losses.

Constant output power mechatronic control systems, whereby the M-F pump servo may decrease the displacement as the system fluid pressure increases and follow a constant power curve, are extremely desirable requirement in many F-M mechatronic control systems.

They enable the optimum size of the prime mover to be used in the fluidical circuit and prevent overloading. The control lever sets the required output velocity from the drive but should the load increase causing a rise in the system fluid pressure, the control will automatically decrease the output velocity along the required power line. These mechatronic controls are most useful for automotive vehicles and are usually weather-proofed.

The constant fluid pressure mechatronic control is similar in construction to the constant output power mechatronic control and, in many cases; the same actuator and control piston is used.

Castings and main components are batch-produced so that the cost is minimised and the mechatronic controls are easily settable to the customer's requirements. This control is used to maintain a constant output torque over the whole velocity range by means of the servo actuator reducing the M-F pump angle to zero while maintaining a constant fluid pressure over the whole velocity range. This characteristic may be also particularly useful for automotive vehicles.

Applications in the automotive industry often require remote mechatronic control together with integral output power mechatronic control and a precise velocity control is easily available with these components, especially when the zero to full velocity response is slow.

When the emergency stop button is depressed, all solenoid fluidic valves instantly allow the swash control actuator to zero the main M-F pump. M-M mechatronic control of automotive vehicle drives is usually more practicable and economical than E-M mechatronic control.

Simple M-M mechatronic control systems using a combination of foot pedal and hand control with overriding features, has been developed and used, especially on tractors and loaders and, in many cases, it is possible to arrange for these mechatronic controls to be strong enough to return the M-F pump stroke to zero when the fluid pressure on the servo actuator has failed.

Automotive vehicles require a M-M mechatronic control system whereby the control lever is usually loaded towards zero by a spring box so that it will fall to neutral should there be any driving accident or malfunction.

It can be seen from the aforementioned mechatronic control descriptions that many combinations are available for use with F-M drives. These combinations, when used with a wide range of M-F pumps and F-M motors, can be seen to offer comprehensive and economical solutions to the problems of variable velocity.

2.5.2 Fluidostatic F-M Transmission Arrangement for the F-M DBW AWD Propulsion Mechatronic Control System

A fluidostatic F-M transmission transfers power by means of pressurised oily-fluid flowing from a positive displacement M-F pump to a positive displacement F-M motor, as shown in Figure 2.98 [WALLACE 1969]. These must not be confused with fluido-kinetic F-M transmissions that use a kinetic fluidic energy of the oily-fluid to transfer energy from the M-F pump to the F-M motor.

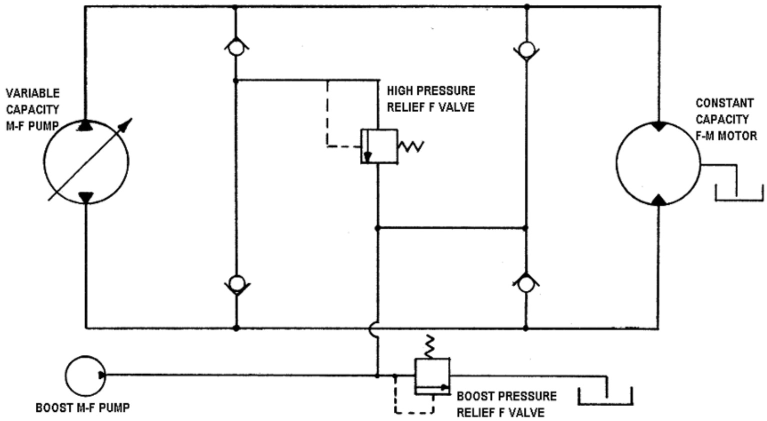

Fig. 2.98 Principle layout of a fluido-static F-M transmission arrangement for the F-M DBW AWD propulsion mechatronic control system [WALLACE 1969].

The most usual type of positive displacement M-F pump, of which there are several, is the axial piston M-F pump and this is found in some 90% of fluido-static F-M transmissions.

The other basic requirement of a fluido-static F-M transmission is a positive displacement F-M motor. There are a number of different types of F-M motors that are generally used and the final choice will normally depend on: power, velocity, accuracy of velocity control, and cost.

In order to understand how a fluido-static F-M transmission operates, we must first examine how the two basic components function.

As mentioned previously, M-F pumps are usually variable-flow axial piston units.

<u>*Axial Piston M-F Pumps*</u> – These can be divided into two main classes:

- ❖ Connecting rod M-F pumps;
- ❖ Slipper pad M-F pumps.

<u>*F-M Motors*</u> – The choice of F-M motor may be usually determined by the factors listed in row 1 of the Table 2.2 [WALLACE 1969].

Table 2.2 Advantages and disadvantages of the various FM motors [WALLACE 1969].

Type	Power	Velocity	Ease of velocity control	Efficiency	Life	Cost
Axial piston	Large	High	Good	High	Good	High
Radial piston	Large	Low	Good	High	Good	Medium
Vane	Small	Medium	Medium	Medium	Medium	Low
Gear	Medium	High	Poor	Low	Medium	Low
Planetary gear	Small	Medium	Poor	Medium	Medium	Low

The figures quoted in the table are, like all generalisations, open to dispute but may serve as an indication of the advantages and disadvantages of the various types.

Axial piston F-M motors are also available in variable capacity form. It must be remembered that with this type of F-M motor, a reduction of oil capacity may increase the velocity. A foolproof method of preventing excessive reduction of capacity must be designed, or the F-M motor can be speeded up to destruction.

In general, fluido-static F-M transmissions are used because they offer one or more of the following desirable features:

- For given output power and velocities, F-M motors are smaller than the equivalent E-M motors and can be sited in positions that would be difficult or impossible with E-M motors;
- Constant power can be achieved over a wide velocity range;
- Simple control of torque of the output range;
- Smooth stepless control of velocity;
- Fast reversal without shock;
- Automatic overload protection;
- High efficiency;
- Comparatively low cost, automatic control of torque, velocity and so on.

Servo Control – During the last century, some very sophisticated forms of mechatronic control for axial piston M-F pumps have been developed. These basically employ an axial piston M-F pump with integral cylinders to control swash-plate tilt. Flow to the cylinder from some external source is controlled by means of an electro-magnetically operated solenoid servo-fluidical valve.

A closed loop F-M mechatronic control system supplies an input signal to the solenoid servo-fluidic valve that controls M-F pump tilt and therefore power output. Thus, extremely small amounts of electrical energy can be used to control very large power outputs at the F-M motor, so providing a tremendous power amplifier. The mechatronic control loop is closed by means of a feedback signal from the F-M motor that is compared with the input signal and that by means of the servo fluidical valve adjust the M-F pump tilt accordingly.

Such an F-M mechatronic control system is comparatively costly but velocity control down to ± 0.1% over the full load range can be achieved and automotive vehicle fields of application are being opened to fluido-static F-M transmissions when they are linked with mechatronic control.

Auxiliary Equipment and Fluidic Circuits

The diagram shown in Figure 2.98 is a simple fluido-static F-M transmission fluidic circuit. This incorporates a boost M-F pump, relief fluidic valves, and so on. In addition to the above-mentioned fluidic circuit, a system of cooling the oily-fluid may be necessary, particularly with closed-loop fluidic circuits, that is, a closed loop fluidic circuit is one in which the fluid flows from the M-F pump to the F-M motor and is returned from the motor direct to the pump and not to a tank.

Closed-loop mechatronic control systems are, of course, essential for applications where bi-sensibility rotation of the F-M motor is required. These mechatronic control systems are also desirable where only one sense of rotation is required because, in this way, a smaller boost M-F pump can be used.

When considering the size of boost M-F pump required, it is important that this is not underestimated in size, particularly with high angular velocity, high flow M-F pumps.

Shift Dynamics of F-M Transmission with F-M Differential

The fluidic power circuits used in the locomotion powertrain of **all-fluidic vehicles** (AFV) or F-M heavy-duty machines are divided in two classes:

- ❖ The closed fluidic power circuit schemes (fluido-static F-M transmissions in the true sense);
- ❖ The open fluidic power circuit schemes, generally simpler and less demanding as far as mechatronic control requirements are concerned.

In any case, a number of specifications need to be met that come from the AFV operating envelope. Among them, the overall ratio of extreme values of torque or angular velocity is very important.

In general, high values of such ratio and high ECE or ICE power, force the automotive designer to implement a big or complex F-M transmission that is very expensive and time consuming.

To overcome the problem, it is sometimes possible to identify at least two operating conditions of the AFT or F-M heavy-duty machine [ZAROTTI 1997]:

- ❖ The '*steady working*' condition (where the primary requirement is torque);
- ❖ The '*transfer working*' condition (where the primary requirement is angular velocity).

Consequently, the basic F-M transmission is equipped with a device able to switch between the two conditions according to the independent input of the vehicle's driver or machine **human operator** (HO).

How the output shaft characteristic (torque T vs. angular velocity ω) changes is shown in Figure 2.99 in a simple case of an F-M transmission whose corner power coincides with the ECE or ICE power (if the F-M transmission has more F-M motors, the angular velocity is individual and the torque is summed) [ZAROTTI 1997].

The '*steady working*' condition is described by the ABC sequence, AB being the fluidical pressure limiting range and BC the full flow range (the slope of both curves is affected by efficiencies or losses).

Conversely, the '*transfer working*' condition is described by the DEF sequence that comes from ABC through the same scale factor τ (velocity ratio of the switching device). By assuming constant efficiencies, points B and E are on the same power curve.

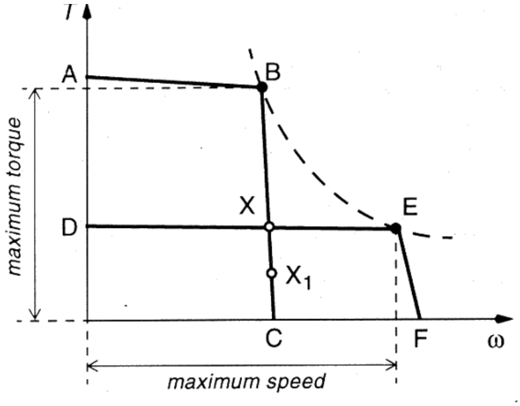

Fig. 2.99 Characteristics of two-velocity F-M transmission [ZAROTTI 1997].

If the AFV resistance is velocity independent, the possible shift points are located within the XC segment (steady working) and the EF segment (transfer working).

Conversely, if the AFV resistance is velocity dependent, that is, it increases with velocity, the XC segment becomes smaller X_1C.

As to the implementation of the shifting device, the following options are available [ZAROTTI 1997]:

- ❖ A two-velocity F-M transmission (gearbox) that has the advantage of a relatively free gear ratio, but the disadvantage of being only feasible when the fluidical power F-M transmission has just one M-F pump and one F-M motor (in principle, use with more F-M motors is possible, but one gearbox is required for each F-M motor with proper synchronisation of the relevant mechatronic controls);
- ❖ A F-M differential (series-parallel) connection of the driving F-M motors that has the advantage of being simple, but the disadvantage of having a fixed gear ratio. Moreover, it is feasible only when the F-M transmission has two F-M motors and, consequently, the equivalent gear ratio is 1 : 2 (in principle, the F-M differential (series/parallel) connection is feasible with any number of F-M motors, but two is the general case).

In the fluidic power circuit shown in Figure 2.100, the supply flow is given by a fixed displacement M-F pump that has (in parallel) a relief fluidical valve to limit the maximum value of fluidic pressure [ZAROTTI 1997].

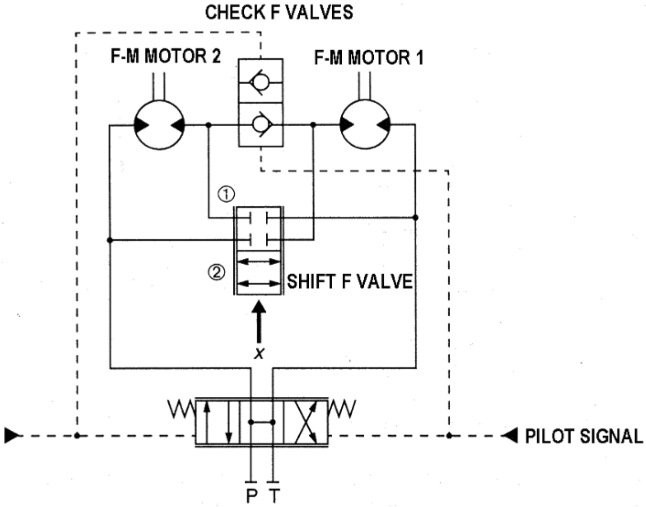

Fig. 2.100 Principle layout of an F-M differential (series/parallel) fluidic power circuit [ZAROTTI 1997].

Two fixed displacement F-M motors are parts of a symmetrical network based on a shift fluidical valve that moves continually between its extreme positions 1 and 2 (corresponding to the *series* (F-M differential operated) and *parallel* (F-M differential locked) connection, respectively.

A couple of check fluidic valves is located between the first and second F-M motors (one for each sense of rotation), and the proper fluidic valve is automatically selected by the pilot signal of the directional fluidic valve. The advantage of this fluidic power circuit scheme is that the cross opening of the shift fluidical valve orifices is avoided, and the intermediate check valve reacts in an adaptive way to any changes of the relative fluidic pressure at its ports.

2.5.3 Conclusion

While using F-M drives, it is of dominant significance to guarantee that the duty cycle and performance parameters of the automotive vehicle to be adapted are perfectly assumed. Application engineering emphasises close cooperation between the fluidics engineer and the automotive vehicle designer so that the existing performance of the vehicle cannot only be equalled but, in many cases, improved and the F-M mechatronic control system made more versatile. In many cases, the dynamic braking capability of F-M drives can be used to simplify automotive vehicle design and the characteristic of reversibility can be used by removing MTs, SATs, FATs and CVTs (gear boxes) and M-M clutches.

The protection of F-M drives by anti-stall mechatronic controls and high capacity cross-line relief fluidic valves provides automatic torque limiting for the automotive vehicle and enables the mechanical components of the F-M transmission to be designed to the optimum. It is a relatively simple matter to alter the response of the servo control on the F-M drive and in doing this, acceleration or deceleration may be mechatronically controlled. This characteristic is used in automotive vehicles where inertia is stored up in the vehicle during operation, such as in off-road vehicles. The F-M drive is capable of accepting regenerated power whereas this is normally dissipated by braking and/or cornering (skid steering), but the ECE or ICE, or prime mover will in turn have to accept this return flow of power. In many instances, harsh deceleration or acceleration may be dissipated in wheel or track slip but with adjustment of the servo response, this can be eliminated and power used more effectively.

The basic closed-loop fluido-static circuit has already been discussed, and in automotive F-M drives, the heart of the F-M DBW AWD propulsion mechatronic control system is usually the power pack. This unit generally consists of the prime mover and variable displacement M-F pump with its mechatronic control system. The reservoir and fluido-static circuit, including high oily-fluid pressure, low oily-fluid pressure, and selector fluidical valves, is also mounted integrally on the unit so that the only connections to be made upon installation of the F-M drive are the supply, return, and drain lines to the F-M motor(s), that is, usually mounted adjacent to the automotive vehicle. This means that the power pack can be remotely sited and the interconnecting pipe work that is usually manipulated on site is the remaining task to be completed upon installation. The power pack together with its filters and cooler, can be tested at the manufacturers and sealed to despatch. Cooling is often necessary when transmitting relatively high powers in the F-M drive and this can be effectively and cheaply done by passing a low fluid flow/low fluid pressure boost supply through oil to water cooler. Should water not be available, an air blast fan cooler is used. The potential for automotive F-M drives grows steadily and, as stated, many hundreds of these are already in operation.

Automotive vehicle scientists and engineers ensure that the applications are tailored to suit the job and that a comprehensive service is available to the customer. A combination of competitive cost, installation advantage, low mass, and versatile mechatronic control when added to the infinitely variable velocity characteristic of the F-M drive, effectively demonstrates its potential in the automotive field. The demand for F-M drives running on fire-resistant fluids especially increases the output of the mining and metallurgical industries, and with M-F pump and power pack sited in a safe area, the need for flame-proofed electrics is eliminated.

The introduction in the market of high torque/low velocity F-M motors, at high values of fluid pressure, has eliminated the need for any intermediate gearing on many applications. Machinery in the automotive industry field often requires variable velocity and high output torque at relatively low powers. These F-M motors giving output torques of up to 38 kNm (30,000 lbf, ft) are obviously the answer for these applications.

It is not possible to give a list of all types of applications in this chapter but two groups shown below give an indication of the scope [O'SULLIVAN 1969].

Materials Handling Equipment

- ❖ Fork lift trucks;
- ❖ Dump trucks;
- ❖ Transporters;
- ❖ Pipe laying machines;
- ❖ Mine cars.

All-Terrain Vehicles, Earth Moving & Agricultural Machines

- ❖ Wheeled and tracked vehicles;
- ❖ Wheeled and crawler tractors;
- ❖ Shovel loaders;
- ❖ Snow ploughs and blowers;
- ❖ Road rollers;
- ❖ Combine harvesters;
- ❖ Mining locomotives.

The lists of applications shown usually require accuracy of velocity control up to 5% and are therefore suitable for relatively simple F-M drives not employing E-F servo controls.

The F-M differential (series/parallel) connection of two F-M motors is a simple way the change the operating characteristics of a fluidostatic F-M transmission with open circuit architecture, but it has a few intrinsic dynamic problems that come to light during the shift from one condition to the other. Because they are mainly due to the metering profiles of the shift fluidical valve, a difference approach (without cross-opening of the orifices within the fluidical valve) has been introduced.

2.6 ECE/ICE HF DBW AWD Propulsion Mechatronic Control Systems for Hybrid-Fluidic Vehicles

2.6.1 Foreword

The author has been involved with **hybrid-fluidic vehicle** (HFV) technology for nearly 30 years and so is able to write with some authority concerning **hybrid-fluidic** (HF) technology, what it's about, what's available today, and what's coming our way and how it can be of benefit all.

HFVs typically combine the **internal combustion engine** (ICE) or **external combustion engine** (ECE) of a conventional vehicle with the **fluido-fluidical** (F-F) accumulator and **fluido-mechanical/mechano-fluidical** (F-M/M-F) motor/pump of an **all-fluidic vehicle** (AFV). The combination offers low emissions with the power, range, and convenient fuelling of conventional (gasoline and diesel) vehicles.

The inherent flexibility of HFVs makes them well suited for military and civil vehicles and personal transportation. They are powered by two energy sources - an **energy conversion device** (ECD) such as an ICE, or ECE or even FC, and an **energy storage device** (ESD) such as F-F accumulators. The energy conversion unit may be powered by gasoline, diesel, methanol, compressed natural gas, hydrogen, or other alternative fuels. They have the potential to be two to three times more fuel-efficient than conventional vehicles. HFV emissions vary depending on the vehicle and its configuration. But in general, HFVs have lower emissions than conventional vehicles because an F-M motor is used with an ICE or ECE, which offsets how often the ICE or ECE is used and how it is used, therefore reducing liquid or gas fuel use and emissions. In addition, HFVs have the potential to operate in *'fluidic only'* mode where the vehicle can operate with no emissions, which is optimal in congested areas and in areas where emissions are of greatest importance.

An HFV is an optimised mix of various components, namely:

- ❖ F-M motors/controllers;
- ❖ Fluidical energy storage systems, such as F-F accumulators;
- ❖ Hybrid power units such as ICEs or ECEs;
- ❖ Fuel systems for hybrid power units;
- ❖ Transmissions;
- ❖ Emission control systems;
- ❖ Energy management and systems control;
- ❖ Thermal management of components;
- ❖ Light mass and aerodynamic body/chassis;
- ❖ Low rolling resistance (including body design and wheel-tyres);
- ❖ Reduction of accessory loads.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
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To all intents and purposes, the expression HFV deals with a large variety of automotive vehicles that include a minimum of two energy sources to power their drive trains. Unlike the pure F-F accumulator-powered AFVs that had a real range of less than 80 km (50 mi) prior to requiring recharging, hybrids have a great deal more flexibility close to that of conventional automotive vehicles.

Hybrids also do not depend exclusively on their ECEs or ICEs for all the mechanical energy they need to run; so they have enhanced fuel economy and lower greenhouse exhaust gas emissions when compared with equivalent conventional automotive vehicles [FIJALKOWSKI 1985B, 1986, 1996A, 2000C; CHAN AND CHAU 2001; CHAN 2002; WOUK 1997, 2000; VALENTINE TECHNOLOGIES INC., USA; HAWKINS 2008].

What is a hybrid-fluidic (HF) system?

Synthesis between a **primary energy source** (PES), for example, an ECE or ICE, and/or even FC and a **secondary energy source** (SES), for example, an F-F accumulator or **motorised and/or pumped flywheel** (M&PF) that supplies or absorbs an F-M/M-F motor/pump – attaining different functions because of changed energy arrangements.

The typical configurations of different ICE HE DBW AWD propulsion mechatronic control systems are shown in Figures 2.101 and 2.102 [FIJALKOWSKI 1985B; VALENTINE TECHNOLOGIES INC., USA; HAWKINS 2008].

In a parallel design, the ESD and F-M propulsion system are connected directly to the vehicle wheels. The primary ICE or ECE is used for highway driving; the F-M motor provides added power during hill climbs, acceleration, and other periods of high demand.

In a series design, the primary ICE or ECE FC is connected to a **mechano-fluidical** (M-F) pump that produces fluidicity which charges the low- and/or high-pressure F-F accumulators driving a F-M motor that powers the wheels. HFVs can also be built to use the series configuration at low speeds and the parallel configuration for highway driving and acceleration. Unlike AFVs, the F-F accumulators in HFVs do not need to be plugged into a charger. Instead, they are recharged using regenerative braking or by an on-board M-F pump. The HF transmission arrangement for HF DBW AWD propulsion mechatronic control systems leads to drastically improved HFV concepts [VALENTINE TECHNOLOGIES INC., USA].

The main advantages are greatly improved SFC, emission, functionality and simplicity. It is based on a fluidostatic CVT, a **fluidic energy store** (FES), i.e., an F-F accumulator or a **mechanical energy store** (MES) namely, an M-M flywheel, and an E-TMC ECU or a **central powertrain controller** (CPC) that controls all HF transmission components. This technique permits low polluting and efficient production and use of energy.

The expected average improvements are:

- Fuel saving – 60%;
- Pollution reductions – 75%.

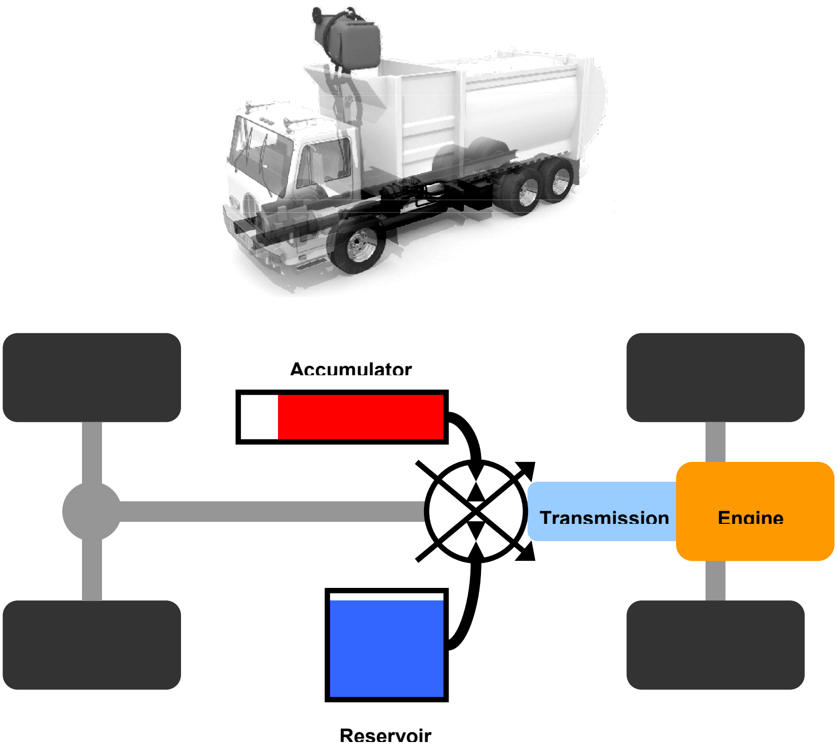


Fig. 2.101 Parallel hybrid fluidic vehicle: Fluidic launch assist (FLA) augments the conventional drivetrain [HASKELL; HAWKINS 2008]

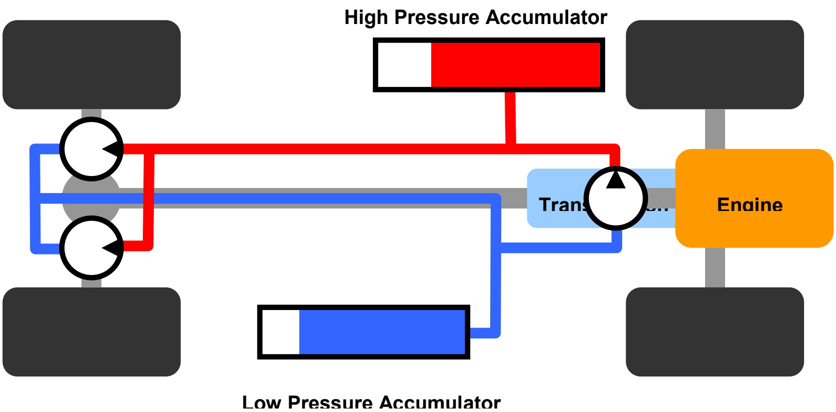


Fig. 2.102 Series hybrid fluidic vehicle: decouples engine from wheels: runs ECE or ICE at optimal angular speed. Shuts off when not needed; opens door to alternative ICE: Free piston, HCCI [HAWKINS 2008]

Further alterations that may be directly noticed by the driver are a more comfortable drive due to fast and shiftless acceleration from zero to maximum velocity. A fully active HF DBW AWD propulsion mechatronic control enhances the com-fort and safety noticeably.

The simplicity of the HF transmission arrangement, as shown in the following pages, is visible when comparing number and size of the HF transmission components and their arrangement in a conventional '*M-M transmission*' and a new concept '*HF transmission*' HFV [VALENTIN TECHNOLOGIES INC., USA].

M-M Transmission Arrangement

- MT (gearbox);
- M-M clutch;
- drive shafts;
- M-M differential;
- Starter.

HF Transmission Arrangement

- wheel-hub F-M motors;
- fluidic energy store (FES) that is F-F accumulator, or mechanical energy store (MES) that is M-M flywheel;
- ECE or ICE driven M-F pump;
- F valves, tubes, hoses.

An ECE or ICE, a cooling system, a tank, a CH-E/E-CH storage battery and an on-board M-E generator are less than half of its present size. These results in mass reductions of approximately 15% for a medium-size passenger vehicle with a curb mass of 1,500 kg (3,400 lbs).

The components of the HF transmission can be arranged alongside each other with a great degree of freedom, allowing the best use of space and distribution of mass. The best distribution of axle loads, for example 50 : 50%, and a reduced height of the barycentre (centre of gravity) can be easily achieved. This and the reduced unsprung mass of the wheels amount to increased safety and driving comfort.

The functionality of the automotive vehicle may be increased without additional cost and dimension due to the ease of controllability of the HF transmission and other components. The fluidostatic M-F pump driven by a significantly smaller and simplified ECE or ICE, charges the FES (F-F accumulator) with a pressurised oily-fluid. The ECE or ICE may be cut-off by the E-TMC ECU or CPC when the latter is filled.

The FES (F-F accumulator) provides the wheel-hub F-M motors on each wheel with energy in the form of a pressurised oily-fluid to accelerate and drive the HFV. During braking and cornering (pivot skid steering), the in-wheel-hub F-M motors become M-F pumps and transmit the braking and cornering energy back to the FES. The size of the wheel-hub F-M motors are such that they can provide sufficient braking torque to lock the wheels under all circumstances and very high torque to accelerate the HFV at all values of vehicle velocity.

The easy control of torque and velocity of each wheel and its suspension leads to an efficient, fully active DBW AWD propulsion mechatronic control.

The infinite adjustability of the wheel-hub F-M motors is mechatronically controlled by the E-TMC ECU or CPC, giving the HF transmission a variety of additional functions, such as

- ❖ Anti-locking brake system (ABS);
- ❖ Anti-slip brake system;
- ❖ DBW AWD propulsion mechatronic control system;
- ❖ Locked M-M or F-M differentials.

The fluidostatic principle allows additional features that further improve the functionality and use of energy: constant or variable velocity drive for auxiliary power units as needed, for example, M-E generator, M-F pumps, and comfort fluidics, namely, active suspension, park-automatic, and so on, as shown in Figure 2.103 [VALENTIN TECHNOLOGIES INC., USA].

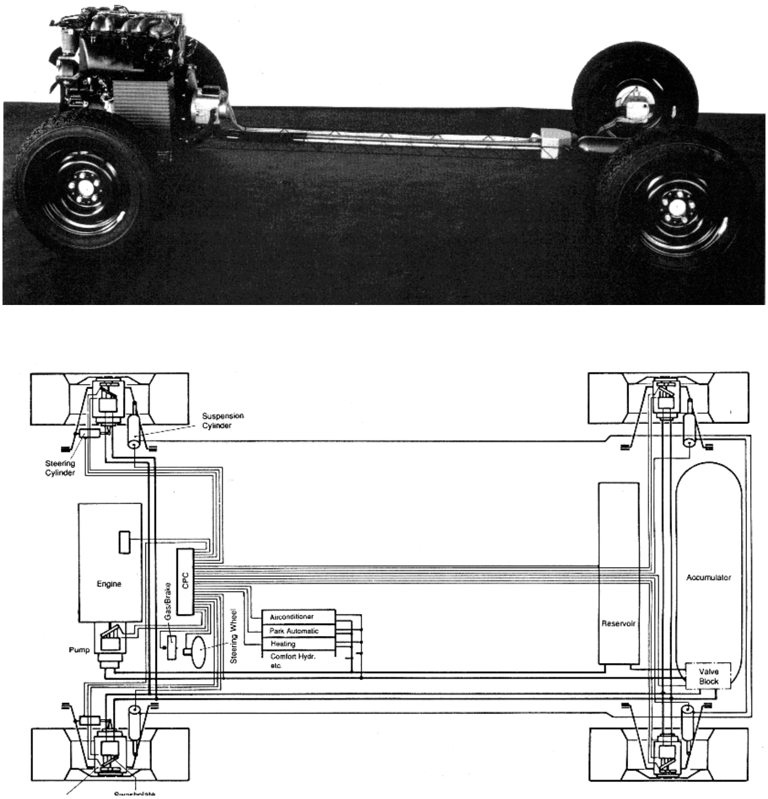


Fig. 2.103 Principle layout of the HF transmission arrangement for The HF DBW AWD propulsion mechatronic control system [Valentin Technologies Inc. (USA)].

The mass distribution for the passenger vehicle is assumed to be 50 : 50% under static and 75 : 25% under maximum dynamic (braking) conditions. The size of the in-wheel-hub F-M motors is based on the maximum torque requirements under dynamic conditions such as braking under full load. The maximum value of fluidic pressure of the fluidostatic circuit is 41 MPa (6,000 psi).

The size of the M-F pump on the ECE or ICE is based on the use of nearly full ECE or ICE power at constant velocity of 403 rad/s (3,850 rpm) and a fluidostatic circuit pressure of 17 MPa (2,500 psi). The displacement (swash-plate angle) of the M-F pump may be reduced above this pressure to remain in '*constant torque or power mode*'. Other torque and velocity ranges can be selected to operate the ECE or ICE at the point of best efficiency and lowest level of pollution.

A revised specification for the ECE or ICE, running at constant torque and velocity simplify its design and improves its efficiency. It is assumed that the pollutant emission can be improved significantly due to reduced SFC per kilowatt, the constant operating mode, a reduced maximum value of ECE or ICE temperature (CO, NO_X) and, an always constant air to fuel ratio (CO, NO_x, HC).

No compromises have to be made to obtain a useful torque characteristic and smooth running over a wider angular velocity range. The in-wheel-hub F-M motors determine the driving/torque characteristics. One motor at constant values of angular velocity and low values of acceleration, and two motors at significant levels of acceleration, may propel the HFV.

The E-TMC ECU or CPC corrects the steering position needed to balance the off-centre thrust during one-wheel-drive if needed. At least two wheels are actuated during braking. An AWD function, with or without locked M-M differentials, can be selected through the driver. The E-TMC ECU or CPC selects these modes automatically if wheels are spinning during acceleration or are locked during braking.

<u>*Start and Acceleration*</u>

The driver turns the key to activate the E-TMC ECU or CPC. The latter senses the position of the accelerator foot pedal and opens the fluidic valve at the FES (A-F accumulator) and provides the wheel-hub F-M motors with pressurized fluid.

The swash-plate at the **steered, motorised and/or pumped wheels** (SM&PW), as shown in Figure 2.104, may be adjusted from zero to a large angle to produce sufficient torque to accelerate the HFV [VALENTIN TECHNOLOGIES INC., USA].

An increased fluidic pressure at the accelerator foot pedal creates a greater swash-plate angle and a faster acceleration.

For low and medium values of acceleration, only one in-wheel-hub F-M motor may be activated. At high values of acceleration or traction forces, two or more motors may drive the HFV. The E-TMC ECU or CPC may correct the steering to compensate for off-centre thrust of the wheels. It also senses the revolution of all wheels and calculates its correct angular velocity, depending on the steering **hand-wheel** (HW) position. If the values of angular velocity are too high, the wheel is slipping. The E-TMC ECU or CPC may reduce the torque (swash-plate angle) to prevent this situation.

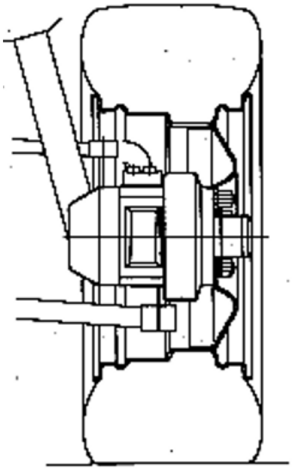


Fig. 2.104 Principle layout of the steered, motorised, and/or pumped wheel [Valentin Technologies Inc. (USA)]

Rolling
The HFV drives at a constant velocity if there is no difference between the position of the accelerator foot pedal and the vehicle velocity.

The number of wheels driven may depend on the tractive force needed and may be selected by the E-TMC ECU or CPC, or the driver through a push button.

A smooth transition to a coasting mode can be reached by moving the swash-plate to zero or to the near zero position.

Braking
The driver presses the brake foot pedal, the E-TMC ECU or CPC directs the swash-plates into reverse. The in-wheel-hub F-M motors become M-F pumps and the braking energy flow back to the FES (F-F accumulator) in the form of pressurised fluid. The torque of the wheel-hub F-M motor is given through the swash-plate angle and the fluidic pressure of the FES. The E-TMC ECU or CPC calculates the desired angle, based on this fluidical pressure and the force at the brake foot pedal and adjusts the swash-plate accordingly. If the values of angular velocity are too low, the wheel is locked. The E-TMC ECU or CPC may reduce the torque (swash-plate angle) to pre-vent this situation.

Fluidical Energy Store Management
Before the final portion of FES (fluidical accumulator) has been consumed, the E-TMC ECU or CPC may direct pressurised fluid to the M-F pump at the ECE or ICE. The M-F pump, working as an F-M motor, starts the ECE or ICE and may become an M-F pump again, filling the FES with a pressurised oily-fluid when the ECE or ICE is running. The latter may be cut-off if the FES is filled. If significant *G*-forces act on the HFV (e.g., during an accident), the fluidical pressure maintaining the non-flammable gas of the FES may be immediately deflated. This E-T &FES management allows the ECE or ICE to run at only constant revolution and torque while filling the FES.

Different fluidic pressure rates of the FES on the fluidical circuit are compensated through a varying swash-plate angle – meaning constant torque – at the M-F pump. This operating cycle allows a noticeably smaller, simplified ECE or ICE with increased efficiency.

The E-TMC ECU

The main functions of the *E-TMC* ECU or CPC have been described above. Hard- and software are the same for various types of HFVs. The characteristic of the powertrain (ECE or ICE and H-F transmission) may be determined through different programs. In addition to these functions, the E-TM+C ECU can manipulate the torque on each wheel to improve the driving stability of the HFV. The inclusion of the mechatronic control for the active suspension results in a fully active DBW AWD propulsion mechatronic control.

A typical HF transmission arrangement for the HF DBW 2WD propulsion mechatronic control system of a heavy-duty truck, the so termed hydrostatic drive, with brake energy recovery, is shown in Figure 2.105 [FPDA 2004].

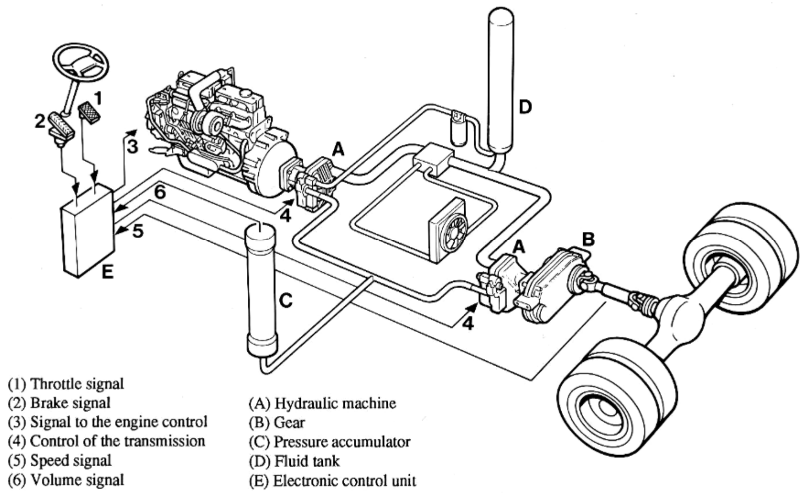


Fig. 2.105 HF transmission arrangement for the F-M DBW 2WD propulsion mechatronic control system of a heavy-duty truck [FPDA 2004].

An interesting concept of the HF transmission arrangement for the HF DBW 2WD propulsion mechatronic control system of a heavy-duty tractor for transportation of containers on or off *'Ro-Ro'* type vessels is shown in Figure 2.106.

Owing to the **inertial mechanical energy store** (IMES), that is, the **engined and/or pumped flywheel** (E&PF) application in a heavy-duty tractor (see Fig. 2.106), can not only produce great fossil fuel savings but also low pollutant emissions. It is especially valid in loading compartments of *'Ro-Ro'* type vessels.

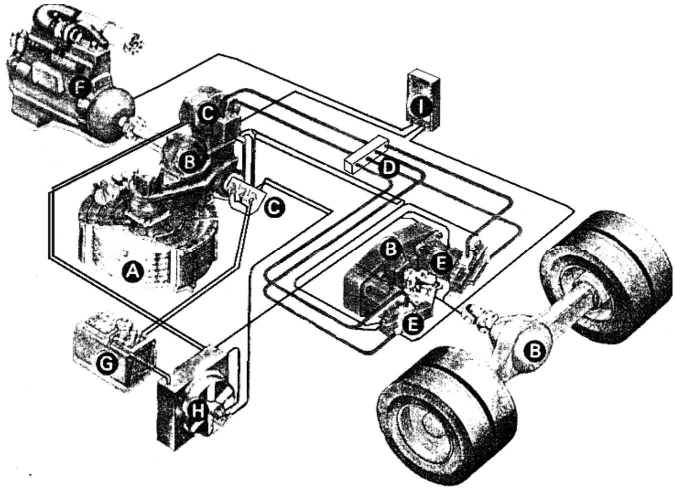


Fig.. 2.106 HF transmission arrangement for the FM DBW 2WD propulsion mechatronic control system of a heavy-duty tractor LMV for transportation of containers on or off '*Ro-Ro*' type vessels [KALMAR - Sweden].

Propelled by a diesel engine (F), the E&PF (A) reaches an angular velocity up to 1,047 rad/s (10,000 rpm), and then gradually converts its mechanical energy to fluidic energy in the fluidical propulsion installation that, by means of a F-M motor and M-M differential (B), propels the drive wheels of the heavy-duty tractor. Because of the high mass of the E&PF, this HFV can run with a load of 25 Mg and turned-off ICE over 70 m inside the loading compartment of a *'Ro-Ro'* type vessel.

2.6.2 Conclusion

The concept of the HF transmission arrangement is made possible by a fluido-static F-M motor with drastically improved technical data for significantly reduced costs.

M-F/F-M pumps/motors – axial types are currently used on heavy-duty machines, such as caterpillars, automotive applications, and other equipment where CVT or high-power density is needed.

The innovative M-F/F-M pump/motor has shown significant improvements in all areas and should almost entirely eliminate the disadvantages. The advanced technical data broadens the range of applications and simplifies current HF transmission arrangements. The main factors are improved efficiency and power to mass ratio but, most noticeably, a drastically increased transformation ratio.

Current trends in fluidics (hydraulics) [FPDA 2004]:

- Tier III & IV emission reductions may result in increased ICE or ECE cost/complexity;
- Idle management is a growing issue with on-highway equipment;
- Fuel price increases are accelerating technology shifts;
- Engine computers are serving as CAN-bus gateways for other vehicle systems;
- Fluidical (hydraulical) equipment companies are redefining themselves as motion mechatronic control system providers (application focused);
- Fluidics (hydraulics) has a new list of competitors, electrical-mechanical;
- Fluidics (hydraulics) is finding new opportunities with intelligent systems, telematics, energy recovery, and HF transmission arrangements.

Brake energy recovery gains [FPDA 2004]:

- Fuel savings, 20 -- 50% because of brake energy recovery and optimised running of the transmission and engine;
- Emission savings 20 -- 50% because of the same reasons;
- Secondary control facilitates skid control, slip control, and cruise control;
- Enables acceleration from still-stand with the ICE or ECE shut down or idle;
- Reduced ICE or ECE cooling requirements;
- Potential for smaller power ICE or ECE required;
- Eliminates losses from a torque converter;
- Resulting in new fluidics (hydraulics) components:
  - Variable displacement M-F pump and F-M motor technologies with optimised improved mechatronic controls, higher efficiencies, and increased power density;
  - Intelligent, light-mass F-F accumulators;
  - CAN-bus-based mobile microelectronic controllers that communicate with the ICE or ECE.

2.7 E-M DBW AWD Propulsion Mechatronic Control Systems for Battery Electric Vehicles

2.7.1 Foreword

Several attempts have been made to manufacture marketable **all-electric vehicles** (AEV), often termed **battery-electric vehicles** (BEV) and/or **fuel cell-electric vehicles** (FCEV), but the problem is inevitable comparison with equivalent petrol propelled automotive vehicles having a travel vehicle velocity of well over 100 km/h, a full-tank range of a few hundred kilometres, and refuelling in a few minutes. With an increasing shortage of fossil fuel, AEVs may become attractive for personal transport, especially in and around towns, or, in the absence of rural public transport, for routine trips to the nearest rail station. AEVs are quiet, non-polluting, easy to start and control, and cheap to run (largely because routine maintenance is negligible). Such AEVs give adequate personal mobility without the use of fossil fuel, and may be the first to appear in quantity in the not-too-distant-future.

AEV technology is under rapid development and several types are in operation. Each AEV uses different technologies and E-M trans-mission arrangements. Most are converted from standard ECE or ICE-driven vehicles.

BEV development preceded the development of automotive vehicles with ECEs or ICEs. *Thomas Davenport* built the first CH-E/E-CH storage battery-powered vehicle in the United States of America in 1835 [BRAESS AND REGART 1991, KRADY ET AL. 1995]. Easy mechatronic control and starting of E-M motors and a lack of petrol stations promoted the use of AEVs. However, fast development of ECEs and ICEs and the discovery of the starter motor halted development of BEV technology. The use of BEVs was restricted to a small number of local delivery trucks and passenger cars.

Increasing air pollution in the late 1960s prompted the development of experimental BEVs. But the automotive industry significantly reduced vehicular emissions that again halted BEV development. In the early 1970s, a fossil-fuel shortage following Arab oil embargoes renewed interest in AEVs, but generated only a few inadequate BEVs. The major problem with these was their relatively small operating radius (conventional fossil fuels have about a 20 times greater energy density than CH-E/E-CH storage batteries).

Increased automotive industry interest occurred recently when the **California Air Resource Board** (CARB) mandated that 2% of all new automotive vehicles lighter than 1700 kg in California must produce zero tailpipe exhaust emissions by 1988 [RIEZENMAN, 1992, KRADY ET AL. 1995].

The proportion of **zero-emission vehicles** (ZEV) increased to 5% by 2001 and 10% by 2003.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_22,

Currently, AEVs are the only commercially visible ZEVs [MOORE, 1993, KRADY ET AL. 1995]. All major automotive manufacturers started programmes in the late 1980s to produce viable BEVs by 1998. At the turn of the 20th century, electrically driven vehicles were relatively common. However, the low storage capacity of the PbAcid storage battery resulted in a limited operating range and in excessive mass. This almost eliminated the use of electrically powered vehicles. Today, they are used only in special situations such as conveyances in exhibition grounds, golf courses, and enclosed buildings.

The acceptance of BEVs is judged based on their performance, reliability, lifespan, and cost. Various CH-E/E-CH storage batteries and their developments are a motivating force behind the performance and cost of AEVs; the demand is to have high power and long life. Although, the unknown long-term reliability of proposed CH-E/E-CH storage battery configurations, such as **lithium-sulphur** (LiS), **lithium polymer** (LiPolymer), **lithium ion** (LiIon), **nickel-metal-hydride** (NiMH), **nickel-cadmium** (NiCd), **sodium-sulphur** (NaS), and **lead acid** (Pb-Acid) is a significant unknown. Thus, advances in **storage battery** (SB) technology are absolutely necessary. The some **hybrid-electric vehicles** (HEV) use NiMH storage batteries, but they cannot function for limitless periods of time using storage-battery power.

Some automotive manufacturers plan to submit PbAcid storage batteries (a larger, more specialised design than conventional ones) on the majority of their future BEVs. These CH-E/E-CH storage batteries are large, heavy packages (battery packs) that take up an enormous amount of space in the vehicle. Normally, the supplementary, CH-E/E-CH storage battery's mass causes slower BEV than their conventional ECE or ICE counterparts. Although currently far more expensive than PbAcid storage batteries, LiS, LiPolymer, LiIon, NiMH or NiCd storage batteries are advantageous because they are environmentally friendly, recyclable, reliable, and easy to maintain.

Besides, when contrasted with PbAcid storage batteries, LiS, LiPolymer, LiIon, NiMH or NiCd storage batteries supply a relatively high specific energy (Wh/kg), meaning that a minor storage-battery mass can deliver the same energy as a heavier mass. For instance, in reality, a NiMH storage battery can be about half the mass of a PbAcid storage battery (and the overall mass of the AEV) and store the same amount of energy. In addition, the specific power (W/kg) – a measure of a CH-E/E-CH storage battery's acceleration performance – of NiMH storage batteries has enhanced greatly over the recent years (for example, 600 W/kg to over 1200 W/kg). Down the road, it appears the cost of NiMH storage batteries may decline.

For the future, some manufacturers believe that LiS, LiPolymer or LiIon storage batteries may be the best solution. For example, LiIon storage batteries have nearly twice the specific energy of NiMH storage batteries but necessitate significant circuitry to prevent over-charging and under-charging. They also necessitate thermal management and are considered to have safety problems.

Although CH-E/E-CH storage batteries are currently the dominant **secondary energy source** (SES) of electrical energy in AEVs, other **all-electric** (AE) configurations are feasible. AEVs could use ultracapacitors or ultrainductors or even ultraflywheels to supplement a CH-E/E-CH storage battery [FIJALKOWSKI 1997A, 2000B]. Ultracapacitors or ultrainductors are devices that store large amounts of electrical energy; an ultraflywheel, on the other hand, is a device that stores kinetic mechanical energy.

Principally, CH-E/E-CH storage batteries submit higher specific energy but have less specific power than ultracapacitors or ultrainductors or even ultraflywheels. Thus, E-M DBW AWD propulsion may be the basis of practically all automotive vehicle powertrains in the long term. These drives, regardless of the origin of the power source, may require storage devices such as ultracapacitors, ultrainductors, CH-E/E-CH storage batteries, or a combination of both. Ultracapacitors or ultrainductors are of particular interest to AEV and HEV designers. They are capable of providing a rapid surge of power and allow the super-fast collection, storage, and discharge of the electrical energy necessary for automotive applications. They are light in mass and suited to capturing or providing the high currents associated with regenerative braking and full throttle-valve acceleration. By using ultracapacitors or ultrainductors, automotive scientists and engineers can minimise electric loads that can drastically reduce the life of a CH-E/E-CH storage battery and allow better management of the *'rapid change of state'* events associated with day-to-day driving. The beauty of ultracapacitor or ultrainductor power management and storage systems is that they have the flexibility to be used in different applications under different programmes, no matter what the hybrid or FC powertrain needs. The most critical system that is necessary to construct a BEV is the E-M transmission arrangement for the E-M DBW AWD propulsion mechatronic control system that provides the tractive effort to propel it [MADER AND GERTH 2004].

This mechatronic control system in a BEV, for example, consists of a CH-E/E-CH storage battery and its AC-DC charger, a multiphase DC-DC chopper (drive control), and a gear or gearless brushed DC-AC/AC-DC mechanocommutator electromagnetic motor/generator, as shown in Figure 2.107 [SEIFFERT AND WALZER 1991].

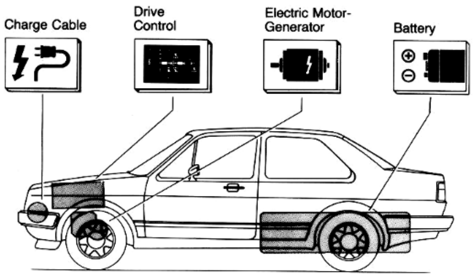


Fig. 2.107 Positioning of the electrical energy components in the BEV [VW -- *City Stromer*; SEIFFERT AND WALZER 1991].

The CH-E/E-CH storage battery is the source of electrical energy. The multiphase DC-DC chopper converts the storage battery's output DC voltage to a variable E-M motor's input DC voltage. The E-M motor provides the mechanical energy to move the BEV. By controlling the voltage to the E-M motor, the AEV can be driven at different vehicle velocities on any on- and/or off-road grade. The main drawback of BEVs is their range, the distance that can be driven before needing to recharge the CH-E/E-CH storage battery.

A large step forward has been accomplished with the superior LiS, LiPolymer, LiIon, NiMH, NiCd or NaS storage battery. The **storage battery** (SB) is housed in an oblong case and is positioned in the vehicle's central cavity between the boot and the front seats.

Most BEVs are fitted with axles of conventional M-M differential design, still the most convenient for torque transmission to a pair of driving wheels. It has been shown that there is scope for improvement in performance by modifying the lubricant viscosity; the axles are normally fitted with extra gear reduction nose-pieces or external chain-and-sprocket reductions, and a fully run-in M-M differential may absorb up to 1.5 kW at the maximum value of the vehicle velocity. Oils of lower viscosity have been used without excessive gear wear, although the noise is greater. F-M or P-M transmission arrangements have found only limited application. Some forms cannot compete as alternatives to E-M DBW AWD propulsion mechatronic control systems for driver-type vehicles, but may be suitable for some industrial applications where the infinitely variable characteristics makes elaborate DBW AWD propulsion unnecessary.

Steered, motorised and/or generatorised wheels (SM&GW) with brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or IPM magnetoelectrically-excited wheel hub motors/generators may also create E-M differentials [FIJALKOWSKI 1990, 1995A, FIJALKOWSKI AND KROSNICKI 1994].

E-M/E-M motors/generators built into the wheels are extensively used in AEVs, sometimes with low angular velocity designs of reduced length and increased diameter. The electrically powered wheels, i.e., SM&GWs can be used as well for pivot-skid steering, thus improving manoeuvrability.

In general, the small amount of energy recoverable does not warrant the cost and complexity of a E-M DBW AWD propulsion mechatronic control system necessary for regeneration, although it reduces brake maintenance (a major operating stipulation).

Certain AEVs might benefit from regeneration if enough braking and/or cornering duties were involved; this might be possible by use of the AEV, enabling the E-M/E-M motors/generators to generate while braking and/or cornering (pivot-skid steering). AEVs are affected to a greater extent than other automotive vehicles by the rolling resistance of wheel tyres. Radial ply tyres provide a suppler casing and, as a result, the loss due to flexing of the walls is less. A saving of 12% in electrical energy consumption (or increase of 15% in range) can be obtained. An advantage is that radial ply tyres are less sensitive to departures from optimum inflation pressure.

Nowadays, experiments show that a sufficiently large range for densely populated areas can be covered by purely electric propulsion. Such an AEV would primarily be suitable as a second passenger vehicle or as conveyance to and from work.

2.7.2 E-M Transmission Arrangements for the E-M DBW 2WD Propulsion Mechatronic Control System

An E-M transmission arrangement has been used in almost every transportation application that ECE or ICE-powered automotive vehicles have used, including light cars and vans to large city buses.

Most BEVs use the body and mechanical parts of commercially available ECE- or ICE-powered automotive vehicles (see Figs 2.108 and 2.109).

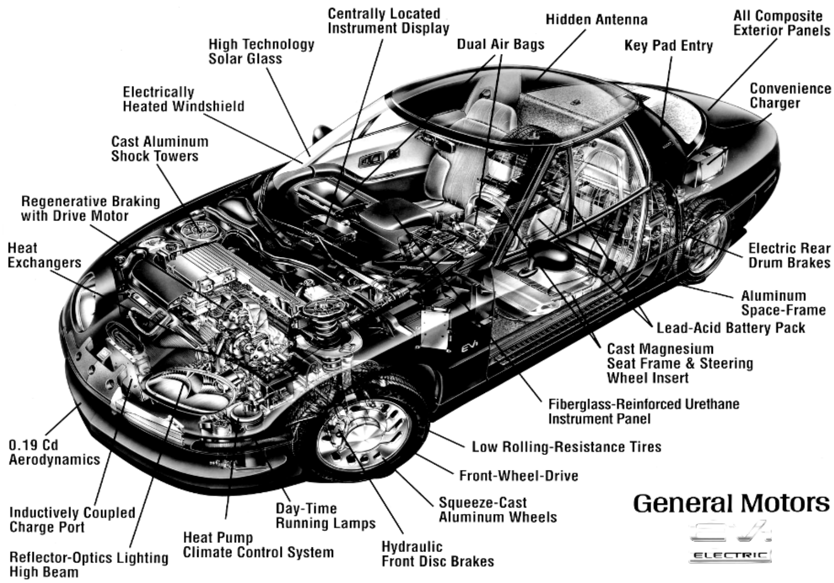


Fig. 2.108 Positioning of the electrical energy components in the BEV -- *EV1* [General Motors; CHESTNUT 2001].

The major BEV components are

- ❖ M-M transmission arrangement that consists of the M-M transmission, differential, power steering, etc.;
- ❖ E-M/M-E motor/generator, or alternatively SM&GWs with a brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or IPM magneto-electrically-excited wheel-hub motors/generators;

- ❖ BEV microcontroller that is a single-chip microprocessor-based controller; it monitors the status of each of the major components and initiates mechatronic control or protection actions as needed;
- ❖ CH-E/E-CH storage battery pack that provides electrical energy for the BEV propulsion;
- ❖ Charger that rectifies the AC network voltage for charging of the CH-E/E-CH storage battery;
- ❖ Climate mechatronic control system that includes efficient air conditioning and heating systems;
- ❖ Auxiliary supply system that supplies the headlights, instruments, door opener, auxiliary E-M motors (e.g., for the sunroof), power steering, and so forth.

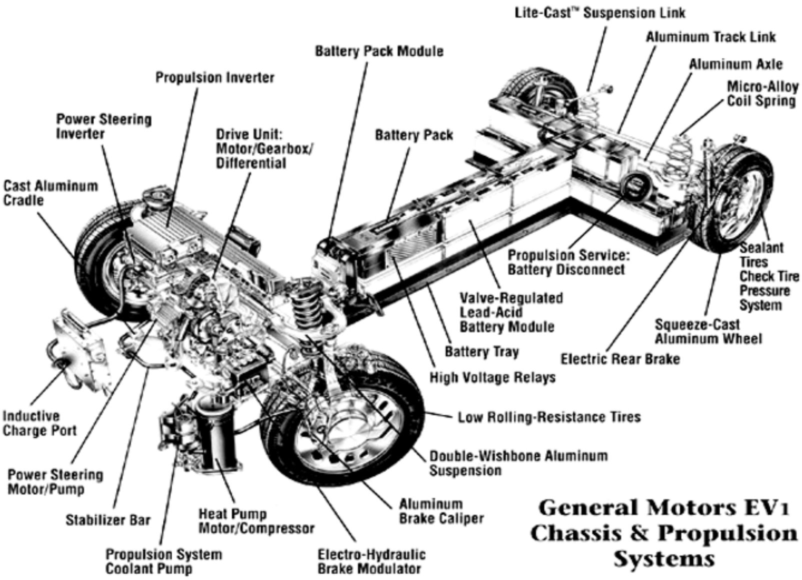


Fig. 2.109 Positioning of the BEV – *EV1* chassis and propulsion systems [General Motors; CHESTNUT 2001].

The location of the major components depends upon the BEV type and construction. Several other E-M transmission arrangements, used by BEVs are currently available. BEV technology is being developed at a fast pace and several new types are currently being tested.

In some BEVs, the major components identified in Figure 2.107 are combined. Some of the components, such as the protection system and auxiliary supply system, are similar to those used in standard ECE- and/or ICE-powered automotive vehicles. For instance, an alternative E-M transmission arrangement features two CH-E/E-CH storage battery modules for better mass distribution and two **interior permanent magnet** (IPM) E-M/M-E motors/generators that are mounted directly on the rear axle shafts, is shown in Figure 2.110 [STEPLER 1991].

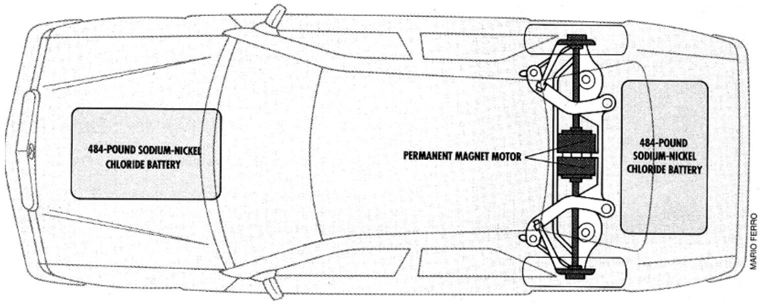


Fig. 2.110 Positioning of the electrical energy components in the BEV –Mercedes-Benz *190ES* [Daimler-Benz and AEG; STEPLER 1991].

Powering the BEV's E-M motors are maintenance-free sodium-nickel chloride storage battery packs. Accounting for some 360 kg (800 lb) of the BEV's total mass of 1,500 kg (total weight of 3,349 lb), the CH-E/E-CH storage battery can be recharged in 12 h.

An evacuated double-wall steel box provides thermal insulation for the storage battery's solid electrolytes and molten electrolyte of sodium aluminium chloride.

The CH-E/E-CH storage battery operates at a temperature of 584 K (311 ^{o}C; 518 ^{o}F) to 670 K (397 ^{o}C; 662 ^{o}F). The BEV's interior may be heated by using CH-E/E-CH storage battery temperature [STEPLER 1991]

2.7.3 E-M Transmission Arrangements for the E-M DBW 2WD and/or 4WD Propulsion Mechatronic Control System

To increase the total efficiency of an E-M transmission arrangements for a DBW 2WD and/or 4WD propulsion mechatronic control system, the **application specific integrated matrixer** (ASIM) **macro**electronic converter-based **commutators** (ASIM macrocommutators) and **application specific integrated circuit** (ASIC) **artificial intelligence** (AI) **neuro-fuzzy** (NF) **micro-**electronic computer-based **controllers** (ASIC AI NF microcontrollers) include the optimum control that is considered to be the variable factors of the mechanical energy-storing high-velocity **motorised and/or generatorised flywheels** (M&GF) with the twin-disc flywheel's E-M/M-E motors/generators, respectively; chemical energy-storing CH-E/E-CH storage battery; and **steered, motorised and/or generatorised wheels** (SM&GW) with the in-wheel-hub E-M/M-E motors/generators, respectively.

The DBW 2WD and/or 4WD propulsion mechatronic control system for an environmentally friendly BEV may be designed so that brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or magnetoelectrically-excited in-wheel-hub motors/generators may be installed on the inner side of each SM&GWs.

The structure features are

- ❖ Reduction in mass of the BEV and higher mechanical energy efficiency of the novel axleless E-M transmission arrangement achieved by eliminating the MT or SAT or FAT or CVT, M-M differentials, propeller shafts, driveshafts, and other driving gears that are required for moving conventional automotive vehicles;
- ❖ Effective use of space for in-wheel-hub motors/generators;
- ❖ Achievement of an ideal E-M DBW 2WD and/or DBW 4WD propulsion performance, for instance, controlling the two or four SM&GWs independently.

For contemporary environmentally friendly BEVs, a single in-wheel-hub E-M/ M-E motor/generator may be capable of motoring a maximum output power of 25 - 50 kW and a maximum torque of 425 kNm. The maximum value of theangular velocity at the top-gearless vehicle velocity of 180 km/h may be 26 rev/s.

In Figure 2.111 a BEV that is called a '*Poly-Car*' is shown. The powertrain consists of four SM&GWs with brushless AC-AC, AC-DC-AC, or DC-AC/ AC-DC macrocommutator reluctance and/or magnetoelectrically excited in-wheel- hub motors/generators [FIJALKOWSKI 2000D].

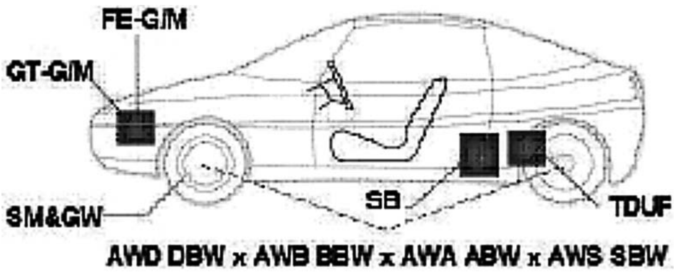


Fig. 2.111 High performance, all-round energy-efficient BEV termed the '*Poly-Car*' [FIJALKOWSKI 2000D].

The latter, as well as its armatures, IPM exciters, and ASIM macrocommutators, and the charge AC-DC rectifier form compact units.

The AC-AC, AC-DC-AC, or DC-AC/AC-DC macrocommutators' mechatronic controls also allow for electrical energy recovery in braking, cornering, and during downhill coasting. The CH-E/E-CH storage battery is protected by a staggered deep-draw protective scheme that prolongs its life. A charger is carried onboard, making it possible to charge the **storage battery** (SB) on any fused outlet. A BEV is not suitable, however, for very long distances, because, the reach of the vehicle is too short and the eight-hour recharging period is too long.

The full-time E-M DBW 2WD and/or 4WD propulsion mechatronic control system offers two main advantages:

- Increased traction obtainable from the four SM&GWs that is especially useful on soft or slippery ground;
- If the two front SM&GWs run into a ditch, they tend to be forced downwards, except when the AE DBW 2WD propelled HEV is driven in reverse, in which case, the disadvantage of the lower traction of AE DBW 2WD-propelled HEV remains.

In a full-time E-M DBW 4WD-propelled HEV starting, with the single SM&GW, efficiency in a part-load operation may be increased if low torques are not equally distributed onto each SM&GW. It may be better to start with single SM&GW first and to increase its torque to the rated value before the next may start. This mode of starting may be repeated for all SM&GWs. Of course, the yaw stability of the BEV has to be guaranteed. Thus, synchronous and/or differential modes of operation of the two SM&GWs of a single FWD or RWD are to be preferred. Then, the torque and/or angular velocity controls of the AE DBW 4WD propulsion mechatronic control system's SM&GWs represent a compromise between high part-load efficiency and driving stability.

Automotive scientists and engineers have taken the next step forward a *Poly-Car'* BEV high-performance DBW 4WD in-wheel-hub E-M motor test automotive vehicle. After removing the ECE or ICE, fuel tank, M-M transmission, M-M differential, drive shaft, and other DBW 4WD propulsion components from a production vehicle, newly developed outer-rotor in-wheel-hub E-M motors were installed on all four SM&GWs. Fitted under the floor between the front and rear SM&GWs in the place vacated by the conventional DBW 4WD propulsion components, a CH-E/E-CH storage battery may power the in-wheel-hub E-M motors.

The in-wheel-hub E-M motor may deliver a maximum the output value of 25 – 50 kW and its unique attribute is its outer-rotor structure. In the conventional type of in-wheel-hub E-M motor, as used in the past, the rotor turns inside the stator.

The outer-rotor in-wheel-hub E-M/M-E motor/generator, however, uses a hollow doughnut structure that sites the rotor outside the stator. The major benefits of this arrangement are as follows:

- The arrangement creates increased power output and easier torque and creates useless the speed reducer, which decreases energy losses and suppresses the augmentation of unsprung mass.
- Removal of the speed reducer makes the in-wheel-hub E-M motor easier to install into the wheel housing.
- The doughnut structure creates space in the centre of the in-wheel-hub E-M motor for the brake assembly and other components.

The outer-rotor structure also permits the in-wheel-hub E-M motor to be installed on the front SM&GWs, something not practicable until now due to the presence of SBW AWS conversion components.

From the viewpoint of DBW 4WD propulsion and 4WB BBW dispulsion components, AEVs and HEVs have evident advantages over conventional ECE- or ICE-powered automotive vehicles. These advantages may be as follows:

- ❖ Torque generation of an in-wheel-hub E-M motor is very fast and precise for both accelerating and decelerating. This should be an advantage. **Anti-lock braking system** (ABS) and **traction control system** (TCS) should be integrated into *'full TCS'* since an in-wheel-hub motor can both accelerate or decelerate the SM&GW. Its performance should be prepared in advance if the driver can fully use the fast torque response of the in-wheel-hub E-M motor [FIJALKOWSKI AND KROSNICKI 1990, FIJALKOWSKI 1990, HORI ET AL. 1998].
- ❖ An in-wheel-hub motor can be attached to each SM&GW. With miniature E-M motors like in-wheel-hub E-M motors [FIJALKOWSKI AND KROSNICKI 1990, FIJALKOWSKI 1990, JOHNSTON 2000], even the generation of anti-directional torque is feasible on left and right SM&GWs. In automotive engineering, such an approach is known as **direct yaw-moment control** (DYC) [SHIBATA ET AL. 1992, MOTOYAMA ET AL. 1992]. Distributed in-wheel-hub E-M motors may enhance its performance.
- ❖ An in-wheel-hub E-M motor's torque is easily comprehensible. Some uncertainty exists in driving or braking torque generated by an in-wheel-hub E-M motor, relative to that of ECE, ICE, or F-M brake. Therefore, an unsophisticated 'driving force observer' may carry out a real-time observation of driving/braking force between the wheel tyre and on/off road surface [SAKAI ET AL. 2000].
- ❖ This second advantage may add a great deal for some applications similar to the estimation of on/off road circumstances. Optimistically, these represent the novel approach for vehicle motion control.

High-Density Inertial Mechanical Energy-Storing High-Angular-Velocity Twin-Disc Ultra-Flywheel with In-Flywheel E-M/M-E Motor/ Generator - An auxiliary **inertial mechanical energy store** (IMES), i.e., the secondary-energy-source, high-density mechanical energy-storing high-angular-velocity **twin-disc ultra-flywheel** (TDUF) with a brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator twin composite-disc flywheel motor/generator, i.e., IMES with an integrated electrical machine that can operate as an in-flywheel M-E generator (discharging the IMES) or as an in-flywheel E-M motor (charging IMES) as required.

The TGUF, shown in Figures 2.111 and 2.112 exploits the unusual magnetic repulsion in superconductors: non-superconducting elements are then dispersed in superconducting material, to *'pin'* the magnetic fluxes of the levitation magnet and suspension magnet, respectively [FIJALKOWSKI AND KROSNICKI 1995B, FIJALKOWSKI 1998, 1999A, 2000D]. This means that magnet disc shaped rotors can be levitated above and suspended under the superconductor disc-shaped stator, and so, because there may be a slice of air between the two, the magnet disc shaped rotors can rotate freely in the opposite senses (arrows) of rotation's direction.

These properties could make it possible to construct high-density mechanical energy-storing super-high-angular-velocity TDUFs with near-frictionless magnetic bearings.

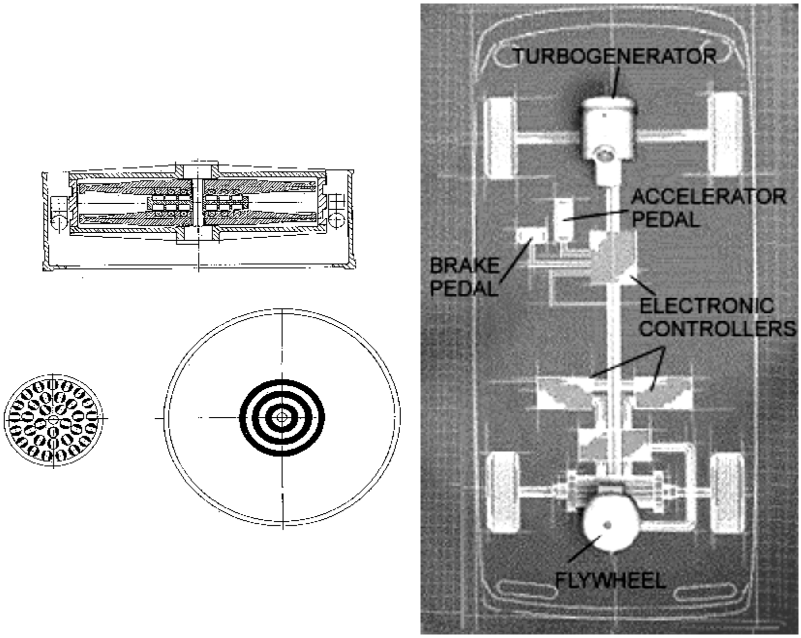


Fig. 2.112 Principle layout of a high-density mechanical energy-storing TDUF – Left image; layout of an M-M transmission arrangements for E-M DBW 2WD propulsion – Right image [FIJALKOWSKI AND KROSNICKI 1995B, FIJALKOWSKI 2000D; CHAN AND CHAU 2001 – Left image, DRIESEN 2006 – Right image].

The prototype may consist of two disc-shaped rotors, made of Sm-FE-Ti-B, Sm-Fe-Mo, or Nd-Fe-B magnet rings embedded in aluminium that may float 10 mm above and under a stationary superconducting disc-shaped stator. The latter may contain plenty of yttrium-based bulk superconductors, cooled by liquid nitrogen. Both discs may be about 30 cm in diameter.

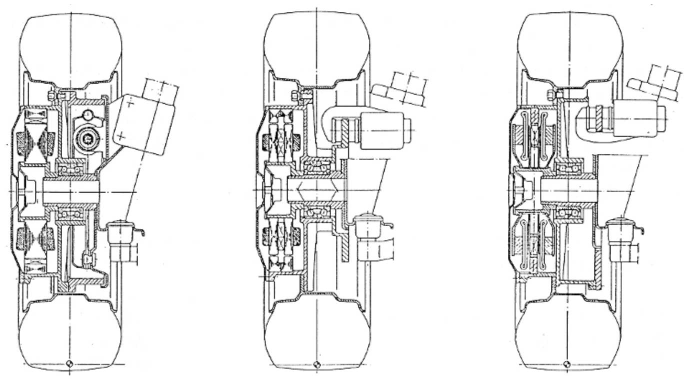
On a large scale, such a high-density mechanical energy-storing super-high-angular-velocity TDUF of 26.18 rad/s (250,000 rpm) can help the topmost compact AE BEV prime mover, and CH-E/E-CH storage battery balance their power requirements.

The TDUF could store kinetic mechanical energy during periods of the BEV's low velocity cruising and regenerative normal coasting (low mechanical energy usage) and regenerative normal braking and/or cornering during the pivot skid steering and then generate electrical energy to meet the peak power demands during periods of rapid-acceleration starting, hill climbing, as well as high-velocity travelling and cruising.

Steered, Motorized and/or Generatorised Wheels (SM&GW) - In-wheel-hub E-M/M-E motors/generators applied to planetary-geared and/or planetary-gearless mechatronically-controlled SM&GWs there may be low-angular-velocity (low frequency), brushless DC-AC/AC-DC macrocommutator IPM magnetoelectrically-excited in-wheel-hub motors/generators.

The rotating housing may be made in the form of wheel hubs, designed to fit standard rim sizes. The mechatronically-controlled in-wheel-hub E-M/M-E motor/generator APVT may allow complete freedom in the design of smart AEVs.

The in-wheel-hub E-M/M-E motor/generator may require minimum space and may be installed directly into the rim of the SM&GW because of its compact design. The result may be substantially increased ground clearance and the space between the direct-driven SM&GWs may be used to locate implements, for example.



(a) (b) (c)

Fig. 2.113 Principle layouts of the planetary-gearless mechatronically-controlled steered, motorised and/or generatorised wheels (SM&GW) with brushless AC-AC or AC-DC-AC or AC-DC/AC-DC macrocommutator reluctance and/or IPM magnetoelectrically-excited in-wheel-hub motors/generators [FIJALKOWSKI 1985A, 1990, 1997C, FIJALKOWSKI AND KROSNICKI 1994].

Figure 2.113 shows the principle layouts of the planetary-gearless SM&GWs with brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and magneto-electrically excited [unwound **mild-soft-iron** (MSI) outer rotor and wound and IPM inner stator] in-wheel-hub motors/generators.

The wheel-hub is designed so as to realise high stiffness with fewer materials by using *'modal (resonance frequency) analysis'* and, together with the use of specially sealed, double row angular contact ball bearings, lubricated-for-life, and having pre-adjusted internal clearance, an excellent torque/mass ratio [Nm/kg] is realised, which is no comparison with the other in-wheel-hub motors/generators, and even with the conventional brushed DC-AC/AC-DC mechanocommutator in-wheel-hub motors/generators, it is still better [FIJALKOWSKI 1990, 1985A, 1997C, FIJALKOWSKI AND KROSNICKI 1994].

The planetary-gearless mechatronically-controlled SM&GW with a brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or magnetoelectrically-excited in-wheel-hub motor/generator may completely eliminate backlashes or hysteresis that are inevitable.

The SM&GW hub may be designed using finite-element modal analysis methods and double-row angular contact ball bearings can be used to support the outer rotor, resulting in high radial stiffness and slim construction. The high torque and light mass previously mentioned result in a lower torque/mass ratio [Nm/kg] being obtained.

The novel *'single-shaft'* DBW 2WD and/or 4WD propulsion mechatronic control systems are also expected to be smaller in size, lighter in mass, more energy efficient, less expensive, durable and reliable, as well as being better suited to high-volume manufacture than any other well-known mechatronic control systems under development today. Thus, the wheel that is steered, motorised and/or generatorised is fitted with an in-wheel-hub motor/generator. [FIJALKOWSKI 1990, 1997C, FIJALKOWSKI AND KROSNICKI 1994].

As a result of the solid-state high-power ASIM AC-AC, AC-DC-AC or DC-AC/AC-DC macrocommutator design principle [FIJALKOWSKI 1997], the following features can be obtained:

- Full torque for AEV or HEV starting is directly exerted on the wheel without loss of efficiency caused by intermediate mechanical reduction gearing – planetary gearless;
- Low in-wheel-hub motor armature current while the AEV or HEV accelerates;
- Gradual torque application to eliminate mechanical shock;
- Superior smoothness in torque and/or angular velocity control through outstanding by high torque at low angular velocity performance;
- Superior AE and/or HE DBW 2WD and/or 4WD propulsion mechatronic control – in-wheel-hub E-M motor rotor angular velocity can be controlled within $\pm \pi/30$ rad/s over the full 0 – 160 km/h velocity range;
- Superior propulsive efficiency – efficiency can be up to 86% at full load;
- Very smooth rotation, even under slow angular velocity from very low to the maximum velocity values;
- Constant torque throughout the full rotation – flat torque/angular velocity characteristics make for high controllability;
- Regenerative braking and/or cornering – the in-wheel-hub E-M motors can also act as in-wheel-hub generators, the with electrical load being applied to provide braking and/or cornering during the pivot skid steering;
- Built-on parking and emergency brake;
- Reversible;
- Free-wheeling;
- Extremely low noise;
- In-wheel-hub mounting for simple alignment;
- Minimum space requirement;

- ❖ Lighter mass – there are no conventional toothed gearboxes and planetary reduction gearing, long propeller shafts or drive shafts, M-M differentials, or axles – complete freedom in the design of smart AEVs or HEVs;
- ❖ High torque/mass ratio;
- ❖ Low maintenance – clean and free from maintenance by its nature;
- ❖ Competitive price with high performance;
- ❖ Emergency power plant – the M&GF's M-E generator output can be used to provide of 50 or 500 Hz as well as 60 or 400 Hz power supply.

Many other planetary-gearless SM&GWs with AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or IPM magnetoelectrically-excited in-wheel-hub motors/generators have been conceived. Whether or not all of these **magneto-mechano-dynamical** (MMD) electrical machines qualify as E-M/M-E motors/generators tends to be a controversial question. Whatever their form is, the common operational mode is that a discrete quantum of angular rotation occurs in response to a pulse. For continual rotation to take place, a properly coded pulse train must be applied so that there is a sequential *'stepping'* motion of the outer rotor. In essence, the pulse coding is such that a rotating magnetic field is produced. One of the salient features of these MMD electrical machines is the ability to repeat positional data. No feedback loop is required for such a performance.

The principal layout of a particularly interesting planetary-gearless SM&GW with a MMD electric machine of this kind, is the one with the AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and IPM magneto-electrically excited (unwound MSI outer rotor as well as wound and IPM inner stator) in-wheel-hub motor/generator shown in Figure 2.111(b). It is evident that there are no windings on the MSI outer rotor, no slip rings, and no mechano-commutator with sliding-copper segments and carbon brushes.

The nature of the inner-stator polyphase (three- or five-phase) winding is also not evident. If the inner stator is a six-pole, three-phase structure with a large number of '*teeth*', then the outer rotor is also toothed and magnetised so that the south pole occupies one-half of the peripheries while the north pole occupies the other half. Although the inner stator has only six poles and the outer rotor has only three poles, the presence of '*teeth*' on both members affords a large number of opportunities for the positional '*lock-up*' of the outer rotor. Poles N1, S4, N7 and S10 form the first phase; poles N2, S5, N8 and S11 form the second phase; poles N3, S6, N9 and S12 form the third phase.

The in-wheel-hub motor/generator with different pole numbers on the unwound MSI outer rotor, as well as the wound and IPM inner stator, can provide traction if the stator polyphase winding phase-coils are sequentially energised. Here the unwound MSI outer rotor is made to *'chase'* sequentially switched wound and IPM inner-stator poles.

As soon as magnetic alignment occurs, the attracting pole is de-energised. A variation of this basic scheme employs *Hall*-effect elements to directly sense the position of either the outer rotor itself or a suitably magnetized disc on the shaft.

The in-wheel-hub motor/generator adopts the '*IPM bias*' method, the IPM made of SM-Fe-Ti-B, Sm-Fe-Mo or Nd-Fe-B rare-earth metal alloy, is located at the centre of the inner-stator core.

Both the IPM and the polyphase armature winding phase coils on the inner stator create the magnetic field and the output torque is proportional to the square of the sum of both magnetic fields. Thus, the torque is proportional to the square of the sum of the magnetic flux of the IPM inductor and the inner-stator's poly-phase armature winding.

Significantly, the in-wheel-hub motor/generator is designed both as reluctance and as an IPM magnetoelectrically excited in-wheel motor/generator. Moreover, it is described as an IPM inductor (unwound MSI outer rotor as well as wound and IPM inner stator) in-wheel-hub E-M/M-E motor/generator. The finite-element method may be used to optimise the shape of the outer rotor and inner stator '*teeth*', for optimum magnetic flux distribution – to minimise cogging at the maximum value of torque. The outer rotor design also helps to minimise torque. Torque ripple is a result of saturation of the magnetic circuits.

In in-wheel-hub E-M motors/generators, balanced three-phase sine wave excitation is used, resulting in a torque ripple as low as 5% without any ripple compensation. This ripple occurs at the maximum output value of torque; in the range where the torque/current characteristic is linear, the observed ripple is no greater than 2%.

A high-angular-velocity sample and hold circuit used to monitor in-wheel-hub E-M motor current and constant-current feedback may be used to minimise the fall in in-wheel motor torque with angular velocity.

The result is an in-wheel-hub motor that is capable of fast acceleration and deceleration, as well as stable operation at high values of angular velocity.

The planetary-gearless SM&GW uses a variable reluctance stepping in-wheel-hub E-M/M-E motor/generator with IPM inductor, operated as an AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and IPM magnetoelectrically excited in-wheel-hub motor/generator. The magnetic circuit elements are composed of high-energy-product rare-earth SmFeTiB, SmFeMo or NdFeB magnets for in-wheel E-M motor high efficiency.

Torque/angular-velocity characteristic of the DC-AC/AC-DC macrocommutator reluctance and IPM magnetoelectrically excited in-wheel-hub motor is very flat. It means fast acceleration, even at high velocity ranges and good controllability. Thus, an in-wheel-hub E-M motor makes it possible to adjust the propulsion torque and braking force independently at each wheel without the necessity for any M-M transmission, drive shaft, or other complicated mechanical components. Experience in tropical climate zones has underlined the fact that AEV and HEVs using SM&GWs with in-wheel-hub E-M motors necessitate the capability to operate at high ambient temperatures. Test reports claim that measuring vehicle frame temperatures of over 70°C have been measured. Such conditions may easily cause in-wheel-hub E-M motors to fail.

Thin-air gaps in-wheel-hub E-M motors, in which the iron core is eliminated and the windings (coils) are wound onto an aluminium structure, conducting heat directly to the mounting, have proved capable of reliable operation despite high temperatures.

Dynamic-Absorbing Steered, Motorised and/or Generatorised Wheels (SM&GW) - A dynamic-absorbing in-wheel-hub E-M motor DBW AWD propulsion mechatronic control system uses the in-wheel-hub motors to absorb vibration, which enhances handling, safety, and comfort in AEVs and HEVs. These dynamic-absorbing SM&GWs overcome disadvantages existing in-wheel-hub E-M motor DBW AWD propulsion mechatronic control systems that have down-graded the applicability of those systems.

Installing E-M/M-E motors/generators inside the wheel-hubs helps to control each wheel independently which provides for first-rate road-handling performance. It also eliminates the necessity for the M-M differential and driveshaft (or chains and sprockets) and therefore allows greater freedom in designing automotive vehicles. Designers may provide more space to the driver and passengers without increasing the overall mass and size of the vehicle.

An intractable disadvantage of in-wheel-hub motors/ generators has been the mass that they add to each wheel. That influences comfort and road-holding performance unfavourably, and it has restricted the applicability of in-wheel-hub E-M/M-E motors/generators in AEVs and HEVs. New technology overcomes this disadvantage by using in-wheel-hub E-M/M-E motors/generators to absorb vibration. The in-wheel-hub motors/generators themselves operate as vibration shock absorbers (dampers). Their own vibrations absorb that from the on/off road and wheel-tyres, which permits for enhanced traction and a more-comfortable ride than is practicable with other systems or with other modes of AE or HE DBW AWD propulsion.

In dynamic-absorbing SM&GWs (Fig. 2.114), dynamic shock absorbers suspend the shaftless in-wheel-hub E-M/M-E motors/generators to insulate them from the unsprung mass [BRIDGESTONE 2003].

Fig. 2.114 Dynamic-absorbing steered, motorised and/or generatorised wheel [Bridgestone Corporation; BRIDGESTONE 2003]

The in-wheel-hub E-M motor's vibration, as well as the vibration from the on/off road and wheel-tyres damp each other, which enhances a road-handling performance. The flexible coupling (Fig. 2.115) consists of four cross guides that transfer smoothly the drive power from each in-wheel-hub E-M/M-E motor/generator to its wheel.

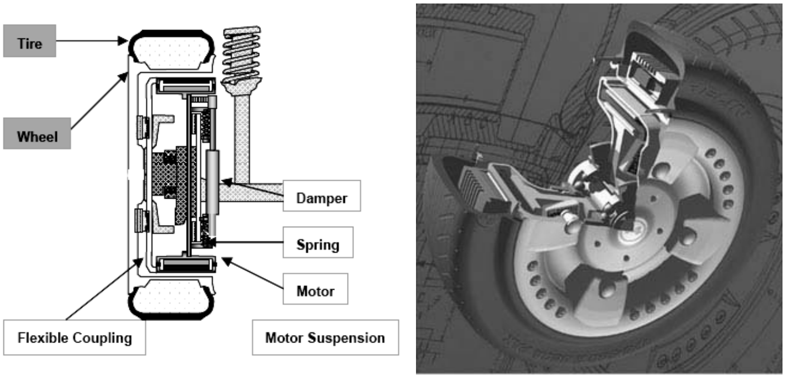


Fig. 2.115 Layout of the dynamic-absorbing steered, motorised and/or generatorised wheel [Bridgestone Corporation; BRIDGESTONE 2003]

The cross guides balance the continuous, satisfactory shifting in the rotational positioning of the in-wheel-hub E-M/M-E motor/generator and wheel.

Analytical comparisons of the performance of a conventional AEV or HEV with a single E-M/M-E motor/generator, an AEV or HEV equipped with conventional SM&GWs with in-wheel-hub motors and an AEV or HEV equipped with dynamic-absorbing SM&GWs emphasise differentials in road-handling performance (contact force fluctuation) and necessary quality (vertical acceleration frequency) on a rough on/off road surface.

The dynamic-absorbing in-wheel-hub motor DBW AWD propulsion mechatronic control system results in enhanced road-holding performance and a more comfortable ride than is practicable with conventional systems. It also offers advantages over conventional, single E-M motor AEVs and HEVs in safety and comfort [BRIDGESTONE 2003].

Electro-Mechanical (E-M) Differentials – While the basic principles of the E-M transmission arrangements for a E-M DBW 2WD and/or 4WD propulsion mechatronic control system remain the same for virtually all categories of AEVs, the actual arrangements vary – for instance, some may have DBW 2WD propulsion, that is either **front-wheel drive** (FWD) or **rear-wheel drive** (RWD), and others DBW 4WD propulsion. Another requirement stems from the fact that, when the AEV is cornering, the outer SM&GWs must roll faster than the inner ones that will be traversing circles of smaller radii, yet their mean value of wheel angular velocity, and mean value of vehicle velocity, may be required to remain constant.

So far as effectiveness of traction is concerned, FWD is better than RWD, especially on difficult terrain including ice or snow. This is partly because the mass of the CH-E/E-CH storage battery on the front SM&GWs enables them to grip the road surface better. This also applies to rear CH-E/E-CH storage battery RWD AEVs.

Principally, however, the advantage is gained by virtue of the fact that the propulsive force, i.e., tractive effort is always delivered along the line in which the front SM&GWs are steered. Another factor is that front SM&GWs tend to climb out of holes or ruts, whereas rear SM&GWs tend to thrust the front undriven wheels deeper down and, in any case, not necessarily in the sense (arrow) of direction in which they are being steered.

The application for full-time DBW 4WD propelled AEVs may grow rapidly over the next few years. This is due to increasing demand for AEVs with higher performances and power. It is well known that the distribution of gross tractive effort (thrust) and slip between the front and rear SM&GWs of DBW 4WD and/or 4WS SBW AEVs has considerable effect on the efficiency of operation. The function of a series electrical connection is to transfer the electrical energy from the EES to both the front and/or rear SM&GWs.

The **centre-wheel-drive** (CWD) E-M differential, in the series electrical connection, is also necessary to distribute the drive equally between the front and/or rear SM&GWs, and to allow for the fact that when the AEV is driven in a circle, the mean values of the wheel angular velocity of the front SM&GWs are different from those of the rear SM&GWs and therefore the values of the wheel angular velocity of the two FWD and RWD units must differ too.

Other factors include different degrees of wear and, perhaps, different values of the wheel-tyre pressure. Thus, a CWD E-M differential improves steering response and traction performance by controlling the angular-speed difference between the FWD and RWD units. Provision is usually made for locking this differential out of operation to improve the performance and reliability of traction when the AEV is driven over slippery ground.

For AEVs intended mainly for operation on soft ground, the CWD E-M differential may be omitted from the drive E-M powertrain line, but some means of disengaging DBW 4WD propulsion, leaving only a single pair of SM&GWs to do the driving, is generally provided for use if the AEV is required to operate on metalled roads.

As it is well known from the principle of *Ackermann*'s SBW 2WS conversion, the front SM&GWs always tend to roll further than the fixed-geometry rear SM&GWs, because their radius of turn is always larger, a parallel electrical connection (cabling) can be interposed between the EES as well as FWD and RWD units and the CWD E-M differential may be omitted from the E-M powertrain line drive (see Fig. 2.116).

In practise, this usually takes the form of two separate FWD and RWD units, single on each front and rear SM&GWs on which there are rotary controls that can be locked by the driver, but the driver has to stop and alight to do so. As soon as the driver again drives the AEV on firm ground, however, the driver must remember to unlock the FWD and RWD units.

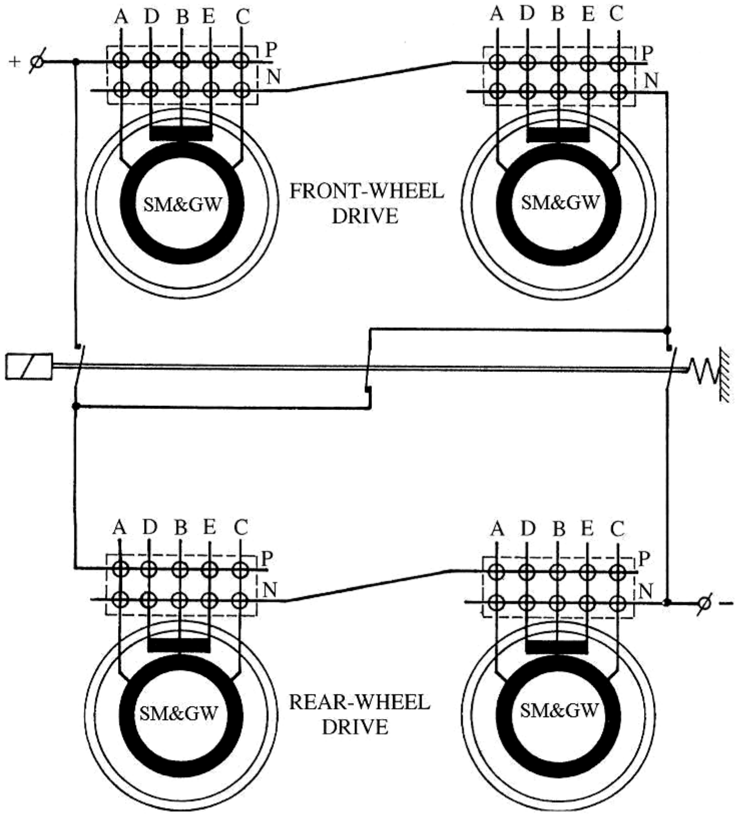


Fig. 2.116 Elementary wiring connection for axleless, full-time DBW 4WD E-M transmission arrangement with the torque proportioning front-wheel drive and rear-wheel drive as well as centre-wheel drive electro-mechanical differentials [FIJALKOWSKI 1997C].

Should the rear SM&GWs lose traction, on the other hand, and therefore tend to rotate further than the front ones, the drive may be automatically transferred to the front SM&GWs, even if they are in the freewheeling mode.

A conventional M-M DBW 4WD automotive vehicle has numerous disadvantages in comparison to a 2WD version: its fuel consumption is poorer, it is heavier, due to the presence of the drive shaft and other components, and it also requires a floor tunnel for the drive shaft to pass through.

Accordingly, it may be decided to use E-M DBW 4WD to optimise (minimise) these disadvantages and to ensure adequate performance in actual driving, for instance, as the AEV shown in Figure 2.117 [MITSUBISHI 2005]. Also, the reduction of fuel consumption in DBW 4WD may be minimised by using DBW 4WD propulsion only when necessary and by recuperating braking and/or cornering mechanical energy using both the FWD and RWD.

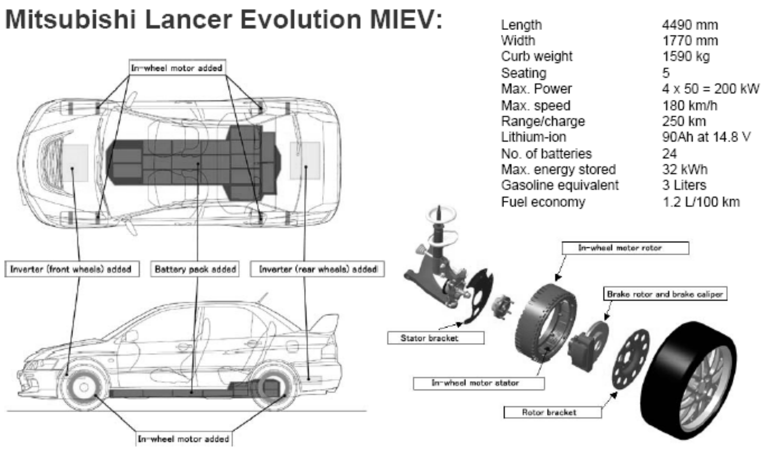


Fig. 2.117 Lancer Evolution *Mitsubishi* intelligent electric vehicle
[Mitsubishi Corporation Press Release of August 24, 2005].

<u>*CH-E/E-CH Storage Batteries*</u> - A CH-E/E-CH storage battery consists of two or more cells that may be linked in series (to provide multiples of cell voltage) and/or in parallel (to provide more capacity [Ah] from the resulting voltage). In Figure 2.118, the *Ragonne* plot (log-log plot) of different CH-E/E-CH devices is presented [DLA 2008].

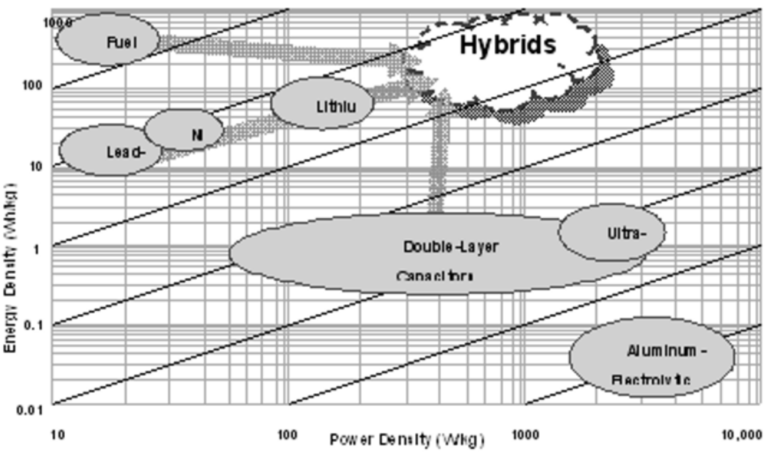


Fig. 2.118 *Ragonne* plot of different CH-E/E-CH devices
[U.S. Defence Logistics Agency; DLA 2008].

An overview of the properties of the different CH-E/E-CH storage batteries is presented in Table 2.3. The values in the table are typical ones and can vary with different manufacturers. For example, a **lithium-polymer** (LiPo) storage battery with a '6s2p' configuration has two parallel sets of six cells in series. It weighs 1.117 kg, and provides a capacity of 7.40 Ah. Since a LiPo cell has a nominal voltage of 3.7 V_{DC} that of this battery is 22.2 V_{DC}.

Table 2.3 Properties of the different CH-E/E-CH storage batteries: overview

Technology / Properties	PbAcid	NiCd	NaNiCl	NiZn	NiMH	LiIon	LiPo	LiS
Specific energy [Wh/kg]	35	40 to 80	90	55	50 to 120	70 to 580	100 to 220	250 to 2500
Energy per volume [Wh/dm^3]	90	85 to110	140	130	150 to 175	190 to1810	200 to 900	320 to 2800
Specific power *) [W/kg]	120	130	150	150	165	180 to 550	2400	1500
Cycle life**)	800	300 to 700	1500	300	400 to 800	305 to 1000	300 to 500	200 to 300
Operating emperature	Ambient	Ambient	300 °C	Ambient	Ambient	Ambient	Ambient	Ambient

***) Peak power density at 80 % DOD (depth of discharge) over 30 s;**

****) Cycle life (80 % of initial capacity)**

Nickel-metal hydride (NiMH) and **nickel-cadmium** (NiCd) cells have a nominal voltage of 1.2 V_{DC}, thus requiring three in series to give the voltage of one Li-Po cell.

Most CH-E/E-CH storage batteries used in advanced applications employ secondary (rechargeable) cells, although primary (disposable) cells offer some performance advantage.

For instance, the AEV may achieve 60 -- 90 min rides with rechargeable CH-E/E-CH storage batteries, but 80 -- 100 min with single-use units. An endurance of three hours is reported with a rechargeable battery, but four hours with a disposable unit.

Extreme endurance basically depends on employing two or more storage batteries in parallel, and cells of high specific energy. Endurance may be traded against payload.

Specific energy has recently increased dramatically, from 60 Wh/kg of the NiCd storage battery to 80 Wh/kg for NiMH, 160 Wh/kg for Li-Ion and 200 Wh/kg for today's Li-Polymer storage batteries.

The major emphasis for AEV applications has been on reducing CH-E/E-CH storage battery mass, thus making possible increases in payload and/or endurance.

However, today's storage batteries are still not completely user-friendly. Early NiCd storage batteries had to be fully discharged before recharging, otherwise they would not take a full charge.

The NiMH storage batteries that followed may cause corrosion and may explode if abused. Likewise, LiIon storage batteries may be dangerous if mistreated.

The nominal voltage for a LiIon cell is 3.6 V_{DC}, and, like the LiPolymer cell, it may be seriously damaged by discharging below 2.8 V_{DC}. If the cathode should reach 100^{o}C it may emit pure oxygen, producing a high risk of fire.

The LiPolymer storage battery first appeared in the mid-1990s. The anode is carbon in which lithium ions are dissolved, while the cathode is lithium cobalt oxide or lithium manganese oxide. The electrolyte is a polymer film in which lithium is dissolved.

The electrodes and electrolyte form three sheets that are laminated together, thus avoiding the need for a metal casing. The LiPolymer cell may be extremely thin and is normally manufactured as a long sheet, which is rolled or folded, then sealed in a soft plastic cover. If wired in parallel, these cells must be *'balanced'* to ensure uniform voltages so that none will drop below 2.8 V_{DC}.

The solid polymer electrolyte of a LiPolymer is not flammable; hence such batteries are somewhat less hazardous than their LiIon forbears.

However, they need to be 'broken in' with a series of short discharges, and they also need careful charging. If more than 4.235 V_{DC} is applied, they may explode and catch fire, and the flames cannot be extinguished with water.

Shorting the CH-E/E-CH storage battery may also cause an explosion. Over-discharging LiPolymer storage batteries, which would render them useless, is avoided by using a **low-voltage cut-off** (LVC) that prevents it falling below 3.0 V_{DC}.

The next stage of development is represented by solid-state lithium storage batteries, giving 300 -- 400 Wh/kg.

In late 2008, the author rode his *Melex* golf cart with a rechargeable **lithium-sulphur** (LiS) storage battery using cells rated at 350 Wh/kg.

Whereas, in earlier rides, using LiPolymer cells, the *Melex* had an endurance of 70 min, the innovative cells lasting more than two hours.

When used in conjunction with solar arrays, it is anticipated that in time LiS storage batteries may sustain such AEV for the night time part of multi-day missions. Despite these advances, it is noteworthy that the specific energy of gasoline (20 kWh/kg) is around 50 times that of the supreme CH-E/E-CH storage battery foreseen in the near-term.

2.7.4 Conclusion

Automotive mechatronics opens the way for a new concept of smart full-time E-M DBW 2WD and/or 4WD propulsion mechatronically-controlled, environmentally friendly BEV designs and permits a radical new concept of all-round energy efficient automotive vehicles.

The preliminary results are as follows:

- Compact, mechatronically-controlled SM&GWs with brushless AC-AC, AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or IPM magnetoelectrically-excited in-wheel-hub motors/generators converting electrical energy to mechanical energy, or reverse; thus providing *'single-shaft'* E-M DBW 2WD and/or 4WD propulsion mechatronic control system, and offering the ability to remain mobile after the loss of a single SM&GW or even three SM&GWs; improved draw-bar pull characteristics; improved obstacle crossing; improved efficiency; greatly enhanced specific power per unit mass [kW/kg] and specific power per unit volume [kW/dm^3], i.e., reduction in mass and volume of the propulsion mechatronic control system; reduction in SM&GW mass through the adoption of new materials; elimination of MTs or SATs or CVTs and M-M clutches; and greater flexibility in design of smart AEV layout.
- Compact high-power ASIM macrocommutators, capable of switching and controlling very large electrical currents;
- Compact low-power ASIC AI NF microcontrollers, capable of controlling and monitoring power and loads within the E-M DBW 2WS and/or 4WS propulsion mechatronic control system to provide effective power delivery as well as propulsion (torque/angular velocity) controls.

The 'Poly-Car' BEV may incorporate the latest design features for improved tractive performance as well as mobility and steerability in varying difficult cross-country terrain conditions too. This strong, aluminium-alloy ultralight-body all-round efficiency, environmentally friendly BEV may be especially useful for sand, mud, snow, or ice. Its low profile and heavy-duty construction may also make it ideal for use as a **manned and/or unmanned ground vehicle** (MGV/UGV) for people with special needs (disabled and older drivers).

2.8 ECE/ICE HE DBW AWD Propulsion Mechatronic Control Systems for Hybrid-Electric Vehicles

2.8.1 Foreword

The author has been involved with **hybrid-electric vehicle** (HEV) technology for nearly *25* years. Readers can't open a newspaper, listen to the radio, or turn on the television without hearing about increased fuel prices, wars in foreign lands, or the impact people are having on the environment.

In this chapter we discuss hybrid technology, what it's about, what's available today and what's coming our way and how it can benefit all users. HEVs typically combine the **internal combustion engine** (ICE) or **external combustion engine** (ECE) or even the **fuel cell** (FC) of a conventional **automotive vehicle** (AV) with a **chemo-electrical/electro-chemical** (CH-E/E-CH) storage battery and **electro-mechanical/mechano-electrical** (E-M/M-E) motor/generator of an **all-electric vehicle** (AEV). The combination offers low emissions with the power, range, and convenient fuelling of conventional vehicles, and they never need to be plugged in.

The inherent flexibility of HEVs makes them well suited for military and civil fleets and personal transportation. They are powered by two energy sources - an **energy conversion device** (ECD) such as an ICE or ECE or even FC and an **energy storage device** (ESD) such as CH-E/E-CH storage batteries or ultra-capacitors. The energy conversion unit may be powered by gasoline, diesel, methanol, compressed natural gas, hydrogen, or other alternative fuels. HEVs have the potential to be two to three times more fuel-efficient than conventional vehicles. Their emissions vary, depending on the vehicle and its configuration. But, in general, they have lower emissions than conventional vehicles because an E-M motor is used with an ICE or ECE, or even FC, which offsets how often the ICE, ECE, or FC is used and how it is utilized, therefore reducing liquid or gas fuel use and emissions. In addition, HEVs have the potential to operate in *'electric only'* mode. In this mode, the vehicle can operate with no emissions, which is optimal in congested areas and in areas where emissions are of greatest importance. An HEV is an optimised mix of various components, namely:

- E-M motors/controllers;
- Electrical energy storage systems, such as CH-E/E-CH storage batteries and ultracapacitors;
- Hybrid power units such as ICEs or ECEs or even FCs;
- Fuel systems for hybrid power units;
- Transmissions;
- Emission control systems;
- Energy management and systems control;
- Thermal management of components;

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
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- Light mass and aerodynamic body/chassis;
- Low rolling resistance (including body design and wheel tyres);
- Reduction of accessory loads.

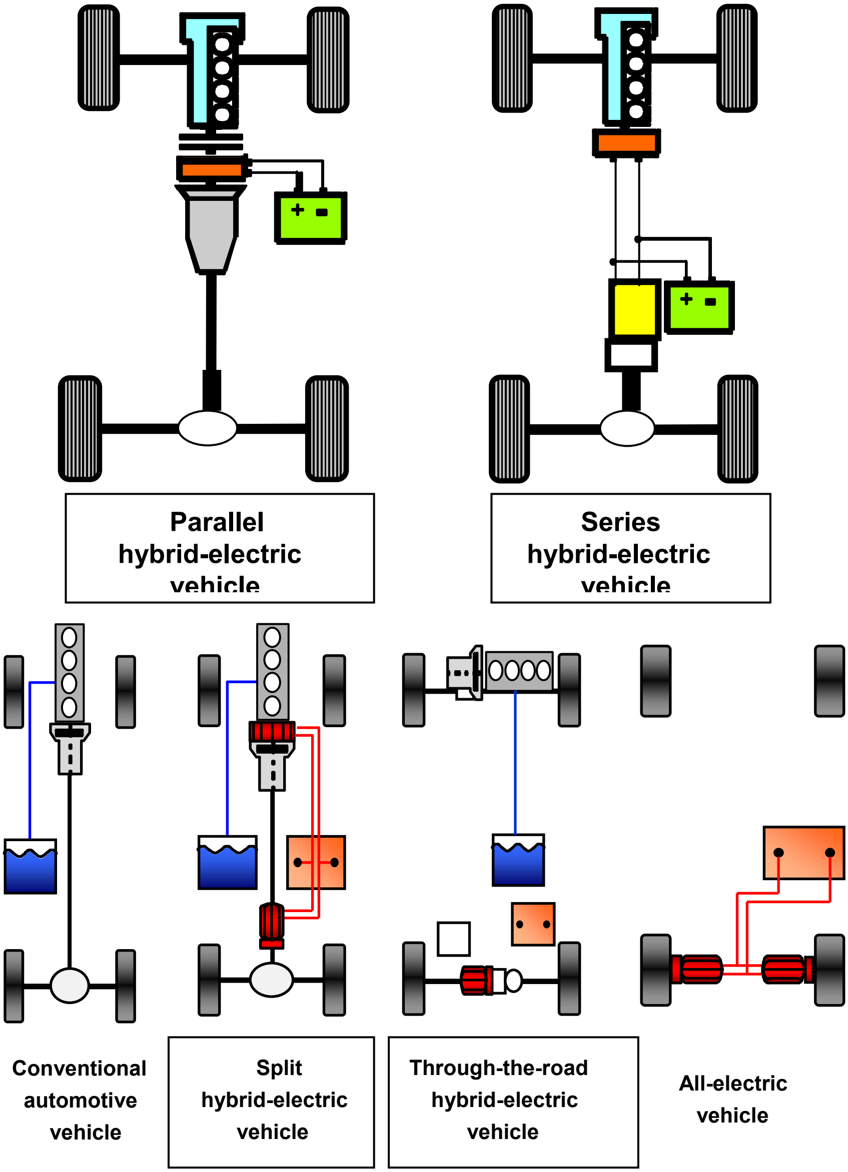


Fig. 2.119 Typical configurations of different hybrid-electric (HE) 2WD and/or DBW 4WD propulsion mechatronic control systems [FIJALKOWSKI 1985B; RAULT 2002; ALDERTON 2006].

To all intents and purposes, the expression HEV deals with a variety of automotive vehicles that include minimum two energy sources to power their drivetrains.

Unlike the pure CH-E/E-CH storage battery-powered AEVs that had a real range of less than 160 km (100 mi) prior to necessitating a recharge, hybrids have a great deal more flexibility which is close to that of conventional vehicles.

Hybrids also do not depend exclusively on their ECEs or ICEs for all the mechanical energy they need to run, so they have enhanced fuel economy and lower greenhouse exhaust gas emissions when evaluated with equivalent conventional automotive vehicles [FIJALKOWSKI 1985B, 1986, 1996A, 2000C; CHAN AND CHAU 2001; CHAN 2002; WOUK 1997, 2000].

What is a hybrid-electric (HE) system?

Synthesis between a **primary energy source** (PES), for example,: an ECE or ICE, and/or even FC and a **secondary energy source** (SES), for example, a CH-E/E-CH storage battery or a capacitor or inductor battery or even a **motorised and/or generatorised flywheel** (M&GF) that supplies or absorbs an E-M/M-E motor/generator -- attaining different functions because of changed energy arrangements.

The typical configurations of different ICE HE DBW AWD propulsion mechatronic control systems are shown in Figures 2.119 and 2.120 [FIJALKOWSKI 1985B; RAULT 2002; THS II 2004; ALDERTON 2006]. Thus, HEVs that employ a CH-E/E-CH storage battery in arrangement with a PES may be capable of making available unpolluted transportation without the range limitation of AEVs. They drop into the categories of **low-emission vehicles** (LEV) or **ultra low-emission vehicles** (ULEV). There are four major categories being built on: series, parallel, parallel/series, split, and through-the-road hybrids [FIJALKOWSKI 1985B].

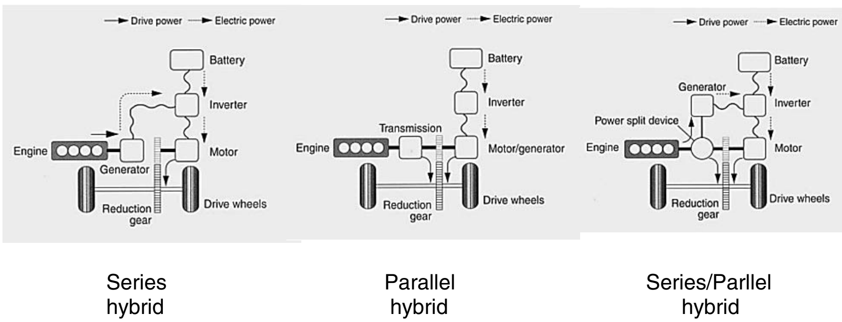


Fig. 2.120 The typical configurations of different hybrid-electric (HE) DBW 2WD propulsion mechatronic control systems [Toyota Hybrid System –THS II 2004]

The differences between these categories are in the HE transmission arrangement and mechatronic control strategy of the HEV's drivetrain. HEVs can have a parallel design, a series design (see Fig. 2.121) [WOUK 1997], or a combination of the two, termed a split design or even a through-the-road design.

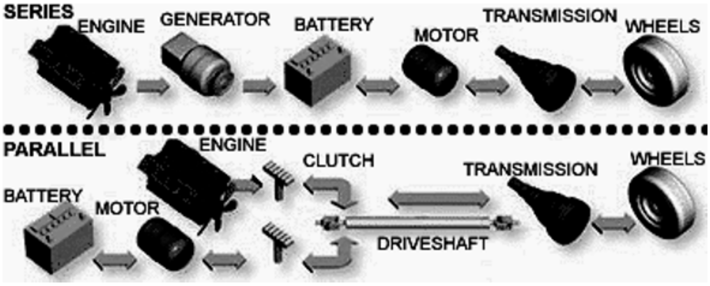


Fig. 2.121 Hybrid electric vehicle (HEV) classification [WOUK 1997; DRIESEN 2006].

In a parallel design, the ECD and E-M propulsion system is connected directly to the vehicle wheels. The primary ICE, ECE, or FC is used for highway driving; the E-M motor provides added power during hill climbs, acceleration, and other periods of high demand. In a series design, the primary ICE, ECE, or FC is connected to a **mechano-electrical** (M-E) generator that produces electricity. The electricity charges the CH-E/E-CH batteries which drive an E-M motor that powers the wheels. HEVs can also be built to use the series configuration at low speeds and a parallel configuration for highway driving and acceleration. Unlike AEVs, the CH-E/E-CH batteries in HEVs don't need to be plugged in to recharge. Instead, they are recharged by regenerative braking or by an on-board M-E generator.

Through-the-road (TTR) **hybrid-electric** (HE) transmission wheel arrangements for the HEV consist of separated power trains that are connected to each other by means of the road or ground surface and, normally, they can operate collectively and simultaneously. The ICE or ECE and/or the auxiliary **electrical energy stores** (EES) and **electrical energy boosters** (EEB) are regarded as **pollutant emission capability** (PEC) in individual units. The application of the HEV's electrical power boosting with low **specific fuel consumption** (SFC) and low power can be transmitted directly from the combustion engine and/or the auxiliary EEBs has the capability of power sharing between them as well as turning the ICE or ECE on and off for auxiliary electrical power boosting to the combustion engine in conjunction with the HEV's high-accelerating starting, great gradient ability (hill climbing), high-velocity passing, and high-deceleration antitorque emergency braking; or for auxiliary power boosting to the HEV's auxiliary EES in conjunction with the vehicle's wheel-driven EEBs recharging and the HEV's high-deceleration regenerative braking and/or cornering (pivot skid steering). However, because of the combustion engine is frequently in operation, liquid fuel constitutes a substantial fraction of the total energy used.

In addition, the application of an onboard microprocessor-based highest level HEV controller (commander) for dual mechatronic control of an ICE or ECE and auxiliary EESs has opened up wide possibilities for improving fuel saving.

Many demands are made on equipment and auxiliary electrical power boosting methods used in HEVs. Operational economy has become increasingly important with the growing costs of fossil fuel. It has not become profitable to invest in HEVs as an alternative to, or replacement of, existing advanced combustion engines.

Series HE Transmission Arrangement - The indispensable features of a series HE transmission arrangement are that the E-M motor supplies all the mechanical energy to drive the driven wheels. The electrical energy to the M-E motor is supplied by a CH-E/E-CH storage-battery pack which is charged from the M-E generator driven by an ECE or ICE. While the HEVs are parked, the CH-E/E-CH storage battery can also be charged from an external AC-DC charger. In the other words, in a series HE transmission arrangement, a PES, i.e., an ECE or ICE propels an onboard M-E generator, and supplies a traction E-M motor to propel the HEV's driven wheels, uses this generated electrical energy. This is termed a series H-E transmission arrangement because the mechanical energy flows to the driven wheels in series, i.e., the ECE or ICE output mechanical energy and the E-M motor output mechanical energy are in series.

A series HE transmission arrangement can operate a small-power output combustion engine in the energy conversion efficient operating zone more or less regularly, generate and supply electrical energy to the E-M/M-E motor/generator, and effectively charge the CH-E/E-CH storage battery. It has two electric machines – an M-E generator (that has the identical structure as an E-M motor) and an E-M motor.

Parallel HE Transmission Arrangement - In a parallel HE transmission arrangement, the same electrical energy from the CH-E/E-CH storage battery or mechanical energy produced by the PES can be used to propel the driven wheels. In this transmission arrangement, the electrical energy to propel the HEV can be provided entirely from the CH-E/E-CH storage battery, entirely from the PES, or an arrangement of the two. In other words, in a parallel HE transmission arrangement, the propulsion forced from the PES, that is, the ECE or ICE, and traction E-M motor propel the HEV's driven wheels independently.

An alternative configuration of parallel HE transmission arrangement is the power-assisted hybrid. In a CH-E/E-CH storage battery energy assisted configuration, the electrical energy is stored in a battery pack that can be used afterwards to supply ephemeral bursts of mechanical energy indispensable for fast acceleration, high-velocity passing, and hill climbing. Thus, HE transmission arrangements consist of the integration of two energy conversion and two energy storage units.

For propulsion, the E-M motor in combination with an ECE or ICE, a CH-E/E-CH storage battery and liquid fuel tank are used for energy storage. In such transmission arrangements, advantages of the ECE or ICE, resembling high performance and extensive range autonomy from infrastructures, can be combined with low polluting exhaust emissions and the low noise of the electric propulsion.

In a parallel HE transmission arrangement, both the ECE or ICE and the E-M motor propel the driven wheels and the propulsive mechanical energy from these two mechanical energy sources can be used to the existing circumstances. This is termed a parallel HE transmission arrangement because the mechanical energy flows in parallel to the driven wheels.

In this HE transmission arrangement, the CH-E/E-CH storage battery is charged by altering the E-M motor to operate as an M-E generator, and the electrical energy from the battery is used to propel the driven wheels.

Even if it has an uncomplicated construction, the parallel HE transmission arrangement cannot propel the driven wheels from the E-M motor at the same time as concurrently charging the CH-E/E-CH storage battery in view of the fact that it has no more than one electrical machine.

Series/Parallel HE Transmission Arrangement -- The series/parallel HE transmission arrangement connects the series and/or parallel HE transmission arrangements so as to maximise the advantages of both, and the high-energy conversion efficiency maximises the benefits.

It has two electric machines, and is reliant on the propulsion circumstances, using only the E-M motor or the propulsive mechanical energy from both the E-M motor and the ECE or ICE, so as to attain the uppermost energy conversion efficiency level. Besides, the split HE transmission arrangement propels the driven wheels at the same time as concurrently generating electrical energy by means an M-E generator.

Through-The-Road (TTR) HE Transmission Arrangement -- A split HE transmission arrangement for the H-E DBW AWD propulsion mechatronic control system consists of separated power trains that are connected to each other by means of the road or ground surface and, normally,they can operate collectively and multaneously. The ECE or ICE and/or the auxiliary **electrical energy stores** (EES) and **electrical energy boosters** (EEB) are regarded as individual units.

2.8.2 Series HE Transmission Arrangements for the HE DBW 2WD Propulsion Mechatronic Control System

In a series HE transmission arrangement for the HE DBW 2WD propulsion mechatronic control system (Fig. 2.122), the ECE or ICE drives a M-E generator that charges the CH-E/E-CH storage battery and supplies or absorbs the mechatronically controlled two E-M/M-E motors/generators, respectively [WÄLTERMANN 1997]. Two IPM E-M/M-E motors/generators (so-termed tandem electrical machine, 2 × 30 kW) are used to the RWD autonomously. This electric machine receives its electrical energy either from a CH-E/E-CH storage battery (for example, NiCd or NiMH) or by an arrangement of the ICE and onboard M-E generator that is the **energy supply unit** (ESU).

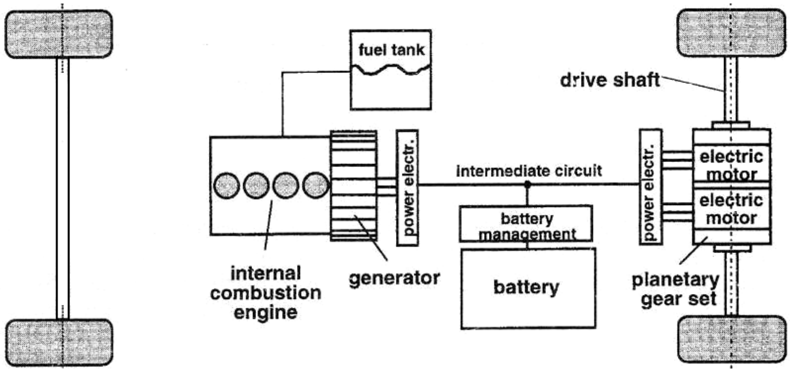


Fig. 2.122 Principle layout of a series HE transmission arrangement for the H-E DBW 2WD propulsion mechatronic control system [WÄLTERMANN 1997].

This HE DBW 2WD propulsion mechatronic control system has the advantage that the HEV may be driven entirely electrically, in, for instance, inner cities. However, if more mechanical energy is needed, or if the CH-E/E-CH storage battery has a low **state-of-charge** (SoC), the ICE may be started to supply additional electrical energy by means of the onboard M-E generator.

Thus, at variance with AEVs, the operating range is like that of a conventional vehicle and relies simply on the capacity of the fuel tank. Because of the complete mechanical decoupling of traction drives and ESU, the ICE may be functioned '*ad infinitum*' at its highest energy conversion efficiency and/or in areas of low exhaust emission. Two E-M/M-E motors/generators (the so-called tandem electrical machine) propel or dispel the HEV, respectively.

In this transmission arrangement, the ECE or ICE acts at a constant value of the angular velocity with maximum energy conversion efficiency. The mechatronic control simplifies the MT or SAT or FAT or CVT and M-M differentials. The one disadvantage of this HE transmission arrangement is that both the ECE or ICE and the electric propulsion have to be rated to a maximum value of the power output. An alternative problem is its low overall energy conversion efficiency. In the circumstance of the series HE transmission arrangement, the E-M/M-E motors/generators carry out all propulsion. These acquire or generate electrical energy directly from an ECE or ICE-driven M-E generator and from the CH-E/E-CH storage battery. At this instant, the action of the combustion engine can be limited to its dominant range, all-mechanical energy, on the other hand, has to be converted into electrical energy before being converted once more into mechanical energy. In the circumstance of the series HE transmission arrangement, all propulsion is performed by the on-board electro-energetic system allowing the combustion engine to function in an extremely slim range. While in this limited range action, comprehensive application of the uppermost energy conversion efficiency of the combustion engine can be used, the feature that -- in comparison to the parallel concept -- at least 50% more of the mechanical energy has to be converted into electrical energy and, vice versa, will cause higher SFC. Polluting exhaust gas emissions, however, can be mechatronically controlled and zero exhaust emissions should be possible.

2.8.3 Series HE Transmission Arrangements for the HE DBW 4WD Propulsion Mechatronic Control System

In a series HE transmission arrangement for the HE DBW 4WD propulsion mechatronic control system (Fig. 2.123), the ECE or ICE drive a M-E generator that charges the CH-E/E-CH storage battery and supplies or absorbs the mechatronically controlled four E-M/M-E motors/generators, respectively

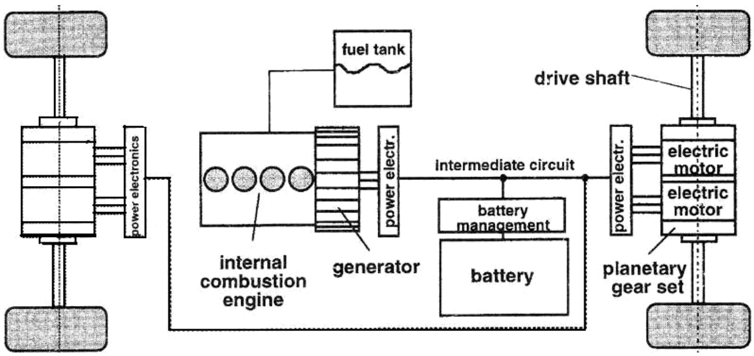


Fig. 2.123 Principle layout of a series HE transmission arrangement for the HE DBW 4WD propulsion mechatronic control system [WÄLTERMANN 1997].

Four IPM E-M/M-E motors/generators (the so-termed two-tandem electrical machines, 2 × 30 kW) are autonomously used to the FWD and RWD [WÄLTERMANN 1997]. These electrical machines also take delivery of their electrical energy either from a CH-E/E-CH storage battery (for example, NiCd or NiMH) or by an arrangement of the ICE and onboard M-E generator that is the ESU. This HE DBW 4WD propulsion arrangement offers the feature that the HEV may be propelled entirely electrically, for instance, in inner cities). But if more mechanical energy is needed, or if the **storage battery** (SB) has low SOC, the ICE may be started to supply additional electrical energy by means of an onboard M-E generator. Thus, at variance with AEVs, the operating range is related to that of a conventional one and relies only on the capacity of the fuel tank. As a result of the complete mechanical decoupling of traction drives and ESU, the ICE may be continuously operated at its uppermost energy conversion efficiency and/or in areas of low exhaust gas emission.

The HE DBW 4WD propulsion arrangement is projected for a focus-class automotive vehicle (mass: about 1.0 Mg plus mass of the CH-E/E-CH storage battery). Downgrading discharge of the storage battery the HEV has a constant power of about 53 kW (limited by the onboard M-E generator). When a M-E generator and CH-E/E-CH storage battery power are added, a peak power of 60 kW may be attained until the storage battery has achieved its minimum SOC. This creates the following HEV performance: a maximum value of the vehicle velocity: 160 km/h, a maximum value of the hill-climbing ability: 35%. In E-M mode (switch for the driver), the power from the storage battery is limited to 30 kW and a maximum value of the vehicle velocity is limited to 100 km/h. When driving at 50 km/h, an operating range of approximately *100 km* may be attained.
Energy-Supply Unit (ESU) -- With reference to the alternative series HE DBW 4WD propulsion arrangement, it is necessary to recognise how the electrical energy is generated on board. Different ICEs may be used for driving the M-E generator. With the series HE DBW 4WD propulsion mechatronic control system, the angular velocity of the ECE or ICE is absolutely autonomous of the vehicle velocity. As a result, not only conventional ECEs and/or ICEs are appropriate but also AGTs that are based on the FTB system, the Fijalkowski engine and the Stirling engine are indispensable for a conventional drivetrain. The onboard M-E generator is a brushless AC-DC macrocommutator IPM synchronous generator. The outer rotor structure and the water-cooling of the generator and AC-DC macrocommutator permit extremely high-power densities. The rotor angular velocity is controlled by a CAN-bus interface. For a compact structure, the rotor of the M-E generator is installed directly to the crankshaft of the ICE. Therefore, no ICE torque may be delivered to the engine mountings; the latter may be calculated much softer to prevent engine vibrations.
Tandem E-M Motor - The part to be subsequently explained is the tandem E-M motor that is composed of two separate brushless DC-AC macrocommutator IPM magnetoelectrically-excited synchronous motors installed on one flange and driving the rear or front wheels in absolute autonomy. Similar to the on-board M-E generator, it is an outer rotor structure. The tandem E-M motor may have 2×27 kW constant power output and 2×30 k W peak power output (delta connected). The electrical machines and their ASIM AC-DC/DC-AC macrocommutator may be water-cooled. The tandem E-M motor torque control is also affected by means of a CAN-bus interface. Figure 2.124 shows the tandem E-M motor.

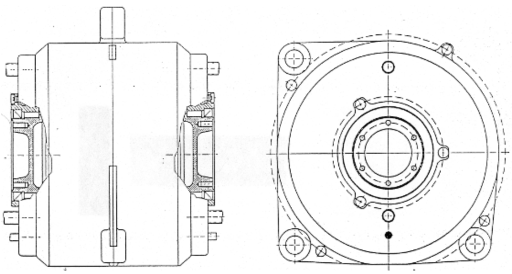


Fig. 2.124 Tandem E-M motor [Fichtel and Sachs].

CH-E/E-CH Storage Battery -- A NiMH storage battery may be used as an **electrical energy store** (EES) and as a shock absorber between the ESU and traction tandem E-M motors, To cut off the storage battery from the transitional circuit, a main switch is used that has been installed into a switch cupboard.

2.8.4 Series HE Transmission Arrangements for the HE DBW 2WD and/or 4WD Propulsion Mechatronic Control System

The high-performance, all-round energy-efficient, mechatronically-controlled tri-mode HEV, termed the *'Poly-Supercar'*, shown in Figure 2.125, may be an advanced ultra-light hybrid that means it will be electrically-powered by a high-density mechanical energy-storing, high-angular-velocity M&GF pack that is backed up by **primary energy sources** (PES), a small hydrogen (metal-hydrate) combustion **gas turbine-generator/motor** (GT-G/M) that is based on the **Fijalkowski turbine boosting** (FTB) system, or the **Fijalkowski engine-generator/motor** -(FE-G/M) and electrified highway or powered roadway designed to extend the HEV's range.

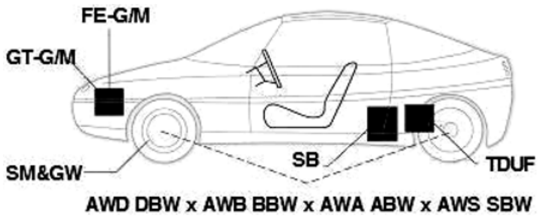


Fig. 2.125 Series HE transmission arrangement for the high-performance, all-round energy-efficient HEV termed the *Poly-Supercar* [FIJALKOWSKI 2000D].

On purely M&GF power, the HEV is expected to achieve a range up to 500 km. The PES, when used, will extend that range to 1,000 km, yet still allow the HEV to meet even CARB's requirements for **zero-emission vehicles (**ZEV).

The road-powered HEV reflects the fact that it may derive most or all of its electrical energy from electric cables buried in conventional-looking roadways. Underneath the road surface, electric cables (conductors or even superconductors) may be threaded through metal road channels called core elements. The cables may carry an electric current that will create an electromagnetic field.

The HEV termed the *Poly-Supercar,* travelling on the electrified highway or powered roadway, may extract electrical energy from this electromagnetic field through an inductive pickup mounted underneath the vehicle. The transfer of electrical energy between these two elements will occur contactlessly (without a physical power connection between the roadway and the HEV).

The electrical energy extracted from the roadway will be used to recharge a high-density mechanical energy-storing high-angular-velocity M&GF in the HEV and to power the vehicle's traction in-wheel-hub motors/generators on each SM&GW for the HE DBW 4WD propulsion mechatronic control system and other AE functional systems. While travelling off the electrified highway or powered roadway, the HIV's onboard AGT-G/M or FE-G/M and M&GF provide electrical energy, just as in a conventional parallel HE transmission arrangement. While lighter in mass than in a conventional parallel HE transmission arrangement, this onboard M&GF may be crucial to the vehicle's DBW 4WD propulsion mechatronic control system design. By providing an **electrical energy source** (EES) in the absence of an electrified highway or powered roadway, this M&GF may minimise the number of lane-kilometres (lane-miles) that must be electrified or powered. It is estimated that if 2 or 3% of lane-kilometres in a region were electrified or powered, this would enable greater regional mobility.

The electrified highway or powered road will operate at a high frequency of 21 kHz and will feed energy to the HEV. A high-frequency system is designed to eliminate the acoustic noise found in existing roadways operated at a frequency of 400 Hz.

Triad Hybrid Power Systems **-** A generation change in triad (tri-mode) **hybrid power systems** (HPS) is taking place. For over 20 years, the author has been performing **research-and-development** (R&D) work, at the Automotive Mechatronics Institution, Cracow University of Technology, Poland, on novel very advanced crankless prime movers, that is the ECE, termed the automotive **gas turbine-generator/motor** (GT-G/M) that is based on the **Fijalkowski turbine boosting** (FTB) system, shown in Figure 2.126 (a), or the 2-, 4- or even 5-stroke thermo-dynamic cycle, twin-opposed-piston, crankless ICE, termed the **Fijalkowski engine-generator/motor** (FE-G/M), shown in Figures 2.126 (b) and (c) [FIJALKOWSKI 1985A; 1986]. The AGT-G/M that is based on the FTB system, was conceived in the 1980s and first presented and published in February, 1985 at the *Autotechnologies '85: International Forum on New Automotive Technologies,* in Monte Carlo, Monaco [FIJALKOWSKI 1985A].

The FE-G/M, was also conceived in the 1980's and first presented and published in October, 1986 at the *Eighth Electric Vehicle Symposium* in Washington, DC [FIJALKOWSKI 1986]. It has one or more moving parts, a three-shaft AGT-G/M configuration, or a piston-rod assembly. For instance, the FE-G/M is constructed of one or more pairs of directly opposed pistons with respective cylinders and heads, and one or more **interior permanent magnet** (IPM) arrays fixed to the connecting rod between them, or driven by a double-ended cam **mechano-mechanical** (M-M) camshaft, or a **giant-electro-rheological fluid** (GERF), or a **nano-magneto-rheological fluid** (NMRF) **translational motion-to-rotary motion** (TM-RM), or a **rotary motion-to-translational motion** (RM-TM) mechatronic commutator, that is a TM-RM/RM-TM **fluido-mechanical** (F-M) mechatronic commutator that replaced the conventional ICE M-M crankshaft [FIJALKOWSKI 1985A; 1986; 1994; 1998; 1999C; 2000C].

(a)

(b)

(c)

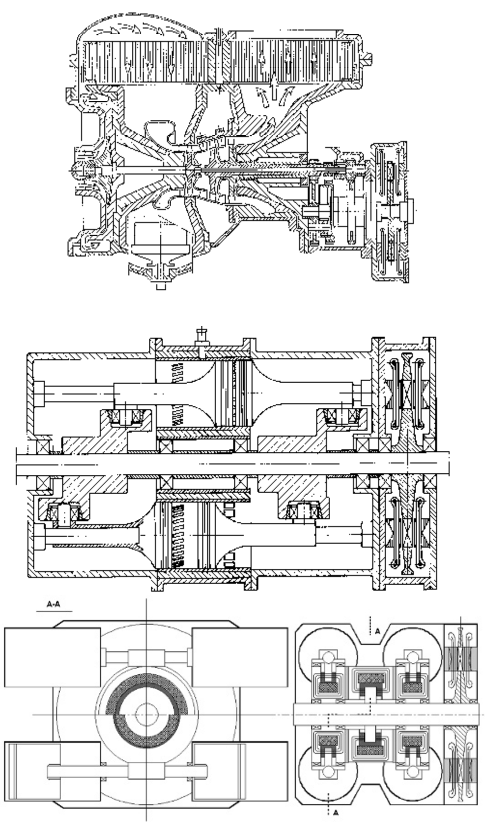
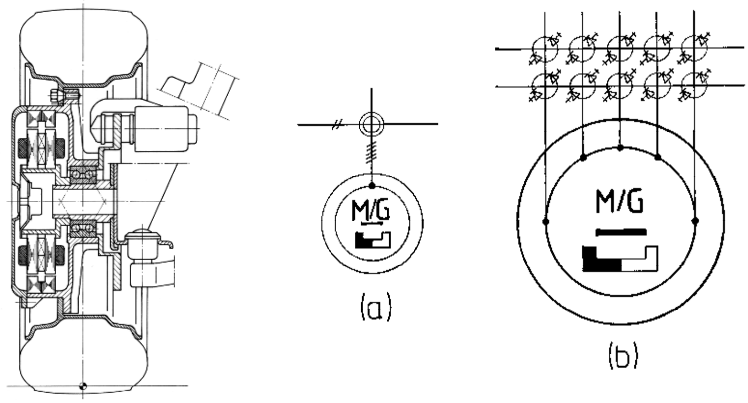


Fig. 2.126 Principle layouts of the automotive gas turbine generator/motor (GT-G/M) that is based on the Fijalkowski turbine boosting (FTB) system in a three-shaft turbine configuration (a), the Fijalkowski engine generator/motor (FE-G/M) with its double-ended cam M-M camshaft - 5-stroke thermodynamic cycle, disconnected twin-opposed piston configuration (b) or with its NMRF TM-RM/RM-TM mechatronic commutator and RM-RM mechatronic clutch transverse and longitudinal sections – 2 or 4-stroke thermodynamic cycle, rigidly connected twin-opposed piston configuration (c) [FIJALKOWSKI 1985A; 1986; 1998; 1999C; 2000C].

For example, the piston-rod assembly shuttles back and forth in a straight line from compression-ignition to compression ignition in its opposing cylinders. Mechanical energy from combustion and expansion of the fuel mixture is concentrated in a straight line, and because the pistons are not experiencing angular loading in the cylinders (as seen in conventional crank engine configurations), friction is substantially reduced and this translates to greater mechanical energy output. Further, with the elimination of the M-M crankshaft, its friction and mass are substantially reduced resulting in even greater mechanical energy output. For instance, the new crankless prime mover, termed GT-G/M or FE-G/M may propel the HEV cross-country at over 60 km/h and 160 km/h on good roads – certainly not a high-speed unit but adequate for its purposes [FIJALKOWSKI 1985A].

A DBW 2WD and/or 4WD propulsion mechatronic control system may provide the HEV with estimable climbing ability (up to π/4 rad) on firm surfaces). The two SM&GWs on each side of the HEV's hull-wheeled unit may have an independent ABW 4WA suspension. The two front and the two rear SM&GWs (Fig. 2.127) are driven and/or absorbed individually by four DC-AC/AC-DC macrocommutator reluctance and/or IPM magnetoelectrically-excited in-wheel-hub motors/generators, respectively, and the angular velocity of each SM&GW may be arbitrarily controlled by a driver-vehicle and terrain-vehicle real-time expert system, incorporating a mathematical model-following **fuzzy-logic** (FL) programmable and **neural-network** (NN) learning motion mechatronic control [FIJALKOWSKI 1990]. For changing the adhesion coefficient, two kinds of the tyres may be used, namely summer- and winter-type. The accelerometers may be also attached at the geometric centre of the HEV's body.



(A) (B)

Fig. 2.127 Layout of the steered, motorised and/or generatorised wheel (SM&GW) - (A) and the physical model of the brushless DC-AC/ AC-DC macrocommutator reluctance and IPM magnetoelectrically-excited in-wheel-hub motor/generator - (B) [FIJALKOWSKI 1984; 1990].

The author considered a novel mobility and steerability concept of HEVs with E-M differentials. The use of these novel triad hybrid mobility and triad hybrid steerability enhancing concept DBW AWD propulsion mechatronic control systems for HEV opens up wide possibilities for improving fossil and non-fossil fuel economy, cutting initial and whole-life DBW AWD propulsion costs, protecting the environment, and improving distribution of terrain thrust (gross tractive effort) as well as keeping both the net motion resistances of the DBW AWD propulsion and SM&GW sinkages (rut depth) low not only by increasing the velocity of travel but also decreasing the rolling resistances of all the SM&GWs.

The ability of the HEVs to retain a sufficient level of mobility may exist, even if they have lost single or more SM&GWs. Using differential torque and/or speed controls of the outer SM&GWs as well as current and/or voltage controls of the inner SM&GWs, can increase the lateral motion control effect, especially when recovering from braking with the inner SM&GWs acting as the AC-DC macro-commutator wheel-hub generators, because the front gravitational forces on the HEVs become greater than the respective rear ones. At the same creep, this leads to greater horizontal (longitudinal and lateral) forces. The experimental proof-of-concept DBW AWD propulsion mechatronic control systems used on HEVs satisfy nearly all the same essential requirements as for the running gear systems used on conventional vehicles [FIJALKOWSKI, 1986; 1990, 1994], namely:

- ❖ To apply an E-M *'single-shaft'* DBW AWD propulsion mechatronic control system to a complete number of SM&GWs;
- ❖ To allow the outer side of the curve a positive propelling (driving) torque and at the inner side, a negative dispelling (braking) torque, achieving their maximum value for pivot-skid steering;
- ❖ To occupy the minimum volume within the space envelope of the HEV;
- ❖ To distribute the mass of the HEV over relatively a spacious ground surface or soil area. The requirements of the first feature may contribute to a very good soft soil performance of HEVs.

The third feature may tend to conflict with requirements of the first feature.

Triad Hybrid Pivo-Skid Steering – Pivot-skid steering belongs to HEVs consisting of a body-unit of a single pivot point system in which the pivot is not positioned over the axle of either body-unit. In a HEV, steering is realized by bending the vehicle about a pivotal point, and in consequence, is often referred to as pivot-skid steering. It has been realistic to ask just why pivot-skid steering is successful when conventional steering is unsuccessful, but comparative experiments demonstrate that HEVs with pivot-skid steering are capable of extricating themselves from ruts, mud holes, and other obstructions. No particular increase in drawbar pull is perceptible with pivot-skid steering over a conventional vehicle on a straight pull. The advantage in the pivot-skid steered HEV appears to be its ability to *'step'* or *'wiggle'*, and each time (full-time) the HEV is steered, an insignificant forward motion is gained. It is in this manoeuvre that the net tractive effort or drawbar-pull is sensed to somehow increase. Here drawbar-pull is regarded as the tractive effort developed by an HEV as a surplus of motion resistance (net tractive effort). Since the drawbar-pull is obviously increased (motion resistance reduced) during the steering manoeuvre, it may be concluded that there must be something anomalous to pivot-skid steering that creates this increase. It has been found that, when negotiating rutted circumstances, an HEV with pivot skid steering may move the front SM&GWs out of the rut into adjacent soil, whereas this cannot be done with the standard automotive steering system, termed *Ackermann* steering, that uses two pivot points (one at each front wheel), and this creates a more constant wheelbase than does pivot-skid steering.

A $\pi/2$ rad alteration in the sense of direction can be made without forward motion of the HEV. The setting of the steering trunnion near the centre of the vehicle also results in almost perfect tracking of the front and rear SM&GWs. This feature is imperative in avoiding obstructions and, at the same time, enables the HEV to be steered either forward or backward without difficulty, as the steering characteristic of it does not alter with the steering's sense of direction. This steering characteristic makes possible the ready use of dual controls that enable the driver to drive forward or backward with equal ease; and this significantly reduces the necessity of manoeuvring and turning in difficult terrain. One factor noted in experiments is that conventionally steered HEVs are exceptionally more unstable uphill than skid- steered HEVs. Triad hybrid pivot-skid steering is also especially realised through the creation of a differential velocity between the inner and outer SM&GWs by means of three E-M differentials, namely **front-wheel drive** (FWD), **centre-wheel drive** (CWD), and **rear-wheel drive** (RWD) E-M differentials.

On HEVs, the SM&GWs on each side can be driven at various values of the wheel angular velocity in forward and reverse (all SM&GWs on a side are driven at the same rate). There is no explicit steering mechanism – as the name implies, steering is carried out by actuating each side at a different rate or in a different sense of steering direction, causing the SM&GWs to slip, or skid, on the ground. For instance, when the SM&GWs on the left side are driven forward and the SM&GWs on the right side are driven in reverse at the same rate, the result is a clockwise zero radius turn about the centre of the HEV.

Skidding has some disadvantages including wheel wear but for a HEV there is no choice. The reduced friction of a non-paved surface helps to reduce wheel wear. Multiple-drive SM&GWs on each side give greatly increased traction, especially on rough terrain.

The concept of triad hybrid pivot skid steering HEVs is an attractive one in that it opens up much of the capacity between the SM&GWs for things other than steering components, such as carrying cargo. On the other hand, in the case where a HEV is longer than its width (such as in this instance), conventional pivot-skid steering alone doesn't act. Knowing that the maximum value of the turning torque generated by the differential SM&GW torques being applied to the left and right sides, respectively, is a function of the lateral distance from the HEV centre-line to each SM&GW, and the wheel friction force, the resisting torque acting against this turning torque (torque resisting turn) is a function of the fore aft distance from the HEV centreline to each SM&GW and the wheel friction force.

Since on average the distances are greater than the lateral distance from the HEV centreline to each SM&GW, then the torque resisting turn is greater than the maximum value of the turning torque, or reiterated, the torque resisting the turn is greater than the turning torque being generated. That is why; conventional pivot-skid steering doesn't work for HEVs that are longer than they are wide.

The advantage of triad hybrid pivot-skid steering is that it permits the HEV to *'turn on a dime'*, and rapidly alter the steering sense of direction just by letting down the in-wheel-hub E-M motors.

The disadvantage is that it makes less efficient use of its in-wheel-hub E-M motors, and results in random odometry logs because the SM&GWs often slide along the ground surface. Since the steering sense of direction-finding system was tuned to those preceding conventional HEVs, it tended to anticipate that the vehicle would be able to turn very fast, even at high vehicle velocity, but disappointingly that is not the case. This is due predominantly to the pivot-skid steering concept, but perhaps also to the very loose soil. That's why the author would like to put into effect some hardware and software alterations that should enhance its mobility and steerability performance, by proving it down until it realises the recently commanded steering sense of direction.

A very advanced series HE transmission arrangement for the HE DBW 4WD propulsion mechatronic control system is based on a novel E-M **axleless progressively variable transmission** (APVT), a **mechanical energy store** (MES) that I is a high-density, mechanical energy storing, high angular velocity **motorised and/or generatorised flywheel** (M&GF) with the brushless DC-AC/AC-DC macrocom-mutator twin composite-disc flywheel motor/generator and onboard **electronic control instrument** (ECI) that controls all automotive functional systems. These techniques may allow for low pollution and efficient manufacture and use of mechanical energy.

The expected average improvements are: 60% of fossil-fuel savings and 75% of pollution reduction. Further changes that may be directly noticed by the driver are a more comfortable ride due to a shiftless and stepless fast acceleration from zero to maximum values of vehicle velocity.

A full-time series HE DBW 4WD propulsion mechatronic control system may noticeably enhance both comfort and safety.

The simplicity of the novel concept is visible when comparing the number and size of the propulsion mechatronic control system's components and their series HE transmission arrangement in a *'Standard'* and a *'Novel Concept'* HEV:

Standard

- ❖ ECE or ICE;
- ❖ ECE or ICE starter;
- ❖ M-M clutches;
- ❖ MT (gearbox);
- ❖ M-M propeller shafts;
- ❖ M-M driveshafts;
- ❖ M-M differentials;
- ❖ F-M wheel-drum, -disc or -ring brakes.

Novel Concept

- ❖ M-E/E-M generator/motor [an automotive gas turbine-generator/motor (AGT-G/M) or the **Fijalkowski engine-generator/motor** (FE-G/M)];
- ❖ Steered, motorised and/or generatorised wheels (SM&GW);
- ❖ Motorised and/or generatorised flywheel (M&GF);
- ❖ Chemical energy-storing, very advanced CH-E/E-CH storage battery;
- ❖ Solar-cell panel;
- ❖ Inductive pickup;

- ❖ ASIM macrocommutator and ASIC microcomputers;
- ❖ E-M wheel-drum, -disc or –ring brakes.

The ECE's or ICE's fluidic cooling system, fuel tank, onboard M-E generator, and SLI CH-E/E-CH storage battery are less than half of its present size. This results in mass reductions of approximately 300 kg for an automotive vehicle with a present curb mass of 1,200 kg .The components of this series HE transmission arrangement for the HE DBW 4WD propulsion mechatronic control system may be arranged with each other with a great degree of freedom, allowing the best space use and mass distribution. The best distribution of FWD and RWD loads (e.g. 50/50) and a reduced height of the barycentre (centre of gravity) can be easily achieved. This and the reduced unsprung mass of the SM&GWs leads to increased active safety and riding comfort. The functionality of the HEV may be increased without additional cost and mass due to the ease of controllability of the HE DBW 4WD propulsion mechatronic control system's components.

An AGT-G/M that is based on the FTB system or the FE-G/M [FIJALKOWSKI, 1985, 1986], may charge the high-density mechanical energy-storing high angular velocity M&GF with stored mechanical energy. The ECE or ICE may be cut-off by the onboard central ECU when the M&GF is filled and provides the electrical machines (in-wheel-hub motors/generators) on each SM&GW with electrical energy in the form of an electrical current to accelerate and propel the HEV.

During regenerative braking and/or cornering, the electrical machines become in-wheel-hub M-E generators and transmit the braking and/or cornering electrical energy back to the M&GF.

The size of the in-wheel-hub M-E/M-E motors/generators is such that they can provide sufficient braking and/or cornering torques to lock the SM&GWs in all circumstances and very high torque to accelerate the HEV at all values of vehicle velocity. The easy torque and angular-velocity control of each SM&GW may lead to an efficient full-time DBW 4WD propulsion mechatronic control. The infinite adjustability of the in-wheel-hub E-M/M-E motors/generators on each SM&GW may be controlled by the ECI, giving the APVT a variety of additional functions, such as HE DBW 4WD propulsion, lockable FWD and RWD, as well as CWD E-M differentials, ABS and ARS, as well as ESP.

The series HE transmission arrangement will allow additional features that may improve the functionality and use of mechanical energy further: constant and variable angular velocity auxiliary-drive propulsion mechatronic control systems for trade-off power units are needed (e.g. onboard M-E generator, M-F pumps) and comfort fluidics (e.g. park automatic and so on). The mass distribution for the *Poly-Supercar* is assumed to be 50/50 under static and 75/25 under maximum braking and/or cornering dynamic circumstances. The size of the in-wheel-hub E-M motors is based on the maximum torque requirements under dynamic conditions, i.e. braking and/or cornering under full load. One in-wheel-hub E-M motor at constant values of the vehicle velocity and low accelerations, and two in-wheel-hub E-M motors at significant levels of acceleration, may propel the HEV *Poly-Supercar*.

The **artificial intelligence** (AI) ECI corrects the steering position needed to balance the off-centre thrust during SM&GWs are actuated during braking and/or cornering. A HE DBW 4WD propulsion function, with or without locked FWD and RWD as well as CWD E-M differentials, can be selected through the **human- and/or telerobotic driver** (H&TD). The DBW 4WD propulsion mechatronic control system's AI ECI automatically selects these modes if the SM&GWs are spinning during acceleration or locked during braking.

The principle layout of an HE transmission arrangement for the aforementioned HE DBW 4WD propulsion mechatronic control system is shown in Figure 2.128.

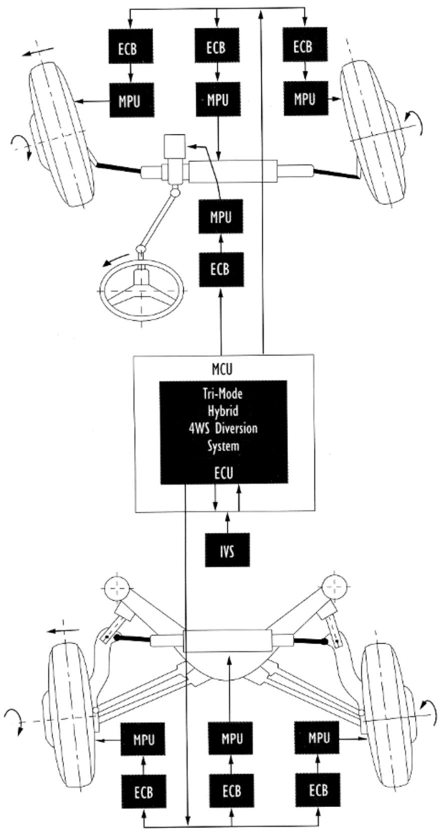


Fig. 2.128 Principle layout of an HE transmission arrangement for the HE 2WD and/or DBW 4WD propulsion mechatronic control systems [FIJALKOWSKI, 1997D; 2000B].

The core of the series HE transmission arrangement for the mechatronic control system can be not only the onboard, high-density mechanical energy-storing super-high-angular-velocity M&GF with a brushless DC-AC/AC-DC macrocommutator twin composite-disc flywheel E-M/M-E motor/generator and high-capacity chemical energy-storing MgH with Ni catalyst, FeTiH, LiPolymer, LiIon, NiMH, NiCd, $NaNiCl_2$, NaS, AgZn, NiC or PbAcid storage battery co-operating with the AGT-G/M that is based on the FTB system, or the FE-G/M and solar-cell panel as well as the electrified highway or powered roadway, but also four SM&GWs with brushless AC-AC or AC-DC-AC or DC-AC/AC-DC macrocommutator reluctance and/or IPM magneto-electrically-excited in-wheel-hub motors/generators and in-wheel-disc **electro-mechanical brakes** (EMB) for each FWD and RWD, and single reciprocating E-M accelerator-pedal actuator, driven by the linear tubular DC-AC macrocommutator pedal-actuator motor, for the right-foot accelerator pedal.

Starting and Acceleration **-** The driver turns the key to activate thee onboard central ECI. The ECI senses the position of the right-foot accelerator pedal and switches on/off the ASIM macrocommutator electrical valves and provides the in-wheel-hub E-M motors on each SM&GW with electrical energy.

The ASIM macrocommutator at the in-wheel-hub E-M motors may be adjusted from zero to larger reference control signals to produce sufficient torques to accelerate the HEV. Increased pressure at the accelerator pedal creates greater reference control signals and faster acceleration. For low and medium acceleration, only one SM&GW may be activated. At high acceleration or tractive efforts, two or more SM&GWs will drive the HEV. The ECI may correct the steering to compensate for off-centre thrust of the wheels. The ECI senses the revolution of all wheels and calculates its correct values of the wheel angular velocities depending on the hand-steering-wheel position. If the values of the wheel angular velocities are too high, the SM&GW slips. The ECI may reduce the torques (reference control signals) to prevent this situation.

Rolling **-** The HEV drives at a constant vehicle velocity if there is no difference between the position of the accelerator pedal and the vehicle velocity of the HEV. The number of wheels activated (driven) will depend on the tractive effort needed and may be selected by the AI ECI or by the driver through a push bottom. A smooth transition to a coasting mode can be reached by moving the reference control signals into zero or near-zero accelerator-pedal position.

2.8.5 Series HE Transmission Arrangements for the HE DBW 6WD or 8WD Propulsion Mechatronic Control System

Series HE transmission arrangements for the HE DBW 8WD propulsion mechatronic control system, for example, include an integrated M-E/E-M generator/motor not only driven through the ECE or ICE but also cranked, respectively, six or eight SM&GWs with the in-wheel-hub motors/generators and the CH-E/E-CH storage battery.

Figure 2.129 shows an overall view of the 6 × 6.6 or 8 × 8.8 or especially 4 × 4.4 HEVs [FIJALKOWSKI 1999].

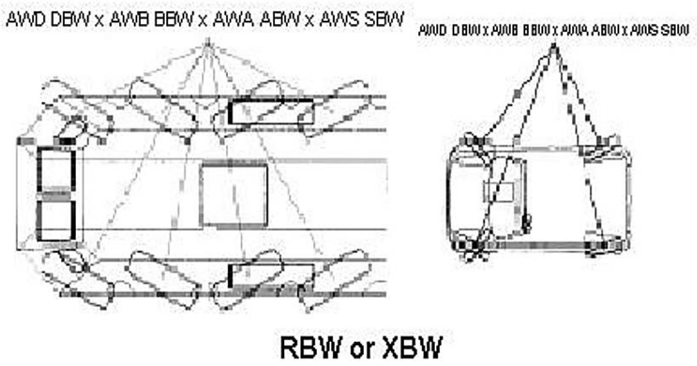


Fig. 2.129 6 × 6.6 or 8 × 8.8 or especially 4 × 4.4 HEVs [FIJALKOWSKI 1999].

Tractive effort is created by the function of six or eight wheels with in-wheel-hub E-M motors. These motors take advantage of IPM technology that presents a high torque and a most advantageous dynamic capacity that is indispensable for challenging traction applications. In-wheel-hub E-M motors are collected into an integrated in-wheel drive that consists of the motor, final-drive mechanism, and service/parking brake modules for enhanced maintenance.

Macroelectronics for IPM E-M/M-E motor/generator mechatronic control and voltage conversion may use state-of-the art ASIM macrocommutators. A hybrid wheel/track tri-mode SBW 4WS conversion mechatronic control system may be developed which complements the independent DBW 8WD propulsion mechatronic control system's capability of controlling the wheels with in-wheel-hub E-M/M-E motors/generators.

The tri-mode HE SBW 6WS or 8WS conversion mechatronic control system may use an arrangement of conventional wheel and skid steering that is conventionally related with tracked vehicles.

At high values of the vehicle velocity, the vehicle use conventional wheel-steer SBW 4WS conversion mechatronic control system that moves the wheel stations through up to 10 deg of turning arc.

At low values of vehicle velocity, the tri-mode HE SBW 6WS or 8WS conversion mechatronic control system may arrange differential wheel velocity between the wheels to induce skid steering to enhance the indispensable steering angle. This feature may give the 6 × 6.6 or 8 × 8.8 HEV innovative mobility capability in familiar areas such as conurbation environments.

In this position, swept volume necessary for steering is minimised and wheel pairs are sustained to accept the advantage of track overlays to the wheels in operational circumstances where supplementary flotation and traction are indispensable.

Figure 2.130 shows a **computer-aided-design** (CAD) integration physical model of the **advanced hybrid electric wheel drive** (AHED) 8 × 8.4 *Phantom* HEV indicating the power and propulsion modules [TRZASKA 2002].

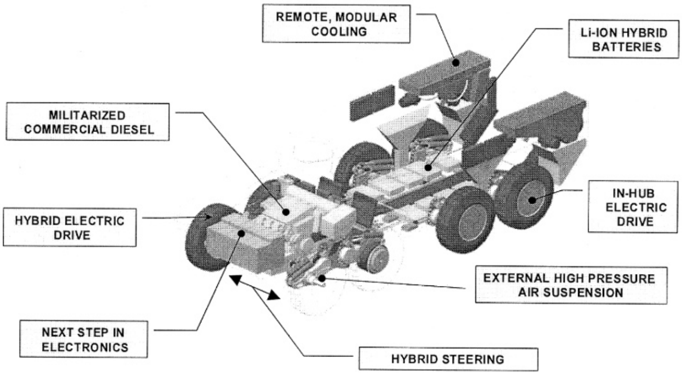


Fig. 2.130 AHED 8 × 8.4 *Phantom* HEV view revealing power and propulsion modules [TRZASKA 2002].

Modular in-wheel drives with E-M/M-E motors/generators provided by the Magnet Motor are installed in each wheel hub. In-wheel-hub motors/generators are rated at 110 kW each.

Figure 2.131 shows the mechatronic architecture of the HE DBW 8WD propulsion mechatronic control system and **energy-and-information network** (E&IN) for a AHED 8 × 8.4 *Phantom* vehicle [TRZASKA 2002].

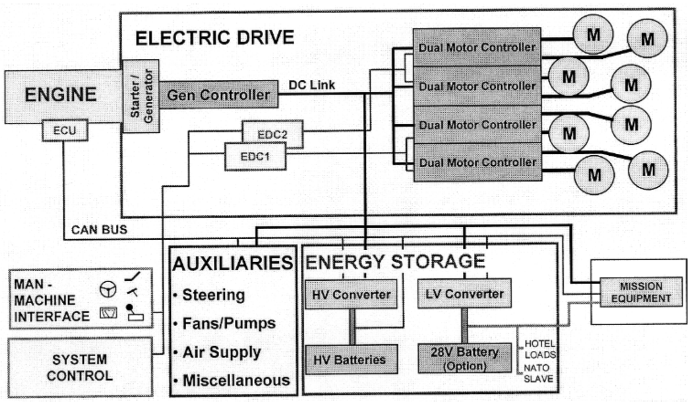


Fig. 2.131 AHED *8 × 8.4 Phantom* HEV power and propulsion architecture [TRZASKA 2002].

The CAN bus (ISO 11519-1) is used as the automotive platform's mechatronic control network

The AHED 8 × 8.4 *Phantom* HEV may operate in four basic modes: HEV, AEV, **electro-mechanical transmission** (EMT), and **auxiliary power unit** (APU). The HEV mode is the basic mode of the vehicle and supplies the driver with improved fuel efficiency and significant *'burst'* power. The AEV mode is used for silent or reduced signature operation. The ET mode is used when the hybrid energy storage system is depleted or inoperative. The APU mode configures the E&IN to provide up to 300 kW at 480 V_{DC} for mission equipment or off-board power requirements.

E-M motor ASIM macrocommutators (in Fig. 2.131 termed *'Dual Motor Controllers'*) are IGBT based rated at 110 kW.

ASIM topography is used to permit the in-wheel-hub motors/generators to be operated as M-E generators for regenerative braking, steering, and traction control. These macrocommutators are packaged in modular dual channel packages that interface into a distribution manifold. The distribution manifold brings cooling, power distribution, motor conductors, and mechatronic control interfaces together in a quick disconnect interface.

An IPM M-E generator rated at 360 kW is mounted on the diesel engine in place of a conventional flywheel. The HE DBW 8WD propulsion mechatronic control system uses an M-E generator macrocommutator (in Fig. 2.131 termed the *'Gen Controller'*) that is both collocated and interchangeable with the E-M motor ASIM macrocommutators.

The prime mover for the DBW 8WD propulsion mechatronic control system is the diesel engine rated at 400 kW. Energy storage is provided through Li-Ion storage batteries [TRZASKA 2002].

2.8.6 Parallel HE Transmission Arrangements for the HE DBW 2WD Propulsion Mechatronic Control System

A parallel HE transmission arrangement consists of an ECE or ICE and electrical propulsion connected by a mechanical gear. The electric propulsion is built with an E-M/M-E motor/generator, ECU and CH-E/E-CH storage battery. The mechanical gear drives the wheels through an M-M differential. In highway driving, the ECE or ICE propels the HEV and charges the storage battery. The motor/generator operates as an M-E generator. In urban driving, the storage battery and the E-M motor drive the HEV. During hill climbing or circumstances when the maximum value of output power is needed, both ECE or ICE, and E-M motors drive the HEV. This transmission arrangement, results in better efficiency, less mass, and lower costs. In the circumstance of the parallel HE transmission arrangement the ECE or ICE, as well as, the E-M/M-E motor/generator can propel or dispel the HEV independently or in addition.

Automotive vehicles equipped with parallel HE transmission arrangements for the HE 2WS DBW propulsion control system in urban traffic is driven predominantly electrically, and if high power is necessary, the ICE takes over.

The supplementary electrical machinery is completed with little loss of comfort or luggage space of the vehicle.

Embedded in place of the conventional ICE's flywheel is a compact DC-AC macrocommutator hyposynchronous squirrel-cage-rotor flywheel E-M motor. On the side to the ICE, as well as on the side to the MT or SAT or CVT, mechatronically activated M-M clutches are installed. The E-TMC system operates as **stop-start** (SS) clutches.

Figure 2.132 shows the drive E-M motor and Figure 2.133 illustrates the operating rule arrangement.

Fig. 2.132 Brushless DC-AC/AC-DC macrocommutator squirrel-cage-rotor hyposynchronous flywheel motor/generator including two M-M clutches [VW-Bosch–LU*K*; STIFFER AND WALKER 1991].

Only if the M-M clutch to the ICE is not turned on, the HEV is driven electrically, and during regenerative braking, electrical energy is being supplied to the CH-E/E-CH storage battery.

If an ICE is propelling the vehicle, the M-M clutch on the ICE side is turned on; the squirrel-cage rotor of the DC-AC macrocommutator asynchronous squirrel-cage-rotor flywheel motor may then function as a flywheel. Besides, this electric drive unit acts as a starter E-M motor and as an onboard M-E generator [SEIFFERT AND WALZER 1991].

The electric power of the automotive vehicle is about 10% of the ICE output power; this is adequate for a speed of 60 km/h on level ground and for hill climbing of up to about 10% in first gear. The ICE is used predominantly for acceleration and for sustaining vehicle velocity above 60 km/h.

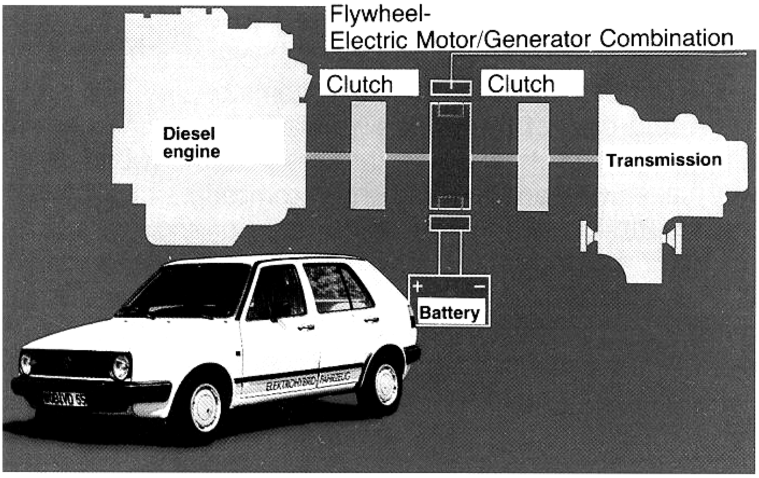


Fig. 2.133 Parallel HE transmission arrangement for the HEV VW *Golf II* [VW-Bosch-LUK; SEIFFERT AND WALZER 1991].

The E-M motor is utilized when the indispensable propulsion power is less than 10% of the ICE output power. This stipulation is experienced most often in urban traffic. Indeed, high-energy CH-E/E-CH storage battery, for example such as LiIon, LiPolymer, NiMH or NaS also can be employed with benefit in HEVs. AE propulsion could be used entirely in inhabited districts where noise and exhaust emissions are particularly unfriendly. Acceleration in this circumstance would be restricted. For long-distance journeys, the electric power supplying a CH-E/E-CH storage battery can be spaced out using an uncomplicated lift tool so that supplementary storage space becomes accessible. In this circumstance only the ICE is used for propulsion; the electric drive unit still operates as a starter E-M motor and as an onboard M-E generator [SEIFFERT AND WALZER 1991].

For the reason that each of the two power plants is designated a duty for that it is principally suitable, the parallel hybrid-electric transmission arrangement is extremely fuel-efficient and environmentally friendly.

Draw a distinction to a conventional ICE-powered automotive vehicle, up to 60% of the fossil fuel is recovered through the supplementary application of electrical energy. The attenuation of exhaust gas emissions varies between 40 – 60%. To recharge the CH-E/E-CH storage battery during the nights necessitates about 15 kWh if this electrical energy is generated from non-fossil sources, the CO_2 emission is downgraded by up to 60% as well [SEIFFERT AND WALZER 1991].

The problems of how the different CH-E/E-CH storage batteries may func-tion under daily traffic load, what their life anticipation is, and that task in daily traffic should be designated to which automotive vehicle concept, may be solved through experimental schedules presently in development.

HEV technology is under development with several other HE transmission arrangements that have been proposed and are being evaluated. One of the major reasons for a HE transmission arrangement for parallel HE DBW 2WD propulsion mechatronic control systems is to radically improve fuel economy and that may also lead to decreased pollutions. One problem of HEVs has been range. In order to be a convincing competitor, a range similar to conventional automotive vehicles has to be offered [DELPRAT ET AL. 2001].

Different mechatronic control methods are suggested. Some automotive scientists and engineers have proposed a strategy based on a fuel consumption criteria and instantaneous minimisation of the equivalent fuel flow [PAGANELLI ET AL. 2000].

They present a comparison between the optimal solution found for a given driving schedule and a strategy proposed by others [SEILER AND SCHRÖDER 1988]. These are appropriate to compare because both apply an instantaneous minimisation criteria [PAGANELLI ET AL. 2000].

The HE transmission arrangement operating point is chosen so that the total efficiency loss is minimised. The global optimisation based on simulated annealing is a guideline, although it cannot be used for real time mechatronic control.

Simulation results show that fuel consumption for the proof-of-concept HEV during European normalised driving cycle is [PAGANELLI ET EL. 2000]:

- ❖ Loss minimising strategy: 7.0 l/100 km;
- ❖ Equivalent consumption minimising strategy: 6.6 l/100 km;
- ❖ Global optimisation based on simulated annealing 6.3 l/100 km.

Two standardised driving cycles are used during tests performed by some automotive scientists and engineers – the city cycle and extra urban driving cycle [KLEIMAIER AND SCHRÖDER 2000].

They propose an optimal mechatronic control vector used on the ICE, the E-M/ M-E motor/ generator and the CVT of the proof-of-concept HEV, shown in Figure 2.134 [PERSSON 2004].

Fig. 2.134 Proof-of-concept HEV, a modified Opel *Astra*
with an optimal mechatronic control vector used on ICE, E-M/M-E motor/generator and CVT
[KLEIMEIER & SCHRÖDER 2000; PERSSON 2004].

The optimal mechatronic control vector is computed with the aid of the programme *DIRCOL* which assists in searching for a numerical solution to optimal mechatronic control problems. Calculating and then using the optimal control vector results in decreased fuel consumption during the city cycle from 6.2 l to 5.0 l/100 km [STRYK 1994].

2.8.7 Series/Parallel HE Transmission Arrangements for a HE DBW 2WD Propulsion Mechatronic Control System

Figure 2.135 outlines of the HE transmission arrangement that combines a series hybrid system with a parallel hybrid system to take maximum advantage of their individual strong points [TAKAOKA ET AL. 2001].

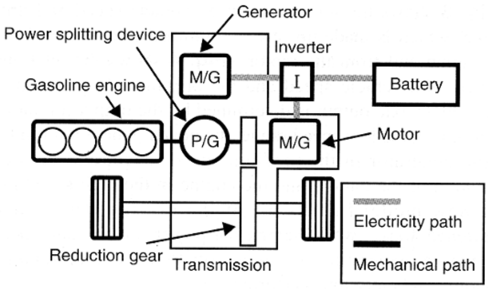


Fig. 2.135 Principle layout of the parallel/series HE transmission arrangement [Toyota Technical Review; TAKAOKA ET AL. 2001].

The changes made this time focused on improving the output performance of the ECE or ICE and E-M/M-E motor/generator and achieving even better fuel economy by increasing their energy conversion efficiencies while reducing emissions. A series/parallel HE transmission arrangement improves the average energy efficiency of the ECE or ICE by stopping them in the low power output range and optimising the operating range. Moreover, it improves thermal efficiency of the ECE or ICE by employing a high ICE's expansion ratio cycle as well as by reducing various friction losses caused by a decrease in the maximum value of the ECE or ICE rotary shaft angular velocity.

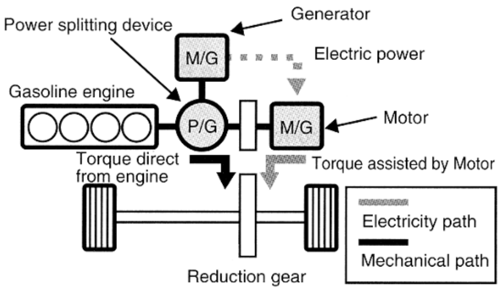


Fig. 2.136 **Principle** layout of the series/parallel HE transmission arrangement: normal torque transfer [Toyota Technical Review; TAKAOKA ET AL. 2001].

Figures 2.136 and 2.137 show the energy flow in the series/parallel HE transmission arrangement [TAKAOKA ET AL. 2001].

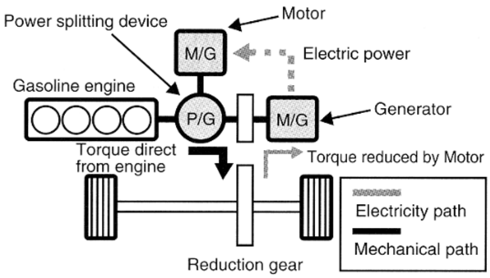


Fig. 2.137 Principle layout of the series/parallel HE transmission arrangement: transmission of torque with energy re-circulation [Toyota Technical Review; TAKAOKA ET AL, 2001].

With normal energy flow, the power output of the ICE is split by a power splitting device such that a portion of the power output is sent directly to the axle of the HEV and a portion is sent to the M-E generator that generates electrical energy for the E-M motor used for assisting torque. Under certain conditions, however, too much torque directly from the ICE is applied to the axle. As a result, mechanical energy from the axle acts on the E-M motor, turning it in effect into a M-E generator such that the torque directly from the ICE to the axle is re-circulated, thereby lowering transmission energy conversion efficiency in that range. Changing the operating range of the ICE to high speed and low load for the equivalent power output enables recirculation to be avoided, but it also reduces the ICE's energy efficiency. An exemplary series/parallel HEV layout with an ICE and two electrical machines is shown in Figure 2.138 [DRIESEN 2006].

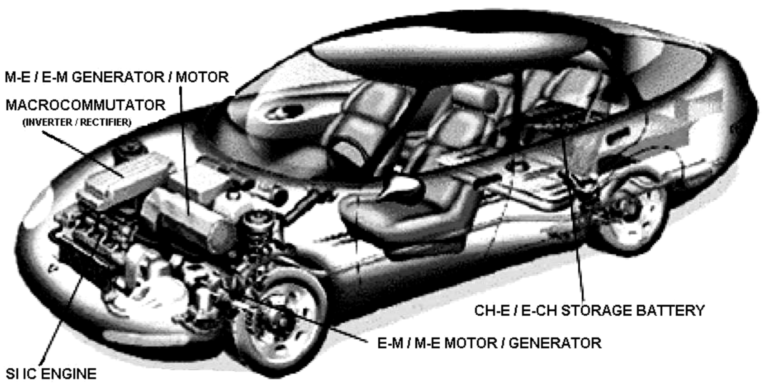


Fig. 2.138 Layout of the series/parallel hybrid-electric vehicle (HEV) [DRIESEN 2006].

In Figure 2.139 is shown the HEV driving circumstances during starting when the ICE remains off to save liquid fuel and the E-M motor drives the series/parallel HEV. No liquid fuel consumption – no exhaust emissions.

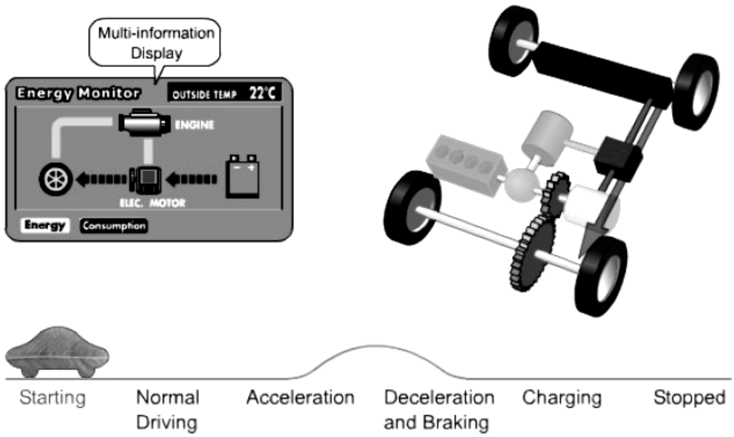


Fig. 2.139 HEV driving circumstances during staring [DRIESEN 2006].

In Figure 2.140 HEV driving circumstances are shown during normal driving when the ICE starts and may drive the series/parallel HEV and produce electrical energy for the E-M motor or is charging the CH-E/E-CH storage battery.

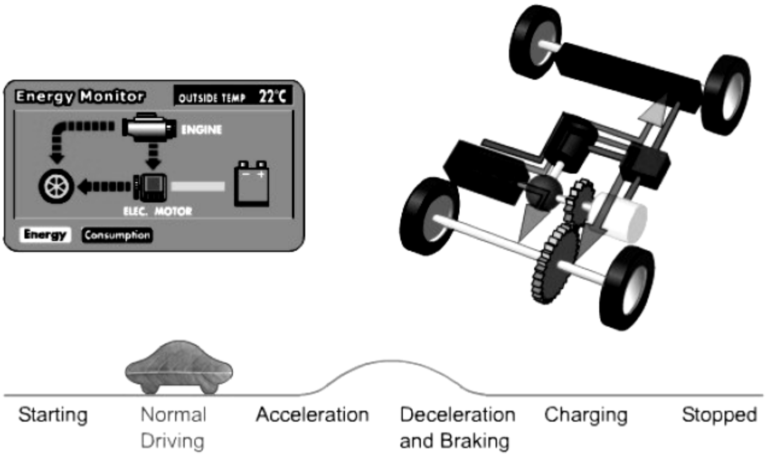


Fig. 2.140 HEV driving circumstances during normal driving [DRIESEN 2006].

In Figure 2.141 HEV driving circumstances are shown during acceleration when maximum power is required, the CH-E/E-CH storage battery may also supply power and boost the series/parallel HEV's performance.

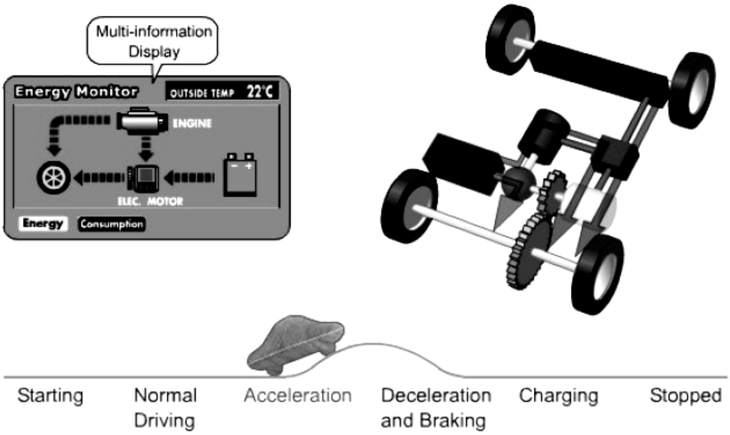


Fig. 2.141 HEV driving circumstances during acceleration [DRIESEN 2006] .

In Figure 2.142 HEV driving circumstances are shown during deceleration and braking the E-M motor is turned into a M-E generator to charge the high-voltage CH-E-CH storage battery. No liquid fuel consumption – no exhaust emissions.

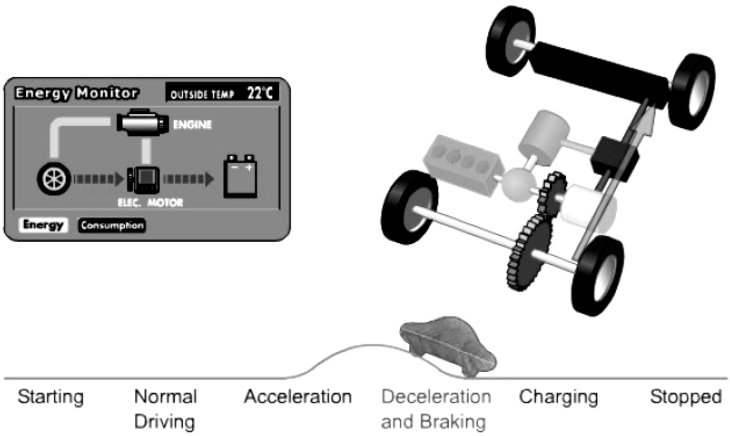


Fig. 2.142 HEV driving circumstances during deceleration and braking [DRIESEN 2006].

In Figure 2.143 HEV driving circumstances are shown during charging when the CH-E/E-CH storage battery gets low and the ICE may automatically start to recharge it.

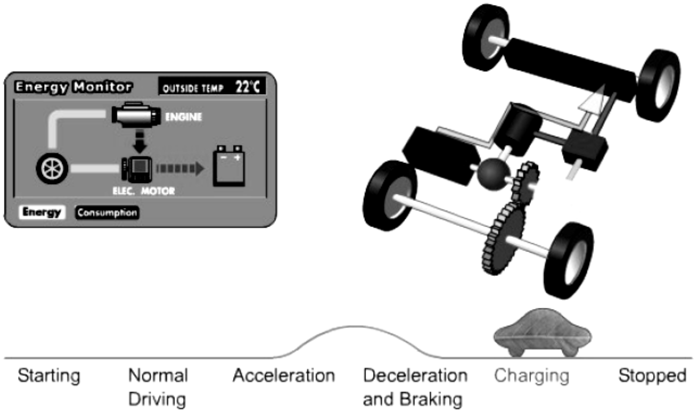


Fig. 2.143 HEV driving circumstances during charging [DRIESEN 2006].

In Figure 2.144 HEV driving circumstances are shown during stopping when the ICE automatically shuts off when the series/ parallel HEV is stopped. No liquid fuel consumption – exhaust emissions.

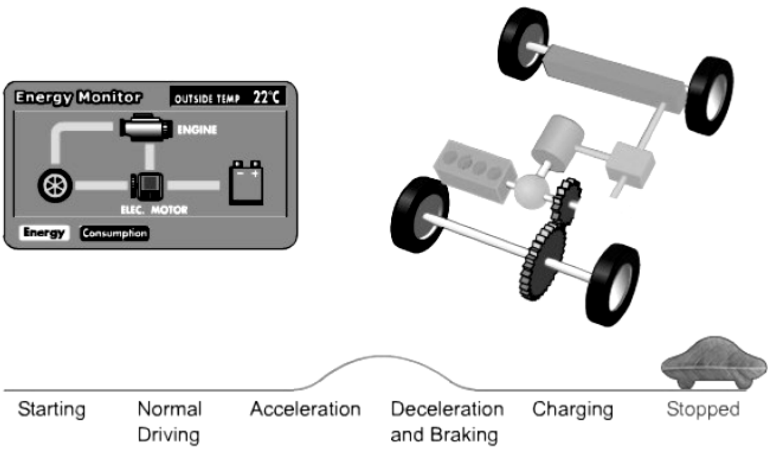


Fig. 2.144 HEV driving circumstances during stopping [DRIESEN 2006].

Further optimising of the ICE operating range is necessary so as to achieve optimum hybrid system energy efficiency. As a result, fuel economy during medium- and high-velocity constant running, in particular, could be improved.

Figure 2.145 shows ICE braking and the fluidical brakes' braking allocation [THS II 2004].

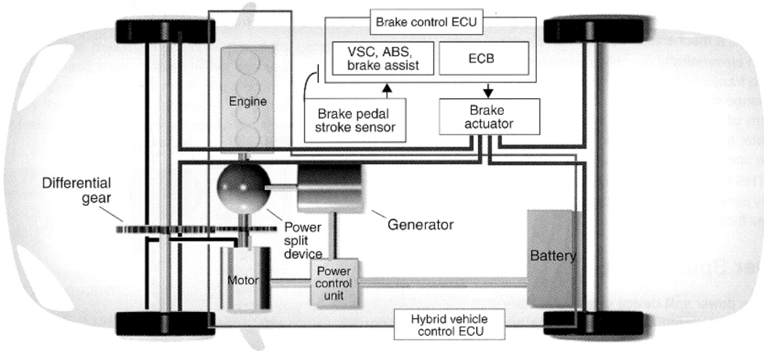


Fig. 2.145 ICE braking and fluidical (hydraulical) brakes' braking allocation [Toyota Hybrid System –THS II].

A regenerative **brake-by-wire** (BBW) **four-wheel-braked** (4WB) dispulsion mechatronic control system is used that, during ICE braking and HEV's braking using the brake foot pedal, operates the E-M motor as a M-E generator, converting the HEV's kinetic mechanical energy into electrical energy that is used to charge the CH-E/E-CH storage battery.

The mechatronic control system is particularly effective in recovering kinetic mechanical energy during inner-city driving, where driving patterns of repeated acceleration and deceleration are common.

When the brake pedal is being used, the mechatronic control system controls the coordination between the fluidical brake of the ECB and the regenerative brake and preferentially uses the regenerative brake, thereby recovering energy, even at lower values of vehicle velocity.

Furthermore, by improving the performance of CH-E/E-CH storage battery input, more electrical energy is recovered.

Additionally, by reducing the friction loss in the DBW 2WD propulsion mechatronic control system, such as in the transmission, the mechanical energy that used to be lost as a driving system loss during deceleration is now recovered, significantly increasing the total amount of recovered kinetic mechanical energy.

Application of regenerative braking improves stopping power and, incorporated with a BBW AWB dispulsion mechatronic control system, provides a better brake pedal for the driver. As an example, in Figures 2.146 and 2.147, are shown indispensable components of the Toyota *Prius* are shown, including the drivetrain or powertrain as well as its DC-AC/AC-DC macrocommutators and CH-E/E-CH storage battery, respectively [WALKER 2006].

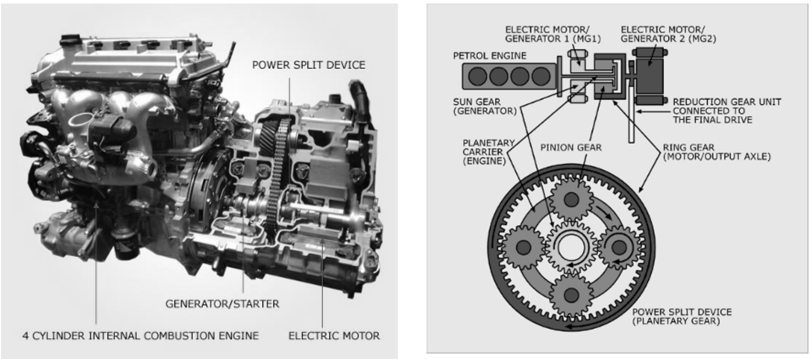


Fig. 2.146 Indispensable components of the Toyota *Prius* drivetrain or powertrain [http://www.cleangreencar.co.nz; WALKER 2006].

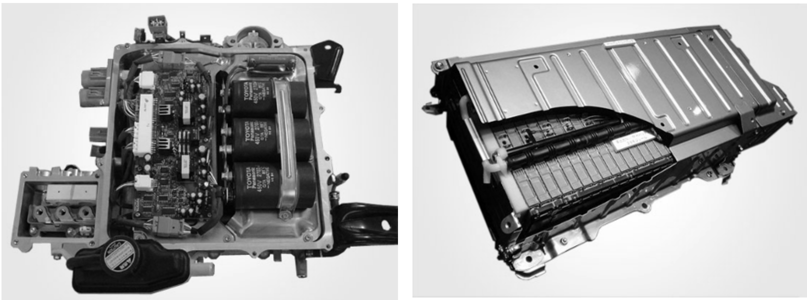


Fig. 2.147 Toyota *Prius* DC-AC/AC-DC macrocommutator (DC-AC inverter/AC-DC rectifier) and *NiMH* storage battery [http://www.cleangreencar.co.nz; WALKER 2006].

The Toyota *Prius* powertrain and drivetrain (see Fig. 2.146) contains three basic components, namely:

- 1.500 cm^3 petrol ICE, 56 kW:
  - Atkinson thermodynamic cycle (vs. Otto);
  - 34 % efficient at 10 kW (13.5 hp).
- Two DC-AC/AC-DC macrocommuator IPM motors/generators:
  - MG1, 18 kW;
  - MG2, 30 kW.
- A planetary gear that allows a continuously variable drive ratio.

The Toyota *Prius* DC-AC/AC-DC macrocommutators and CH-E/ E-CH storage battery (see Fig. 2.147) contains two basic components, namely:

- Two DC-AC/AC-DC macrocommutators (DC-AC inverters/AC-DC rectifiers) matched to E-M/M-E motors/generators:
  - 50 kW total at 500 V_{DC};
  - Liquid cooled under bonnet.

- NiMH storage-battery pack;
  - Nominal 274 V_{DC}, 6.5 Ah (1.8 kWh)
  - 20 W rating at 50 % SOC;
  - Operated between 40-80 % SOC for lifetime (0.7 kWh);
  - Complete pack 54 kg including all management, packaging;
  - Toyota data demonstrates 290,000 km without degredation.

2.8.8 TTR HE Transmission Arrangements for the HE DBW AWD Propulsion Mechatronic Control System

A **through-the-road** (TTR) HE transmission arrangement for the HE DBW AWD propulsion mechatronic control system consists of separated power trains that are connected to each other by means of the road or ground surface and, normally, they can operate collectively and simultaneously. The ECE or ICE and/or the auxiliary **electrical energy stores** (EES) and **electrical energy boosters** (EEB) are regarded as individual units.

The application of the HEV's electrical power boosting with low **specific fuel consumption** (SFC) and low **pollutant emission capability** (PEC) in which power can be transmitted directly from the ECE or ICE and/or the auxiliary EEBs, has the capability of power sharing between them as well as turning the ECE or ICE on and off for auxiliary electrical power boosting in conjunction with the HEV's high-accelerating starting, great gradient ability (hill climbing), high-velocity passing, and high-deceleration anti-torque emergency braking; or for auxiliary power boosting the HEV's auxiliary EES in conjunction with the HEV's wheel-driven EEB recharging and high-deceleration regenerative braking and/or cornering (pivot skid steering).

However, because of the ECE or ICE is frequently in operation, liquid fuel constitutes a substantial fraction of the total energy used. In addition, the application of an onboard microprocessor-based highest level HEV controller (commander) for dual mechatronic control of an ECE or ICE and auxiliary EESs has opened up wide possibilities for improving fuel saving.

Many demands are made on equipment and auxiliary electrical power boosting methods used for HEVs.

Operational economy has become increasingly important with the growing costs of fossil fuel. It has not become profitable to invest in HEVs as an alternative to, or replacement of, existing advanced vehicles.

TTR HE Transmission Arrangement Design Philosophy - A TTR HE transmission arrangement is one in which at least one of the onboard EESs deliver electrical energy. Practically, it is being done with only two onboard EESs and therefore in this section, the author considers only these versions in which there are fossil fuels for the ECE or ICE, and the auxiliary EES that is the CH-E/E-CH storage battery for the auxiliary EEBs.

EEBs that is AC-DC/AC-DC macrocommutator-based brushless type M-E/ E-M dynamotors (generators/motors) having the highest possible angular velocity for a given application, are preferable since they are smaller in size and lighter in mass, and have a higher efficiency and power factor. EESs that are CH-E/E-CH storage batteries are maintained sufficiently charged to boost the ECE or ICE power for high-acceleration, hill climbing, and high-velocity passing.

Thus, the TTR HE transmission arrangement design philosophy is based on using electricity as the remarkable *'artificial fuel'*, with fossil fuel being consumed only to meet the requirements that the pure auxiliary EEB cannot.

Hence, the initial preferred strategy is pure auxiliary EEBs operating at certain output power, then the ECE or ICE is turned on to complete the operation (with an ECE or ICE powertrain used, if required, for mechanical energy boosting). This strategy is expected to result in substantial fossil fuel saving over a comparable conventional ECE or ICE engine powered vehicles because a substantial percentage of normal works can be satisfied by purely E-M operation or with an electrical energy boosting.

The potential fossil fuel saving by the HEVs may be realised if there is an appropriate mechatronic control strategy to govern the function of each component of the split H-E transmission.

<u>*Description of the TTR (Split) HE Transmission Arrangement*</u> - After extensive work of various HE transmissions and wheel arrangements (total number of wheels × total number of driving wheels), as shown in Figure 2.148, were chosen for the HEVs: *DIOTA TETROTA, HEXOTA, OCTOTA* and so on.

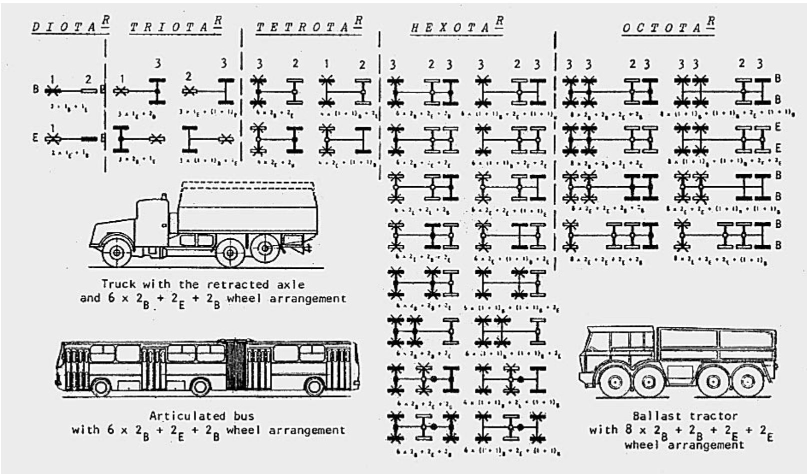


Fig. 2.148 Various TTR HE transmission arrangements:
1 – steering and driving axle; 2 – ICE propelled driving axle; 3 – EEB propelled driving axle;
E – engine propelled wheel; B – booster propelled wheel
[FIJALKOWSKI 1985B].

The main components are as follows:

- ECE or ICE (automotive gas turbine; the Diesel, Otto, Stirling, Wankel engine);
- Electrical energy store – EES (onboard CH-E/E-CH storage battery);
- Electrical energy booster – EEB (AC-DC/DC-AC macrocommutator-based brushless type M-E/E-M dynamotors mechanically connected by means of M-M differential to the driving wheels; DC-AC/AC-DC macrocommutator-based brushless-type E-M/M-E dynamotorised wheels);
- HEV controller (onboard microprocessor-based highest-level **vehicular controller** (VC) , i.e., vehicular commander).

The automotive ECE or ICE and the auxiliary EEBs are mounted on separate power trains, but are mechanically connected to each other, to the output traction by means of the power-splitting natural track, that is, the road or ground surface. The auxiliary EEBs are always rotating when the HEV is running (excluding EEBs connected to the retracted axles that are lifted). They recover most of the excessive power from the ECE or ICE powertrain, thus increasing efficiency, power, and torque multiplication at low values of vehicle velocity. For application where high stall torque is not required, the multi-power train split HE transmission arrangement (Figure 2.143) can be converted to a simplest dual- or single-powertrain split HE transmission arrangement by the omission or exchange of some of the parts or components in a modular HE transmission arrangement. Locating the E-M/M-E motor/generator at the axle not driven by the ECE or ICE can also make available a DBW AWD propulsion mechatronic control system, while reducing mass and inertia by removing the power take-off unit and propulsion shaft indispensable in conventional DBW AWD propulsion mechatronic control systems.

Experimental Proof-of-Concept TTR HE Transmission Arrangement for HEV – TETROTA - In the HEV field, an example study may be represented by the experimental proof-of-concept TTR HE transmission arrangement for the HEV with a $4 \times 2_B + 2_E$ wheel arrangement conceived by the author named *TETROTA*. Figure 2.149 is a simplified representation of the overall TTR HE transmission arrangement [FIJALKOWSKI 1985B].

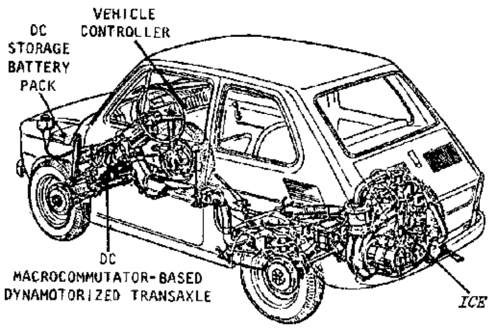


Fig. 2.149 TTR HE transmission arrangement for the HEV Polski FIAT *125p – TETROTA* [FIJALKOWSKI 1985B]

As shown, it may be designed for HEVs and the highest, in order of importance, components of split HE transmission arrangements are:

- ❖ ECE or ICE and M-M transmission for a RWD HEV (for example, Polski FIAT *126p*) – drive is taken from the M-M clutch by an overhead shaft in the M-M transaxle unit to the MT gear trains, then forward to the final-drive unit; this is coupled to the wheel hubs through jointed drive shafts; similar M-M transmission arrangements are used in front ECE or ICE-ed automotive vehicles;
- ❖ AC-DC/DC-AC macrocommutator-based M-E/E-M dynamotorized transaxle - A brushless AC-DC/DC-AC macrocommutator hyposynchronous (induction) squirrel-cage-rotor M-E/E-M dynamotor with an integrated-matrixer macrocommutator, microprocessor-based lower-level macrocommutator controller, and higher-level propulsion controller, and limited-slip M-M differential in the common case, on the same axis as the drive wheels and having a single oil system for cooling and lubrication;
- ❖ **Vehicular controller** (VC) - An on-board microprocessor-based highest-level HEV controller i.e., HEV commander, that integrates data from all HEV mechatronic control systems, controls HEV performance and looks after safety.

The structural and functional block diagram shown in Figure 2.150 depicts the TTR HE transmission arrangement of components in greater detail [FIJALKOWSKI 1985B].

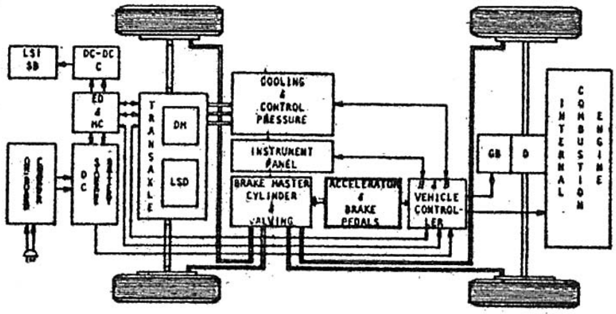


Fig. 2.150 Structural and functional block diagram of the HEV Polski FIAT – *TETROTA* [FIJALKOWSKI 1985B].

The electrical energy flows from the auxiliary EES (onboard CH-E/E-CH storage battery) through **emergency disconnect and main contactors** (ED&MC) to the E-M transaxle AC-DC/DC-AC macrocommutator squirrel-cage-rotor hyposynchronous (induction) M-E/E-M dynamotor that propels the wheels through the co-axial, M-M transaxle's limited slip M-M differential.

The microprocessor-based lower-level macrocommutator controller and highest-level propulsion controller of the transaxle's macrocommutator dynamotor perform the closed-loop macrocommutator-based M-E/E-M dynamotor control functions in accordance with torque commands received from the onboard microprocessor-based highest-level controller, i.e., the HEV commander.

The highest-level HEV controller acts as the modern microcomputer-based control centre for all of the new concept HEV functions - monitoring driver demands through the shift lever, accelerator and brake foot-pedal position signals, and controlling transmission shifting of the ICE propelled axis and regenerative braking operations, as well as the HE DBW 4WD propulsion mechatronic control system '*status quo*', display and bookkeeping functions.

The mechatronic control, monitoring, and automation functions have been integrated into a hierarchical microcomputer-based mechatronic control system.

Protective functions are implemented in a separate system that co-operates with the microcomputer-based mechatronic control system. For this tri-mode HE DBW 4WD propulsion mechatronic control system, the entire system approach centres on the new concept of the integral AC-DC/DC-AC macrocommutator-based dynamotorised transaxle shown in Figure 2.151. This essentially replaces the conventional dynamotor/transaxle assembly of a conventional **front-wheel-drive** (FWD) HE DBW 4WD propulsion mechatronic control system.

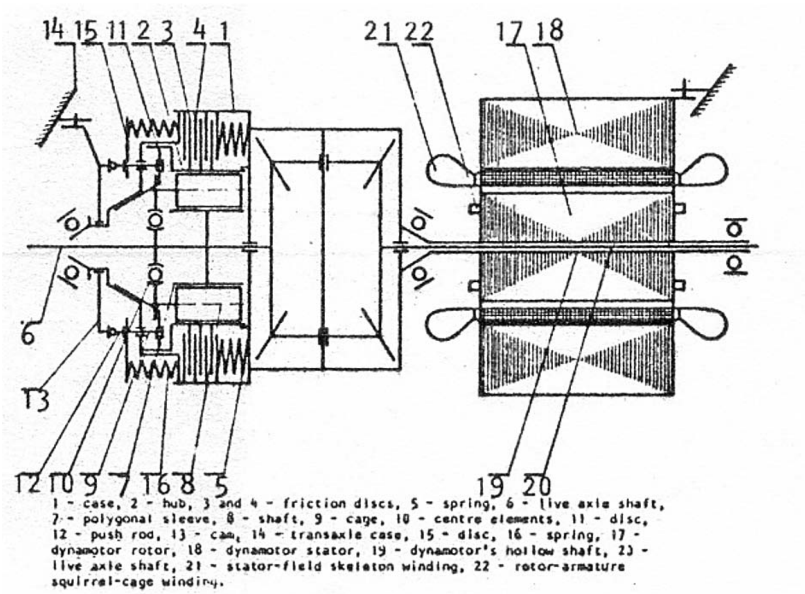


Fig. 2.151 Integral AC-DC/DC-AC macrocommutator dynamotorised transaxle [FIJALKOWSKI 1985B, 1990].

The brushless AC-DC/DC-AC macrocommutator hyposynchronous (induction) squirrel-cage rotor dynamotor (Fig. 2.152) that consists of just a stator and a rotor, has a hollow dynamotor shaft with an M-M differential case placed on the end of the shaft to serve as the input for the limited slip M-M differential [FIJALKOWSKI 1985B, 1987].

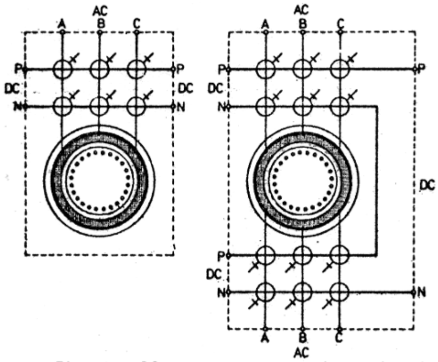


Fig. 2.152 Brushless-type AC-DC/DC-AC macrocommutator-based hyposynchronous (induction) squirrel-cage-rotor dynamotor [FIJALKOWSKI 1985B; 1987].

The AC-DC/DC-AC macrocommutator-based brushless-type dynamotorised transaxle has the following advantages [FIJALKOWSKI 1985B]:

- ❖ It functions automatically and is very rapid (during starting and slipping, the wheel can perform maximum *1* revolution);
- ❖ It fully utilizes the forces of wheel adhesion;
- ❖ It does not lead to the hazard of destructive transaxle components operating overloads);
- ❖ It does not demand special cooling and lubrication oils;
- ❖ It has great durability.

Figure 2.153 shows the main functions and signal routes of the transaxle's brushless AC-DC/DC-AC macrocommutator squirrel-cage rotor asynchronous (induction) dynamotor [FIJALKOWSKI 1985B, 1987, 1996A].

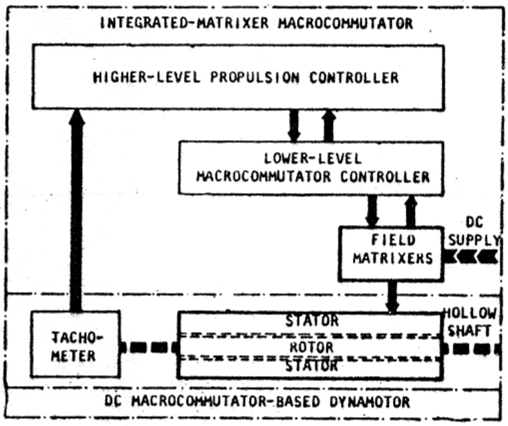


Fig. 2.153 Main functions and signal routes of the transaxle's AC-DC/DC-AC macrocommutator squirrel-cage rotor asynchronous (induction) dynamotor [FIJALKOWSKI 1985B].

The mechatronic control equipment is divided into a *'Higher-Level Propulsion Controller'* and a *'Lower-Level Macrocommutator Controller'*. Both sets of equipment are located in the macrocommutator housing.

The macrocommutator controller incorporates circuits for controlling and monitoring the stator-field **application-specific integrated matrixer** (ASIM) as shown in Figure 2.152). In principle, the input signal to the macrocommutator controller is a torque reference (set point) that is compared with a torque signal obtained by means of suitable control of stator-field ASIM.

The propulsion controller incorporates circuits for controlling and monitoring the transaxle driven by the AC-DC/DC-AC macrocommutator dynamotor. The control mode used is angular velocity control. The reference (set point) for the controlled variable is formed in the onboard microprocessor-based highest-level HEV controller (see Figs 2.150 and 2.153).

The HEV controller that monitors and directs the specific operation of the entire HE DBW 4WD propulsion mechatronic control system is an onboard microprocessor-based configuration that offers substantial advantages.

It allows considerable flexibility in the configuration of the HE DBW 4WD propulsion mechatronic control system, with changes required to modify mechatronic control system response easily implemented. For instance, HEV *TETROTA* response to accelerator foot-pedal input can be adapted to match any desired profile without hardware modifications.

The HEV controller (HEV commander) also senses required torques and angular velocity of the ICE powertrain's joined drive shafts of the mechatronic control system and can set the throttle opening, vary the transmission ratio (if necessary), control the transmission M-M clutch, and shut the ICE down as a function of various inputs.

The HEV controller safety logic must meet the requirements that have led to a fail-safe system that may '*get you home*' under reduced power in the case of failure and may shut the ICE or EES down under the conditions where a failure constitutes a safety hazard.

The HEV controller controls ICE loading to keep it at the angular velocity associated with commanded output power. Usually, the ICE would be operated at full throttle for maximum efficiency and its crankshaft angular velocity controlled by varying the excitation applied to the stator-field winding of an AC-DC/DC-AC macrocommutator dynamotorised transaxle.

The AC-DC/DC-AC macrocommutator dynamotorised transaxle has proved ideal for rough-terrain driving. The built-in automatic mechatronic controls relieve the HEV *TETROTA* driver from deciding when to change gears or whether one of the wheels is about to slip. The HEV controller carries out the throttle commands of the driver in a smooth and continuous way.

It automatically detects impeding wheel slip on each of the drive wheels (there are four on the HEV *TETROTA*) and removes power from any wheel that starts to slip, usually before the driver has even noticed it.

The HEV controller (HEV commander), caters for eight different modes of the HE DBW 4WD propulsion mechatronic control system operation [FIJALKOWSKI 1985B]:

- ❖ EEB alone drive – during this mode of operation, the EEB (the AC-DC/DC-AC macrocommutator dynamotor) is acting as a DC-AC macrocommutator propulsion motor – the HE DBW 4WD propulsion mechatronic control system is not specially designed for lengthy operation in this mode; however a limited range is necessary for use in pollution or noise sensitive areas or after breakdown of ICE;
- ❖ ICE starting – during starting, the EEB is acting as a DC-AC macrocommutator starter motor for the ICE through the power-splitting natural track;
- ❖ ICE and EEB drive – during this mode of operation, the EEB is acting as a DC-AC macrocommutator booster motor to the ICE – this HE DBW 4WD propulsion mechatronic control system operation mode provides power for fast acceleration, hill climbing, and limited high-speed passing and cruising;
- ❖ ICE providing drive with EEB acting as a AC-DC macrocommutator charger generator generating – this mechatronic control system operation mode provides ICE power for low vehicle velocity cruising (the HEV *TETROTA* has a cruising vehicle velocity of 80 km/h) with excess power being used for EES (onboard CH-E/E-CH storage battery recharging);
- ❖ ICE alone drive – the HE DBW 4WD propulsion mechatronic control system is not specially designed for lengthy operation in this mode; however a limited range is necessary for use after breakdown of electrical components;
- ❖ HEV's regenerative normal braking – during HEV normal-deceleration, the EEB, acting as an AC-DC macrocommutator charger generator, is put into the charging mode to recover HEV kinetic mechanical energy;
- ❖ HEV's anti-torque emergency braking – during HEV high-deceleration, the EEB, is acting as a DC-AC macrocommutator dispulsion (anti-propulsion) motor supplied by the EES (onboard CH-E/E-CH storage battery) – this mechatronic control system operation mode provides power for fast-deceleration emergency braking in the case of an accident;
- ❖ **Electrical energy charger** (EEC) charging – the EES, that is the onboard CH-E/E-CH storage battery, may be recharged using onboard EEC with the HEV stationary which can be necessary after a pure electric operation.

The mode of operation and control of the ratio of ICE powertrain power to EEB powertrain power may be achieved by linking the HEV controller directly to the HEV's accelerator foot-pedal. The throttle position, at which the onboard HEV controller switches the EEB (AC-DC/DC-AC macrocommutator dynamotor) from motoring to generating (charging) mode (*Turning Point*) and the ratio of ICE powertrain power to EEB powertrain power for any particular throttle position, can be selected for any particular power management strategy. Both strategies, either for the environmentally favourable HE DBW 4WD propulsion mechatronic control system or for the fuel-saving favourable hybrid, are accomplished with the same propulsion configuration.

The desired target tractive effort value is determined by the accelerator foot-pedal and transmitted by the onboard HEV controller to the ICE and the EEB. The function of the on-board microprocessor-based HEV controller is to adapt the interaction of ICE and EEB to the desired propulsion conditions. By changing the mechatronic control algorithm, the environmentally favourable HE DBW 4WD propulsion mechatronic control system becomes the fuel-saving favourable hybrid.

NB: The majority of conventional parallel HE DBW 4WD propulsion mechatronic control system versions as designed as fuel-saving favourable hybrids [FIJALKOWSKI, 1985B, 2986, 1995A, 2000C].

A simplified representation of the overall split HE DBW 4WD propulsion mechatronic control system versions with $4 \times 2_B + 2_E$ and $4 \times (1 + 1)_B + 2_E$ wheel arrangements is shown in Figure 2.154 [FIJALKOWSKI 1985B]. For instance, the latter version has two **steered, motorised and/or generatorised wheels** (SM&GW) at the front end. Each has the rating power of 35 kW and a tractive effort of 180 kN.

NB: It has been proved that the rolling resistances of a driving wheel are lower than in the case of a free rolling wheel.

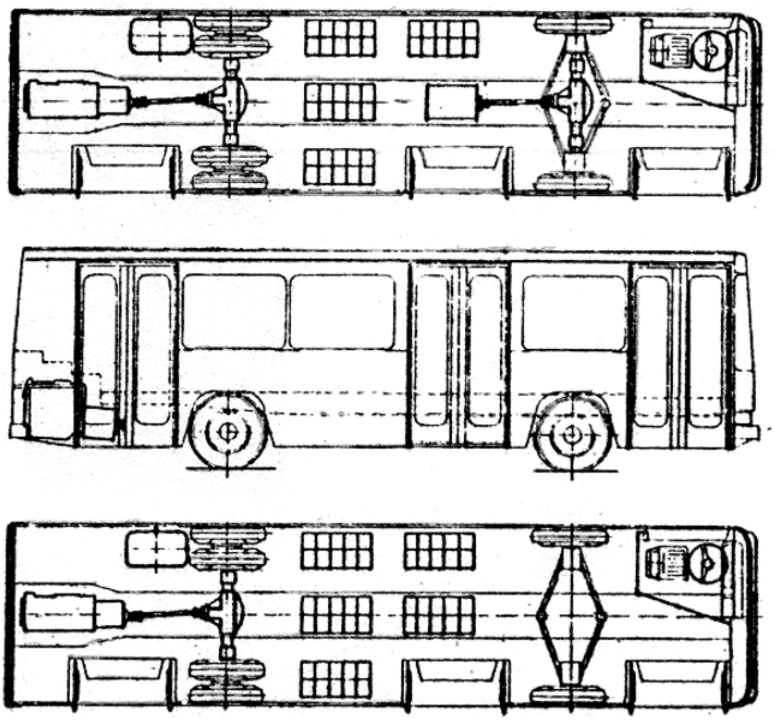


Fig. 2.154 Simplified representation of the overall HE DBW 4WD propulsion mechatronic control system version with $4 \times 2_B + 2_E$ and $4 \times (1 + 1)_B + 2_E$ wheel arrangements [AUTOSAN *H10 – Hybrid*; FIJALKOWSKI 1985B].

An alternative split HE DBW 4WD propulsion mechatronic control system version with a $4 \times 2_B + 2_E$ wheel arrangement has the following structure (See Fig. 2.155) [AR&C 1990].

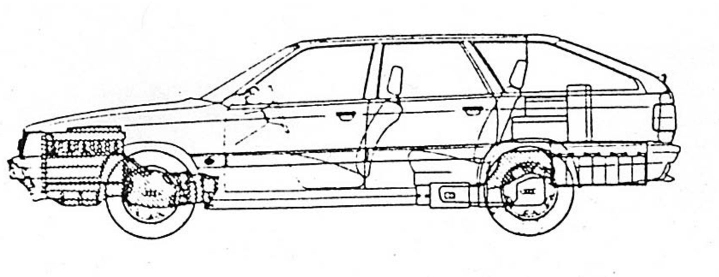


Fig. 2.155 TTR HE DBW 4WD propulsion mechatronic control system version with a $4 \times 2_B + 2_E$ wheel arrangement [AUDI's *Duo Hybrid*; AR&C 1990].

In designing the TTR HE DBW 4WD propulsion mechatronic control system, the drive shaft connecting the **rear-wheel drive** (RWD) differential may be removed to the forward-mounted ICE, and substituted with a direct drive, 9.4 kW (12.6 hp) E-M/M-E motor/generator.

Approximately half of the cost is contributed by a high-performance traction nickel-cadmium (NiCd) storage battery that gives an all-electric range of about 50 km (30 mi) at velocity values of 50 km/h (30 mph).

The traction NiCd storage battery is located under the rear floor of the AEV at the side of the fuel storage tank.

The E-M drive is turned on by adjusting the transmission to '*neutral*', pressing a button signed '*E*' and turning off the ignition key. In the E-M drive mode, a miniature EMP compressor maintains the fluidical systems also operating.

Turning on the ICE without driver intercession disconnects the E-M drive system. Even if the drive units cannot be operated simultaneously, the ICE can and does charge the storage battery while it is running.

The undersized, no-maintenance traction NiCd storage battery only takes three quarters of fully-recharging, because the E-M drives is not in continuous use. Another, alternative split HE DBW 4WD propulsion mechatronic control system's version with a $4 \times 2_B + 2_E$ wheel arrangement has the following structure (see Fig. 2.156) [NISSAN 2002A]:

Both simple and light in mass, the split HE DBW 4WD propulsion mechatronic control system delivers economy for normal city driving, but also adequate $4 \times 2_B + 2_E$ wheel arrangement abilities for weekend use too. The mechatronic control system consists of a RWD unit comprising an E-M motor, M-M clutch and reduction gear, an M-E generator that serves as the **electrical energy source** (EES) for driving the E-M motor, and a 4WD control unit that manages the propulsion system.

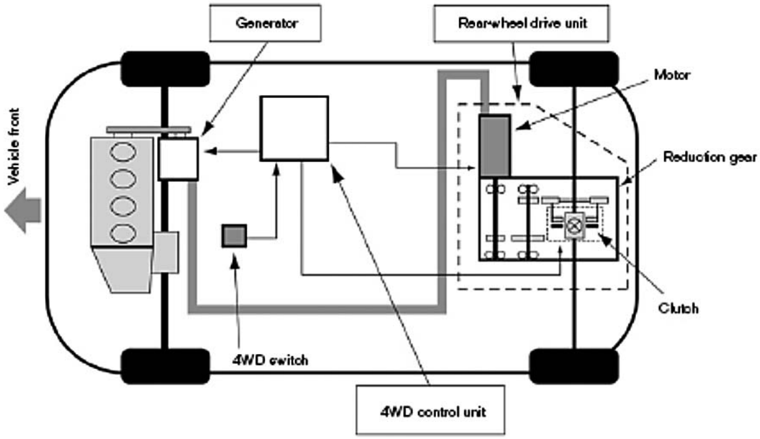


Fig. 2.156 TTR HE DBW 4WD propulsion mechatronic control system version with a 4 × 2_B + 2_E wheel arrangement [Nissan's *YANYA*; NISSAN 2002A].

If the front wheels slip, the 4WD control unit activates the M-E generator to generate electrical energy for functioning the E-M motor installed at the rear of the vehicle. The mechanical energy created by the motor is shifted by means of the clutch to the rear wheels. For the duration of normal driving, the clutch of the RWD unit is disengaged to create a DBW 2WD propulsion mechatronic control system for more economical driving. Because the rear-mounted motor drives the rear wheels, there is no need for a '*propeller shaft*' that creates 4WD capability without sacrificing interior space. Moreover, this approach also provides a lighter DBW 4WD propulsion mechatronic control system, thereby contributing to better fuel economy as well.

2.8.9 Conclusion

Currently automotive scientists and engineers face two major crises: the problems of energy and pollution. The HEV concept is the finest approach in killing two birds with one stone, as it saves liquid fuel energy by optimising the automotive vehicle's power and, simultaneously, it decreases pollution by controlling exhaust emission. It also allows the simplification of the M-M transmission and constructs it in a practical way for *'RBW'* or *'XBW'*. As a rule, HEVs are power-driven by the arrangement of conventional petrol (gasoline) or diesel ICE, that is PES, and CH-E/ E-CH storage battery, that is SES, which supply or absorb the E-M/ M-E motor/generator. ECE or ICE mechanical energy is used to operate wheels and generate the electrical energy used to drive the E-M motor while recharging the CH-E/E-CH storage battery. HEVs deliver up to 50% better fuel economy than conventional vehicles.

The ratios of use between ECE or ICE and E-M/M-E motor/generator varies are conditional on the HE transmission arrangements for the DBW AWD propulsion mechatronic control system. In view of the fact that a series HE transmission arrangement uses its ECE or ICE to generate electrical energy for the E-M motor to propel the driven wheels, The ECE or ICE and E-M/M-E motor/generator do an approximately identical quantity of work.

The development of a series HEV platform that exhibits the key technologies for marketable application, may involve the following three most important subjects:

- ❖ Intelligent energy management and mechatronic control technology based on series HE design for optimisation of ECE or ICE;
- ❖ DBW 4WD propulsion that may improve the efficiency through the E-M differential that substitutes for the M-M differential; wheel mechatronic control system that may enable 4WS SBW conversion with independent ABW 4WA suspension for omni-sensual direction of motion;
- ❖ Intelligent mechatronic control system for coordination of forward collision warning, obstacle avoidance, **stop and go** (S&G) cruise control, and intelligent information platform.

The objectives of R&D works may be as follows:

- ❖ The development of series HEV technology that may achieve a reduction of liquid fuel consumption by 30 – 40% and exhaust emission by 50 – 60%;
- ❖ DBW 4WD propulsion technology that may strengthen drivability and climbing ability with start-up acceleration increased from 0.3 *G* (that of conventional automotive vehicles) to 0.6 *G*, such that the acceleration time for 0 -- 100 km/h may be reduced by 15%.

Series HEV operation modes are as follows:

- ❖ M-E generator charges CH-E/E-CH storage battery;
- ❖ M-E generator turned off ;
- ❖ CH-E/E-CH storage battery supplies electrical energy to E-M motors or in-wheel-hub motors;
- ❖ E-M motors or in-wheel-hub E-M motors powered by both the M-E generator and the CH-E/E-CH storage battery;
- ❖ E-M motors or in-wheel-hub motors collect recyclable electrical energy for CH-E/E-CH storage battery.

In a parallel HE transmission arrangement where the E-M motor is used to enhance the drive given by an ECE or ICE, HEVs can generate better off-the-line acceleration. It uses the ECE or ICE as the major PES, with the E-M motor used to give assistance in the course of fast acceleration, hill climbing, and high-speed passing. Hence, the ECE or ICE is used much more than the E-M/M-E motor/generator. In a series/parallel HE transmission arrangement, a power split device shares the mechanical energy from the ECE or ICE. Consequently, the ratio of mechanical energy transmitting directly to the driven wheels and to the M-E generator is '*ad infinitum*' adjustable. In view of the fact, that the E-M motor may operate on electrical energy (when the latter is generated), the E-M motor may be used more than in a parallel HE transmission arrangement.

A TTR HE transmission arrangement uses the ECE or ICE as the major PES and the E-M/M-E motor generator individually for propelling the different driven-wheel axles. The TTR power-trains are connected to each other by means of the road or ground surface and normally they can operate collectively and simultaneously.

The ECE or ICE and/or the auxiliary EES and EEB are regarded as individual units. ECE or ICE HE transmission arrangements for the DBW AWD propulsion mechatronic control system have the following four features:

- ❖ Mechanical energy-loss attenuation – The HE transmission arrangement without driver intervention prevents the idling of the ECE or ICE (idling stop), thus decreasing the mechanical energy that would usually be dissipated;
- ❖ Mechanical energy recuperation and recover – The mechanical energy that would usually be dissipated as thermal energy (heat) during deceleration and braking is recuperated as electrical energy that is then used to power the starter E-M motor and the traction E-M motor;
- ❖ E-M motor assist – The E-M motor assists the ECE or ICE for the duration of fast acceleration;
- ❖ High energy efficiency operation mechatronic control – The HE transmission arrangement enlarges the HEV's overall energy efficiency by using the E-M motor to operate the HEV under operating circumstances in which the ECE or ICE's energy efficiency is extreme.

The series/parallel HE transmission arrangement has all of these features and for that reason gives both superior fuel efficiency and DBW AWD propulsion performance. Contemporary HEVs rely essentially on gasoline or diesel oil, but HEV can be designed to operate on a dominant assortment of liquid and gaseous fuels, including fossil fuels or a renewable alternative fuel such as bio-diesel oil or ethanol. HEVs necessarily mix a mechanical energy unit, an electrical energy storage system, and a propulsion system. Various arrangements or configurations are feasible.

The power unit may be an ECE or ICE or even FC. The energy storage system may be a CH-E/E-CH storage battery, ultracapacitor, ultrainductor or even ultra-flywheel. Propulsion may be delivered entirely from the E-M motor or from both the E-M motor and power unit.

Various automotive vehicle modifications cause better fuel economy for HEVs than with conventional vehicles.

If an ECE or ICE is used, the ECE or ICE can be smaller in size and lighter in mass because it shares the workload with the E-M motor.

The ECE or ICE can be optimised to operate within a speed range where fuel economy is greatest. HEVs normally use regenerative braking that slows the vehicle by bringing the kinetic mechanical energy under control converting to electrical energy and directing it to the storage battery pack, thus decreasing the energy waste when decelerating.

For the reason that HEVs have mixed arrangements, they are more complicated than either AEVs or conventional vehicles.

Maintenance schedules and the cost of parts and service are required to be greater than for other categories of automotive vehicles. Care requirements to be taken in transporting and refuelling whatever liquid or gaseous fuel is used to power the HEV.

For CH-E/E-CH storage batteries, manufacturers are using various interrupting systems in the high-voltage circuits that cut off the rest of the vehicle from the battery's voltage.

Extreme levels of electrical energy may be present in the storage battery pack, on the other hand, hence it should be considered with great care and recognized as a full fuel tank in an ECE or ICE automotive vehicle.

In the situation of accidents, emergency response personnel will need particular training to meet such hazards as exposure to high-voltage systems and probable leakage of flammable, toxic, or corrosive storage battery chemicals and/or fuel. HEVs are experiencing or exceeding the performance of conventional automotive vehicles. For the reason that they are two to three times as fuel efficient as conventional automotive vehicles, exhaust emissions per kilometre/mile are greatly decreasing. The variety of exhaust emissions rely on the by-products of the specific fuel used.

Contemporary HEVs that use petrol, cut exhaust emissions of greenhouse gases by a third to a half, although not-too-distant ones may reduce exhaust gas emissions by even more.

In most circumstances, HEVs get better fuel economy in four different modes. First, with a **specific fuel consumption** (SFC) (the storage battery pack and E-M motor), HEVs require a significantly minor ECE or ICE than conventional vehicles, and they can decrease their dependence on the ECE or ICE when it is minimum energy conversion efficient (for example, in low values of vehicle velocity and, stop-and-go traffic). Second, as battery electrical energy is accessible, ECEs or ICEs can be halted at idle, submitting a 5 - 10% enhancement in fuel economy. Third, HEVs use regenerative braking to secure a large amount of the energy subsequently lost in braking.

With an outsized storage battery pack and E-M/M-E motor/generator, supplementary energy can be recollected, but getting bigger the size enhances mass. Existing HE transmission arrangements can bring back the majority of the braking kinetic mechanical energy that yields in enhanced fuel economy benefits. Fourth, the majority of HEVs use supplementary energy-conversion-efficient E-M-F pumps that are attached to a major decrease in useful, but not an essential component loads.

In conclusion, HEVs with onboard ECEs or ICEs, for instance, instead of CH-E/E-CH storage battery AC-DC chargers used in AEVs, are supported by some means, as accepting electric propulsion in inner-city, and sustained propulsion with the ECE or ICE operating incessantly at optimum circumstances (that is, minimum pollution) for longer runs. HEVs may be in use until a significant increase in energy/mass ratio is attained by storage batteries.

Normally, HEVs have either an ECE or ICE, or even FCs that is mated to a motor/generator and a storage battery pack. These automotive vehicles are not fully dependent on their ECEs or ICEs or even FCs for all the mechanical energy they require to be in motion. That's the basic definition of an HEV, but the image becomes unclear when one become conscious that automotive manufacturers are developing HEVs with a extensive range of design options, and these have an effect on the feature of subsequent automotive vehicles.

In view of the fact that the majority of HEVs use an ECE or ICE, they can gain from several of the innovations being prepared from ECE or ICE technology. Otherwise, HEVs can be provided with a **compressed natural gas** (CNG), methanol, or hydrogen ECE or ICE.

In addition, HEVs have a variety of identical features that are the same as conventional auto-motive vehicles, for example: inner trim levels, spaciousness, heating and air conditioning systems, stereo/CD players, cruise mechatronic control, and so on.

While early HEVs are all minor automotive vehicles, most modern HEVs are powerfully built. There is no practical motivation why they cannot be recommended for all automotive vehicle categories. Up till now, in a difference of opinion over HEV advantages, current HEVs have significantly enhanced cost and are complicated, a reduced amount of acceleration, if the ECE or ICE is economised, superior mass, and problems about their long-term reliability. Their enhanced cost may preclude them from ultimately being overlooked by the automotive market.

Furthermore, they do not certainly surpass conventionally ECE- or ICE-powered vehicles. There are instances where conventional vehicles can attain identical or better petrol mileage (kilometreage) and/or exhaust gas emission ratings than HEVs, revealing problems over whether the advantages of HEVs are actually worth the cost. However, the comparative advantages of enhanced mileage vs. costs could be greater on larger '*gas-guzzling*' automotive vehicles, similar to **smart utility vehicles** (SUV) and large pickup trucks.

Ultimately, some consider HEVs to be springboards from recently petrol or diesel ICE-powered automotive vehicles to FCs and a hydrogen economy.

2.9 Propulsion Mechatronic Control Systems for Fuel Cell Electric Vehicles

2.9.1 Foreword

The principle of the **fuel cell** (FC) was discovered by the German scientist *Christian Schonbein* in 1838, and the first such unit was produced by the Welsh scientist *Sir William Grove* in 1843. Interest then appears to have lapsed until 1959, when a 5 kW FC was produced by British engineer *Francis Thomas Bacon*. Although a single FC normally produces a voltage of only 0.86 V_{DC}, the concept has more potential than conventional CH-E/E-CH storage batteries, and is particularly applicable to an automotive vehicle equipped with liquid oxygen and hydrogen. In a hydrogen/air FC, the metallic anode and cathode are normally separated by a **proton exchange membrane** (PEM). The anode is coated in a catalyst such as platinum, and fed with hydrogen. This breaks down into positively charged ions (protons), which pass through the PEM to the cathode, and negatively charged electrons, which can produce a current through an electrical load externally en route to the cathode. The cathode is supplied with oxygen (in the form of air), which combines with the hydrogen protons to produce hot water or steam.

The FC is thus a very clean form of power. In the case of a FC using a hydrocarbon fuel (such as diesel or methanol), the waste products are carbon dioxide and water.

The FC operates by generating electrical energy by combining hydrogen and oxygen, but this technology is not '*innovative*' as Sir *William Grove* in fact uncovered this process back in 1839. *"I am convinced that hydrogen and oxygen, the two elements that combine to form water, will one day – either together or as single entities – be an inexhaustible source of heat and light of an intensity of which coal is not capable."* wrote *Jules Verne* in '*The Mysterious Island*' in 1874.

A half-century later, in 1889, *Mond* and *Langer* used porous electrodes in a stack arrangement, similar to modern FC designs, to generate electrical energy. Seventy years after that, in 1959, alkaline fuel cells were used to power the *Allis--Chalmers* tractor – perhaps the first FC automotive vehicle.

ECE or ICE HE technology is a short-term key that can minimise, but not eliminate, the motorist's reliance on fossil fuel. There is an alternative FC HE technology that should be accessible by the 2010s that may eradicate reliance on renewable resources. FCs convert hydrogen and oxygen to electrical energy without experiencing a combustion process; by this means, effectively removing exhaust emissions. They also operate at much higher energy conversion efficiency than ECEs or ICEs, generating double the quantity of energy.

The **fuel cell electric vehicle** (FCEV) has been worked out with FC HE transmission arrangements that operate by using both FCs as the PES and a CH-E/

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_24,

E-CH storage battery as the SES in a ratio that is optimised for the operating circumstances of the automotive vehicle.

The application of the FC HE transmission arrangements lets the automotive vehicle obtain three times the energy conversion efficiency of an ECE- or ICE-powered vehicle. Besides, this environmentally-friendly HEV has a heat-pump air conditioning system that uses a refrigerant with no **hydro-fluorine-carbons** (HFC).

The FC, as shown in Figures 2.157, 2.158 and 2.159 [KAWATSU 2000; CRL 2003; DUNN-RANKIN 2004; FRASER ET AL. 2004], is a CH-E generator that produces electrical energy generated by the process of hydrogen and oxygen reacting to create water. This chemical reaction is the accurate contradictory of the electrolysis of water.

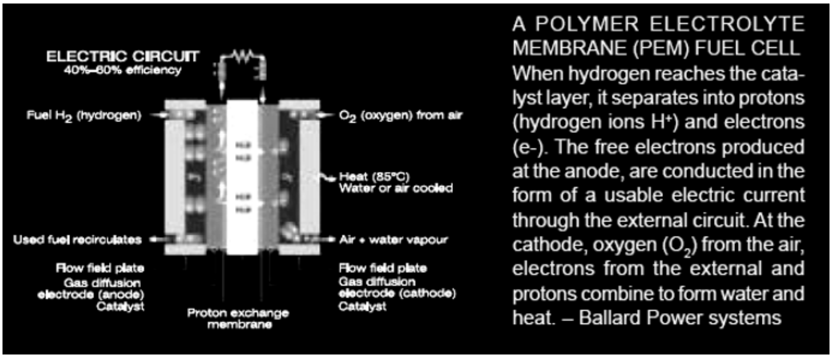


Fig. 2.157 Principle layout of the fuel cell (FC) [CRL Energy LTD; CRL 2003]

For the reason that the FC converts the chemical energy included in hydrogen (the fuel) and oxygen directly into electrical energy, it is not an area under discussion concerning restrictions of the *Carnot* cycle and, when hydrogen fuel is used, it can consequently realise a theoretical energy conversion efficiency of 83%. Besides, the FC can generate electrical energy so long as fuel is regularly delivered.

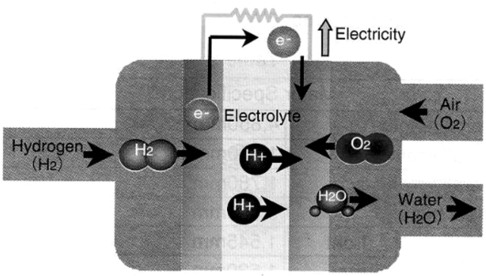


Fig. 2.158 Principle layout of the fuel cell (FC)
[Toyota Technical Review; KAWATSU 2000]

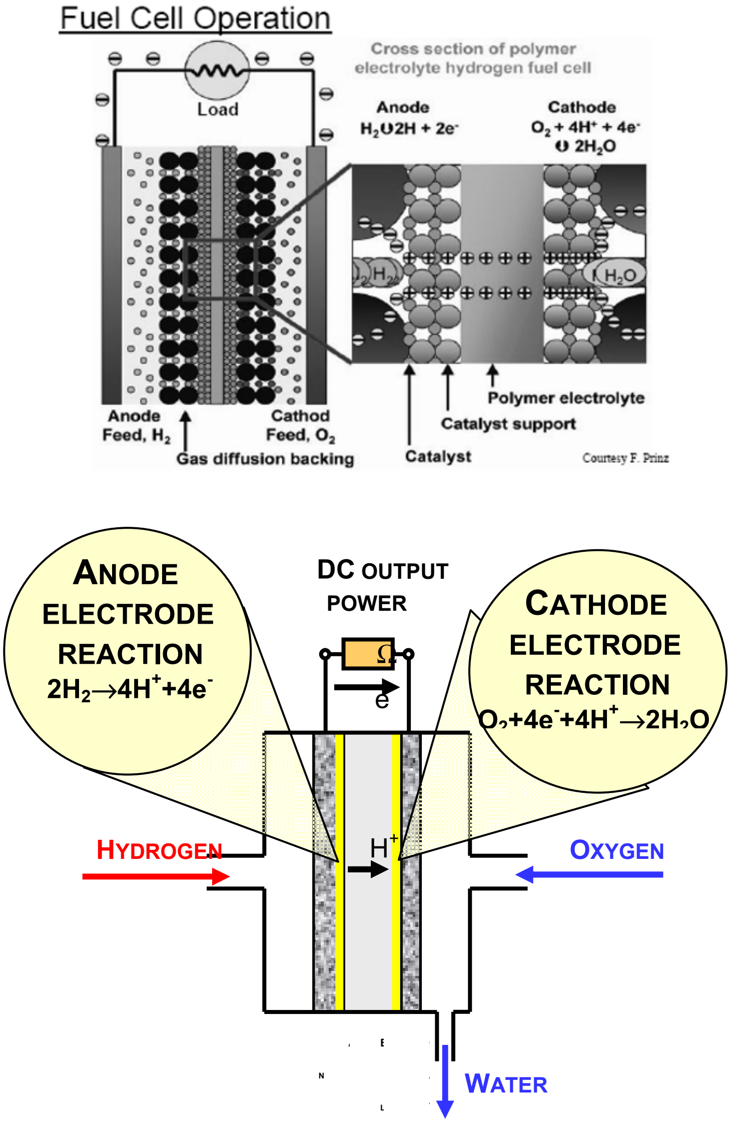


Fig. 2.159 Fuel cell (FC) operation
[F Prinz; DUNN-RANKIN 2004; FRASER ET AL. 2004].

However, with a FC of this category, the following advantages are feasible [KAWATSU 2000]:

- ❖ It would be possible to construct a FCEV vehicle with high-energy conversion efficiency and better fuel economy;
- ❖ For the reason that the FC uses hydrogen as its fuel, if the hydrogen could be contained on board the HEV, it would be possible to construct an actual ZEV whose entire exhaust emission would be water;
- ❖ It would also be possible to use hydrocarbon fuels, rich reformed gas that could be used as the fuel that operates the FC; there would consequently be no constraints on use of fuels usually used for ECEs or ICEs, for example, petrol and diesel oil.

Fuel cells can be classified into various different categories in relation to the differences in the electrolytes and fuels they use (see Fig. 2.160) [DUNN-RANKIN 2004].

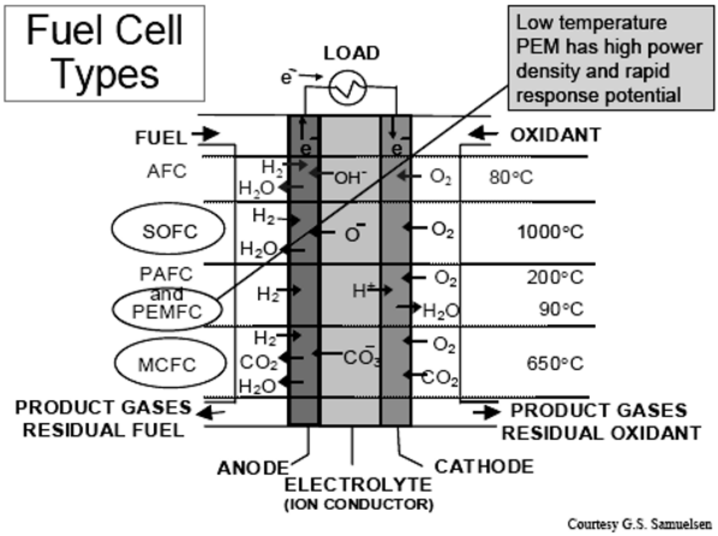


Fig. 2.160 Categories of the fuel cells (FC)
[GS Samuelsen; DUNN-RANKIN 2004].

In particular, the categories are the **solid oxide fuel cell** (SOFC), the **molten carbonate fuel cell** (MCFC), the **phosphoric acid fuel cell** (PAFC), the **polymer electrolyte fuel cell** (PEFC), the **alkaline fuel cell** (AFC), and the **direct methanol fuel cell** (DMFC). Of these, the PEFC, that has a fluoric electrolyte, has the following advantages for application in automotive vehicles [KAWATSU 2000]:

- ❖ The FC can be started with no trouble at normal temperatures its operating value is less than 373 K (100°C), consequently it is ideal for application where there would be recurrent starting and stopping;

❖ For the reason that it is possible to operate the FC at a high electric current density, it is ideal for application where compact size and high power output is needed;
❖ For the reason that the construction of the FC is uncomplicated and maintenance is unpretentious, it is appropriate for use by general customers;
❖ For the reason that the FC can be created from solid materials, it is ideal for application where there is a possibility of impact and vibration.

It should be remarked that the PEFC is also known as the **proton exchange membrane fuel cell** (PEMFC), the **ion exchange membrane fuel cell** (IEMFC), the **solid polymer fuel cell** (SPFC), or the s**olid polymer electrolyte fuel cell** (SPEFC).

The major component of this FCEV is the hydrogen storage tanks that use a hydrogen-absorbing alloy. The latter brings together the high hydrogen absorption properties that are distinctive of hydrogen-absorbing alloys with **body-centred cubic** (BCC) construction and satisfactory absorption and release properties that describe hydrogen-absorbing alloys as *Laves* phase construction [KAWATSU 2000].

Since the arrangement of ingredients and their virtual properties has been optimised, a fine, nanoscale metallic composition has been created. This had the consequence of obtaining better hydrogen storage capacity under normal values of temperature and pressure that had previously been an ineffective aim of BCC construction hydrogen-absorbing alloys, to about twice that of commercially available alloys.

It was also feasible to radically enhance the preliminary initiation and rapidity of hydrogen absorption and release. The performance of this hydrogen-absorbing alloy is shown in Figure 2.161 [KAWATSU 2000].

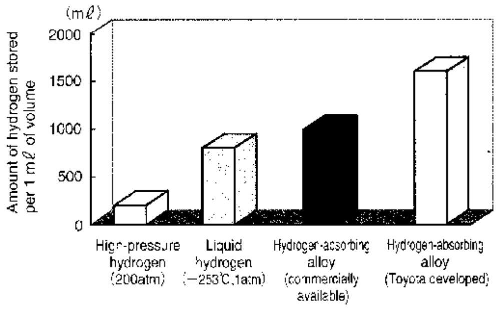


Fig. 2.161 Amounts comparison of stored hydrogen gas [Toyota Technical Review; KAWATSU 2000].

While evaluated at the same volume, the hydrogen-absorbing alloy can store about eight times the amount of gaseous hydrogen enclosed in a high-pressure cylinder. The FCEV with an onboard hydrogen storage device uses 100 kg of hydrogen-absorbing alloy and can store about 2 kg of gaseous hydrogen. The hydrogen storage device, the FC stack, and several supplementary components are mounted under the floor [KAWATSU 2000].

Thus, storing gaseous hydrogen is a dilemma, but the alternative storage techniques, liquid and solid, are also unsatisfactory.

The volume of the hydrogen fuel can be radically reduced if it is altered into a liquid, but to do so consequently necessitates substantial energy to cool the gas to 20 K (–25 °C). Metal alloy hydride storage might be used, but this technique only stores 1 -- 5% of hydrogen by mass, leaving substantial waste.

Recently, some automotive vehicle manufacturers have disclosed a technique to use sodium borohydride that can be liquefied in water with a catalyst to create hydrogen. This complicated technique vanishes behind sodium borate that must be cultivated and recycled. It is indeterminate whether this technology can be cost effective.

As a consequence of the storage dilemma and cost related with an emergent hydrogen infrastructure from a centralised refinery to a service station; some have recommended that reformers should be located on FCEVs, for the reason that there is a suitable petroleum infrastructure. However, there are various technical features with this initiative, namely [MADER AND GERTH 2004]:

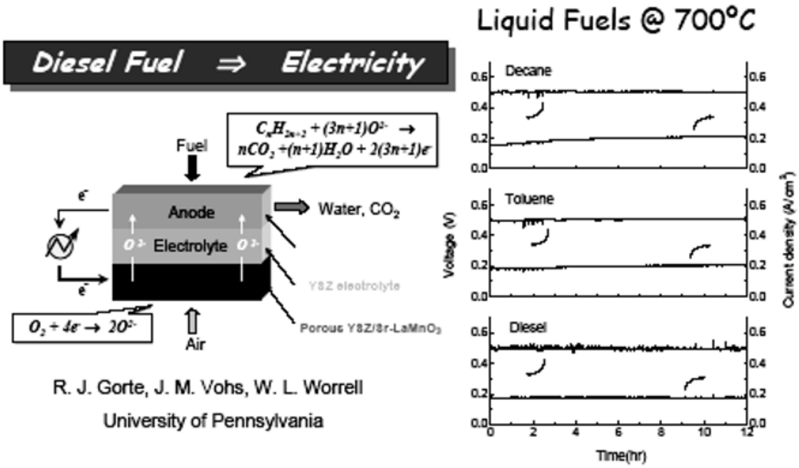
- Reforming techniques would cause emissions other than water vapour, consequently FCEVs would not become certified as ZEVs;
- Contemporary reformers are extremely large and complicated, consequently, the size of the paraphernalia must minimise using more efficient catalysts (so far to be disclosed), or by optimising and inventing minor heat exchangers;
- Onboard reformers must generate an adequate amount of hydrogen for fast start-ups and adjustable quick power requirements whilst generating little or no pollutants at a low cost;
- Petrol is a unproblematic fuel to reform, for the reason that it necessitates high temperature processing;
- Reformers must remove the sulphur content, detergents, anti-oxidants, and corrosion inhibitors detected in the hydrogen formed from petrol prior to storage in the FC stack;
- It might be more effective for refineries to produce a petroleum distillate that is ideal for FCs, but insufficient interest has been shown in this technique.

An alternative to petrol is methanol that can be effortlessly processed into a hydrogen-rich gas using steam or autothermal reforming, but it too suffers from a sulphur content dilemma and its carbon monoxide contaminates must be eliminated.

An alternative dilemma is that the world's methanol infrastructure only produces the equivalent of 6% of the petrol consumption. Substantial savings would be necessitated to produce and distribute methanol [MADER AND GERTH 2004].

Besides, a **direct electro-mechanical oxidation** (DECO) technology may be used for direct diesel fuel-to-electrical energy (electricity) SOFCs and PEMFCs as is shown in Figure 2.162 [NICKENS 2004].

SOFC Generator



PEMFC Generator

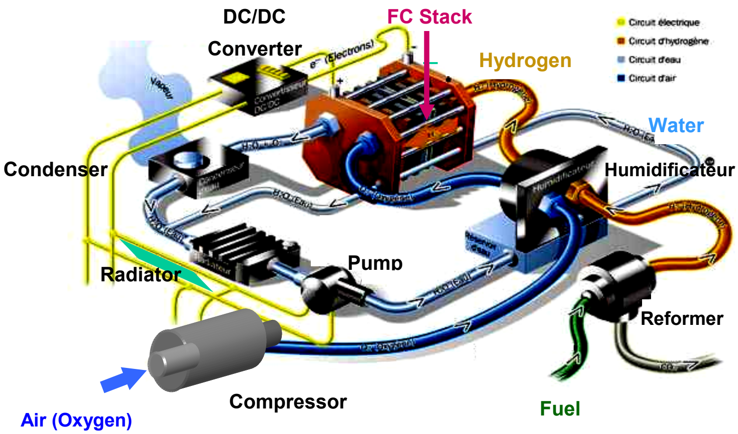


Fig. 2.162 Principle layout of the direct diesel fuel-to-electrical energy solid oxide fuel cell (SOFC) and proton exchange membrane fuel cell (PEMFC) generators [Office of Naval Research; NICKENS 2004 -- Top image; *PSA* – Bottom image].

In summary, the dilemma in emergent and promotion FCEVs is not only contingent upon inventing inexpensive, durable, more efficient FCs and realising a suitable storage medium, but also on the evolution of a hydrogen-based economy. Although some automotive manufacturers have presumed that onboard reforming of petrol or diesel fuels is not feasible, it is maybe too premature in FC technology research to eliminate this.

2.9.2 FC HE Transmission Arrangements for the HE DBW 2WD Propulsion Mechatronic Control System

As was previously mentioned, in principle the FC is an exceptionally uncontaminated energy conversion CH-E generator that may generate electrical energy using hydrogen and oxygen for fuel and create water as its exhaust gas emission.

On the other hand, when functional applications, predominantly automotive ones, are estimated, the dilemma occurs of how to keep the necessary hydrogen onboard a HEV. Two categories of FC HE transmission arrangements have been built-up for the HE 2BW DBW propulsion mechatronic control system.

The first category keeps hydrogen directly onboard, while the second category reforms hydrocarbon fuel onboard the HEV.

A principle layout of the FC HE transmission with a 4 × 2 wheel arrangement and onboard hydrogen storage device is shown in Figure 2.163 [KAWATSU 2000].

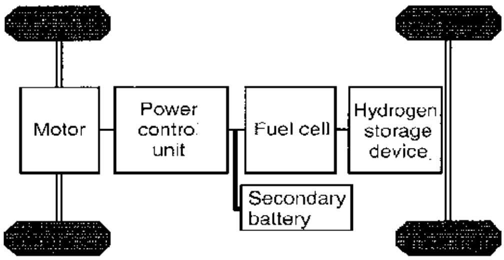


Fig. 2.163 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and onboard storage device [Toyota Technical Review, KAWATSU 2000].

A principle layout of the FC HE transmission with a 4 × 2 wheel arrangement and on-board methanol reformer is shown in Figure 2.164 [KAWATSU 2000].

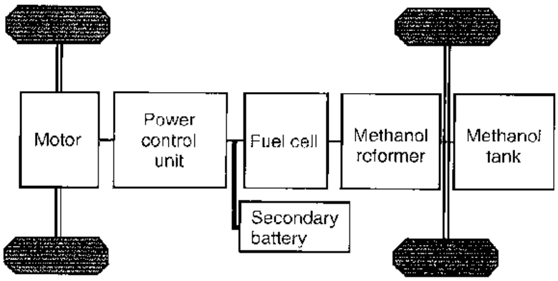


Fig. 2.164 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and onboard methanol reformer [Toyota Technical Review; KAWATSU 2000].

A particular attribute of the FC HE transmission with a 4 × 2 wheel arrangement and onboard methanol reformer is that it is a hybrid system that acts as a PES, that is, the **electrical energy source** (EES) forms a junction with a secondary CH-E/E-CH storage battery (for example, NiMH) that acts as a SES (an electrical energy shock absorber). This lets the FC HE transmission arrangement have continuous accurate mechatronic control over the sharing of electrical energy. It additionally allows the possibility to continuously operate the FC in the high-efficiency functional range. The methanol reformer is a small-scale chemical plant mounted in the HEV. It has been greatly compacted by connecting into a separate component, the discrete parts that develop the methanol reformer, incorporating the fuel vaporisation part, the reforming reaction part, and the CO_2 reduction part. It has also become feasible to get a better starting ability and responsiveness by reducing the thermal energy (heat) capacity of the methanol reformer. Start-up time has been reduced to under 3 min, and response time has been enhanced to less than 10 s. Besides, the reforming efficiency has been enhanced by using a catalyst. Principle layouts of the FC HE transmission with the 4 × 2 or 4 × 4 wheel arrangements and high-pressure gaseous hydrogen tanks are shown in Figures 2.165 – 2.170.

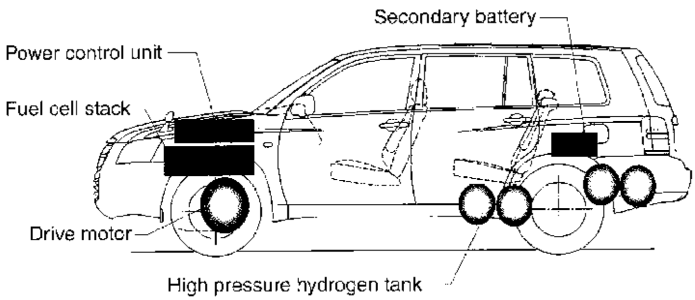


Fig. 2.165 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and high-pressure gaseous hydrogen tank [Toyota's FCHV-4; KAWATSU 2000].

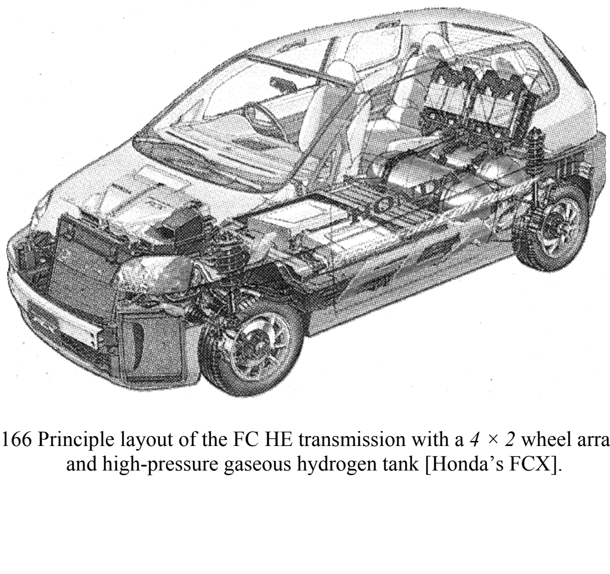


Fig. 2.166 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and high-pressure gaseous hydrogen tank [Honda's FCX].

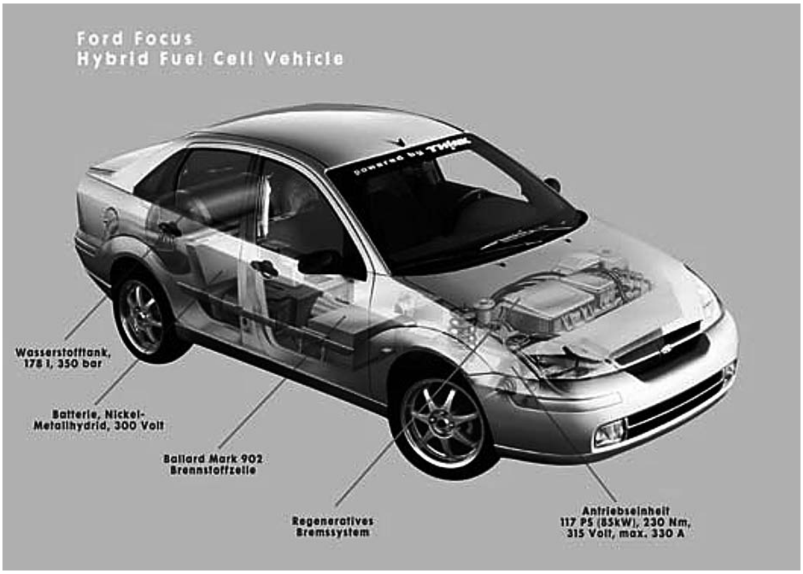


Fig. 2.167 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and high-pressure gaseous hydrogen tank [Ford's *Focus – Hydrogen*; MADER AND GERTH 2004].

Fig. 2.168 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and high-pressure gaseous hydrogen tank [FIAT's *Panda - Hydrogen*].

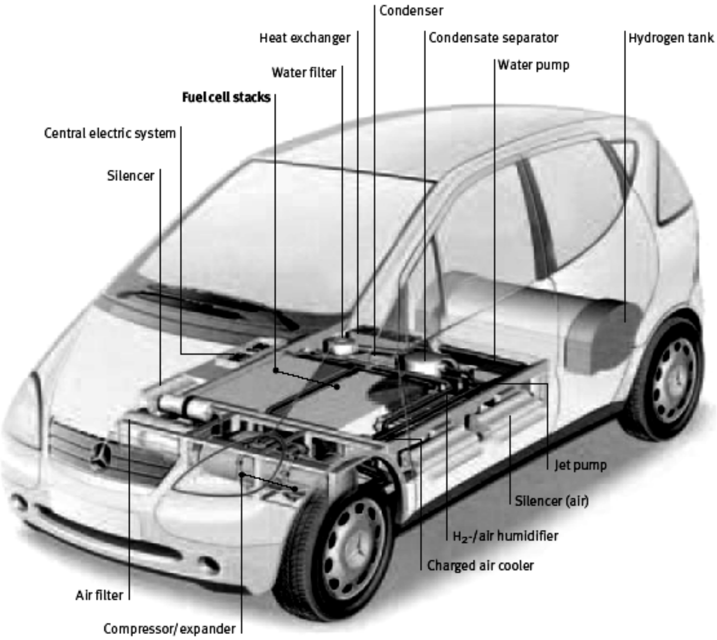


Fig. 2.169 Principle layout of the FC HE transmission with a *4 × 2* wheel arrangement and high-pressure gaseous hydrogen tank [DaimlerChrysler *NECAR 4*; LARSON 2003].

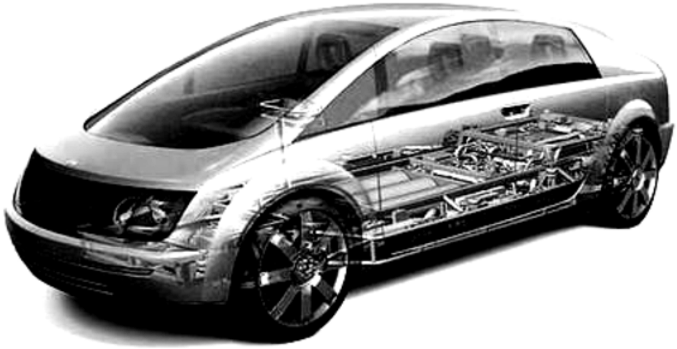


Fig. 2.170 Principle layout of the FC HE transmission with a *4 × 4* wheel arrangement and high-pressure gaseous hydrogen tank [GM's ***Hy**-Wire*; HAMILTON 2002].

In the FCEV shown in Figures 2.165, the FC stack, the power control unit, and the E-M motor are mounted at the front of the HEV, while the four high-pressure gaseous hydrogen tanks are installed under the floor at the rear. The CH-E/E-CH storage battery is kept under the floor or in the luggage compartment [KAWATSU 2000].

The FCEV *'**Hy**-Wire'* has shown in Figure 2.170 uses HE DBW 4WD propulsion technology to provide mechatronic control over operations. It is powered by a FC that, together with the drivetrain, is stored on a skateboard chassis.

This HE transmission arrangement lets the vehicle designers create a number of different body forms while still maintaining roomy interiors [HAMILTON 2002]. Moreover, the 2WD or DBW 4WD propulsion mechatronic control system (for example, with the following major components: PEFC; traction brushless DC-AC/ AC-DC macrocommutator IPM magnetoelectrically-excited synchronous motor/ generator, high-pressure hydrogen storage tank and NiMH storage battery), a rack-and-pinion SBW 2WS or 4WS conversion mechatronic control system and a heat pump air conditioning system that uses CO_2 refrigerant are also included.

For the reason that the FCEV uses a radiator for cooling, the total area of the openings is about 2.5 times that of a normal automotive vehicle, and the front grill has a double frame construction too, that both undergoes high-quality cooling performance and permits the HEV's outer shell to articulate its innovative sight [KAWATSU 2000].

Of course, the FC HE transmission arrangement for the HE DBW 2WD propulsion mechatronic control system is intended to improve fuel economy and goals for excessive responsiveness when the HEV is in transitional circumstances.

The **electrical energy source** (EES) is an HE configuration of the FCs, i.e., the PES and a CH-E/E-CH storage battery, i.e., SES.

The output electrical energy from the FCs and the charging and discharging of the storage battery are mechatronically controlled in relation to the functioning circumstances of the HEV.

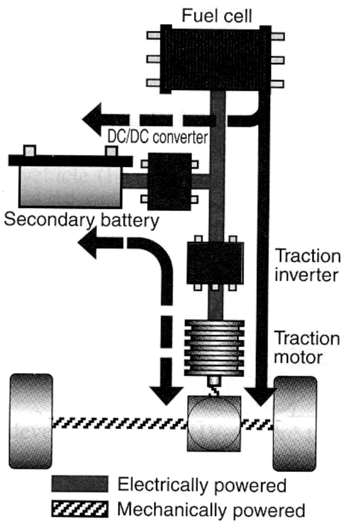


Fig. 2.171 Conceptual layout of the FC HE transmission arrangement [Toyota's FCHV-4; KAWATSU 2000].

A NiMH storage battery with greater energy and power density is used for the storage battery so as to make it possible to run the HEV as an AEV only using the storage battery, thus getting a better fuel economy under low-load circumstances. For instance, as shown in Figure 2.171, the FCs and the traction brushless DC-AC/AC-DC macrocommutator IPM synchronous motor/generator are linked in series so as to obtain better efficiency in the steady circumstances that generally take place during HEV manoeuvres [KAWATSU 2000].

The CH-E/E-CH storage battery, with its low power ratio, is arranged in parallel with the FCs through a DC-DC macrocommutator acting as a DC-DC converter and supplies electrical energy assistance when the FC response is postponed or when the HEV is driven under high loads.

The CH-E/E-CH storage battery also absorbs the electrical energy recovered by regenerative braking and acts as the **electrical energy source** (EES) for AEV function under low loads.

The hybrid control (electric energy control) of the FCs and the CH-E/E-CH storage battery is achieved by controlling the output voltage from the DC-DC converter.

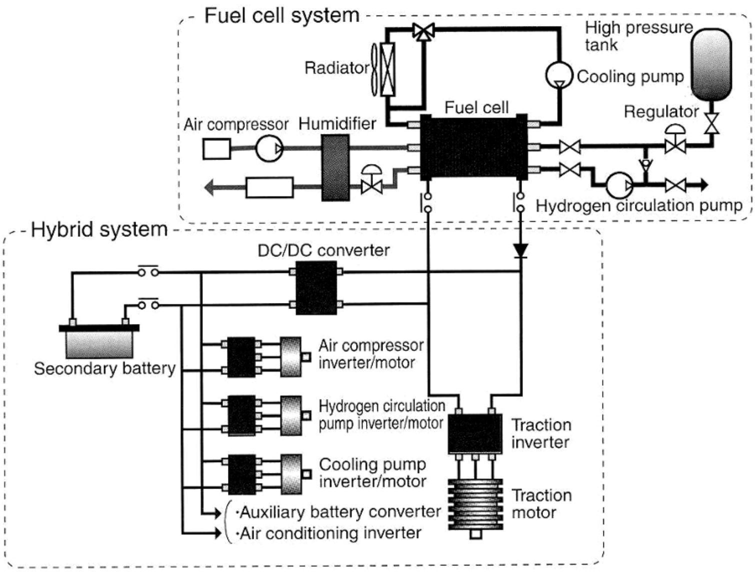


Fig. 2.172 Principal layout of the FC HE transmission arrangement [Toyota's FCHV-4; KAWATSU 2000].

The FC H-E transmission arrangement for the HE DBW 2WD propulsion mechatronic control system is shown in Figure 2.172 [KAWATSU 2000]. This mechatronic control system is separated into two operational discrete systems.

The FC system is the **electrical energy source** (EES) that supplies the HEV's propulsion power, while the hybrid system uses the output power from the FC system with great efficiency.

The FC system is composed of the FCs themselves, fuel supply system parts, and cooling system parts. Hydrogen is delivered to the FCs from the high-pressure storage tanks by means of a regulator. Any residual hydrogen remaining after the FC reaction is restored to the source area of the FCs by an exchange E-M-F pump.

Air is pressurised by an E-M-P compressor, after that it is pumped to the FCs through a humidifier. The latter gets water vapour from the exhaust air of the FCs and uses it to humidify the inward compressed air. An E-M-F pump may flow coolant between the FCs and the radiator.

In addition, mechatronic control of the supplementary parts, for example, the E-M-P compressor, and so on, is optimised in relation to the FC output, consequently the FCs function with a minimum of loss thanks to the supplementary implements.

The hybrid system consists of a FC system, a CH-E/E-CH storage battery, a DC-DC macrocommutator acting as a DC-DC converter, and a traction brushless DC-AC/AC-DC macrocommutator IPM magnetoelectrically excited synchronous motor/generator.

The core of the HEV's propulsion power is the output power from the FCs, but when their output power is not enough, as in fast acceleration, hill climbing, and high-speed passing transitions and high-load manoeuvring, electrical energy assistance is supplied by the storage battery.

In addition, in low-load manoeuvring, the FC supplementary implements are turned off and the HEV is in motion as an AEV using the electrical energy from the storage battery and nothing else. Currently, HEVs have been developed for significantly cleaner and more efficient automotive vehicles. FCEVs, such as, the Honda *Insight* and Toyota *Prius*, particularly, were tested by the **U.S. Department of Energy** (DoE) to evaluate the liquid fuel saving [KELLY AND RAJAGOPALAN 2001].

Obviously, the FC has been developed to become the main energy source in various applications. The FC transit bus that has been designed and developed by the DoE has been acknowledged as a **zero emission vehicle** (ZEV). Its only exhaust emission is in fact water vapour [DOE 2003]. One of the main weak points of the FC is its slow dynamics [GOPINATH ET AL. 2002; NERGAARD ET AL. 2002; LEE ET AL. 2003].

Indeed, the dynamics of the FC is restricted by the hydrogen delivery system that contains M-F pumps and fluidic valves and, in some cases, a reforming process.

Above all, a step electrical energy load may involve enormous variation of the voltage of the automotive 42 V_{DC} EED bus, because the main energy source has a slow dynamic response. Besides, the FCEV has a problem when starting the E-M motor that demands high energy in a short time.

To solve these problems, the FCEV must have an auxiliary energy source to supply high transient energy. High-current ultracapacitor technology has been developed for this purpose [ORTÚZAR ET AL. 2003]. Subsequently, the very quick power response of ultracapacitors may be used to add to the slower power output of the FC to create the compatibility and performance characteristics necessary for FCEVs as shown in Figure 2.173 [THOUNTHONG ET AL. 2005].

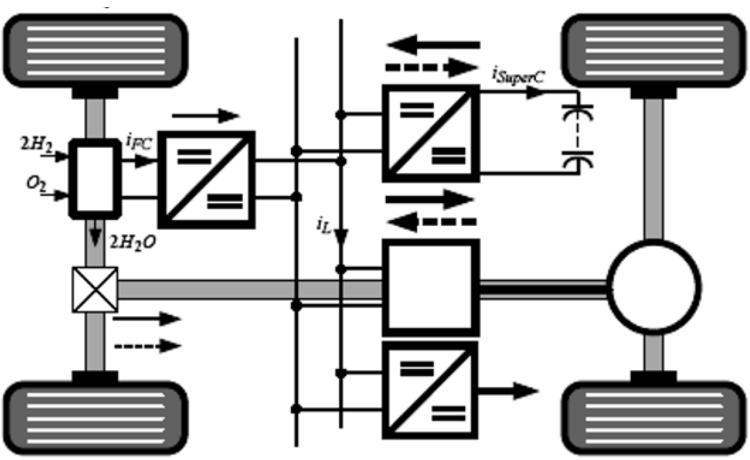


Fig. 2.173 Principal layout of the FC HE transmission arrangement with ultracapacitors [THOUNTHONG ET AL. 2005].

Relative to CH-E/E-CH storage batteries, ultracapacitors have one or two orders of magnitude higher specific power, and much longer lifetimes. Because they are capable of millions of cycles, they are virtually free of maintenance.

Their enormous, rated currents enable quick discharges and quick charges as well. Their quite low specific energy, relative to CH-E/E-CH storage batteries, is in most circumstances the factor that determines the feasibility of their employment in a particular high-power application [DESTRAZ ET AL. 2004].

In Figure 2.173 a FC HE transmission arrangement is shown having a FC as the main energy source and ultracapacitors as the auxiliary energy source. It particularly specifies the mechatronic control algorithm for ultracapacitors' DC-DC macrocommutator (converter).

Experimental results show that ultracapacitor technology is suitable for providing electrical energy in automotive EED systems.

In Figure 2.174 a Chevrolet *Sequel*, which is about the size of a Cadillac *SRX*, is shown. It is the first FCEV to achieve 0 – 96 km/h (0 - 60 mph) in under 10 s and has a 480 km (300 mile) range.

Fig. 2.174 General *Motors* unveiled the Chevrolet *Sequel* that runs on a hydrogen fuel cell and employs the platform architecture *Larry Burns* has been spearheading.
[The New York Times – Jan. 2005]

It has unequalled handling on snow and ice, or uneven terrains. 42% more torque for unparalleled acceleration, and shorter braking distance than an equal size conventional vehicle.

The Chevrolet *Sequel*'s sophisticated RBW or XBW integrated chassis mechatronic control hypersystem replaces the mechanical and fluidical linkages of conventional vehicles with electrical wires and actuators. This means fewer parts to wear out, and because RBW or XBW integrated chassis mechatronic control hypersystems work like a fast computer, the Chevrolet *Sequel* has enhanced acceleration, braking, and overall handling.

2.9.3 Conclusion

Fuel cells have supplied electrical energy on spacecraft since the 1960s, but it was just in the late 1990s that automotive manufacturers became really concerned about them as a alternative for the ECE or ICE. FCs submit greater fuel efficiency than ECEs or ICEs can ever create by using hydrogen and oxygen as fuel (not petroleum) while only emitting water vapour.

An HEV power-driven by a FC HE transmission arrangement has a number of features that a conventional vehicle with an ECE or ICE will certainly not have. The FCEV is in motion without generating any kind of toxic emissions and accomplishes a level of fuel efficiency that far surpasses any con-temporary ECE or ICE. With a maximum energy conversion efficiency of 90%, it submits the maximum specific output (power-from-fuel-ratio) of any known DBW AWD propulsion mechatronic system.

Automotive scientists and engineers have accomplished this substantial gain in fuel efficiency by bringing together two prematurely autonomous mechatronic systems into an advanced FCEV powertrain. In most HE DBW AWD propulsion modes, the recent FC stack submits the one and only source of electrical energy for the FCEV powertrain.

However, the innovative design of a CH-E/E-CH storage battery pack will break down when higher levels of electrical energy are needed. This CH-E/E-CH storage battery pack acts as the **starting, lighting and ignition** (SLI) storage battery for the entire mechatronic system and also supplies supplementary thrust during fast acceleration.

When the driver needs fast acceleration, the FCEV energy management mechatronic system will alter into a boost mode, switching the storage battery into parallel with the **fuel cell** (FC) to supply a supplementary dose of propulsion. This means that the FCEV's energy management mechatronic system can provide enhanced performance than current FC technology supplies on its own for the reason that both mechatronic systems are functioning often in or near to their *'sweet spot'*. This idiom (idiosyncratic to persons who play golf) was formed by automotive scientists and engineers for the optimal operating range of their performance map, in which both energy sources, namely: PES and SES, in co-operation distribute a higher power output than would be anticipated by the nominal maximum value of power. This contemporary hybrid-altering stimulus submits the advantage of specific dimensions. Both the CH-E/E-CH storage battery and the FC cell stack are smart components that have been sophisticated for optimal energy conversion efficiency. Prior to this the HE DBW AWD propulsion mechatronic system can be set up for the motorway on a large scale with hardly any residual evaluations necessary for the solution: fuelling and range remain to symbolise the most important investigations. The FC stack used in the FCEV ought to be so highly developed that it compares to something like a space capsule approved for motorway application. No other FCEV powertrain is stronger, faster and, at the same time, environmentally cleaner than the tandem concept used in the FCEV.

The FC stack acts like a large gas-powered generator delivering electrical energy generated in a **cold-combustion process** (CCP) to the E-M motor. The FC stack used in the FCEV tolerates pure gaseous hydrogen to generate the electrical energy that powers the E-M motor.

The FCEV powertrain includes the FC stack, its gas and air mechatronic control system, and electronic controls for propulsion power. The FCEV drivetrain does not require a conventional gearbox because its E-M motor delivers levels of power and torque previously found only in railway engines.

The FCEV powertrain of the unpolluted and calm automotive vehicle shows the level of technological progress that has been in the imagination of ECE or ICE makers for years.

The intrinsic energy conversion efficiency of FCs symbolises the heart component of this evolution.

A contemporary petrol ECE or ICE, for example is, in the best circumstances, capable of converting 30% of the energy potential of its fuel into power or as a contemporary ECE or ICE can attain about 40%. These rates relate to the load and angular velocity ranges when ECEs or ICEs are functioning at full load under the maximum value of torque enabling the ECE or ICE to function at all high levels of energy conversion efficiency.

In standard circumstances, no automotive vehicle functions in a constant mode of acceleration. With practice indicated by recurrent stop-and-go traffic or angular velocity limits, ECEs or ICEs as a rule function in different modes that substantially decrease the energy efficiency of standard ECEs or ICEs to mean values of less than 20% for diesel ICEs and 15% for petrol (gasoline) ICEs. FCs attains completely different levels of fuel economy from ECEs or ICEs. Within an extensive range of part load operation, the FC's thermodynamic efficiency is evaluated at approximately 60%, with transient peak values increasing to above 90% under low load.

Together with the electric booster mechatronic system, this has as an end result, an overall energy conversion efficiency of above 60%, that is, 3 to 4 times that of ECEs or ICEs.

To enhance the overall energy conversion efficiency of the FCEV all the more, it features two additional developments adjusted to attaining an advantageous energy conversion rate, light-mass construction, and a regenerative braking mechatronic system. The FCEV's light-mass construction uses over 100 mass-optimised components. The technology for manufacturing these components is rooted in a wealth of practices collected from motor racing and advanced material research.

The FCEV's' regenerative braking comprises a very advanced BBW AWB dispulsion mechatronic system with an ECU altering the pressure and motion of the brake foot pedal into fluidic braking power.

For low deceleration rates, the drive E-M motor can operate as an M-E generator brake, enabling up to 95% of all braking actions to be used to generate the electrical energy that is supplied back into the CH-E/E-CH storage battery.

In addition to restricted stress on the BBW AWB dispulsion mechatronic system, this procedure enhances the interior energy conversion efficiency of the entire FCEV. At their simplest, FCs are **chemo-electrical** (CH-E) devices that convert the chemical energy of gaseous hydrogen and oxygen into electrical energy and thermal energy (heat) as well as chemical energy (water). The small numbers of experimental FCEVs made known and developed previously are stimulating, but the FC technology is costly and apparently too *'avant-garde'* for mass manufacture.

An additional barrier to manufacture FCEVs as a mercantile actuality is the lack of a hydrogen infrastructure; for example, there are no service stations with hydrogen M-F pumps for motorists to fill up their tanks [MADER AND GERTH 2004].

A further motivating force after FC development is the ZEV mandate adopted by CARB in 1990 to downgrade air pollution. For instance, the ZEV rule mandates that 10% of all new automotive vehicles sold in the USA by the late 2000s were to have zero emissions - something that only a CH-E/E-CH storage battery-powered AEV could do.

As an alternative, HEVs are unsuccessful as the mass-market responded, and CARB has slowly backed away from its original ZEV mandate. The development of FCs might alter the game [MADER AND GERTH 2004].

The FC H-E transmission arrangement for the HE DBW 2WD propulsion mechatronic control system, with its FC hybrid system including FCs, i.e., the PES and a CH-E/E-CH storage battery (a SES linked in parallel, both optimally mechatronically controlled in relation to the steady and transitional circumstances of the HEV) may be built-up to get better fuel economy while also giving excessive responsiveness in HEV transitional circumstances. While the FCEV is capable of acceleration performance up to that of a conventional ECE- or ICE-powered automotive vehicle, it accomplishes an energy conversion efficiency that is about three times superior.

2.10 Discussion and Conclusions

In this chapter, literature searches have been performed at the databases of the Society of Automotive Engineers (SAE) and the Institution of Electrical and Electronics Engineers (IEEE). Automotive industry, universities, institutes and automotive consultant companies perform R&D work. One major conclusion is that papers published by automotive consultants, for example, AVL or Ricardo, are often torn between the desire to publish and protect own and customers interests. Many results may not be published at all since the R&D work is performed within automotive companies.

The R&D work that is performed is often done, by sponsored, or in close collaboration with vehicle companies. The presented results are often deliberately vague, describing methods and physical and mathematical models rather than explaining in the results detail. Five different R&D groups were identified [ANDERSSON AND JOHANSSON 1998]. This follow-up has not given many of the interesting papers produced by these five groups up to 1998 [PERSSON 2004].

At present, it is difficult, to discern who are the most prominent researchers in **integrated powertrain mechatronic control** (IPMC). Today, there seems to be a much wider R&D group, where it is a difficult task to distinguish any one research group in particular. It appears that the total amount of R&D work in shunt and shuffle has more than doubled over five years [PERSSON 2004].

There are automotive scientists and engineers who publish papers, who are not part of any of the identified research groups, and this must be interpreted as a sign that R&D work is now performed in many more areas than was the case in 1988.

It is difficult to decide how to categorise R&D work results that is an indication that automotive scientists and engineers deal with shunt and shuffle from many perspectives. This also means that traditional R&D work must be combined with the development of a way to standardise results of shunt and shuffle research in order to be able to compare progress and possible ways to implement findings.

During the search it was recognized that most of the groups do not produce any publications that are made public. A typical example of this is the Hitachi group [ANDERSSON AND JOHANSSON 1998] that seemed to have ceased research work. After contact, it was found that the group is still active, but it has not released any publications, nor does it have any official website.

The R&D groups that are within the universities are more open, but still with double interests since different automotive vehicle producers are often sponsors. This must be interpreted as a sign that R&D is strategic for the producers. The implication is that, although time has not permitted a search for it here, some of the results may appear in the shape of patents. Reasons for research on IPMC customer demands for improved driveability, decreased SFC, environmental regulations regarding exhaust emission, and less wear on powertrain components. In an increasingly challenging market, customer demands must be met as far as possible.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_25,

Automotive vehicle manufacturers have to be able to present high quality and top of the line products in order to maintain old and attract new customers. To be a successful player on the market, a vehicle manufacturer must manage all of the following fields:

Short Lead Times in Combination with Innovative Thinking - In today's increasingly intense international competition, there is a need for a modified product development approach. In order to maintain or improve market position, several different methods are required where the objective is to combine short lead times with innovative thinking [MAGNUSSON AND BERGGREN 2001].

Obvious solutions must be questioned, in order to achieve improvements and to find new, advanced concepts for IPMC. When innovation is encouraged, this enables new solutions that, hopefully, may result in competition advantages.

Another important factor to deal with is the increasing level of complexity regarding the number of variables that can be analysed in modern automotive vehicles and the large quantity of research in the shunt and shuffle area. The human mind has very limited capacity when a great number of parameters must be considered in a multifaceted context. It may also be a matter of time and cost when driveability characteristics can be tuned by an increased number of parameters. R&D work methods and strategies for dealing with this complexity must be developed and implemented.

Tools like **computer-aided engineering** (CAE) must be used in a larger extent in order to achieve higher efficiency and shortened lead times.

Knowledge on how the Human Body is Affected by Whole-Body Vibrations - Motion sickness, discomfort, and fatigue may be the results of a poorly treated powertrain. In order to meet customer expectations, a thorough knowledge in physically effects on the human body is a necessity. This is something that is hard to define mathematically but a well-organised and structured way to determine the affects on the human body, as a result of design changes or controller strategies is a competitive advantage.

Accurate Physical and Mathematical Models and Simulations - It is a very clear trend that mathematical model-based **driveline mechatronic control** (DMC), as opposed to traditional DMC, has developed during the recent years. Physical and mathematical modelling is important as is the physical model parameters that are often kept secret. There are no major open model libraries available and no generally accepted physical and mathematical models. Powertrain physical modelling seems to be done mainly either in the size of 2 -- 3 masses and for more accurate physical models 5 -- 15 masses.

Combining Physical and Mathematical Models and Simulations - Results from tests and simulations must be translated into relevant factors. In physical modelling studies, often very little information is provided on how measurements can be interpreted into driveability marks. Driveability is a highly subjective measure. Many of the rating methods are based either on drivers/panels or neural networks trained by these.

The two major players, Ricardo and AVL, provide solutions in translating numeric values into driveability ratings. However, physical and mathematical models and methods for simulations must be developed together with numeric driveability methods in order to be of any use from the driveability aspect. The approach for AVL, who seems to be leading driveability evaluation today, is very clearly to try to implement their knowledge in their software *DRIVE* and relate consultant work to it. A good collaboration between physical and mathematical modelling and results in regards to effects on the driver is essential. Physical and mathematical modelling and simulation is a necessary step towards improved driveability but, in order to be completely successful, a better coupling must be accomplished. Standardisation methods such as, for example, **British Standard** (BS) 6841 (1987) and ISO 2631 (1997) are guidelines, and simulations ought to be able to produce measurements that are needed in order to establish threshold values.

Potential Solutions for Improved Driveability - Different solutions for the problem of longitudinal vibration are presented by a number of R&D groups. However, much still seems to be at the prototype and experimental stage, or at least little has been found about implementation. In this section many suggestions are presented on how to get rid of the problem but few actual results from market-ready automotive vehicles has been found. An obvious reason is that vehicle manufacturers do not wish this to be of general knowledge. In papers that are public, a certain trend to exploit an integrated approach can be noticed. Much effort is put into how to locate the origin of noise and vibrations in a transient situation.

In some literature, physical and mathematical modelling and investigations into the results of a tip-in simulation are presented [CAPITANI ET AL. 2000, 2001; BALFOUR ET AL. 2000; HWANG ET AL. 1998; COUDREC ET AL. 1998], whereas in other references, controller solutions are proposed [BEST ET AL. 1998; RICHARD ET AL. 1999; ZAVALA ET AL. 2002], and constructional suggestions are also presented [REBEIH ET AL. 2002; WANG ET AL. 2000; KAZENI ET AL. 2002].

R&D work is also presented where the root source is studied. In one example, how to predict and then to control the backlash and pass smoothly, thus avoiding the problem of shunt and shuffle, may be investigated [LAGERBERG ET AL. 2001, 2002]. Papers have also been found that systematically attack and solve clonk problems.

Automatic dynamics analysis of mechanical systems (ADAMS) computer software package, distributed by Mechanical Dynamics Inc., may be widely used in the automotive industry for simulating full vehicle dynamics.

Ability to Implement Findings - When simulations show satisfying results, there must be a way to implement the solution in the final product. If a torque sensor is needed, or an applied torque is assumed, this must be possible to reproduce in real life in an accurate enough way. Suggested controllers might call for a precision in torque handling that is not possible with current sensor techniques, why some results must be regarded to still be a bit of experimental stage.

Since few automotive vehicles actually have torque sensors that are necessary for many of the proposed controller techniques, ECE or ICE diagnostics and estimations are important parts of shunt and shuffle research. The most preferred way of measuring or controlling the automotive vehicle is to use already existing sensors or transmitters. The ability to analyse the signals and use these in order to implement research findings will be of great importance in future product development. It is hard to tell what results will show, since the requested ideal circumstances are not realistic. When actuators and sensors can be provided, the results may be implemented in the next generation of automotive vehicles.

Future Challenges - It is not enough to be good at technical R&D work and to implement findings. A clear strategy for future business and fast but well considered decisions on strategic issues are also necessary criteria for a successful vehicle manufacturer. When the combination is realised, this may lead to accomplished objectives of improved driveability, decreased SFC, environmental regulations regarding exhaust emission, and less wear on powertrain components.

Additional Advantages

- Design freedom:
  - Almost arbitrary cockpit design is possible with a comprehensive DBW AWD propulsion mechatronic control system;
  - Input can be reduced to hand controls; could be useful for disabled drivers.
- Adaptability:
  - Controls can be programmed to suit driver preferences; for example, throttle/brake pressures, steering wheel angles;
  - driver position does not need to be fixed. The controls could be designed and easily adapted to different countries.

Safety Aspects

- Considerable safety improvements are possible;
- Conventional steering column and pedals are dangerous for the driver in the event of an accident;
- E-M systems have the potential to be more reliable than conventional F-M systems;
- Increased presence of control allows for the introduction of more safety systems, for example a collision-avoidance system;
- Reliable transmission of information is critical; robust networks are required.

Network Issues

- Networks are already used in automotive vehicles to reduce wiring costs and mass;
- Event-driven networks used, for example, to turn on lights or open windows are not sufficiently robust to handle the transfer of safety critical signals;
- **Time-triggered protocols** (TTP) necessary;
- Reliable network hardware also required; could use redundancy as in aircraft; some fighter aircraft have quadruple-redundant FBW systems.

Difficulties

- Many advantages of DBW AWD technology have been highlighted;
- Virtually no advantages are associated with retaining existing technology;
- Disadvantage: cost;
- Systems in automotive vehicles are severely restricted by unit costs;
- DBW systems are likely to be much more expensive per unit than traditional methods;
- In addition, it is necessary to gain safety approval for most safety-critical systems such as braking.

An accident analysis examination of automotive vehicles in the European Community may be worked out. On the results achieved, solutions can be developed focusing on the most often occurring and most severe traffic accidents with the aim of avoiding them by the integration of driver assistant systems that can be easily linked to a powertrain equipped with intelligent technologies (PEIT) platform [PEIT 2001-2004].

Homologation aspects may be defined as a basis for future homologation of automotive vehicles equipped with an architecture serving as a platform on which applications can easily access within the ensured co-ordinated environment, that is, the central **powertrain controller**, (PTC), all powertrain functionalities necessary in operating the driver's motion wishes in an optimised *'tolerant free'* manner, for instance, **electronic stability programme** (ESP) with steering mechatronic control as an automotive vehicle dynamic stability function could be developed within the project to demonstrate the co-ordinated and ensured access of brakes, steering, ECE or ICE, and TM (gearbox), SAT, FAT or CVT.

Development of a test bench on which the specified powertrain architecture and interfaces, as well as functionalities, may be testable in an environment, in which, a real automotive vehicle may be mounted on a rack.

The vehicle is equipped with interfaces and wheel-tyre mounted E-M motors that are capable of simulating different street and dynamic motion conditions in a static state. Integration of hard- and software of a BBW AWB dispulsion mechatronic control system may be carried out in the vehicle validator test bench. Tests under different situations and weather conditions may prove the high potential of the BBW AWB dispulsion mechatronic control system. Integration of a SBW AWS conversion mechatronic control system capable of interacting with the driver by using force-feedback information is necessary.

Reduction of wiring harness and information flow over the whole powertrain by application of a centralised co-ordination ECU operating via a bus system with a command layer and mechatronic aggregate layer.

Presentation of the PEIT functionalities at the end of the project may demonstrate the key technology functions and the advantages of the *PEIT* approach.

An approach in which all relevant safety functions are co-ordinated and operated out of an ensured environment derived from the avionics industry can be scaled down to automotive needs with low cost opportunities.

The main goal of PEIT is to substantially improve overall traffic safety and traffic efficiency for vehicles by the integration of intelligent technologies into the powertrain.

Compared to accidents with passenger cars, accidents with trucks cause much more heavy damage to property, nearly twice as many bodily injuries, and more than three times the number of fatalities. Thus, focusing on heavy goods vehicles is of prime importance. Using an intelligent powertrain as a basis, vehicles cannot only cope reactively with dangerous situations, but they may be able to predict such situations in combination with additional assistant systems interacting with the powertrain, using only a motion vector as input. So the PEIT powertrain may serve as a platform on which auxiliary systems could be easily integrated independent of the mechatronic aggregates. This may constitute a milestone in safety technology. Analysis of accident scenarios show that more than 40% of accidents might have been avoided if the vehicle had been installed with a warning system.

A still higher level of up to 95% of vehicle safety could be reached by preventing safety critical driving conditions. To achieve this, some of the driving decisions have to be taken away from the driver and be given to a mechatronic control system (removing the driver from the control loop) to maintain drive stability and to reduce braking distance. As an additional benefit, the intelligent powertrain may not only contribute to safety but also result in increased traffic efficiency and driving comfort.

Definition of homologation aspects as a basis for vehicles equipped with the *PEIT* architecture serving as a platform on which applications, can easily access powertrain functionalities within an ensured co-ordinated environment.

The technical work clearly concentrates on the intelligent powertrain architecture to perform the PEIT safety functions. The first step is the specification of a failure-tolerant system, making all safety critical components redundant.

The development of a central PTC and each of the individual systems, SBW AWS conversion and BBW AWB dispulsion mechatronic control systems, fail-tolerant energy management and road friction estimation, grades the second step in creating the intelligent powertrain.

The third major step of the project is the installation of the systems into the demonstration vehicle and the delivery of a vehicle that may contain all the necessary hardware and software components.

The technical work on PEIT ends with an evaluation report of the system's performance based on the results of tests and demonstrations. Parallel to this work, an accident analysis and other enabling measures such as clarification of legal issues concentrating on the homologation aspects are done, which provide the additionally required information for the introduction of PEIT systems.

The major aim for setting up DBW AWD propulsion mechatronic control systems is to obtain a better level of safety. With the aim of realising this, it is essential that the implementation of a DBW AWD propulsion mechatronic control system is robust and failsafe. This necessitates robust sensors, actuators, and control hardware with appropriate levels of redundancy. Besides this, DBW AWD propulsion mechatronic control systems and hardware must produce high resolution and performance so as to realise a high-quality driving feel. Reliable implementation may depend on the automotive vehicle, the safety situation developed for this vehicle, and its future application. The M-M linkages and F-M or P-M actuators that conventionally control braking and steering systems may soon go the way of kerosene lanterns, rumble seats, and bonnet ornaments. They may be replaced with DBW AWD propulsion mechatronic control systems.

At the heart of the DBW AWD propulsion mechatronic control system are smart E-M units that convert the driver's commands from electronic signals to motion.

The DBW AWD propulsion mechatronic control system also affords dynamic feedback to the driver by means of electronic signals. TMC systems are already used in some automotive vehicles.

Everything from designing automotive vehicles, sourcing components, logistics and inventory management to packaging and producing automotive vehicles may be transformed by RBW or XBW integrated unibody, space-chassis, skate-board-chassis, or body-over-chassis motion mechatronic control advanced technologies.

The advanced technology may accelerate the pace of growth in mechatronics in vehicles and curb the application of F-M or P-M and M-M components. Through modular design and elimination of hardware, RBW or XBW integrated unibody, space-chassis, skate-board chassis, or body-over-chassis motion mechatronic control advanced technology may benefit vehicle manufacturers.
Advantages include [WEBER 2003]:

- Increased modularity; fully functional mechatronic modules may reduce assembly time and cost;
- Improved driver interface; the elimination of M-M connections to the ICE throttle and gear-shift transmission may give automotive scientists and engineers more flexibility in designing the driver interface with regard to location, type, feel, and performance;
- Added flexibility; automotive vehicle designers may have more flexibility in the placement of hardware under the bonnet and in the interior to support alternative powertrains, enhance styling and improve interior functionality;
- Lead-time reduction; assemblers may be able to use a lap-top computer to perform soft-tuning capabilities and install custom options, instead of manually adjusting M-M components.

An on-board 42 V_{DC} **energy-and-information network** (E&IN) may allow mechatronic actuators and in-wheel-hub E-M motors that are smaller, with lower mass and improved performance.

Most importantly, these DBW AWD propulsion mechatronic control systems may offer the vital link with driver-assisted systems, including functions such as automatic parking assistance and lane mechatronic controls. DBW AWD propulsion mechatronic control systems improve the driving experience, whilst producing vehicles, that is safer and more reliable.

In enhancing traditional automotive engineering practices with the best practices gained from other sectors, the specific needs of the industry in areas such as packaging and cost must be respected. Changes to the regulatory framework are also required to permit the introduction and approval of such systems. The ICE may be the most dominant propulsion system and survive due to hybrid solutions, decreased SFC, reduced emissions, and other improved technologies [BIRCH 2002].

If hydrogen can be used as the energy source, it may probably be tested in the ICE, since this technology is well known. Though FCs are a great promise for the future, focus may be on improving the ICE [BIRCH 2002, NICKENS 2004].

Why fuel cells for automotive vehicles?

- Cost savings:
  - Higher efficiency;
    - Reduced specific fuel consumption (SFC).
  - Lower maintenance;
    - Reduced on-board workload.
- Reduced emissions:
  - Reduced exhaust emissions;
  - Reduced acoustic and infrared signature;
  - Reduced radar cross-section.

There probably may be a transition period where hybrids and FCs may be used in combination with ECE or ICE.

Major challenges are the system complexity, as well as the infrastructure [BIRCH 2002]. CVT versus six-gear M-M transmission may be another interesting question where the answer may lie in the near future. In consequence of conurbation pollution and the rapid increase in oil prices predicted by the end of the 2010s, there is presently a stimulation to develop AEVs and HEVs for clean, efficient, and sustainable conurbation transport. The AEV or HEV creates application of high-energy density CH-E/E-CH storage batteries and E-M drives for its DBW AWD propulsion mechatronic control systems. The E-M drives are used in different arrangements, either with or without an M-M gearbox or M-M differential. In-wheel-hub E-M motor DBW AWD propulsion mechatronic control systems without any M-M gearing are very attractive to use from the viewpoint of mechatronic control as well as the onboard space accessible.

Conversely, in-wheel-hub E-M motor DBW AWD propulsion mechatronic control systems incline not to have high values of efficiency because of the restricted space accessible for the propulsion and the increase of the unsprung mass.

The challenge is to develop an in-wheel-hub electrical machine (motors/generators) that both encounters the torque requirements and has the lowest mass and size as well as highest efficiency feasible.

To encounter these requirements R&D works have been carried out on novel IPM electrical machine designs with different topologies having an extensive constant power-velocity range and satisfactory torque-to-mass ratio.

Substantial performance estimation necessitates a particular design optimisation of an electrical machine that incorporates finite-element analysis and optimisation algorithms to perfect the electrical machine's multi-dimensionally.

The mechatronic controls of the in-wheel-hub E-M motor for high-quality DBW AWD propulsion mechatronic control, and the control of the energy-flow to and from the CH-E/E-CH storage-battery supply, are also imperative features to respect.

For optimum in-wheel-hub motor DBW AWD propulsion mechatronic control (i.e. torque, velocity, and wheel-slip control), the current supply, frequency, and voltage of the in-wheel-hub motor must be controlled under high-dynamic circumstances.

Thus, DC-AC/AC-DC macrocommutators (inverters/rectifiers) and **digital signal processors** (DSP) are used. Besides, to in-crease the lifetime of the costly CH-E/E-CH storage batteries of the AEV or HEV, it is preferable that the ultracapacitors are charged and discharged by means of DC-DC macrocommutator (choppers) via dynamic electrical-energy flow.

Glossary

Anti-lock braking system (ABS) is a system on automotive vehicles which prevents the wheels from locking while braking; the purpose of this is to allow the driver to maintain steering control under heavy braking and, in some situations, to shorten braking distances (by allowing the driver to hit the brake fully without the fear of skidding or loss of control); disadvantages of the system include increased braking distances under certain circum-stances and the creation of a *'false sense of security'* among drivers who do not understand the operation and limitations of ABS.

ABS return M-F pump - A piston M-F pump that returns the brake's oily fluid to the master cylinder.

ABS return M-P compressor - A piston M-P compressor that returns the brake's air to the master cylinder.

AC-DC commutator - The commutator is a mechanical AC-DC rectifier; for a rotary DC-AC commutator generators, the commutator mechanically switches the armature windings so that the resultant induced source AC armature voltages always act with the same sense of voltage polarisation; this requires a reversal of the armature winding connection every π rad; the induced source AC armature voltages are mechanically rectified to the induced source DC armature voltage via commutator segments that contact the carbon brushes.

AC-DC macrocommutator - The macrocommutator is an ASIM AC-DC rectifier; for a rotary DC-AC commutator generators, the macrocommutator electronically switches the armature windings so that the resulting induced source AC armature voltages always act with the same sense of voltage polarisation; this requires a reversal of the armature winding connection every π rad; the induced source AC armature voltages are electronically rectified to the induced source DC armature voltage via inputs of the ASIM that contact the output of the ASIM via bipolar electrical valves.

Actuator - The component of an open-loop or closed-loop mechatronic control system that connects the electronic control unit (ECU) with the process; the actuator consists of a commutator and a final-control element; positioning electrical signals are converted to mechanical output.

Algorithm - A set of software instructions causing a computer to go through a prescribed routine; because embedded computer ECE or ICE controls have become so common, the algorithms have become essentially synonymous with the control laws for automotive scientists and engineers.

Alternating injection suppression - An adaptation of the number of active ICE cylinders by every two ICE's crankshaft rotations that modulate the ICE torque.

Analog input - Sensors usually generate electrical signals that are directly proportional to the mechanism being sensed; the signal is, therefore, analog-signal or may vary from a minimum to a maximum limit.

Analog signal - A signal in which the information of interest is communicated in the form of a continuous signal; the magnitude of this signal is proportional (or analogous) to the actual quantity of interest.

Analog-to-digital (A/D) converter - An electronic device that produces a digital result that is proportional to the analog input voltage.

ASIC - Application-specific integrated circuit, an IC designed for a custom requirement, frequently a gate array, single-chip microprocessor, or programmable logic device.

ASIM - Application-specific integrated matrixer, an IM designed for a custom requirement, frequently a gate array or single-chip macrocommutator.

ASR deactivation switch - A device to switch off ASR on sand and loose gravel that realises maximum traction on these surfaces.

Automatic throttle valve actuator - An actuator for automatic reduction of the throttle angle in circumstances of extreme acceleration slip.

Braking intervention - Automatic brake action at drive wheels in circumstances of extreme acceleration slip.

Bus - Topology of a communications network where all nodes are reached by links that allow transmission in both senses of direction.

Capacity - Energy storage capability of the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel.

Central processing unit (CPU) - The portion of a computer system or micro-controller that controls the interpretation and execution of instructions and includes arithmetic capability.

CH-E/E-CH storage battery - Self-contained CH-E/E-CH cell/cells or system that converts chemical energy to electrical energy in a reversible process.

Closed-loop mechatronic control - A process by which a variable is continuously measured, compared with a reference variable, and changes as a result of this comparison in such a manner that the deviation from the reference variable is reduced; the purpose of closed-loop mechatronic control is to bring the value of the output variable as close as possible to the value specified by the reference variable in spite of disturbances; in contrast to open-loop mechatronic control, a closed-loop mechatronic control system acts to offset the effect of all disturbances.

Curie temperature - The temperature above which a piezoelectric crystal or piezo-ceramic element no longer reliably retains its original piezoelectric characteristics.

D controller - A controller with the derivative characteristics.

DC-AC commutator - The commutator is a mechanical DC-AC inverter; for a rotary DC-AC commutator motors or actuators, the commutator mechanically switches the armature windings so that the resultant force always acts in the same sense of rotary direction; this requires a reversal of the armature winding connection every π rad; the DC supply to the armature is via carbon brushes that contact the commutator segments.

DC-AC macrocommutator - The macrocommutator is an ASIM DC-AC inverter; for a rotary DC-AC commutator motors or actuators, the macrocommutator electronically switches the armature windings so that the resulting force always acts in the same sense of rotary direction; this requires a reversal of the armature winding connection every π rad; the DC supply to the armature is via the input of the ASIM that contacts the outputs of the ASIM via bipolar electrical valves.

Defuzzification - The process of translating output grades to analog output values.

Depth of discharge (DoD) - Percentage of capacity [Ah] that has been removed from the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel.

Digital signal - A signal in which the information of interest is communicated in the form of a number; the magnitude of this number is proportional to (within the limitations of the resolution of the number) the actual quantity of interest.

Digital signal processor (DSP) **-** A monolithic integrated circuit (IC) optimised for digital signal-processing applications; portions of the device are similar to a conventional microprocessor; the architecture is highly optimised for rapid, repeated additions and multiplications required for digital signal processing; digital signal processors may be im+plemented as programmable devices or may be realised as dedicated high-speed logic.

Driver - A solid-state device used to transfer electrical energy to the next stage that may be another driver, an electrical load (power driver), a wire or cable (line driver), a display (display driver), etc.

ECE or ICE torque control - An actuator for ECE or ICE torque modulation in circumstances of extreme acceleration slip.

Electronic performance (EPC) - Electronic acceleration control.

Final-control element - The second or last stage of an actuator to control mechanical output.

Fuzzification **-** The process of translating analog input variables to input memberships or labels.

Fuzzy logic (FL) - Software design based upon a reasoning model rather than fixed mathematical algorithms; a fuzzy logic design allows the automotive system engineer to participate in the software design because the fuzzy language is linguistic and built upon easy-to-comprehend fundamentals.

Inference engine - The internal software program that produces output values through fuzzy rules for given input values; the inference process involves three steps: fuzzification, rule evaluation, and defuzzification.

Input memberships - The input signal or sensor range is divided into degrees of membership, i.e., low, medium, high or cold, cool, comfortable, warm, hot; each of these membership levels is assigned numerical values or grades.

Jerk sensor - A sensor that measures the third-time derivative of displacement.

Microcontroller unit (MCU) - A semiconductor device that has a CPU, memory, and I/O capability on the same chip.

Open-loop mechatronic control - A process within a mechatronic control system in which one or more input variables act on output variables based on the inherent characteristics of the mechatronic control system; an open loop is a series of elements that act on one another as links in a chain; in an open loop, only disturbances that are measured by the control unit can be addressed; the open loop has no effect on other disturbances.

Output memberships - The output signal is divided into grades such as off, slow, medium, fast, and full-on; numerical values are assigned to each grade; grades can be either singleton (one value) or *Mandani* (a range of values per grade).

PI controller - A controller with proportional and integral characteristics.

PID controller - A controller with the proportional, integral and derivative characteristics.

Protocol - The rules governing the exchange of information (data) between networked elements.

Pulse-width modulation (PWM) - The precise and timely creation of negative and positive waveform edges to achieve a waveform with a specific frequency and duty cycle.

Regenerative braking - Capability of an E-M propulsion acting as an M-E dispulsion to return the kinetic mechanical energy, stored in the vehicle velocity of the AEV or HEV body, to the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel during braking; a type of braking used in all-electric vehicles (AEV) and hybrid- electric vehicles (HEV) in which the drive electro-mechanical (E-M) motor(s) is used as a mechano-electrical (M-E) generator(s) during braking, and it serves as the load to brake the vehicle; this technique is used to reclaim a portion of the energy expended during a vehicle's motion.

Robust - Able to survive and operate properly in a severe environment.

Rule evaluation - Output values are computed per the input memberships and their relationship to the output memberships; the number of rules is usually set by the total number of input and output memberships; the rules consist of *IF inputvarA* is *x*, *AND inputvarB* is *y*, *THEN outvar* is *z*.

Semicustom MCU - An microcontroller unit (MCU) that incorporates normal MCU elements plus application-specified peripheral devices such as higher-power port outputs, special timer units, etc.; mixed semiconductor technologies, such as high-density CMOS (HCMOS) and bipolar analog, are available in a semicustom MCU; generally, HCMOS is limited to 10 V_{DC}, whereas bipolar-analog is suitable up to 60 V_{DC}.

Slip threshold switc*h* - A switch for escalation of a necessary slip threshold on sand and loose gravel that realises maximum traction on these surfaces.

Specific energy (energy density) - Energy storage capability per unit mass of CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel [Wh/kg].

Specific power (power density) - Power delivery capability per unit mass of CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel [*W/kg*].

State of charge (SoC) - The CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel level of charge can be stated as either DoD or SOC.

Switchover valve - A valve to switch-over of the fluidic performance from normal braking to ASR performance.

Throttle valve control (TVC) – This is a ASR actuator for modulation of the throttle angle.

Torque - The moment of rotation tending to make the output shaft of an ECE or ICE turn; torque can be expressed as a force acting perpendicular to a lever arm at a distance from the centre of rotation.

Transaxle - An axle that includes the M-M differential and gearbox.

Wheel slip - The difference between tangential wheel velocity and vehicle velocity; a rolling wheel-tyre with no braking torque on it exhibits null percent (0%) slip; a non-rotating wheel-tyre on a moving vehicle exhibits full percent (100 %) slip.

3/3 ABS valve - A valve with three connections and three positions for ABS wheel pressure modulation.

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PART 3

BBW AWB Dispulsion Mechatronic Control Systems

3.1 Introduction

In this part of the book, the interested readers may consider the longitudinal motion in the *x*-axis of an automotive vehicle. By longitudinal motion we mean how the vehicle responds to braking input. Particularly, so-termed **brake-by -wire** (BBW) **all-wheel-braked (**AWB) dispulsion mechatronic control systems have passed through a dynamic technical development in recent years. For future applications, BBW AWB dispulsion mechatronic control systems with **electro-mechanical** (E-M) actuation have been developed which decouple the energy transfer from the driver to the wheel brakes.

Significant bettering has been seen in automotive vehicle riding and cornering performances in recent years as a result of advances achieved, especially in wheel-tyre and vehicular suspension technology. Due to this, vehicle handling during braking have taken on added importance.

Automotive advanced technologies ought to be applied for designing better brakes, namely [SCHNEIDER 2001; MAGUEY 2002]:

- ❖ Current technologies to apply
  - ➢ **Anti-lock braking system** (ABS);
  - ➢ ABS plus mechatronic **brake force distribution** (BFD);
  - ➢ Emergency **brake assistance** (BA);
  - ➢ Parking assistance – *Parktronic* – parking sensor input;
  - ➢ **Adaptive cruise control** (ACC) – uses radar or laser;
  - ➢ **Electronic stability program** (ESP) – ABS and **traction control system** (TCS);
  - ➢ **Stability control system** (SCS);
  - ➢ **Yaw stability control** (YSC);
  - ➢ **Vehicle dynamics control** (VDC);
  - ➢ Forward collision warning – uses radar or laser;
  - ➢ Variable light distribution – based on turning;
  - ➢ **Brake-by-wire** (BBW) a**ll-wheel-braked** (AWB) dispulsion.
- ❖ Future technologies to foster
  - ➢ **Collision avoidance** (CA);
  - ➢ Automatic **pre-crash brake intervention** (PBI);
  - ➢ **Stop-and-go** (S&G). ACC – ACC for congestion;
  - ➢ Cooperative ACC – communication based;
  - ➢ Rollover treat warning;
  - ➢ Rollover avoidance;
  - ➢ **Active roll stabilisation** (ARS);
  - ➢ Lane keeping;

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- **Intelligent transportation system** (ITS);
- Platoon driving – multiple automotive vehicles as one;
- Automated driving – advanced highways.

BBW AWB dispulsion mechatronic control systems permit vehicle manufacturers to enhance the safety aspects of their vehicles by providing the driver with an enhanced braking performance under both normal and emergency braking circumstances.

BBW AWB dispulsion mechatronic control systems function by continuously monitoring many aspects of a vehicle's operation and by imposing an optimum braking function dependant on vehicle velocity, cornering circumstance, **external combustion engine** (ECE) and **internal combustion engine** (ICE) powertrain dynamics, vehicle loading, and weather circumstances.

BBW AWB dispulsion mechatronic control systems normally require information on brake pedal position and rate of change, and mechatronic sensors may be linked to, or integrated within, the brake pedal to provide information on the driver's braking intentions. Wheel angular-velocity sensors (often part of the vehicle's existing ABS system) provide information on vehicle velocity. The position of the chassis ride height sensors provides information on the vehicle's loading including suspension jounce and rebound, and body roll.

Steering **hand wheel** (HW) position sensors provide additional data on the vehicle's dynamic performance under braking. Inputs from the engine and powertrain sensors may be used to optimise the vehicle's braking, depending on the transmission ratio selected at the time of braking.

The reliability and performance of BBW AWB sensors is critical to the performance of such mechatronic control systems, and the leading edge design and manufacturing technologies used in mechatronic products are the primary reasons for the selection of these products.

3.1.1 Automotive Vehicle Safety Systems

Automotive vehicle safety systems may be broadly classified into passive and active safety systems. Passive safety systems include seat belts, air bags, and additional structural members. The objective of passive safety is to reduce damage to the diver and passengers of a vehicle during and after an accident. [GÜVENÇ 2004].

Active safety systems work before an accident and aim at preventing an accident from happening in the first place. As such, it makes sense to also call them preventive systems. This prevention is achieved by trying to keep the vehicle from exhibiting undesired motions like wheel lock-up, loss of traction, or excessive yaw or roll motion that may eventually result in loss of control of the automotive vehicle's dynamic behaviour by the driver.

Active safety systems may thus, temporarily take the control away from the driver, until the undesired dynamic behaviour is corrected. First, more commonly available preventive and active safety systems like ABS, TCS and ESP are discussed. Rollover threat warning, rollover avoidance, and ARS systems are discussed next. Lane keeping, intelligent transportation, collision avoidance and finally ACC are discussed [GÜVENÇ 2004].

Anti-lock Braking Systems (ABS) **–** Over the years there have been significant advances in automotive engineering thanks to recent development of mechatronics. ABS technology with modern electronic components has shown superior braking performances by conventional vehicles on highways.

The BBW AWB mechatronic control systems equipped with powerful mechatronic devices also allow us to arbitrarily tailor the feel of the force at the brake pedal. Conventionally, however, the braking system has been developed through trial and error on test tracks and that necessitates a great amount of time and cost.

This study attempts to establish an analytical tool to evaluate braking feel to help design optimal braking systems. First, mathematical models of braking systems may be developed and may be confirmed through computer simulations. Second, mechanical impedance at the brake pedal is modelled based on developed braking system models. The feel of the brake pedal is represented in the form of an impedance surface. Third, to provide guidelines to design optimal braking feel, relations between pedal force, pedal stroke, and vehicle deceleration are investigated. An expert test driver evaluation process may be modelled based on the subjective ratings of various braking systems [PARK ET AL. 2005].

ABSs are the oldest and most successful active safety systems in automotive vehicles [GÜVENÇ 2004]. A classic ABS consists of a fluidical (hydraulical and/or pneumatical) modulator, power source, wheel angular-velocity sensors, and an **electronic control unit** (ECU).

ABSs sense impending wheel lock-up and prevent it by reducing the amount of brake fluid or air pressure. ABSs may be viewed as wheel longitudinal slip controllers and are almost standard in present-day vehicles.

Proper ABS design considering all possible ranges of loading, road conditions, and vehicle velocity is still an important challenge and is more demanding for commercial automotive vehicles. Innovative developments in this area may be adaptations of ABS technology to BBW AWB dispulsion mechatronic control systems and to **all-electric vehicles** (AEV), that is, **battery-electric vehicles** (BEV) and **fuel-cell-electric vehicles** (FCEV), as well as **hybrid-electric vehicles** (HEV) with **electro-mechanical** (E-M) motor powered DBW AWD propulsion (traction).

In CHOI AND CHO [2004] for the control of ABS, a physical model of a longitudinal four-wheel with brake actuator has been described and a sliding mode controller with pulse width modulation (PWM) method has been developed for passenger vehicles.

In automotive scientists' and engineers' research, they introduce actuator dynamics of the solenoid-valve type in the system equation and derive the sliding mode control input theoretically. It is proposed using the PWM method to compensate for the discrete nature of actuator dynamics by duty control.

The effectiveness of the proposed control algorithms may be confirmed by testing the vehicle on an in-door test bench that may be specially constructed for the purpose.

Traction Control Systems (TCS) **--** TCSs may also be viewed as longitudinal slip controllers like ABSs but they operate after encountering large amounts of longitudinal slip that occur when wheels spin without traction on the road surface. This happens quite commonly at start-up on icy or muddy roads or a sudden acceleration request during normal driving. In such cases, a TCS intervenes by applying the brake to the wheel that is spinning until traction is achieved. The result is close to optimum traction on all four wheels. TCSs are also becoming standard components on innovative vehicles. The challenges and innovative developments for TCS are similar to those for ABSs.

Future developments may also include the combination of ABS, TCS, and ESP into one standard vehicle dynamics ECU. TCSs are used to prevent wheel slippage and to maximise traction forces [GÜVENÇ 2004].

In PARK AND KIM [2004], an innovative scheme is proposed to enhance vehicle lateral stability with a TCS during cornering and lane changing. This scheme controls wheel slip during cornering by varying the slip ratio as a function of the slip angle. It assumes that a TCS with the ECE or ICE throttle angle is used. The scheme may be dynamically simulated with a physical model of **front-wheel-driven** (FWD) passenger vehicles. Simulation results show that the proposed scheme is robust and superior to the conventional one that is based on fixed slip ratios, during cornering and lane changes.

Electronic Stability Program (ESP) **--** Loss of yaw stability of an automotive vehicle may result from unexpected yaw disturbances like side-wind force, wheel-tyre pressure loss, or μ-split braking due to unilaterally different road pavements such as icy, wet, or dry pavements [GÜVENÇ 2004]. An average driver may exhibit a panic reaction and control authority failure and may not be able to generate adequate steering, braking/throttle commands in such situations.

Vehicle yaw **stability control systems** (SCS) compensate for the driver's inadequacy during panic situations and generate the necessary corrective yaw moments through steering or braking control inputs. Such mechatronic control systems are termed ESP.

The two primary corrective yaw moment generating methods of actuation for ESP systems are compensation using steering commands or using individual wheel braking as it is more easily accomplished through already-existing ABS hardware [ZANTEN ET AL. 1995].

Steering actuation is the second method of generating corrective yaw moments. This may be in the form of an AWS SBW conversion mechatronic control system or through active steering.

In active steering, the **mechano-mechanical** (M-M) steering linkage is complemented by an extra steering E-M motor that provides extra steering moment to the system. This is a fail-safe approach when the M-M steering system is in place in the case of failure of the E-M motor.

Active steering may be used for implementing power steering, vehicle velocity-dependent steering ratio, or a yaw SCS. The disadvantage in the case of the yaw SCS is that the steering wheel may also move as the controller commands corrective steering signals. This is not a very good **man-machine interface** (MMI) as the driver may definitely feel the unpleasant loss of control of the vehicle when the yaw stability controller becomes active. A second disadvantage may be a slight loss of responsiveness, as the whole steering linkage including the steering wheel has to be moved by the E-M motor used for control.

Active steering has been available in some vehicles for a while. In contrast to active steering, **steer-by-wire** (SBW) **all-wheel-steered** (AWS) conversion mechatronic control systems collect only electric connections between the steering HW and the steering actuator. This offers great flexibility and solves several problems at the expense of not having a mechanical backup system.

SBW AWS conversion mechatronic control systems are also available for implementation in production vehicles. This technology enables easy implementation of steering-based ESP systems [ACKERMANN ET AL. 2002; AKSUN GÜVENÇ AND GÜVENÇ 2002; GÜVENÇ 2004].

The biggest overall gain is achieved by combining both steering and braking actuation for more corrective yaw moment when necessary. This is similar to what drivers actually do during their panic reaction.

The simultaneous use mentioned has to be performed in a coordinated manner. Combined and coordinated use also allows the mechatronic control system to switch between actuation methods in the event of an actuator malfunction. A projection into the future of ESP systems may begin with the use of BBW AWB dispulsion and AWS SBW conversion mechatronic control systems in production vehicles and associated changes in the ESP controller [GÜVENÇ 2004].

The use of **ride-by-wire** (RBW) or **x-by-wire** (XBW) integrated unibody, space-chassis, skate-board-chassis, or body-over-chassis mechatronic control advanced technologies may require more work in the future on failsafe design and fault tolerance.

As AEVs and HEVs are becoming more widespread, ESP systems that use the advantages of E-M motor-based propulsion (traction) and dispulsion (braking), if applicable, should be developed. There have also been considerable successful R&D efforts at using **geographical position system** (GPS) information in ESP systems.

Rollover Threat Warning **–** Loss of yaw stability is an important active safety consideration in passenger vehicles. Commercial vehicles have much higher **centre-of-gravity** (CoG) locations as compared to automobiles and thus tend to rollover during impeding loss of yaw stability.

Mechanisms to warn against the threat of rollover and so rollover-avoidance algorithms are, therefore, crucial for the active safety warning/control systems of commercial vehicles. Rollover is divided into the two categories of tripped and untripped rollover.

Active safety systems are concerned with untripped rollover incidents which may be avoided by mechatronic control even though they constitute a smaller percentage of rollover accidents.

Current active rollover-avoidance algorithms cannot avoid tripped rollover and so current warning systems cannot warn drivers of the possibility of a tripped rollover.

Future active safety systems using road sensing through day/night vision cameras, radar sensors, GPS, and map information may detect the possibility of a future tripped rollover by detecting obstacles that may cause a threat and intervene beforehand by modifying the vehicle\s course accordingly.

In order to study the rollover propensity of automotive vehicles and to design rollover avoidance methods in the laboratory and also for later on/off road tests, two untripped rollover creating manoeuvres, namely the *J*-turn and the fishhook manoeuvres, should be known to researchers.

The determination of meaningful and accurate rollover threat indicators is an important first step in developing rollover avoidance schemes.

Several indicators like the **static stability factor** (SSF), the **stability margin** (SM), the **tilt table ratio** (TTR), the **side pull ratio** (SPR), the **rollover prevention metric** (RPM), and **critical sliding velocity** (CSV) have been around for a long time. Some of these indicators or metrics have also been used for passive classification of rollover propensity of automotive vehicles.

Most of the currently available warning systems are based on static roll stability measures combined with monitoring of roll angle or lateral acceleration. A warning is issued when the predetermined threshold is exceeded. The threshold value may be tuned for a particular vehicle to reduce the number of false rollover warnings [GÜVENÇ 2004].

However, such an approach may be inferior in performance as compared to a dynamic rollover threshold indicator. This is due to the fact that the dynamics of the vehicle is neglected when determining the rollover threat in the passive case. Rollover prevention in heavy commercial vehicles with liquid loads that can slosh about is an important active safety application in this area.

In [JIANG 2002] a detailed physical model of the tractor semi-trailer tanker has been developed with a liquid sloshing effect. Lateral acceleration; trailer sprung mass roll angle, and the wheel-tyre load ratio have been proposed as three suitable candidates for use as a rollover threat index.

Also proposed is the use of braking in the event of a rollover threat. This is similar to what some automotive scientists and engineers have proposed concerning the threat of rollover.

In ACARMAN ET AL., [2002] have proposed a rollover prevention method based on anti-rollover braking and in ACARMAN AND CONGENER [2003] a frequency shaped sliding mode control has been applied to rollover prevention of a tanker-truck with a liquid load.

There are more recent efforts on the development of dynamic rollover threat indicators that use a physical model of the automotive vehicle for online extrapolation of the vehicle's motion.

The **time-to-rollover** (T-R) metric has been used quite frequently [CHEN AND PANG 1999A, 1999B, 2001] as a basis for physical model-based rollover threat determination.

The critical rollover event is usually defined as wheel-tyre lift-off or the sprung mass roll angle exceeding a predefined value.

The T-R value is computed at each time instant by simulating a lower-order linear yaw-roll model until the critical rollover event happens at a fixed steering wheel position. The closer T-R is to zero, the more critical is the rollover threat.

Classic T-R values being greater than one second may allow a good driver enough time to slow down and/or do less aggressive steering. A rollover threat signal may then be sufficient to warn the driver.

As commercial vehicles have slower dynamics when compared to SUVs and automobiles, they also have larger T-R values.

Most SUVs have T-R values of 0.5 s or less [CHEN AND PENG 1999A] necessitating the use of a rollover avoidance controller.

In HYUN AND LANGARI [2003] has been proposed predicting the **load transfer ratio** (LTR) of a tractor-semi-trailer in real-time to indicate the rollover treat. A model-based method to compute LTR based on available dynamics-related measurements was used.

Estimating variations in some key parameters due to load changes, online, through simplified relations and regression analysis has also been proposed.

The current state-of-the-art in the calculation of rollover threat is to choose a dynamic model-based measure like T-R and to compute it at selected times during operation of the vehicle and to display it in a form that is more easily understood by the driver.

The display may be in the form of flashing red or yellow indicators (depending on the severity of the situation) and a voice cue that tells the driver to slow down. This is shown in Figure 3.1 [GÜVENÇ 2004].

Fig. 3.1 Rollover warning display [GÜVENÇ 2004].

Development of rollover threat warning systems is an active area of R&D. Dynamic model-based methods that take into account the dynamics of the vehicle and mass as well as mass distribution changes are also being developed. The developed algorithms may need a separate ECU or can reside in the ESP ECU if the rollover threat vindication is bundled with an ESP system. The aim is to reduce the number of false rollover warnings.

Rollover Avoidance – A critical T-R value like one second may be used to trigger an active roll-avoidance mechatronic control system. There are several means of actuation.

These are [GÜVENÇ 2004]:

- ❖ Reducing torque and eventually vehicle velocity through braking or ECE or ICE torque reduction;
- ❖ Individual wheel braking;
- ❖ Active steering;
- ❖ Active anti-roll bars;
- ❖ Semi-active suspensions;
- ❖ Active suspensions.

The most direct and easiest way of controlling undesired roll motion is through the use of active suspensions. Since they entered the automotive industry, the use of active suspension-based anti-roll control has become an interesting and promising field. However, reducing vehicle velocity through braking and/or ECE or ICE torque reduction is the simplest and most easily implementable method.

Individual wheel braking is also a simple means of actuation along with active steering in the presence of an AWS SBW conversion mechatronic control system. However, these two means of actuation also result in yaw motions. There is, thus, the issue of avoiding excessive roll motion when these two methods are used. The presence of several methods makes it possible to combine them for better performance. Rollover avoidance may definitely be a major area of research under preventive and active safety systems.

Major improvements, incorporation into ESP controllers and a higher level of availability should be expected in the future [GÜVENÇ 2004].

Active Roll Stabilisation (ARS) -- Reasons why ARS ought to be used may be considered from the viewpoint of two contradictory requirements, namely agility or comfort as well as optimum handling or maximum ride mechatronic control [HENNING 2006].

How about both contradictory requirements?

- ❖ No passive vehicle safety system is able to serve both requirements;
- ❖ Necessitate the *'intelligent suspension'*, active mechatronic control system controlling the active suspension depending on different driving dynamic circumstances;
- ❖ The consequence may be more stable cornering:
  - ➢ Provides the driver with comfort and overall self-assurance;
  - ➢ Trim down shake and roll.

Layouts of an ARS function and a normal plot of linear roll angle/lateral acceleration characteristic are shown in Figure 3.2 [HENNING 2006].

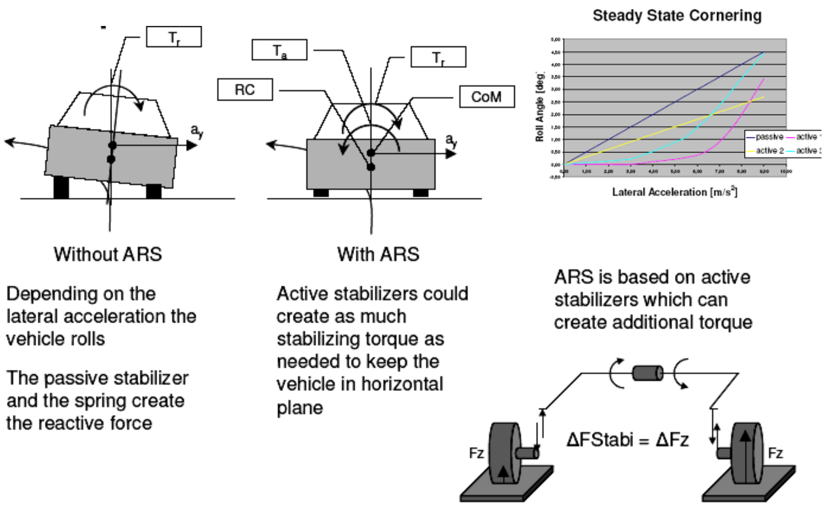

Fig. 3.2 Layouts of an active roll stabilisation (ARS) function [HENNING 2006].

Control strategy of the ARS may be as follows [HENNING 2006]:

- ❖ Passive systems – typical plot of linear angle/lateral acceleration characteristic;
- ❖ + Active systems: capability of reducing roll and increasing comfort;
- ❖ Different strategies possible:
  - ➢ Only reducing roll angle;
  - ➢ Step-by-step decreasing of mechatronic control influence;
  - ➢ Minimising roll angle up to a specified limit, then feedback to driver.

Supplementary features of the ARS are as follows [HENNING 2006]:

- ❖ Roll reduction dependent on lateral acceleration;
- ❖ Roll reduction dependent on anti-parallel deflection.
  - ➢ For example, driving over bumps leads to a stabiliser torsion; this effect may be compensated using active suspension systems and roll detection:
    - ✓ Increasing comfort when cornering;
    - ✓ Less shake and rolling moves when driving over pot-holes.
  - ➢ Influences driving dynamics – active decision for understeer characteristics:
    - ✓ Increase agility at low values of vehicle velocity;
    - ✓ Increase stability at high values of vehicle velocity.

Lane Keeping – A considerable number of accidents occur due to vehicles that stray from their own lanes. Such undesired lane changing may be due to accidental steering input by the driver or, more usually, due to a tired or drunken driver. Overworked and therefore sleepy heavy-duty vehicle drivers are quite common in some countries.

Near-ideal highway driving conditions like those on some of the world's highways where the driver drives with a set cruise control without having to provide any steering or throttle/brake commands for a long time may also be the cause of loss of concentration while driving even though the driver is not tired nor drunk. A lane-departure warning system is quite useful in such circumstances. The warning system usually works by first sending sound and vision (flashing warning) cues to the driver. The next steps in the case of an unreasoning driver are to create a virtual rumble strip by vibrating the steering wheel and to shake the driving seat. In the event that all of these warning fail, a lane-keeping system should take control of the vehicle.

A lane keeping system works by using a day/night video camera and a real-time image-processing algorithm to determine the lane to be followed. This may be complemented by GPS and map data. This information is input as the reference trajectory to a steering controller. Active steering or an AWS SBW conversion mechatronic control system should be used [GIVEN 2004].

Intelligent Transportation Systems (ITS) – It should have been noted by now that developments in preventive and active safety systems are leading towards the possibility of semi-autonomous and autonomous driving. Autonomous driving or intelligent transportation systems (ITS) have been the subject of much R&D activity in prominent automotive R&D centres for several decades [GÜVENÇ 2004]. The current result is several highway and test-track demonstrations of platoons of vehicles or combination of vehicles on different tracks that drive automatically without driver intervention [ÖZGÜNER 2003].

Obviously, the roadmap of future developments in the automotive area is taking the route to autonomously driven automotive vehicles. There have also been related major advances in inter-vehicle communications.

The trend right now is complementing inter-vehicle communication with information showers from the road to the vehicle [FUJISE 2004].

The future possibilities that ITS and information technology offer are very valuable and have much potential. However, for widespread acceptance and use of ITS systems, several important issues have to be solved. The most important one is being able to demonstrate ITS technology under actual road conditions and also in cases involving non-ITS automotive vehicles. The ITS mechatronic control systems have a large level of fault tolerance built into them and should be equipped with most of the preventive and active safety systems to be ready for unexpected situations. The first commercial use of ITS technology is expected in truck convoys where one monitoring driver may be able to drive a convoy of trucks. Work on off-road use of ITS technology has also started through racing [GÜVENÇ 2004].

Collision Avoidance – The trend towards autonomous driving requires the capability of determining and avoiding obstacles in the path of the vehicle [Güvenç 2004]. R&D work on incorporating collision avoidance technology into active vehicle safety control is relatively innovative [FERRARA AND GIACOBINI 2004] and benefits from the well-established theoretical and practical results on obstacle-avoidance methods for mobile robots.

Automotive vehicles, however, are much faster than mobile robots that may stop and wait to take the required avoiding action, if necessary. In both cases, moving obstacles are harder to avoid.

Collision avoidance may be broken down into two categories. The first one is determination of a non-collision path between obstacles whose locations have been determined. The second case is the sudden and unexpected detection of an obstacle with imminent collision.

The collision-avoidance algorithm should urgently perform *n* evasive manoeuvres in the case. This is a difficult situation to handle as the evasive manoeuvre should avoid other possible collisions and loss of lateral or roll stability of the vehicle.

Collision-threat warning and indication may be viewed as a prerequisite for designing a collision-avoidance system. Collision indicators are available commercially and suffer from false warnings.

The use of in-vehicle communication of the brake signal has been proposed for a collision indicator based on a detailed study involving road tests [PENG 2004].

A dynamic model-based collision indicator metric may be defined and calculated in real-time in a manner similar to rollover metric discussed previously. The dynamic **time-to-collision** (T-C) metric may need to involve the dynamics of a vehicle that might be collided with along with the original vehicle's dynamics for accuracy.

Collision indication and collision-avoidance technology are very important but are still ripe areas of preventive and active safety systems research where much more progress needs to be made [GÜVENÇ 2004].

Cruise Control (ACC) **–** The system uses a radar sensor to detect the vehicle being followed and adapts to reductions in vehicle velocity. If the vehicle being followed increases its velocity above the set limit, it is not followed, resulting in ordinary cruise control at the set value of the vehicle's velocity. The ACC system should also differentiate between vehicles in other lanes and try not to follow them [GÜVENÇ 2004]. Operation on roads with many bends should be given close attention. The controller should not exhibit unpredictable or sudden jumps in the desired value of the vehicle's velocity if the lead vehicle goes out of radar view on a curved road. ACC technology has advanced to the level that it is now available commercially.

Improvements to the control strategies used still need to be carried out. If the pursuit distance drops to about 30 m, one can than start talking about a **stop-and-go** (S&G) ACC system. This is more difficult as the dynamics of slowing down and speeding become more important.

A higher level of demand for S&G ACC systems is expected in the future. In European cities where S&G traffic actually means bumper-to-bumper operation, the development of a true S&G assistant may be useful. This is a difficult problem as it involves a multiple automotive vehicle scenario, transient ECE or ICE and vehicle dynamics, and CA simultaneously.

Note that this problem becomes relatively easier to overcome in AEVs or HEVs that have the luxury of E-M motor shut-down during stopping and smooth and easier to control during start-up [GÜVENÇ 2004].

3.1.2 Brake-By-Wire All-Wheel-Braked Dispulsion

The advanced technology concept of **ride-by-wire** (RBW) or **x-by-wire** (XBW) integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis mechatronic control systems may be replacing indispensable mechanical, fluidical components by electrical ones.

It was originally used as **fly-by-wire** (FBW) integrated aircraft mechatronic control systems for aircrafts only, but now the automotive industry is obviously paying greater than before attention.

As in aeronautics, this method has an enormous predisposition for putting innovative design into practice. For instance, it may be doable to design the interior of an automotive vehicle with completely different M-M, F-M and/or P-M connections between the steering wheel or the drive and/or brake pedals and the ECE or ICE compartment.

Innovative automotive customer interfaces may also be feasible – for example, a joystick instead of a steering wheel. As advanced technology continues to evolve, mechatronics is playing a major role in developing automotive mechatronic control systems that contribute to the driver's safety, comfort, and peace of mind. This notion is becoming most evident in the latest braking technology.

Automotive vehicle manufacturers are taking that technology leadership further with innovative brake technology termed BBW AWB dispulsion. This dispulsion means that the F-M or P-M braking system in a vehicle is partly or completely replaced by an E-M braking system. With this innovative system, the brake pedal generates an electrical signal to act on the E-M brake actuators placed on every wheel.

There are three ways to implement a BBW AWB dispulsion mechatronic control system [BRUCE 2002]:

- **Electro-fluido-mechanical brake** (EFMB);
- **Electro-pneumo-mechanical brake** (EPMB);
- **Electro-mechanical brake** (EMB).

Electro-Fluido-Mechanical Brake (EFMB) -- The BBW AWB dispulsion function is realised through F-M pumps and additional electrically controlled fluidical valves. There is no mechanical M-M connection between the brake pedal and the FMB system. Instead, the brake pedal sends electrical signals to an actuator that acts on the FMB system. It is possible to make an F-M backup that delivers an emergency function with reduced brake force. If the system detects a fault, the complete EFMB system may be shut down and a direct brake fluidical circuit may be closed with the help of some fluidical valves [HEDENETZ AND BELSCHNER 1998].

Electro-Pneumo-Mechanical Brake (EPMB) -- The BBW AWB dispulsion function is realised through P-M compressors and additional electrically controlled pneumatic valves. There is no M-M connection between the brake pedal and the PMB system. Instead, the brake pedal sends electrical signals to an actuator that acts on the PMB system. It is possible to make a P-M backup that delivers an emergency function with reduced brake force. If the system detects a fault, the complete EPMB system may be shut down and a direct brake pneumatic circuit may be closed with the help of some pneumatic valves [HEDENETZ AND BELSCHNER 1998].

Electro-Mechanical Brake (EMB) -- The BBW AWB dispulsion function is based on E-M actuators. The brake force and brake control is realised by electrical components. There is no possibility to make an M-M backup so the EMB system has to be operational even if a fault occurs [HEDENETZ AND BELSCHNER 1998].

The EMB system is based on two or four, or even more E-M callipers, an integrated electric parking brake, and a pedal-feel emulator. In full AWA BBW dispulsion, where all mechanical links are removed, there are no fluidical fluids or gases, pipes, or fluidical valves. These are replaced with electronic sensors, electronic microcontrollers, and E-M actuators that control the brake callipers.

The BBW AWB dispulsion mechatronic control system incorporates conventional ABS, ESC, emergency BA and balanced front and rear braking as well as special features for starting on hills and wheel-by-wheel (sequential) braking.

Like **electric power steering** (EPS), this new technology enables modular vehicle designs, providing far greater flexibility to the automotive vehicle manufacturer than today's braking systems [PSA 2001].

Advantages:

For the environment:

- Residual wear between brake pads and discs or rings (brake drag) is reduced or eliminated, resulting in better **specific fuel consumption** (SFC);
- The elimination of fluidic fluids or gases and components reduces the environmental impact of **end of life vehicle** (ELV);

For safety:

- Electronic control ensures faster, more accurate response to the drivers commands;
- Electronically controlled brakes improve the vehicle's dynamic behaviour (braking responsiveness, vehicle stability, real-time front and rear, as well as side-to-side brake-force distribution and hill holding);
- The pedal feel emulator, without fluidic links, simplifies the addition of new features; these include brake-pedal position adjustment, and fold away brake-pedals to facilitate entry or improve safety;
- By eliminating conventional ABS fluidic units, brake F-M booster and master F-M cylinder, the technology increases passive safety;
- Unlike conventional hand brakes, the electric parking brake also includes an ABS feature.

For driveability:

- Braking is easier because of improved consistent *'pedal feel'* that is completely tuneable;
- Parking brake operation is simpler and safer;
- Electronic control introduces new design opportunities.

3.2 Automotive BBW AWB Dispulsion

Automotive vehicle manufacturers are currently developing some innovative BBW AWB dispulsion mechatronic control systems that incorporate different levels of mechatronics into braking to produce several advantages. Through superior mechatronic brake engineering, some automotive vehicle manufacturers are moving very quickly to advance the technical potential of conventional **fluido-mechanical brake** (FMB) or **pneumo-mechanical brake** (PMB) systems to an **electro-mechanical brake** (EMB) system that may function completely all-electrically. As they realise their visions of integrating mechatronics into complete chassis system solutions, they are developing technologies that are cutting-edge, with tremendous benefits to customers and, most importantly, users.

Recently, every automotive brake manufacturer has been working on the full-time anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control systems [NEWCOMB AND SPUR 1967; ERVIN AND WINKLER 1986; WELLS AND MILLER 1993; FIJALKOWSKI & KROSNICKI 1994; FIJALKOWSKI 1995; BALZ ET AL. 1996; CHEW 1996; SCARLETT 1996].

One disadvantage of using fluid or air pressure -- the standard for automotive vehicle brakes for about *70* years -- is that modern vehicles have difficulty fitting the parts under the bonnet or hood as the Americans say. ABW BBW may first come in a hybrid form, retaining some fluidics (hydraulics or pneumatics). Now it may be mechatronic.

As automotive technology enhances, more and more M-M systems are being substituted by mechatronics. For instance, with reverence to under-vehicle automotive systems, ordinary shocks and struts have been substituted with mechatronic dampers. Spiral springs have been substituted with computer-controlled air spring suspensions. Until now, most of these alterations have been restricted to top-end comfort or performance vehicles. Why? Cost is one motivation. The other is reliability [CARLEY 2004].

Mechatronics may present substantial enhancements in many fields of automotive vehicle mechatronic control, but only if the innovative systems are without any problems and reliable, which has not always been the case. The brake pedal operates with a computer that advises four fast-acting fluidical valves, precisely how hard to put into operation the brakes on each wheel. A backup master F-M or P-M cylinder comes into play only if there is an ominous problem or electrical breakdown.

A conventional **electro-mechano-fluidical** (E-M-F) pump or **electro-mechano-pneumatical** (E-M-P) compressor and a high-pressure oily-fluid or air (gas) reservoir (or accumulator) provides *'permanently-on'* full brake pressure at each wheel. The computer-oriented modulator fluidical valves control how much fluid or air pressure really activates the brakes at each wheel. In the innovative system, the outsized vacuum brake booster is currently obsolete

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_27,

EFMB, EPMB, and EMB are three BBW AWB dispulsion mechatronic control systems that represent the future of brake technology. EFMB or EPMB is the first application and uses elements of current *'wet'* fluidical systems, while EMB is a *'dry'* electrical system that may eliminate fluidical lines and brake fluid or air that traditional FMB or PMB systems rely on.

EFMB or EPMB uses a mechatronic actuation unit with pedal feel simulator (PFS) and sensors for detecting the driver's intentions. The signal of this unit and other sensors are transmitted by wire to an ECU. Together with the F-M (H-M and/or P-M) unit, the ECU applies the optimum brake oily-fluid or air (gas) pressure on the conventional wheel brakes in the same way as current brakes do. F-M (H-M and/or P-M). EMB, conversely, generates the braking pressure in the brake callipers, directly at the wheels, by means of linear or rotary E-M motors controlled by an ECU. This system also uses a PFS and sensors for interpreting the driver's intentions. The ECU sends signals to each wheel where an E-M motor applies the proper brake fluidic or pressure. This system requires no fluidic lines and therefore no brake oily-fluid or air (gas). EFMB, EPMB, and EMB all optimise braking by applying pressure to wheels independently as needed, a major advantage over traditional systems [CONTINENTAL TEVES INC. 2003].

All systems also have several other advantages that are revolutionary in design and safety. EFMB, EPMB and EMB have shorter braking and stopping distances, improved crash worthiness, reduced mass, size, and number of components for better packaging and easier assembly, eradication of pedal vibration when ABS is activated, and the ability to interface with future traffic guidance systems. Another critical benefit to the systems is that they integrate other current mechatronic technologies such as ABS, TCS, ESP, and VSC. These systems operate from the same ECU and use the same electronic signals, eradicating the need for additional components on top of existing systems.

Automotive scientists and engineers are currently designing innovative BBW AWB dispulsion mechatronic control systems, using **artificial intelligence** (AI) tools to speed up the **research and development** (R&D) work.

Automotive vehicle manufacturers are set to introduce innovative and highly advanced RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis mechatronic control hypersystems that may eliminate accelerator and brake pedals from vehicles [SKF 2002].

EFMB, EPMB or EMB BBW AWB dispulsion technology could replace brake pedals. Steering, brakes, gear change, and clutch are all mechatronically controlled using RBW or XBW integrated unibody, space-chassis, and body-over-chassis mechatronic control technology in the latest concept vehicles.

At the heart of each system there is a smart E-M actuating unit under intelligent mechatronic control. Signals from the driver's control unit are interpreted by a logic system that ensures appropriate behaviour from each DBW AWD propulsion, BBW AWB dispulsion, ABW AWA suspension, or SBW AWS conversion mechatronic control system [SKF 2002].

The driver's control unit blends familiar design elements from today's proven **man-machine interface** (MMI) with the benefits of full RBW or XBW operation. The resulting mechatronic control arrangement dispenses with the steering column and the accelerator and brake pedals – providing automotive designers with unprecedented freedom to pursue unconventional interiors. The left and right steering control yokes that are mechanically linked feature full travel of some 20 deg. The mapping to the movement of the front wheels is under full mechatronic control, with feedback to the driver being provided as a function of the loads acting on the steering rack, by an appropriate high -torque E-M motor. The level of *'feel'* experienced by the driver is fully programmable, as is the relationship between the movements of the front wheels. Control of the braking system is duplicated on both the left and right yokes of the driver's control unit and is actuated by squeezing the handgrips. The mechan-ical design incorporates progressive resistance and a small, but discernible, free-play at beginning of the movement provides a tactile indication of when the brakes begin to operate. The system controls each brake as an individual subsystem under an umbrella mechatronic control arrangement for the complete braking EFMB, EPMB or EMB BBW AWB dispulsion mechatronic control system [SKF 2002].

The simple BBW AWB dispulsion mechatronic control system in an automotive vehicle (Fig. 3.3) demonstrates the importance of a consistent membership view in a distributed real-time application [KOPETZ AND BAUER 2002].

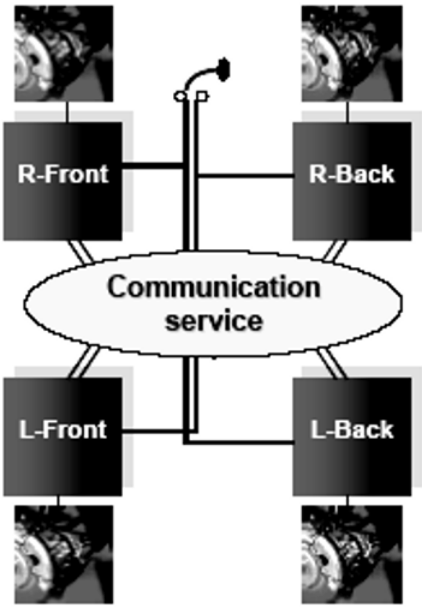

Fig. 3.3 Simple BBW AWB dispulsion application [KOPETZ AND BAUER 2002].

In this application, the four nodes that control the brakes at four wheels of a vehicle are connected by a **fault-tolerant** (FT) communication system.

The R-Front and the L-Back node accept the brake-pedal fluid or air pressure from a fail-silent brake-pedal sensor; the L-Front and R-Back node accept the brake-pedal fluid or air pressure from the other fail-silent brake-pedal sensor.

Every wheel node informs all other nodes about its view of the brake-pedal sensors, performs a distributed algorithm to allocate the brake force to each wheel, and controls the brake at its local wheel.

The brake is assumed to be designed in such a way that autonomously embraces a defined state, for example, *'wheel free running – no brake force applied'* in the case where the wheel node crashes or the electrical energy or mechanisms fail.

As soon as the other three wheels learn about the failure at one wheel, they redistribute the brake force to the other wheels in order that the vehicle is stopped safely by three braking wheels.

The time interval between the instant of brake failure and the instant of redistribution of the brake-force, that is, the error detection interval, is *'a safety critical parameter of this application'*. During this error detection interval, the braking BBW AWB dispulsion mechatronic control system is in an inconsistent state.

It has been conjectured that there is potential for a fatal accident if this inconsistent state is not detected and corrected within, at most, a few sampling intervals [KOPETZ AND BAUER 2002].

Consider the scenario where the R-Back node has an outgoing link failure. In this scenario, the other three nodes may assume the R-Back node has failed (since they don't receive any message from the R-Back node), but the R-Back node may think it is operating correctly, since it receives all messages from the other nodes.

This scenario illustrates the need for a distributed membership protocol to detect and eliminate safety-relevant inconsistencies in a distributed real-time system.

If the fault-hypothesis of the **time-triggered architecture** (TTA) is violated and the distributed agreement protocol cannot reach a consistent conclusion, the TTA activates its *'clique avoidance'* algorithm to inform the application of the grave situation.

In such a situation it is up to the application to decide how to proceed: to inform a rapid restart to re-establish consistency as soon as possible (for example, if a massive transient is assumed to have been the cause of the problem), or to continue with inconsistent data (that is not recommended).

The BBW AWB dispulsion mechatronic control system, shown in Figure 3.4, may be implemented over a network of six programmable mechatronic nodes that communicate using a **time-triggered communication protocol /class-C** (TTP/C) [HEINER AND THURNER 1998; KOPETZ ET AL. 1998].

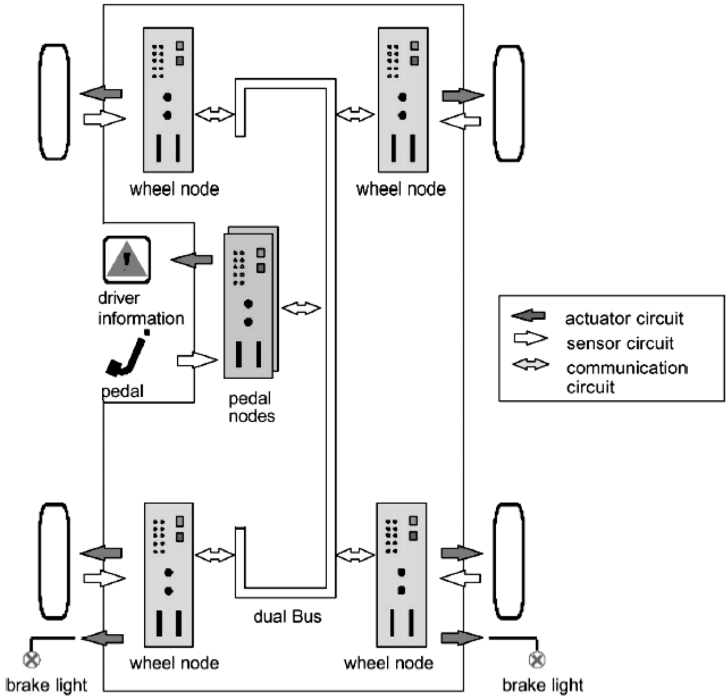

Fig. 3.4 Architecture of the BBW AWB dispulsion mechatronic control system [HEINER AND THURNER 1985].

Two of those nodes, the brake-pedal nodes, are physically located near the brake pedal. Their function is to continuously read and broadcast the braking demand on two replicated busses.

On the receiving end, there are four wheel nodes. By processing this information and sensory feedback from wheel-load, rotational acceleration, and oily-fluid or air (gas) pressure sensors, each node calculates the value of the braking fluid or air pressure that is fed to an actuator that then applies the actual braking fluid or air pressure on the corresponding wheel of the vehicle. The overall system delivers a number of sophisticated braking functions that include braking proportional to each wheel's load, ABS and ESP functions [HEINER AND THURNER 1985].

3.2.1 Requirements for a BBW AWB Dispulsion

There are high safety requirements on BBW AWB dispulsion mechatronic control systems. After a fault, the system has to be operational until a safe state is reached.

The driver must be able to rely as much on the innovative braking system as she/he does on present braking systems. To get a safe BBW AWB dispulsion mechatronic control system, the communication system must be able to manage hard real-time requirements. The software has to be verified with respect to those requirements. Since the BBW AWB dispulsion mechatronic control system depends on a constant power supply, two independent supplies are also needed. The actual values measured by the sensors at the brake pedal and at the wheels also have to be reliable. To meet this request, the sensors have to be replicated and compared. Another requirement is that the BBW AWB dispulsion mechatronic control system must be as good as (or better than) present conventional braking systems in lifetime, availability, maintainability, and costs [HEINER AND THURNER 1985].

3.2.2 Reasons to use BBW AWB Dispulsion

If the safety requirements can be met, there are several advantages for introducing BBW AWB dispulsion instead of using FMBs or PMBs in vehicles [BRUCE 2002]:

- ❖ Assistance functions like ABSs, BAs and ESPs may be realised by using only software and sensors; additional M, F or P components may be superfluous [HEDENETZ AND BELSCHNER 1998];
- ❖ Electrical interfaces instead of fluidic interfaces allow easier adaptation of assistance systems [HEDENETZ AND BELSCHNER 1998];
- ❖ Reduction of packaging problems; there may be fewer parts inside the vehicle if drivers do not have any mechanical links between the brake components as they have in a fluidic or pneumatic based system; it may also result in lighter mass [HEDENETZ AND BELSCHNER 1998];
- ❖ No brake fluid or air may be needed; the advantages are that it is ecological and the maintenance is simple;
- ❖ No M-M links between the brake components and the ECE or ICE compartment that improves the passive safety; this means that there are no mechanical parts can hurt the driver collision [HEDENETZ AND BELSCHNER 1998];
- ❖ Reduced costs of assembly during line production [HEDENETZ AND BELSCHNER 1998];
- ❖ It is easier to adjust the braking system to right-steered vehicles;
- ❖ The proportion between the pedal force and the pedal position can be set to a desirable value;
- ❖ The interface between the driver and the brake can easily be done more flexible; perhaps a disabled driver could use a joystick instead of a brake pedal;
- ❖ BBW AWB may be cheaper than today’s system if many assistance functions are required;
- ❖ It may be possible to test every single brake system at the supplier;

- When a trailer is involved, brakes may respond simultaneously on both carriage and trailer [BANNATYNE 1999];
- Minimised brakes wear; spreads load across wheels more evenly [BANNATYNE 1999].

3.3 Basics of Automotive Vehicle Braking

It is necessary to have knowledge of the technology correlated with contemporary auto-motive vehicles' BBW AWB dispulsion to understand the wheel-tyre to on/off-road interface, vehicle dynamics during braking, and the components of a BBW AWB dispulsion mechatronic control system. This section examines these issues to enhance the level of that knowledge.

3.3.1 Wheel-Tyre to On/Off-Road Interface

The longitudinal frictional braking force generated at each wheel of an automotive vehicle during a braking manoeuvre is a function of the normal force on the wheel and the coefficient of friction between the wheel-tyre and the on/off-road surface. The relationship between the mass on wheel and the resultant longitudinal frictional braking force is exposed in Eq. (3.1).

$$F_x = \mu_x \operatorname{sgn}(x) \frac{m_w}{g} , \tag{3.1}$$

where F_x - resultant frictional braking force in the *x-axis* longitudinal direction [N];
μ_x - wheel-tyre to on/off-road longitudinal coefficient of *Coulomb* friction in the *x–axis* longitudinal direction;
m_w - static and dynamic mass on the wheel [kg];
g - acceleration due to gravity [m/s^2];
x - displacement in the *x-axis* longitudinal direction [m].

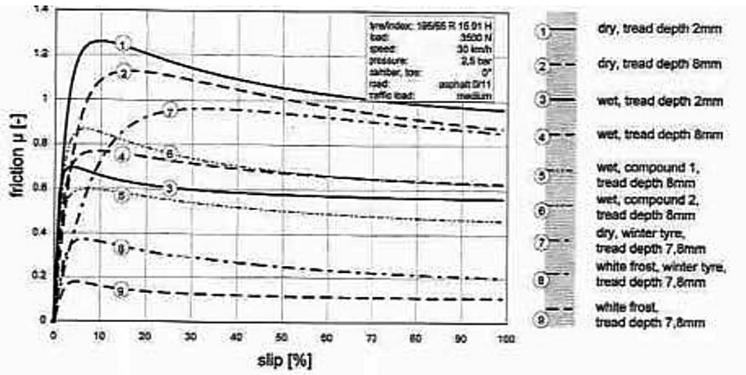

Fig. 3.5 *Coulomb* friction versus percentage wheel-tyre slip on various on/off-road surfaces [*RACE*LOGIC; THOMAS 1998].

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The wheel-tyre to on/off-road longitudinal coefficient of *Coulomb* friction is not a constant but is a function of factors, well known as being a kind of on/off-road surface and the comparative longitudinal slip between the wheel-tyre and the on/off- road. Particular curves describing wheel-tyre to on/off-road longitudinal coefficient of *Coulomb* friction as a function of wheel-tyre slip on various on/off-road surfaces are shown in Figure .3.5 [THOMAS, 1998].
From Figure 3.5 and Eq. (3.1), the following statements are induced [THOMAS 1998]:

- ❖ The existence of longitudinal frictional braking forces depends on wheel-tyre slip; if the wheel-tyre is rolling at the same tangential velocity as the on/off-road surface then there is no longitudinal frictional braking force; this relationship is essential in appreciative braking and is not easily seen wheel-tyre slip other than near 100% (no wheel angular velocity) is hard to detect without mechatronic devices;
- ❖ The peak value of the longitudinal frictional braking force takes place under circumstances of comparatively little slip; this shows that violent use of frictional FMBs, PMBs, EFMBs, EPMBs, or EMBs that initiates a 100% slip usually does not generate the most frictional braking force and a uniformly modulated, controlled brake fluid or air pressure, or brake voltage, respectively, affected by a skilled driver or because the ABS has a tendency to present shorter stops on nearly all on/off-road surfaces;
- ❖ The longitudinal frictional braking force created alters significantly with different on/off-road surfaces; the effect of this relationship is apparent to both driver and passengers in terms of stopping distance and deceleration if dry asphalt braking is contrasted with braking on ice;
- ❖ Usually, beyond the peak value of friction coefficient achievable on a specified on/off-road surface, the slope of the curve becomes negative; this observable fact (in a basic manner demonstrating that, beyond the slip ensuing in the peak value of frictional braking force, additional brake-pedal force ensues in less braking) explains why a skilled driver can obtain shorter stopping distances than can a less skilled driver and why a mechatronically-controlled ABW BBW dispulsion mechatronic control is as sophisticated as it is; also, the amount of '*peak value'* in the coefficient of friction curves alters significantly with different on/off-road surfaces; additional gain in longitudinal frictional braking force can be obtained because of slip control on on/off-road surfaces such as ice rather than on dry asphalt, for instance.

An additional feature of an automotive vehicle's rubber wheel-tyres of great consequence in braking is lateral frictional brake force versus wheel-tyre slip.

Lateral frictional brake force is the force preventing a wheel-tyre from sliding in a direction normal to the direction of the vehicle.

The equation for result-ant lateral frictional braking force is:

$$F_y = \mu_y sign\ (y)\frac{m_w}{g}\ , \tag{3.2}$$

where F_y resultant frictional brake force in the *y-axis* lateral direction [N];
μ_y - tyre-to-road lateral coefficient of *Coulomb* friction in the *y-axis* lateral direction;
y - displacement in the *y-axis* lateral direction [m].

The lateral coefficient of coulomb friction becomes slower once a wheel-tyre begins to slip longitudinally, as can happen during braking. Too great wheel-tyre slip at the rear wheels of a vehicle and the resulting loss of lateral frictional braking force will aid instability as the rear of the vehicle tends to slide sideways with relatively small lateral frictional braking forces. Too great wheel-tyre slip and the resulting loss of lateral frictional brake force on the front wheels of a vehicle will aid to loss of steerability, this phenomenon is frequent during panic stops on low lateral coefficient on/off-road-surfaces such as ice, as a hard application of the frictional FMBs, PMBs, EFMBs, EPMBs, or EMBs puts the rubber wheel-tyres in 100% slip.

3.3.2 Automotive Vehicle Dynamics during Braking

An *Euler--Lagrange* IInd order differential equation for dynamic braking performance can be obtained from *Newton*'s second law written for the *x-axis* longitudinal direction. The sum of the external forces acting on a vehicle body in a given direction is equal to the product of its mass and the acceleration in that direction.

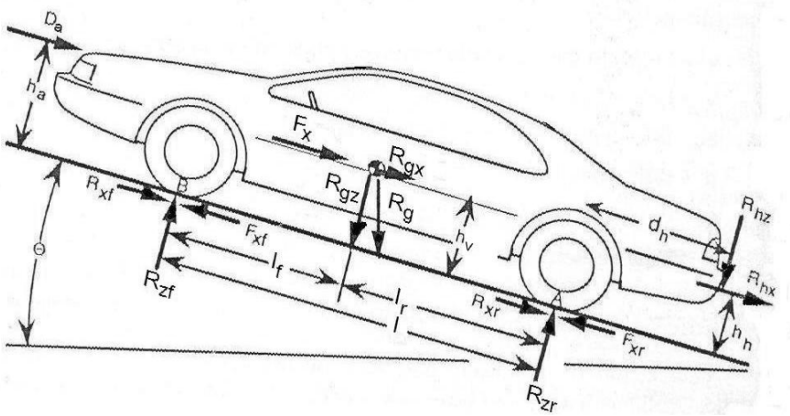


Fig. 3.6 Arbitrary forces acting on an automotive vehicle [GILLESPIE 1992].

Relating this law to straight-line automotive vehicle braking, the significant factors are shown in Eq. (3.2) and the sum of the forces acting on the vehicle is shown in Figure 3.6 [WONG 1978; GILLESPIE 1992].

$$\Sigma F_x = m_v\, a_x = m_v\, d_x = F_{xf} + F_{xr} + D_{xa} + m_v\, g \sin\Theta + f_r\, m_v\, g \cos\Theta\,, \quad (3.2)$$

where m_v - mass of the automotive vehicle [kg];
a_x - linear acceleration in the forward sense of longitudinal direction [m/s^2];
g - linear acceleration due to gravity [m/s^2];
$d_x = a_x$ - linear deceleration in the forward sense of longitudinal direction [m/s^2];
F_{xf} - front-wheel brake (FWB) force [N];
F_{xr} - rear-wheel brake (RWB) force [N];
D_{xa} - aerodynamic drag (considered to be acting at a point) [N];
$f_r = (R_{xf} + R_{xr})/m_v\, g \cos\Theta$ - rolling resistance coefficient;
Θ - uphill grade (angle of on/off road surface) [rad].

The front and rear brake force expressions come up from the torque of the brakes in conjunction with rolling resistance consequences, bearing friction, and driveline drags. An absolute analysis of the deceleration necessitates all-inclusive know-how of all these forces functioning on the vehicle.
Constant Deceleration -- A simple and fundamental relationship can be derived for the case where it is reasonable to assume that the forces functioning on the vehicle may be constant throughout a brake application. The simple equations that result provide an appreciation for the basic relationships that govern braking manoeuvres.

$$d_x = \frac{F_{xt}}{m_v} = -\frac{dv}{dt}\,, \qquad (3.3)$$

where F_{xt} - total value of all longitudinal deceleration forces on the automotive vehicle [N];
v - instantaneous value of the vehicle velocity in the forward sense of direction [m/s].
t - instantaneous value of time [s].

This equation can be integrated (given that F_{xt} = const) for a deceleration from the initial value of the vehicle velocity to the final value V_0 , to the final value of the vehicle velocity V_f .

$$\int_{V_0}^{V_f} dv = -\frac{F_{xt}}{m_v}\int_0^{t_a} dt\,, \qquad (3.4)$$

$$V_0 - V_f = \frac{F_{xt}}{m_v} t_a \ , \tag{3.5}$$

where t_a - time for a vehicle velocity alteration [s].
V_0 - initial value of a vehicle velocity [m/s];
V_f - final value of a vehicle velocity [m/s].

If frictional braking forces are assumed constant and the vehicle velocity effects on aerodynamical drag and rolling resistance are neglected, the time for a vehicle velocity alteration can be derived from *Newton*'s Second Law [GILLESPE 1992]:

$$t_a = \frac{m_v}{F_{xt}} (V_o - V_f) \ . \tag{3.6}$$

For the reason that velocity and distance are correlated by $v = dx/dt,$ one substitute for "*dt*" in Eq. (3.3), integrates, and gains the relationship between vehicle velocity and distance:

$$\frac{V_0^2 - V_f^2}{2} = \frac{m_v}{F_{xt}} x_a \ , \tag{3.7}$$

where x_a - stopping distance travelled during the deceleration in the forward sense of longitudinal direction [m].

The distance travelled during a vehicle velocity alteration can also be derived from *Newton*'s second law [GILLESPIE, 1992]:

$$x_a = \frac{m_v}{F_{xt}} \left(\frac{V_0^2 - V_f^2}{2} \right) \ . \tag{3.8}$$

These approximations indicate that the time to stop is proportional to vehicle velocity and the stopping distance is proportional to the square of the vehicle velocity.

In the circumstances where the deceleration is a full stop, then $V_f = 0$ and x_s is the stopping distance, x_s. Then

$$x_s = \frac{V_0^2}{2(F_{xt}/m_v)} = \frac{V_0^2}{2 d_x} \ , \tag{3.9}$$

and the time to stop is as follows:

$$t_s = \frac{m_v V_0}{F_{xt}} = \frac{V_0}{d_x} \ , \tag{3.10}$$

where t_s is the time to stop [s].

Thus, all other belongings being equal, the time to stop is proportional to the vehicle velocity, despite the fact that the stopping distance is proportional to the vehicle velocity squared, i.e., doubling the vehicle velocity doubles the time to stop, but quadruples the stopping distance.

Deceleration with Wind Resistance – The aerodynamic drag on a vehicle is dependent on vehicle drag factors and the square of the vehicle velocity. To determine the stopping distance in such circumstances, a more complicated expression is necessary but can still be integrated. To analyse this

$$\Sigma F_x = F_b + C_a v^2 \ , \tag{3.11}$$

where: F_b - total brake force of front and rear wheels;
C_a - aerodynamic drag factor.

Therefore:

$$\int_0^{x_s} dx = m_v \int_{V_0}^{0} \frac{v}{F_b + C_a v^2} \, dv \ . \tag{3.12}$$

This may be integrated to obtain the stopping distance:

$$x_{sa} = \frac{m_v}{2 C_a} \ln\left(\frac{F_b + C_a V_0^2}{F_b} \right) . \tag{3.13}$$

Braking Mechanical Energy and/or Power – The mechanical energy and/or power absorbed by a braking system can be substantial during a typical maximum-effort stop. The mechanical energy absorbed is the kinetic mechanical energy of motion for the vehicle, and is thus dependent on the mass:

$$E_b = \frac{1}{2} m_v \left(V_0^2 - V_f^2 \right) . \tag{3.14}$$

The brake power absorption may vary with the vehicle velocity, being equivalent to the brake force times the vehicle velocity at any instant of time.

Thus, the brake power dissipation is greatest at the beginning of the stop when the vehicle velocity is highest.

Over the entire stop, the average braking power absorption may be the braking mechanical energy divided by the time to stop. Thus:

$$P_{b\,med} = \frac{1}{2}\frac{m_v V_0^2}{t_s} \ . \tag{3.15}$$

Computation of the brake power is information from the standpoint of appreciating the performance required from a brake system.

Dynamic Vehicle Mass Transfer - During braking, the dynamic vehicle mass transfer (shift) that occurs is a function of the height of the barycentre (the centre of gravity), the static mass of the automotive vehicle, the wheelbase, and the deceleration rate. Equation (3.16) describes this dynamic vehicle mass shift, namely:

$$m_{vd} = \frac{h_v}{l} m_{vs} \frac{d_x}{g} - \frac{h_a}{l}\frac{D_{xa}}{g} \ , \tag{3.16}$$

where m_{vd} - dynamic mass of the automotive vehicle [kg];
m_{vs} - static mass of the automotive vehicle [kg];
h_v - height of the vehicle barycentre (centre of gravity height) [m];
h_a - height of the aerodynamical drag centre [m];
l - automotive vehicle wheelbase [m].

Brake Proportioning – The braking decelerations achievable on an automotive vehicle are simply the product of application level and brake gains (torque/ pressure or torque voltage) up to the point where lockup may occur on one of the FWB and RWB axles. Lockup reduces the brake force, and results in some loss of ability to control the vehicle.

It is well recognised that the preferred design is to bring both FWB and RWB axles up to the lockup point simultaneously. Yet, this is not possible over the complete range of operating circumstances to which an automotive vehicle may be exposed.

Balancing the brake outputs on both the FWB and RWB axles is achieved by '*proportioning*' the fluid or air pressure, or electrical voltage appropriately for the foundation brakes installed on the vehicle.

Proportioning then adjusts the brake torque output at the front and rear wheels in accordance with the peak values of the traction force possible.

The Ist order determinants of peak values of the traction force on an FWB or RWB axle are the instantaneous mass and the peak value of the friction coefficient.

During braking, a dynamic vehicle mass transfer (shift) from the RWB axle to the FWB axle occurs such that the vehicle mass on an RWB or RWB axle is the static plus the dynamic vehicle mass transfer contributions.
Thus for a deceleration, d_x :

$$m_{vf} = \frac{l_f}{l} m_v + \frac{h_v}{l} m_v d_x = m_{vfs} + m_{vd} \ , \tag{3.17}$$

$$m_{vr} = \frac{l_r}{l} m_v + \frac{h_v}{l} m_v d_x = m_{vrs} + m_{vd} \ , \tag{3.18}$$

where m_{vfs} - front axle static vehicle mass [kg];
m_{rfs} - rear axle static vehicle mass [kg];
$m_{vd} = (h_v/l)\, m_v\, d_x$ - dynamic vehicle mass transfer [kg];
$l = l_f + l_r$ - wheelbase of the automotive vehicle.

Considering a FWB and RWB automotive vehicle, this vehicle mass transfer is additive to the front wheels and subtractive to the rear wheels during braking, as shown in Eqs (3.17) and (3.18), respectively,

$$F_{xf\,\max} = \mu_{xp}\, sign(x) \left(m_{vfs}\, g + \frac{h_v}{l} m_v\, d_x - \frac{h_a}{l} D_{xa} \right) , \tag{3.19}$$

$$F_{xr\,\max} = \mu_{xp}\, sign(x) \left(m_{vrs}\, g - \frac{h_v}{l} m_v\, d_x + \frac{h_a}{l} D_{xa} \right) , \tag{3.20}$$

where $F_{xf\,max}$ - maximum value of friction force in the forward sense of longitudinal direction on the front wheels [N];
$F_{xf\,max}$ - maximum value of friction force in the forward sense of longitudinal direction on the rear wheels [N];
μ_{xp} - peak value of *Coulomb* friction coefficient;
m_{vfs} - static mass on the front wheels [kg];
m_{vrs} - static mass on the rear wheels [kg].

Simplifying Eq. (3.2) for the case of $\Theta = 0$ rad and negligible aerodynamical drag and rolling resistance, yields the following:

$$\Sigma F_x = m_v\, d_x = F_{xf} + F_{xr} \ .$$

Solving for d and substituting in simplified Eq. (3.19) and (3.20) yields Eqs (3.21), and (3.22), respectively,

$$F_{xf\,\max} = \mu_{xp}\, sign(x)\, \frac{m_{vfs}\, g + (h_v / l) F_{xr\,\max}}{1 - \mu_{xp}\, sign(x)\, h_v / l}\ , \tag{3.21}$$

$$F_{xr\,\max} = \mu_{xp}\, sign(x)\, \frac{m_{vrs}\, g + (h_v / l) F_{xf\,\max}}{1 - \mu_{xp}\, sign(x)\, h_v / l}\ . \tag{3.22}$$

These relationships indicate that the maximum value of brake force on the front wheels is dependent on the brake force on the rear wheels through the deceleration and the associated forward mass transfer and, in similar fashion; the braking force on the rear wheels is dependent on the brake force on the front wheels. Through application of the preceding equations, BBW AWB dispulsion mechatronic control systems designers can determine the total brake force required achieving the desired deceleration, and the braking dispulsion mechatronic control system components can be sized appropriately. Safety and legal requirements dictate that BBW AWB dispulsion mechatronic control systems designers consider deceleration under conditions of loaded and unloaded vehicles as well as under the circumstances of a partially failed BBW AWB dispulsion mechatronic control system, either half-system failures or loss of brake boost to the entire BBW AWB dispulsion mechatronic control system. Because of these considerations and numerous others, such as desired customer brake-pedal stroke and pedal force/deceleration expectations, vehicle BBW AWB dispulsion mechatronic control system sizing is a complicated engineering feat usually accomplished with the aid of an automotive vehicle simulator computer program.

3.3.3 Automotive Vehicle Braking Forces

The forces on an automotive vehicle producing a given braking deceleration may arise from a number of sources. Though the brakes are the primary source, there are others sources which may be discussed.

Rolling Resistance – One of the major vehicle resistance forces on level ground is the rolling resistance of the wheel-tyres. At low values of the vehicle velocity on a hard pavement, the rolling resistance is the primary motion resistance force. In fact, aerodynamic resistance becomes equal to the rolling resistance only at values of vehicle velocity of circa 80 – 100 km/h (50 – 60 mph). For off-highway, level-ground operation, the rolling resistance is the only significant retardation force.

While other resistances function only under certain circumstances of motion, rolling resistance is present from the instant the wheels begin to turn. In addition, rolling resistance has another undesirable property – a large part of the mechanical energy expended in a rolling wheel is converted into thermal energy (heat) within the wheel-tyre. The consequent temperature rise reduces both the abrasion resistance and the flexure fatigue strength of the wheel-tyre material, and may become the limiting factor in the wheel-tyre performance. There are at least seven mechanisms responsible for rolling resistance [GILLESPIE 1992]:

- ❖ Energy loss due to deflection of the sidewall of wheel-tyre near the contact area;
- ❖ Energy loss due to deflection of the tread elements;
- ❖ Scrubbing in the contact patch;
- ❖ Wheel-tyre slip in the longitudinal and lateral directions;
- ❖ Deflection of the on/off-road surface;
- ❖ Air drag on the inside and outside of the wheel-tyre;
- ❖ Energy loss on bumps.

Considering the automotive vehicle as a whole, the total rolling resistance is the sum of the resistances from all the wheels. Rolling resistance always opposes vehicle motion; hence, it aids braking. The total rolling force, R_x, may be

$$R_x = R_{xf} + R_{xr} = f_r \left(m_{vf} + m_{vr} \right) g = f_r \, m_v \, g \ , \qquad (3.23)$$

where R_{xf} - rolling resistance of the front wheels [N];
R_{xr} - rolling resistance of the rear wheels [N];
f_r - rolling resistance coefficient;
$m_v = m_{vff} + m_{vr}$ - mass of the automotive vehicle [kg].

For theoretically correct calculations, the dynamic vehicle mass, including the effects of acceleration and deceleration, trailer towing forces, and the vertical component of the air resistance, is used. However, for vehicle performance, the changing magnitude of the dynamic vehicle mass complicates the calculations without offering significant improvement in accuracy. Furthermore, the dynamic vehicle mass transfer between the FWB and RWB axles has minimal influence on the total rolling resistance (aerodynamic lift neglected). For these reasons, static vehicle mass is sufficiently accurate for computation of rolling resistance in most circumstances. All of these considerations apply, in a strict sense, only for straight-line motion. For vehicles that are subjected to lateral forces (cornering or aerodynamic loading), the direction of rolling resistance deviates from the direction of actual travel, and the tractive force or brake force must overcome the vectorial results of the side force and rolling resistance. Note that the total force is independent of the distribution of masses on the axles (static or dynamic). Rolling resistance forces are nominally equivalent to about 0.01 G deceleration (0.3 ft/s^2).

Aerodynamic Drag – The drag from air resistance depends on dynamic air pressure and is thus proportional to the square of the vehicle velocity. At low values of vehicle velocity, it is negligible. At highway normal values of the vehicle velocity, it may contribute a force equivalent to about 0.03 g (1 ft/sec^2).
Driveline Drag – The ECE or ICE transmission and final drive contribute both drag and inertia effects to the braking function. The inertia of these components adds to the effective mass of the vehicle, and warrants consideration in brake sizing on the drive wheels. For instance, the drag arises from bearing and gear friction in the M-M transmission and differential, and ECE or ICE braking. The latter is equivalent to the '*motoring*' torque (observed on a dynamometer) arising from internal friction and air pumping losses. It is worth noting that the pumping losses disappear if the ICE is driven to a value of the crankshaft angular velocity high enough to float the valves. Thus, ICE braking disappears when an ICE over-revs excessively. This can be a serious problem on low-velocity truck ICEs where valve float may occur above 419 rad/s (4,000 rpm), and has been the cause of runaway accidents on long grades. On a **manual transmission** (MT) with AM clutch engaged during braking, the ECE or ICE braking is multiplied by the gear ratio selected. Torque-converter (TC) transmissions are designed for power transfer from ECE or ICE to the driveline, but are relatively ineffective in the reverse sense of direction; hence, ECE or ICE drag does not contribute substantially to braking on vehicles so equipped. Whether or not driveline drag aids in braking depends on the rate of deceleration. If the vehicle is slowing down faster than the driveline components would slow down under their own friction, the drive wheel brakes must pick up the extra load of decelerating the driveline during the braking manoeuvre. On the other hand, during low-level decelerations, the driveline drag may be sufficient to decelerate the rotating driveline components and contribute to the braking effort on the drive wheels as well.
On/Off-Road Uphill/Downhill Grade – An on/off-road grade may contribute directly to the braking effort, either in a positive (uphill) or negative (downhill) sense. Grade is defined as the rise over the run (vertical over horizontal distance). The additional force on the vehicle arising from grade, R_g, is given by

$$R_g = m_v \, g \sin\Theta \;\cdot \tag{3.24}$$

For small values of the on/off-road angle typical of most grades:

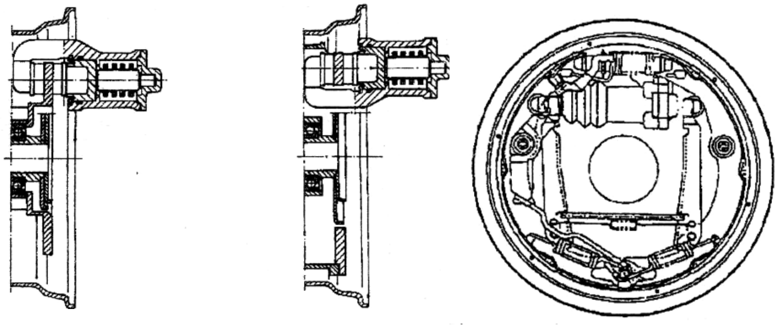
$$\Theta[rad] \cong Grade = Rise \,/\, Run \;\;,$$

$$R_g = m_v \, g \, \sin\Theta \cong m_v \, g \;\cdot$$

Thus a grade of 4% (0.04) may be equivalent to a deceleration of ± 0.04 g (1.3 ft/s^2).

3.3.4 Components of the BBW AWB Dispulsion Mechatronic Control Systems

Automotive brakes in common practices are three types – disc, ring, and drum as shown in Figure 3.7 [FIJALKOWSKI AND KROSNICKI 1997].



(a) (b) (c)

Fig. 3.7 Disc (a), ring (b) and drum (c) brakes [FIJALKOWSKI AND KROSNICKI 1997].

The torque produced by the brake functions to generate a braking force at the ground and to decelerate the wheels and driveline components is

$$F_b = \frac{T_b - J_w\,\alpha_w}{R_t}\ , \tag{3.25}$$

where: F_b - brake force [N];
J_w - angular inertia of wheels and driveline components [kg m^2];
α_w - angular deceleration of wheels [rad/s^2];
R_t - rolling radius of the wheel-tyre [m].

Except during a wheel lockup process, α_w is related to the deceleration of the automotive vehicle through the radius of the wheel-tyre, i.e., $\alpha_w = a_x/R_t$, and J_w may be simply lumped in with the vehicle mass for convenience in calculation. In that circumstance, the braking torque and braking force are related by the relationship

$$F_b = \frac{T_b}{R_t}\ . \tag{3.26}$$

Disc and/or Ring Brakes -- In disc and/or ring brakes, force is applied equally to both sides of a rotor (in the form of a disc or ring), and the braking function is achieved through the frictional action of inboard and outboard brake pads against the rotor (disc or ring). The pads are contained within a calliper, as is the wheel fluidical or pneumatical cylinder.

Although not a high-gain type of braking, disc and/or ring brakes have the advantage of providing relatively linear braking with lower susceptibility to fading than drum brakes. Force applied to the rotor by the pads is a function of fluid or air pressure in the BBW AWB dispulsion mechatronic control system and the area of the wheel fluidical or pneumatical cylinder (or cylinders, as the design dictates). Static brake torque T_{bs} can be computed using the following equation:

$$T_{bs} = E_b A_c p_a R_b , \tag{3.27}$$

where E_b - brake effectiveness factor: ratio of the disc or ring rubbing surface force to the input force on the shoes;
A_c - wheel fluidic or pneumatic cylinder area [m^2];
p_a - application fluid or air pressure [Pa];
R_b - brake radius [m].

Drum Brakes - Historically, drum brakes have seen common usage because of their high value of the braking factor and the easy incorporation of parking brake features. On the negative side, drum brakes may not be as consistent in torque performance as disc and/or ring brakes. The lower values of the brake factors of disc brakes require a higher value of actuation effort, and development of integral parking brake features has been required before disc brakes could be used at all wheel positions. The brake factor has mechanical advantages that can be used in drum brakes to minimise the actuation effort required. For instance, the drum brake consists of two shoes pivoted at the bottom.

The application of an actuation force pushes the lining against the drum generating a friction force whose magnitude is the normal load times the coefficient of friction of the lining material against the drum. The moment of rotation about the pivot point produced by the friction force on the '*leading*' shoe functions to rotate it against the drum and increase the friction force developed. This '*self-servo*' function yields a mechanical advantage characterised as the '*brake factor*', a '*trailing*' shoe on which the friction force functions to reduce the application force. The brake factor is much lower, and higher application forces are required to achieve the desired braking torque. For example, using two leading shoes, two trailing shoes, or one of each can obtain different values of the brake factor.

The '*duo-servo*' brake has two leading shoes coupled together to obtain a very high value of the brake factor. The consequence of using high values of the brake factor is sensitivity to the lining coefficient of friction, and the possibility of more noise and squeal. Small changes in the lining coefficient of friction due to thermal energy (heating), wear, or other factors cause the drum brake to behave more erratically.

Since disc brakes lack this self-actuation effect, they generally have better torque consistency, although at the cost of requiring more actuation effort.

The differences between the three types of brakes can usually be seen in their braking torque properties during a stop. On drum brakes, the braking torque may often exhibit a '*sag*' in the intermediate portion of the stop.

It has been hypothesised that the effect is the combination of temperature fade and vehicle velocity effects (braking torque increases as vehicle velocity decreases).

Disc and/or ring brakes normally show less braking torque variation in the course of a stop. With an excess of these variations during a brake application, it can be difficult to maintain the proper balance between front and rear braking effort during a maximum–effort stop.

Ultimately, this can show up as less consistent deceleration performance in braking manoeuvres resulting in longer stopping distances [GILLESPIE 1992].

The torque from the drum or ring brake normally increases almost linearly with the actuation effort, but the levels that vary with the vehicle velocity and the thermal energy (heat) absorbed through the temperature generated.

Thus

$$T_b = f(F_a, v, E_t) \ , \tag{3.28}$$

where T_b - braking torque [Nm];
F_a - actuation effort [N];
v - vehicle velocity in forward sense of longitudinal direction [m/s];
E_t - thermal energy [Ws].

In drum brakes, force is applied to a pair of brake shoes in a variety of configurations, including leading/trailing shoe (simplex), duo-simplex, and duo-servo.

Drum and/or ring brakes feature high gains relative to disc and/or ring brakes, but some configurations tend to be more non-linear and sensitive to fading and other brake-lining coefficient-of-friction changes.

The static brake torque relationship expressed by Eq. (3.24) presented for disc and/or brakes are equally applicable to drum brakes with design-specific changes for drum-brake radius and effectiveness factor. By design, the brake or ring radius for a drum or ring brake is one-half the drum or ring diameter.

The effectiveness factor represents the major functional difference between drum and/ or disc brakes; the geometry of drum and/or ring brakes may allow a torque to be produced by the friction force on the shoe in such a manner as to rotate it against the drum and increase the friction force developed. This function may yield a mechanical advantage that significantly increases the gain of the drum brake and the effectiveness factor as compared with disc brakes.

The dynamic brake-force calculation for drum and disc and/or ring brakes is more complex since the brake-lining coefficient of friction is a function of temperature; as the lining heats during a braking manoeuvre, the effective coefficient friction increases and less fluid or air pressure or electric voltage is needed to maintain a constant brake torque.

Booster and Master Cylinder - Figure 3.8 is a schematic diagram of a brake pedal, a vacuum booster, and a master cylinder.

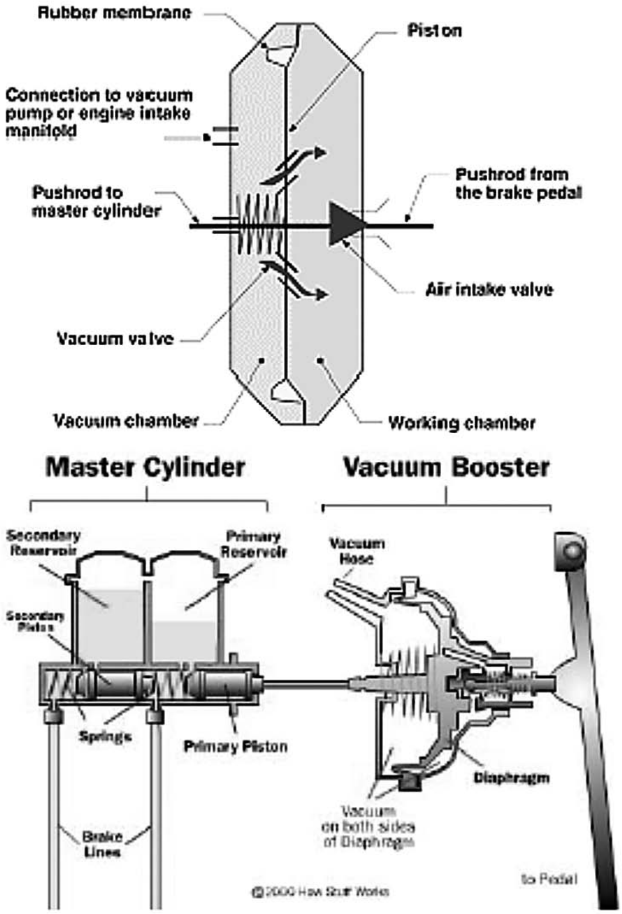


Fig. 3.8 Layout of the brake pedal, vacuum booster, and master cylinder [How Stuff Works; ROMANO 2000].

In actual practice, in passenger vehicles, as well as light and medium trucks the mechanical force gain due to the brake-pedal geometry is usually 3 to 4 and the gain through a vacuum booster is typically 5 to 9 after the booster reaches its crack point and before run-out occurs. Therefore, force applied by the driver may be multiplied by a factor of 12 to 36 at the master cylinder in order to achieve the fluid or air pressure necessary for braking. The resulting fluid or air pressure in the master cylinder p_{mc} is as follows:

$$p_{mc} = \eta \frac{F_{hd}\, k_{mg}\, k_{bb} - F_s}{A_p} \,, \tag{3.29}$$

where η - mechanical energy efficiency;
F_{driver} - driver force on the brake pedal [N];
k_{mg} - mechanical gain primarily related to the brake pedal assembly geometry and the instantaneous return spring force;
k_{bb} - brake booster gain, a function with the non-linearities of a minimum crack force being necessary to initiate boost and a run-out phenomenon resulting in a decreased force gain after a given input force is applied;
F_s - return spring force [N];
A_p - area in the master cylinder on which the force is acting (chamber piston area) [m^2].

Master cylinders are separated into primary and secondary chambers to better safety by avoiding total BBW AWB dispulsion mechatronic control system loss in the case of a failure in one portion of the sphere. The most common configuration is shown in Figure 3.8 with two chambers in a single bore [ROMANO 2000].

Proportioning Fluidical or Pneumatical Valve - Due to the dynamic vehicle mass transfer (shift), as shown in Eq. (3.16), brake fluid or air pressure that are appropriate for high-deceleration braking on front wheels usually are too high for the rear wheels; the result is that the rear wheels may tend to lock during braking. This problem can be decreased significantly through the use of proportioning fluidical or pneumatical valves. Standard proportioning for fluidical or pneumatical valves allow equal front and rear brake oily-fluid or air (gas) pressure during low input pressures (corresponding to low deceleration rates and little dynamic vehicle mass shift) but decrease the gain through the fluidical or pneumatical valve to less than one when a fixed input pressure (crack oily-fluid or gas pressure) is reached.

More complex mass-sensing fluidical or pneumatical valves are used in some applications when necessary, such as when dynamic vehicle mass transfers (shifts) and vehicle-mass changes are wide enough to make a fixed proportioning fluidical or pneumatical valve become insufficient for proper braking in all conditions.

Mass-sensing fluidic or pneumatic valves feature a means to measure the mass on the rear wheels and adjust the gain through the fluidical or pneumatical valve accordingly.

Figure 3.9 shows a layout of the two most common passenger vehicle as well as light and medium truck 4WB BBW dispulsion mechatronic control systems including proportioning fluidical (hydraulical or pneumatical) valves [CAGE 1994].

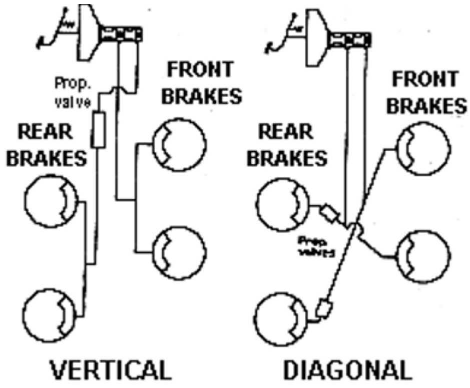


Fig. 3.9 Schemes of vertical and diagonal split 4BW BBW dispulsion mechatronic control systems [CAGE 1994].

The vertically split 4WB BBW dispulsion mechatronic control system typically used on **rear-wheel drive** (RWD) vehicles and the diagonally split 4WB BBW dispulsion mechatronic control system is typically used on **front-wheel drive** (FWD) vehicles.

Widespread use of diagonally split 4WB BBW dispulsion mechatronic control systems has been a direct result of the popularity of FWD vehicles. Current law requires a half-system (fluidical or pneumatical) failure stopping rate that is difficult to meet if the half system is the rear brakes (on a vertically split 4WB BBW dispulsion mechatronic control system) and the vehicle mass is significantly shifted towards the front as it is in FWD automotive vehicles.

Diagonally split 4WB BBW dispulsion mechatronic control systems afford the use of one front brake regardless of the half-system failure, and FWD automotive vehicles can be made to pass the legal requirements despite the large difference between the mass on the front and on the rear wheels. However, diagonally split 4WB BBW dispulsion mechatronic control systems require two proportioning fluidic or pneumatic valves and tend to require more sophisticated plumbing than the vertically split 4WB BBW dispulsion mechatronic control systems.

3.4 BBW AWB Dispulsion Mechatronic Control Systems

The *'R'* in RBW or *'X'* in XBW is a wildcard for automotive mechatronic control systems like driving (as well as ECE or ICE throttling and gear shifting, if any), steering, braking, or absorbing (damping).

We have described the development of BBW AWB dispulsion mechatronic control systems. BBW AWB dispulsion means no more AM, AF, and/or AP links between the braking actuators on each driven or undriven wheel and the brake pedal.

The necessary braking force is computed from the driver's input at the brake pedal unit (BPU) and transmitted separately to the driven or undrivenwheel actuators.

In the first generation of BBW AWB dispulsion mechatronic systems with EFMBs or EPMBs, all the control functions are implemented in one main ECU only.

An F-M (H-M and/or P-M) backup mode is now fitted for safety motives to make braking certain in the circumstances of an ECU outage or electrical failure.

In the next generation, the F-M or P-M back-up mode may no longer be indispensable, for the reason that there may be an autonomous braking system with its own ECU on every wheel.

So there may be at least four autonomous ECUs that represent a multi-redundant system – a method well known from aircraft construction.

EMBs are even now under development by the automotive scientists and engineers and still have to be tested before mass production.

The second generation EMB BBW AWB dispulsion mechatronic control system may have advantages for both manufacturer and consumer – from manufacture to a lifetime of service.

The possessions and behaviour of the brake may be easy to adjust by altering software parameters and electrical magnitudes instead of adapting M-M and/or F-M (H-M or P-M) gears. Therefore, it may be much easier to integrate innovative features, for instance, **electronic stability control** (ESC), **vehicle dynamics control** (VDC), **vehicle stability control** (VSC), **brake assist** (BA), **electronic parking brake** (EPB), **global chassis control** (GCC) or RBW or XBW integrated unibody, space-chassis, skateboard-chassis or body-over-chassis motion mechatronic control hypersystems, and the next generation of **adaptive cruise control** (ACC) features.

Diagnostic features are a supplementary advantage. For instance, in Figure 3.10 ingredients of VDC are shown [TÖRNGREN 2005].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
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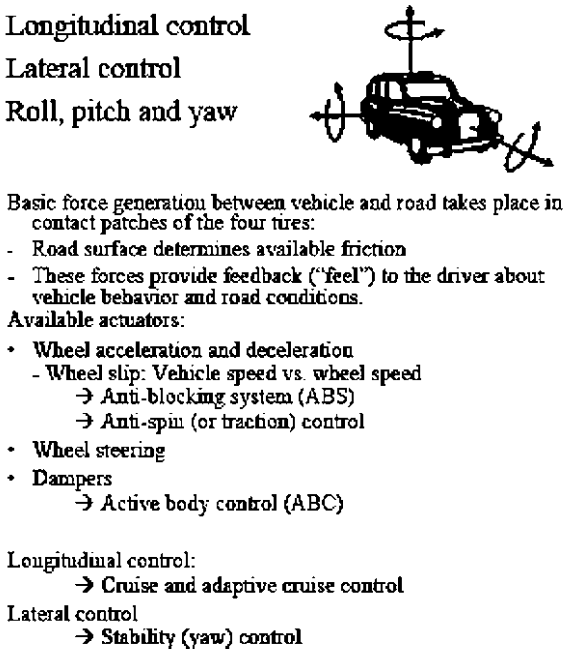


Fig. 3.10 Ingredients of vehicle dynamics control (VDC) [TÖRNGREN 2005].

An EMB BBW AWB dispulsion mechatronic control system looks deceptively simple. As shown in Figure 3.11 [MOTOROLA INC. 2001], electrical or optical wires convey the driver's pressure from a sensor on the brake pedal to the micro-controller that relays the signal to EMB actuators at each wheel.

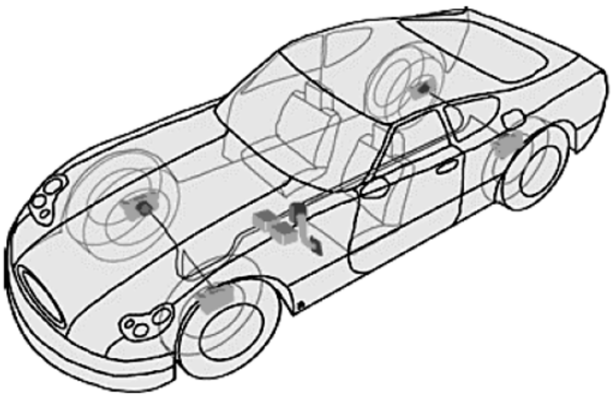


Fig. 3.11 Principle layout of the EMB BBW AWB dispulsion mechatronic control system [MOTOROLA INC.2001].

In turn, the modulator actuators squeeze the brake pads against the brake disc or ring to slow and stop the vehicle. In a conventional automotive vehicle, the fluidics would respond to pressure on the brake pedal to squeeze the pads.

For drivers, optimum mechatronic control of the braking behaviour of every discrete wheel represents a higher braking performance. The feel of the brake pedal is also considerably enhanced and naturally attuned to different requirements. And because the necessity of brake fluid is eradicated, the environment benefits too.

Each driven or undriven wheel actuator of an EMB may be composed of a brushless DC-AC macrocommutator **interior permanent magnet** (IPM) magnetoelectrically-excited synchronous motor, a gear, and a spindle arrangement that may be housed in a conventional *Colette*-type calliper. The brake force mechatronic control may be provided with the highest feasible safety system using a **fault-tolerant** (FT) system and redundant fail-safe power management (42 V_{DC}).

BBW AWB dispulsion mechatronic control systems replace the M-M or F-M (H-M or P-M) links connecting the brake pads to the brake pedal that eradicates the necessity of brake fluid or air. This technology may enhance braking comfort and pedal feel, and may also escalate braking efficiency over short distances.

Indeed, some drivers never apply the full brake force and therefore never take advantage of the ability of the BBW AWB dispulsion mechatronic control system to minimise the vehicle stopping distance.

The BBW AWB dispulsion mechatronic control system works by detecting the rapid initial depression of the brake pedal and then applying the full braking force automatically. This both removes the dwell delay time and also ensures that the full brake fluid/air pressure or full brake voltage is applied. The result is that the stopping distance is significantly reduced for drivers in on-road situations. These control systems have been shown to reduce the average stopping distance significantly and are therefore one of the most significant contributions to road safety for many years.

As FMBs replaced **mechano-mechanical brake** (MMB) systems in automotive vehicles several decades ago, EFMB and EMB BBW AWB dispulsion mechatronic control systems are poised to replace the present FMB systems in the automotive industry in the near future.

Conventionally, a driver's feeling of safe vehicle control (SVC) was permanently correlated to the reliability of the mechanical gears.

As vehicle performance has enhanced 'ad infinitum', the ultimatum to apply higher forces for vehicle handling has also become greater than before.

Year after year, innovative M-M, F-M (H-M and/or P-M) and mechatronic devices and mechatronic control systems have been invented to increasingly support the driver in controlling the automotive vehicle.

Safety was ensured by the high reliability of components and by simply adding redundant features that have continuously increased the complexity of the mechatronic control systems used.

Human Driver-to-Automotive Vehicle Interface - The move towards the EMB represents a breakthrough in brake system technology. The driver's wish to apply the brakes is detected by sensors monitoring the brake pedal movement. The electrical signal containing the information on pedal position is transferred to the redundant **brake masters** (BM) that control the actuators on the brake callipers by wire only. Since this system does not incorporate any mechanical replacement system and the system failsafe mode does not exist, innovative safety are under development [BELSCHNER ET AL. 1998; DILGER ET AL. 1998; KOPETZ AND THURNER 1998].

The BPU for an EMB system (Fig. 3.12 [SLANEC 2002]) is being provided with new functions that can be classified into two categories:

- ❖ Transmission of the driver's wish to actuate the brake to the brake masters;
- ❖ Generation of braking pedal feel and feedback from the brake system to the driver.

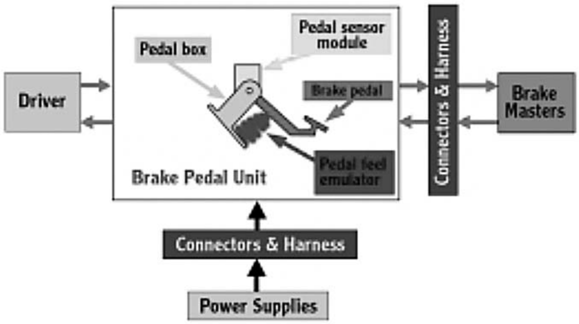


Fig. 3.12 System interfaces of the brake pedal unit (BPU) for electromechanical brakes (EMB) [SLANEC 2002].

Currently, automotive scientists and engineers would like to focus on some safety and reliability aspects of the generation and transmission of the brake pedal position information to the brake masters. Nevertheless, the generation of the system feedback to the driver is also considered as a safety-critical function of a BPU for an EMB system [BILL, 1999].

Brake Pedal Position Sensing - At first sight, brake pedal position sensing looks easy. There are many solutions for sensing the position of the accelerator pedal used for mechatronic control of ECE or ICE management.

Why can't these be easily adopted for EMB systems? First of all, the concepts of such sensor units are based on failsafe requirements that are sufficient for mechatronic control.

The EMB system, however, requires fail-silent/fail-operational features. This means that if a single fault occurs at any time, the system must remain operational and tolerate this fault. Secondly, a small signal drift at the accelerator pedal rest position – for instance, due to mechanical wear or ageing of mechatronic components – may be classified from the ECE or ICE mechatronic control viewpoint as not safety-critical.

For the EMB, such signal drift may have catastrophic consequences, such as driving the vehicle with unintentionally applied brakes. Thirdly, the signal evaluation and diagnostics for the current accelerator pedal sensors are performed in the ECE or ICE mechatronic control module. In order to fulfil the redundancy requirements for the EMB, the complexity of the system may drastically increase if the same strategy is utilised.

Design Approach - The biggest challenge for the design is to consider not only the above-mentioned safety requirements but also to ensure high reliability and to propose a commercially feasible solution. This can be achieved by an iterative design approach using combined hazard-analysis techniques and FMEA [STOLZL ET AL. 1998].

The first step is to identify the hazards. Figure 3.13 shows the hazards and the related effects for the **brake pedal sensor unit** (BPSU) or an EMB system [SLANEC 2002].

- *Loss of brake*
  Brake cannot be activated
- *Reduced deceleration*
  Braking distance increases
- *Unwanted increased deceleration*
  Deceleration increases at low pedal travel
- *Undesired sudden braking*
  Unwanted abrupt braking applied to vehicle
- *Undesired constant braking*
  Brakes are constantly activated whilst vehicle is moving
- *Retarded braking*
  Greater pedal travel needed to activate brake

Fig. 3.13 Hazards and effects due to failures of the brake pedal unit (BPU) for electromechanical brakes (EMB) [SLANEC 2002].

The design concept should start by first considering one sensor and checking the risk. If necessary, hazard controls have to be implemented for the next iteration. This process should continue until the remaining risks are classified as low [FAA, 2004]. In parallel, the reliability and the costs have to be reviewed during each iteration stage.

Brake Pedal Sensor Unit - The BPSU for an EMB system is under development and it is a stand-alone unit [SLANEC 2002]. This means that the unit provides and processes the required information with sufficient redundancy.

All information is passed to the brake masters by a **fault-tolerant** (FT) bus system (for example, TTP/C or FlexRay) on two or even three independent channels. The safety strategy is based on the following:

- ❖ Comprehensive self-diagnosis;
- ❖ Dynamic redundancy;

- ❖ Combined design redundancy and design diversity;
- ❖ Galvanic decoupling of redundant elements;
- ❖ Multiple independent power supplies with sufficient buffers;
- ❖ Adaptive learning system for dynamic brake pedal rest position detection;
- ❖ Data communication using a time-triggered, **fault-tolerant** (FT) bus system.

The availability of comprehensive self-diagnosis enables the application of dynamic redundancy, which helps to reduce the number of precise redundant position sensors to two. This has a positive effect since it reduces the complexity and the costs as well as increasing the reliability with regard to static redundancy.

The two accurate angular-position sensors may be eddy-current sensors with an accuracy of < 0.1°.

In addition, analytical redundancy is partially implemented by introducing a data-matching factor. Two microcontrollers condition the signals and transmit data to the brake masters. One rough *Hall*-sensor encoder may be used to prevent common-cause failures through design diversification.

In addition, a rough evaluation of the two main signals is performed. Galvanic decoupling of redundant elements, three independent power supplies (and three independent connectors for series production parts), and different program codes in each microcontroller, contribute further to the prevention of common cause failures.

An adaptive learning system is currently being developed for the dynamic detection of the peda-rest position of conventional brake and clutch systems. The dynamic recognition and update of the pedal-rest position is essential for avoiding some hazards.

For the prototypes only, data communication to the brake masters is implemented via a controller area network (CAN) to TTP/C adapter by two independent node-to-nodes CAN bus channels.

The CAN message on each channel contains the following information [SLANEC 2002]:

- ❖ Pedal-position -- Sensor 1;
- ❖ Pedal-position -- Sensor 2;
- ❖ Pedal-velocity -- Sensor 1.

Greater pedal travel needed to activate brake dynamic redundancy:

- ❖ Pedal-velocity -- Sensor 2;
- ❖ Pedal-position -- Encoder;
- ❖ Data-matching factor;
- ❖ Diagnostics -- μC 1;
- ❖ Diagnostics -- μC 2;
- ❖ Synchronisation counters for the microcontrollers.

Figure 3.14 shows a screen-shot of the above CAN messages [SLANEC 2002].

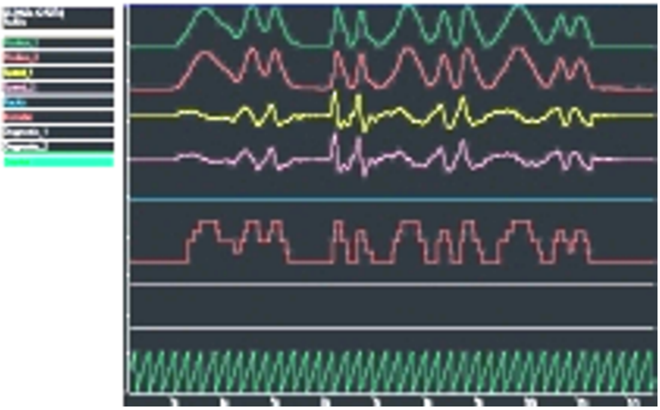


Fig. 3.14 Screen-shot of CAN messages on one channel [SLANEC 2002].

***Fail-Silent/Fail-Operative Matrix* -** The matrix has shown in Figure 3.15 demonstrates the required fail-silent/fail-operational capability for a single fault [SLANEC 2002].

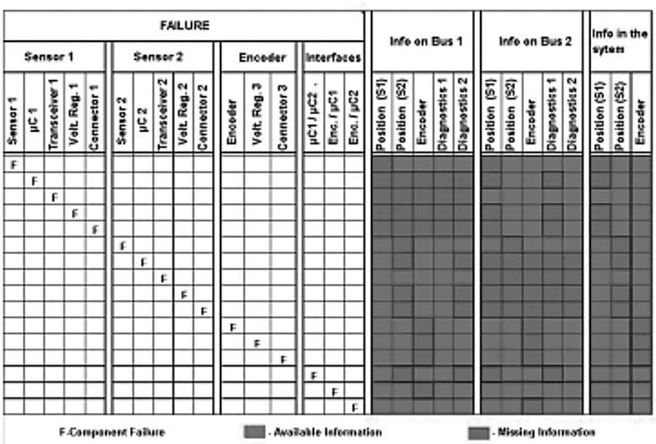
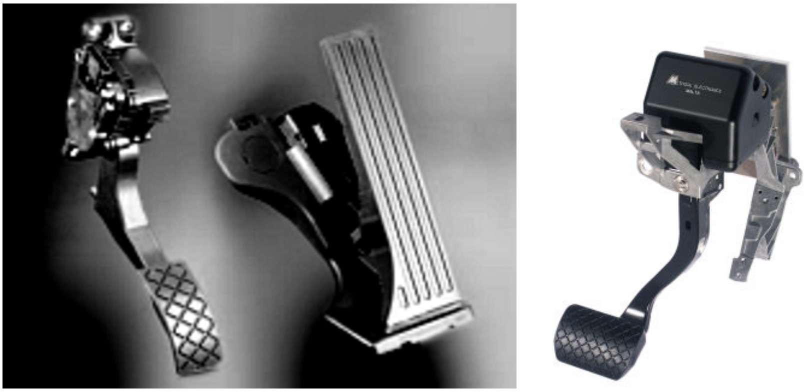


Fig. 3.15 Fail-silent/fail-operational matrix [SLANEC 2002].

If one component or link within the sensor unit fails, certain information may not be available on one or both bus channels. In this case, the brake system still has at least two sources of information on the pedal position. It is assumed that the chosen bus system must be fault-tolerant.

Current Status -- Prototypes of the BPSU shown in Figure 3.16. The unit is assembled in a pedal box (PB) that is currently in series manufacture [SLANEC 2002; ADWIN 2006].



(a) (b)

Fig. 3.16 Prototypes of the brake pedal unit (BPU) for electromechanical brakes (EMB): the pedal sensor module (PSM) and a passive pedal feel emulator (PFM) are assembled in a pedal box (PB) [ADWIN 2006 (a); AUDI -- SLANEC 2002 (b)].

The pedal-feel emulated by mechanical springs is only passive. For the prototypes only, one industrial connector is used instead of three independent connectors. Validation testing of the sensor unit performance using **hardware-in-the-loop simulation** (HILS) techniques shows that the concept that is based on dynamic redundancy, and meets the safety requirements without compromising theoretical reliability and commercial feasibility [SLANEC 2002].

SLANEC [2002] covers the development of an innovative hybrid BBW AWB dispulsion mechatronic control system for an automotive vehicle. The BBW AWB dispulsion mechatronic control system under investigation includes a set of eddy-current electric machines, a driveline mounted generator, an EFMB system, and a pedal-force control system.

The control algorithms include electronic brake-force distribution, independent wheel torque control, brake torque blending, pedal force control, panic brake assist, closed loop torque control for E-M-F or E-M-P actuators (for example, E-M-F pump or E-M-P compressor, and fluidical valves) and eddy-current electrical machines, driveline generator control, or CH-E/E-CH storage battery power management, regenerative braking, and VDC algorithms including ABS, YSC and EFMB- or EPMB-based TCS algorithms.

AMESIM® [2004] focuses on an overview of the hybrid BBW AWB mechatronic control system and then briefly describes the theoretical development of a predictive YSC algorithm for the proposed BBW AWB dispulsion.

Simulation results and some experimental results are presented. Besides, sample in-vehicle test results are presented for an ABS control algorithm similar to the predictive YSC. An EFMB or EPMB or EMB BBW AWB dispulsion mechatronic control system, a next-generation braking system, may stop automotive vehicles by electrical signal rather than by the FMB systems shown in Figure 3.17, as used on most conventional brake systems today [AMESIM® 2004].

The BBW AWB technology is expected to offer increased safety and vehicle stability to consumers and it may provide benefits to manufacturers who may be able to combine vehicle components into modular assemblies using cost-effective manufacturing processes [AMESIM® 2004].

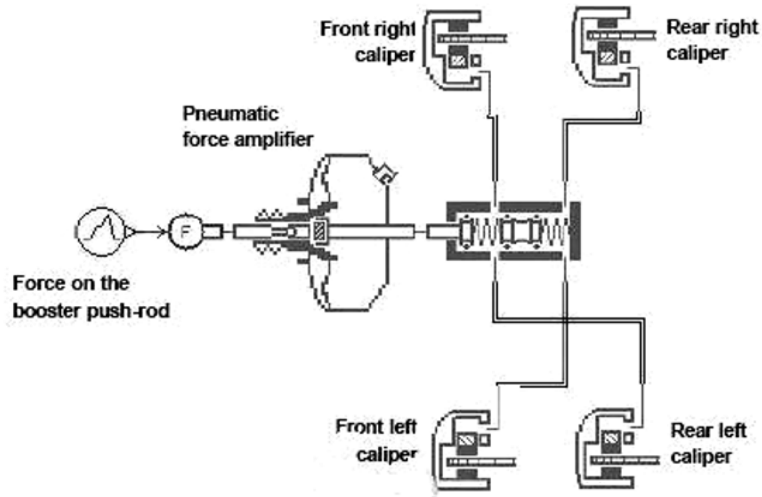


Fig. 3.17 Conventional FMB system [AMESIM® 2004].

Summing up, the EMB BBW AWB dispulsion mechatronic control systems represent the following advantages [AMESIM® 2004]:

- ❖ Eliminates fluidic lines and substitutes with E-M actuators;
- ❖ Environmentally friendly due to lack of brake fluid or air;
- ❖ Lower servicing requirements; no necessity to exchange/bleed brake fluid or air;
- ❖ Much easier integration of different mechatronic control systems: ABS, ESP system, traffic management systems, and so on;
- ❖ Braking conceivably the most unmistakable safety-critical system, therefore safety standards must be high.

Current options available include F-M, P-M or E-M actuation. Sensors may be required for the braking actuator. Other sensors and information may also be required, such as lateral acceleration, yaw rate, and so on, for the EMFB, EMPB or EMB BBW AWB dispulsion mechatronic control system's calibration and other features. Braking actuation may be achieved through several methods. As an example, a simple BBW AWB dispulsion mechatronic control system is shown in Figure 3.18 [MCDERMID AND PUMFRET 2003].

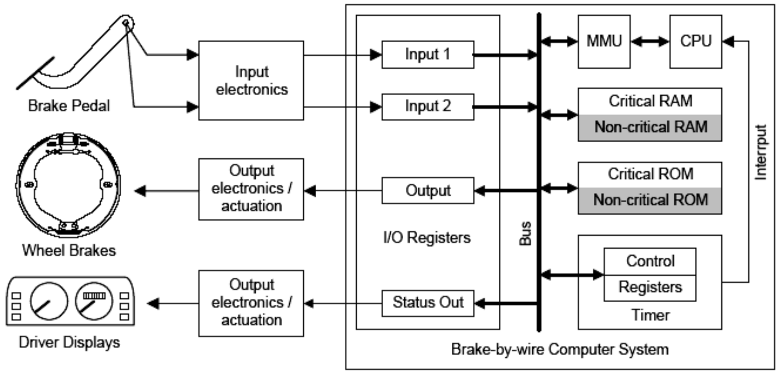


Fig. 3.18 Simple EFMB, EPMB or EMB BBW AWB dispulsion mechatronic control system [MCDERMID AND PUMFREY 2003].

Braking inputs from a pair of sensors on the driver's brake pedal are converted by processing mechatronics into digital values available to the software, in particular registers in the **input/output** (I/O) map.

The software includes a routine that reads these registers and calculates a required braking value that is placed in an output register from where further mechatronics convert it into drive signals to the brake actuator. The programme code is stored in part of the programme ROM and runs on the microprocessor, using some of the RAM locations as workspace. If braking control is safety critical, then all these parts of the system must be regarded as *'intrinsically critical'* [MCDERMID AND PUMFRET 2003].

The simple EFMB, EPMB or EMB BBW AWB dispulsion mechatronic control system also includes a **memory management unit** (MMU) that performs the mapping between logical and physical memory locations. The registers that define this mapping are regarded as *'primary controls'*: they are not actually involved in braking calculations, but directly affect resources that are introduced.

The example, a simple BBW AWB dispulsion mechatronic control system incorporates other functions that are not critical, including functions to display the status of the system on the dashboard.

The parts of the programme ROM containing the code for these functions, the status output register, and RAM locations used only by the status display functions, may be regarded as *'non-critical'* resources.

If ones assume that the software is implemented as a set of application functions running on top of an operating system, then the operating system must be capable of providing suitably segregated access to all the system resources [MCDERMID AND PUMFRET 2003].

3.5 Anti-Lock EFMB or EPMB BBW AWB Dispulsion Mechatronic Control Systems

3.5.1 An Introduction to Anti-lock Braking

This section reviews several basic ABS concepts. When the readers finish this section, they should be able to answer the following questions [FHWA-MC 1998]:

- ❖ What is an ABS?
- ❖ Why are ABSs standard on most commercial vehicles?
- ❖ How does an ABS work?
- ❖ What are the major features and benefits of ABSs?
- ❖ How should a ABS-equipped automotive vehicle be driven during a road test?

What is an ABS? **-** ABSs are mechatronic control systems that monitor and control wheel slip during vehicle braking. They may improve vehicle mechatronic control during braking, and reduce stopping distances on slippery (split or low coefficient of friction) on/off road surfaces by limiting wheel slip and minimising lockup. Rolling wheels have much more traction than locked wheels. Reducing wheel slip improves vehicle stability and control during braking, since stability increases as wheel slip decreases. ABSs may be applied to nearly all types of automotive vehicles and may be successfully integrated into F-M and P-M or even E-M braking systems (including E-M over F-M and P-M). The equipment requirements specify that ABSs on automotive vehicles, especially on truck-tractors and full trailers, must control the brake fluid or air pressures to at least one front axle and one rear axle. For example, the ABSs on semi-trailers and dollies must control at least one axle of the vehicle. Additionally, the ABSs on tractors must control one of the rear axles with two modulator fluidical valves so that the brake oily-fluid or gas (air) pressure on one end of the axle is independent of the brake fluid or air pressure on the other end. The performance of a P-M braking system may require an ABS on additional axles. In the USA, for instance, the **National Highway Traffic Safety Administration** (NHTSA) [FHWA-MC 1998] defines an ABS as a portion of a service brake system that automatically controls the degree of rotational wheel slip during braking.

- ❖ Sensing the rate of angular wheel rotation;
- ❖ Transmitting signals regarding the rate of wheel rotation to one or more devices that interpret these signals and generate responsive controlling output signals;
- ❖ Transmitting those signals to one or more devices that adjust braking forces in response to the signals.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_30,

Other aspects of the NHTSA rule stipulate that [FHWA-MC 1998]:

- ❖ ABSs on trailers must be capable of being powered by the trailer's stop lamp circuit;
- ❖ New tractors provide constant electrical power to a tractor-to-trailer electrical connector for powering trailer ABSs;
- ❖ Automotive vehicles required to have an ABS also have a yellow ABS malfunction indicator lamp that lights up to indicate most malfunctions;
- ❖ The power unit's ABS malfunction lamp should be *'in front of and in clear view'* of the driver; it lights when the ignition key is first switched *'ON'* for a bulb check;
- ❖ The ABS malfunction lamp on trailers should be mounted on the left-side of the trailer, near the rear side marker lamp;
- ❖ Air-braked tractors and trucks that tow other air-braked vehicles have an in-cab warning lamp that indicates malfunctions in any towed trailer's or dolly's ABS; its location and function are the same as for the powered unit's ABS malfunction lamp;
- ❖ Trailer and dolly ABSs should have the equipment needed to send an ABS malfunction signal to the towing vehicle; a towing trailer must also be able to relay an ABS mal-function signal from the automotive vehicle it is towing to the vehicle towing it.

How Do ABSs Work? **-** Mechatronic controls allow an ABS to adjust brake fluidical or pneumatical pressure faster and more accurately that can drivers.

An ABS is more effective on slippery roads because it tailors the brake fluid or air pressure at the wheel to maximise vehicle braking and stability. It consists of several key components: **electronic control unit** (ECU), wheel angular-velocity sensors, modulator fluidic valves, and exciter rings.
Here's how these components work together [FHWA-MC 1998]:

- ❖ Wheel angular-velocity sensors constantly monitor and send electrical pulses to the ECU at a rate proportional to the wheel angular velocity;
- ❖ When the pulse rates indicate impending wheel lockup, the ECU signals the modulator fluidic valve(s) to reduce and/or hold the brake application to the wheel(s) in question;
- ❖ The ECU then adjusts the fluid or air pressure, seeking adjustment that gives maximum braking without risking wheel lockup;
- ❖ When the ECU acts to modulate the brake fluid or air pressure, it may also (on most automotive vehicles) turn off the retarder (if so equipped) until the risk of lockup is over;
- ❖ The ECU continually checks itself for proper operation if it detects a malfunction/failure in the electrical/electronic system. It may shut down part of the ABS – depending upon the system and the problem; when this happens, the malfunction lamp lights.

An ABS adjusts brake fluid or air pressure much faster and more accurately that may drivers. It's faster because [FHWA-MC 1998]:

- ❖ Mechatronic controls are very fast;
- ❖ ABS modulator fluidic valves are physically closer to the brakes than is the driver's foot brake valve (brake pedal).

It is more effective, too, because an ABS can tailor the brake fluid or air pressure to each wheel or set of wheels to provide maximum braking/stability. Some automotive vehicles also use a TCS in conjunction with ABS. Traction control helps the ABS to improve vehicle traction by minimising wheel slip on the drive axle during acceleration. If a wheel on the drive axle starts to slip, the TCS automatically brakes the wheel slightly, transferring ECE or ICE torque to the wheels with better traction. If all the drive wheels start to slip, the TCS may also reduce power. TCSs are referred to by several different names, depending on the vehicle manufacturer. These include [FHWA-MC 1998]:

- ❖ **Automatic traction control** (ATC);
- ❖ **Traction control** (TC);
- ❖ **Automatic slip regulation/anti-spin regulation** (ASR).

How Should a Driver Drive an ABS-equipped Automotive Vehicle during a Road Test? - It is consensus of brake expert that drivers should brake an ABS-equipped vehicle just as they would brake a non-ABS-equipped vehicle. The proper braking technique is to maintain a steady, modulated brake application. Modulated, in this case, means applying only the fluidical (hydraulical or pneumatical) pressure required to achieve the desired deceleration. Do not slam on the brakes to make a vehicle velocity correction or routine stops.

When operating on slippery on/off road surfaces, with or without an ABS, it is strongly recommended that driver's depress the clutch when braking. ECE or ICE braking itself may cause the drive wheels to slip. Usually, any retarder may automatically be disabled when the ABS is used. Much of what is taught about fluidical ABSs doesn't apply to pneumatical ABSs.

Thus, it's important to remember the following [FHWA-MC 1998]:

- ❖ Brake as if no ABS is present, with a modulated application as described previously;
- ❖ Unless certain that the entire combination vehicle has a working ABS, don't stamp on the brakes in a panic situation – one or more wheels could lock and cause the vehicle to jacknife; even then, be careful because a driver may still jacknife or lose control if the vehicle is travelling too fast;
- ❖ Do not expect to feel the brake pedal pulsing or hear strange sounds when the ABS activates on air-braked vehicles; these automotive vehicles do not transmit pulsing pneumatical pressure to the driver's foot and the driver probably may not hear the system cycling;
- ❖ Operate mixed combination vehicles (with and without an ABS) the same way as one would operate totally non-ABS combination vehicles; apply only the brake fluid or air pressure needed to achieve the desired deceleration while ensuring vehicle stability; monitor the combination vehicle behaviour and back off the brake pedal, to keep the units under control.

What Are the Features and Benefits of ABS? The major features and benefits offered by Abs are as follows [FHWA-MC 1998]:

- Features:
  - Control of steering, drive and trailer wheels;
  - Fully safe electrical/electronic system;
  - Traction control;
  - Self-diagnosing system;
  - Diagnostic tool compatibility;
  - ABS malfunction indicator lamp.
- Benefits:
  - Increases steering and vehicle stability during braking;reduces possibility of jacknifing and trailer swing; reduces wheel-tyre flat spotting;
  - If the electrical/electronic system fails, the ABS is shut off, returning the vehicle to normal braking; on some systems, the ABS is only shut off at the affected wheels;
  - An optional feature that controls excessive wheel spin during acceleration, reducing the possibility of power skids, spins or jack-nifes;
  - Built-in system that makes maintenance checks quick and easy;
  - ABS are compatible with automotive industry standard hand-held and computer-based diagnostic tools; blink codes and other diagnostic schemes may also be used for troubleshooting, if other tools are not available;
  - Informs the driver and technician that an ABS fault has occurred; the warning lamp may also transmit blink code information; it does not signal all possible faults.

3.5.2 ABS Component Descriptions and Operation

This section describes the design and operation of ABS components. When the readers complete this section, they should understand the purpose and function of all major ABS parts including the ECU, the modulator's fluidical valve, the wheel angular-velocity sensor, ABS malfunction/ indicator lamp, ABS diagnostic components, and traction control.

Modern ABSs all feature the following major components, shown in Figure 3.19, for s classic anti-lock BBW AWB dispulsion mechatronic control system [FHWA-MC 1998]:

- Electronic control unit (ECU);
- Modulator fluidic valves;
- Wheel angular-velocity sensors (pickup and exciter);
- ABS malfunction indicator lamps;
- Diagnostics.

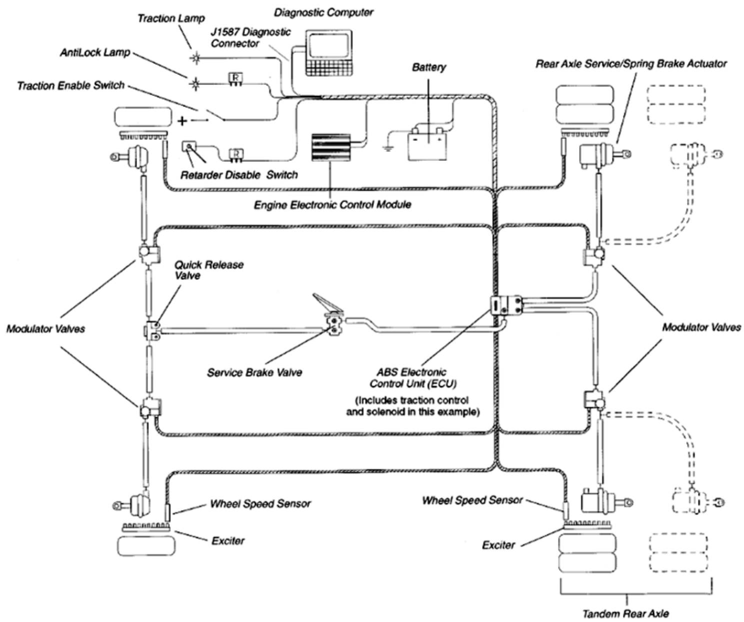


Fig. 3.19 Classic tractor ABS schematic [FHWA-MC 1998].

Electronic Control Unit (ECU) - The ECU processes all ABS information and signal functions. It receives and interprets voltage pulses generated by the sensor pickup as the exciter teeth pass by and uses this information to determine [FHWA-MC 1998]:

- ❖ Impending wheel lock-up;
- ❖ When/how to activate the ABS modulator's fluidic valves.

The ECU connects to the following ABS components: wheel angular-velocity sensors, modulator's fluidic valves, power source, ground, warning lamps, blink code switch, diagnostic connector [SAE J1587], and retarder control device, usually by relay or data link [SAE J1922/J1939].

The ECU also makes self-diagnostic checks during normal operations. During braking, the ECU uses voltage pulses from each wheel angular-velocity sensor to determine any wheel angular-velocity changes.

If the ECU determines that the pulse rate of the sensed wheels indicates imminent lock-up, it cycles the ABS modulator's fluidical valves to modify the brake fluid or air pressure as needed to provide the most efficient braking possible. The ECU sends signals to the ABS malfunction indicator lamp or blink code lamp to communicate the ABS faults. It also sends signals to the retarder control to disengage the retarder when the ABS is working.

When the ABS stops modulating the brake fluidical or pneumatical pressure, the ECU permits retarder use once again.

Technicians can communicate with the ECU through a standard diagnostic connector [SAE J1587]. They can also read and clear fault codes stored in the ECU and run various diagnostic tests with this connector. The type of ECU used and its location (in cab or frame) vary per manufacturer.

Modulator's Fluidical or Pneumatical Valves ABS modulator's fluidical or pneumatical valves regulate the fluid or air pressure to their brakes during ABS action. When not receiving commands from the ECU, the modulator's fluidical or pneumatical valve allows fluid or air to flow freely and has no effect on the brake oily-fluid or air (gas) pressure. The ECU commands the modulator's fluidical or pneumatical valve to either [FHWA-MC 1998]:

- ❖ Charge the fluid or air pressure to the brake chamber;
- ❖ Hold the existing fluid or air pressure.

However, it cannot automatically apply the brakes, or increase the brake application fluid or air pressure above the level applied by the driver. The modulator's fluidical valve, and relay's fluidical valve typically contains two electromagnetic solenoids. They may also be separate, inserted into the service line to the brake chamber after any relay's fluidical valve, located as close as practicable to the chamber itself.

When the modulator's fluidical valve is separate, it has to control more fluid- or airflow and, therefore, includes two larger diaphragm fluidical valves that are controlled by the electromagnetic solenoids. It usually has three ports: the supply port, the delivery port, and the exhaust port [FHWA-MC 1998].

- ❖ The supply port receives fluid or air from a quick-release relay's fluid ical valve;
- ❖ The delivery port sends fluid or air to the brake chambers;
- ❖ The exhaust ports vents fluid or air from the brake chambers.

Typically, when an ECU controlling a separate modulator's fluidical valve detects impending wheel lockup, it activates the solenoids to close the supply port and open the exhaust port. When enough fluid or air is vented to prevent wheel lockup, the exhaust fluidic valve may close and the ECU may – depending on the situation – either [FHWA-MC 1998]:

- ❖ Keep the supply port closed to maintain existing fluid or air pressure;
- ❖ Open the supply port to allow the application of brake fluid or air pressure to increase and repeat the cycle.

Wheel Angular-Velocity Sensors The wheel angular-velocity sensor has two main components: the exciter and the pickup. Other components include associated wiring and mounting equipment. The exciter is a ring with notched teeth. The most commonly used exciter has 100 evenly spaced teeth, but the number of teeth can vary depending on the system design. The component is known by several names: sensor ring, tooth wheel, tone ring, and exciter. The pickup is commonly called *'the sensor'*. It contains a wire coil/magnet assembly that generates pulses of electricity as the teeth of the exciter pass in front of it.

The ECU uses the pulses to determine actual (measured) values of the wheel angular velocity and rates of acceleration/deceleration. The strength of these electrical pulses decreases rapidly with slight increases in the gap between the pickup and the exciter. Wheel angular-velocity sensor location varies. It can be located anywhere on the axle to sense wheel angular velocity. The sensor can be an assembly containing both exciter and a pickup with a fixed gap. Or, a pickup and the exciter can be mounted separately on different parts of the axle assembly. The sensor pickup is a sealed unit and typically of elbow or straight design. On most ABS fluid- or air-braked vehicles, the pickup is located in the mounting flange on the wheel end. The exciter usually is either mounted on, or integrated with, the wheel hub. Since the output of the pickup decreases so rapidly with slight increases in the exciter-pickup gap, it is imperative that the wheel end and sensor gap be maintained within the manufacturer's specifications. When the wheels of only one tandem axle have wheel angular-velocity sensors, they are usually placed on the axle whose wheels are most likely to lock first during braking. On a tandem with a four-spring suspension, the sensors are generally on the lead axle. On a tandem with air suspension, the sensors are generally located on the trailing axle. The arrangement and number of sensors and modulator define the ABS configuration fluidical valves used.

The most common configurations for power units are [FHWA-MC 1998]:

- ❖ **Four sensors/four modulators** (4S/4M);
- ❖ **Six sensors/four modulators** (6S/4M);
- ❖ **Six sensors/six modulators** (6S/6M).

Common configurations for trailers are 2S/1M, 2S/2M, 4S/2M and 4S/3M.

ABS Malfunction Indicator Lamps **-** Automotive vehicles required to have an ABS must have ABS malfunction indicator lamps. These lamps must be yellow and light up when the ABS has a *'malfunction that affects the generation or transmission of response or control signals'* in the ABS. ABS malfunction indicator lamps are not required to light up for every type of malfunction. However, the lamps are required to light up for short periods of time for a bulb check whenever the ABS starts to receive electrical energy. The warning lamps for trailers and dollies are not required to light up for a bulb check unless the automotive vehicle is stopped. All trailers/dollies built must feature an external ABS malfunction indicator lamp as part of the ABS. All new trailers must be capable of activating an in-cab trailer warning lamp. In-cab ABS indicator lamps are typically located on the instrument panel. The exact location and appearance vary according to automotive vehicle/component manufacturer.

ABS Diagnostics **-** Although not required by law, all fluid- or air-brake ABSs have a self-diagnostic capability. On truck-tractors and single-unit or straight trucks, an ABS provides this information to technicians through the malfunction indicator lamp and/or an electronic diagnostic tool that plugs into an on-board diagnostic connector.

The connector is typically located inside the tractor cab just underneath the left end of the instrument panel. It is usually the same connector that is used to troubleshoot electronic engines [FHWA-MC 1998].

Truck-tractors and trucks may also use the ABS malfunction indicator lamp to signal stored fault information through a blink code. Automotive vehicles using this system have a switch to activate the blink code system. Other ABSs may also have **light-emitting diode** (LED) lamps on the ECU to indicate problems. ABS used on trailers sometimes have a place to connect an electronic diagnostic tool. The connector is either on a pigtail to the ECU, on the outside of the ECU, or inside the ECU box. Others have either LED lamps on the ECU box or number codes displayed inside the ECU that give diagnostic information.

Traction Control Systems (TCS) **-** TCSs are designed to prevent wheel spin in the power mode. Traction control attempts to regain traction by braking the spinning wheels, and sometimes by throttling back the ECE or ICE power, Unlike an ABS, traction control can automatically apply the brakes. The driver does not need to depress the brake pedal for traction control to engage.

Traction control electronics are integrated into the ABS ECU. The system applies the brakes on the spinning wheel(s) when the wheel angular-velocity sensors tell the ECU that a wheel is accelerating at a much faster angular velocity than the wheel on the other end of the axle. It does this by energising a solenoid fluidical or pneumatical valve that directs reservoir fluid or air pressure to the relay's fluidical valve and simultaneously activates the modulator fluidic valves to keep the fluid or air pressure from the brake chambers.

The ECU then directs the modulator's fluidical valve to open, and pulse fluid or air into the brake chamber on the spinning wheel until wheel angular velocity balance is regained. On some systems, the ECU may throttle back the ECE or ICE power if both wheels are spinning too fast. If all the drive wheels on a tractor are spinning too fast, the tractor can become unstable, spin, or jacknife.

Traction control is especially valuable when a light drive-wheel load might allow the wheels to spin under power, or when a tractor is pulling multiple trailers. The law does not require traction control, but it is a common ABS option [FHWA-MC 1998].

3.5.3 Anti-lock EFMB or EPMB BBW AWB Dispulsion

Although anti-lock concepts have been known for decades, widespread use of anti-lock (also called anti-skid and ABS) began in the 1980s with EFMB or EPMB BBW AWB dispulsion mechatronic control systems developed with digital, single-chip microprocessors/microcompuers/microcontrollers replacing the earlier analog electronic control units (ECU).

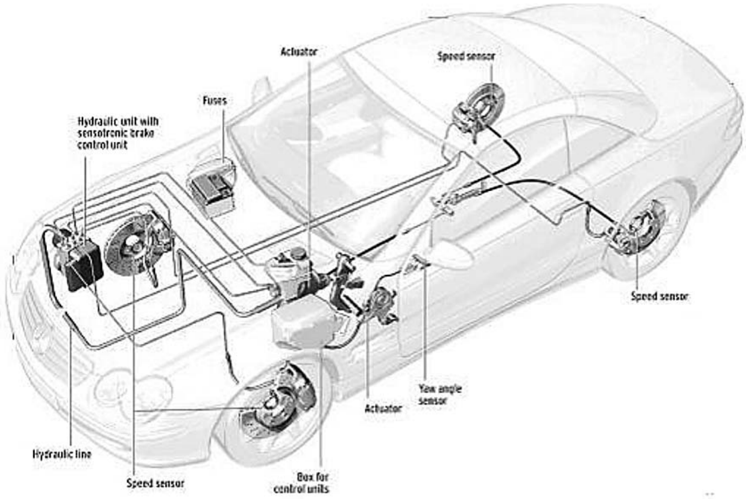


Fig. 3.20 Anti-lock EFMB BBW AWB dispulsion mechatronic control system [Mercedes-Benz; BERGER 2002].

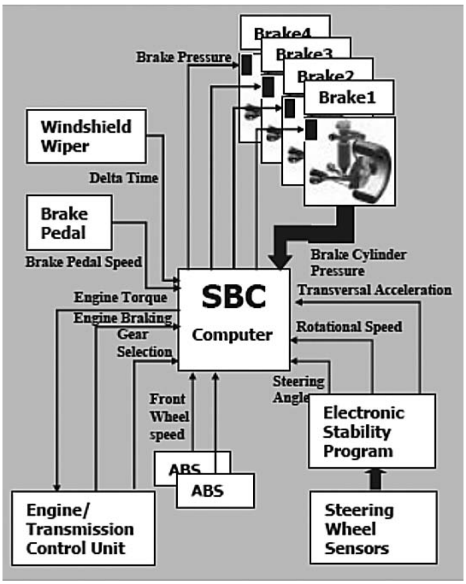


Fig. 3.21 Sensotronic brake control (SBC) system [Mercedes-Benz; CADENCE 2003].

An exemplary anti-lock BBW AWB dispulsion mechatronic control system that communicates over a high-speed data bus FlexRay™, termed the Mercedes-Benz **sensotronic brake control** (SBC) system, is shown in Figure 3.20 [BERGER 2002].

A structural and functional block diagram of the SBC unit is shown in Figure 3.21 [CADENCE 2003].

An anti-lock EFMB or EPMB BBW AWB dispulsion mechatronic control system consists of a fluidic modulator and fluidic power source that may or may not be integrated with the BBW AWB dispulsion system's master cylinder and booster, wheel angular velocity sensors, and an ECU.

The fundamental function of an anti-lock EFMB or EPMB BBW AWB dispulsion mechatronic control system is to prohibit wheel lock by sensing impending wheel lock and taking action through the fluidic modulator to reduce the brake oily-fluid or air (gas) pressure in the wheel sufficiently enough to bring the wheel angular velocity back to the slip-level range necessary for near-optimum braking performance.

The automotive vehicle manufacturers that invented ABS, TCS, ESP and VSC may launch the world's first manufactured vehicle equipped with an EFMB or EPMB BBW AWB dispulsion mechatronic control system that provides faster, more sure-footed brake response, especially in emergencies.

The brake pedal works with a microcomputer that advises four fast-acting fluidic valves exactly how hard to apply the brakes on each wheel. A backup master F-M (H-M and/or P-M) cylinder comes into play only if there's an ominous problem or electrical breakdown.

With split-second accuracy, the system may change the brake fluid or air pressure on each wheel over uneven surfaces and can even increase the brake fluid or air pressure on just the outside wheels when braking in turns, taking advantage of the higher loading during cornering.

Even ABS, TCS, ESP, and VSC work more efficiently since they are more deeply integrated with the brakes, instead of functioning as parallel systems.

A special electrically driven E-M-F pump or E-M-P compressor and a high-pressure fluidic reservoir (or fluidic accumulator) provide *'permanently-on'* full brake oily-fluid or air (gas) pressure at each wheel. The computer-operated modulator fluidic valves control how much fluid or air pressure actually operates the brakes at each wheel. For instance, in the innovative EMB BBW AWB dispulsion mechatronic control system, the bulky vacuum brake booster is now obsolete. If the driver switches her or his foot quickly from thr accelerator pedal to the brake pedal, the EFMB or EPMB BBW AWB dispulsion mechatronic control system recognises the early signs of an emergency situation and reacts automatically. With the help of the high-pressure fluidic reservoir, the system raises the fluid or air pressure in the brake connectors and instantaneously moves the pads onto the brake discs or rings that may then spring into action with full force as soon as the brake pedal is pressed.

At highway values of the vehicle velocity, this pre-loading of the braking system reduces stopping distance by about 3%.

In addition, the anti-lock EFMB or EPMB BBW AWB dispulsion mechatronic control system automatically senses when the road is wet and imperceptibly applies the brakes just enough to keep the discs or rings dry so that brake operation remains fast and consistent in the rain. An especially valid safety related automotive application that is seeing significant technology advancements is anti-lock EFMB or EPMB BBW AWB dispulsion mechatronic control systems. These are increasingly common, almost a standard feature in today's automotive vehicles.

As shown in Figure 3.22, the EFMBs or EPMBs are mechatronically controlled and fluidically powered [NEEDHAM 2002].

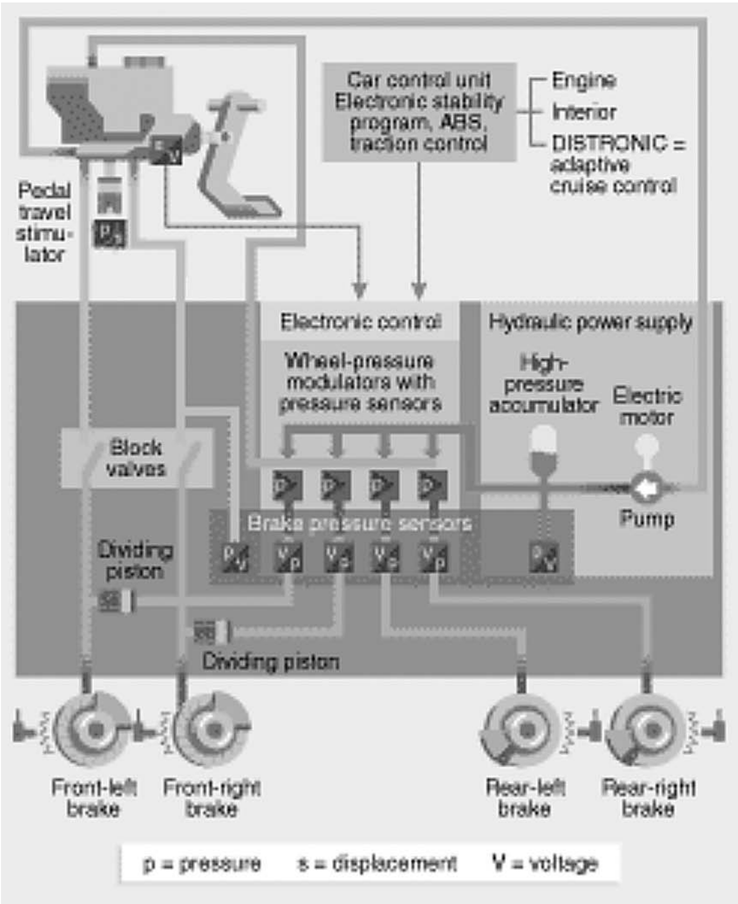


Fig. 3.22 Mechatronically controlled and fluidically powered EFMBs [Mercedes-Benz; NEEDHAM 2002].

The controller apportions braking to each wheel individually based on the forces acting on the automotive vehicle to optimise road grip. If the mechatronic control systems fail, the block fluidical valves (left) open to directly brake the front wheels. The dividing pistons (check fluidical valves) isolate the disabled system.

The pedal feels no different than with fluidically controlled brakes. But between the driver and the wheels, the mechatronics are more than just a straight, lighter-mass replacement of a fluidically controlled and powered system.

Based on driver input (such as steering angle), the motion of the vehicle (actual values of the wheel velocity, yaw), the *g* forces acting on it, ECE or ICE shaft angular velocity, and transmission gear selected, the controller drives the modulator's fluidical valves to produce the optimum brake fluid or air pressure at each individual wheel.

For example, if a driver enters a turn too fast and brakes, the mechatronics may apply most of the brake force to the two wheels on the outside of the turn to reduce the chance of skidding. The result is effectively a four-way split in braking functions as opposed to the twin, diagonally split systems, used on conventional automotive vehicles with completely FMBs or PMBs (see Fig. 3.20).

With no fluidics to feed oily-fluid or air (gas) pressure back into the brake pedal when the ABS function kicks in during a panic stop, the pedal remains vibration free.

And how's this for mechatronic legerdemain: In such an emergency stop, sensors detect the quick removal of the driver's foot from the accelerator pedal and signal the controller to prime the system with higher oily-fluid or air (gas) pressure and move the pads lightly against the discs (this is imperceptible to the driver). As soon as the driver's foot presses the pedal, full brake force is applied using the high-pressure fluidic accumulator.

According to NEEDHAM [2002], this results in a roughly 3% reduction in stopping distance depends from highway values of the vehicle velocity. At about 60 km/h (40 mph), the reduction is about 2 m (6.5 ft).

An E-M-F pump or E-M-P compressor pressurises the system and a fluidical accumulator. This arrangement can deliver full braking fluid or air pressure, even with the ECE or ICE off. And a *'dry braking function'* presses the pads lightly against the discs every 10-15 s to keep them dry and ready for use when the windshield wipers are running.

If the controller fails or malfunctions, block values automatically slide open to connect the front brake discs to the brake pedal's F-M (H-M and/or P-M) cylinder that may now act as a conventional master cylinder producing 80% of front braking power. Dividing pistons (check valves) in the front brake fluidical circuits also isolate the backup system fluid or air pressure from the rest of the circuit.

An ABS, shown in Figure 3.23 [ANDERSSON 2003], comprises a sophisticated mechatronics package wherein a typical system includes individual wheel velocity sensors, electrically controlled fluidic valves, E-M motor powered M-F pump or M-P compressor, and an ECU.

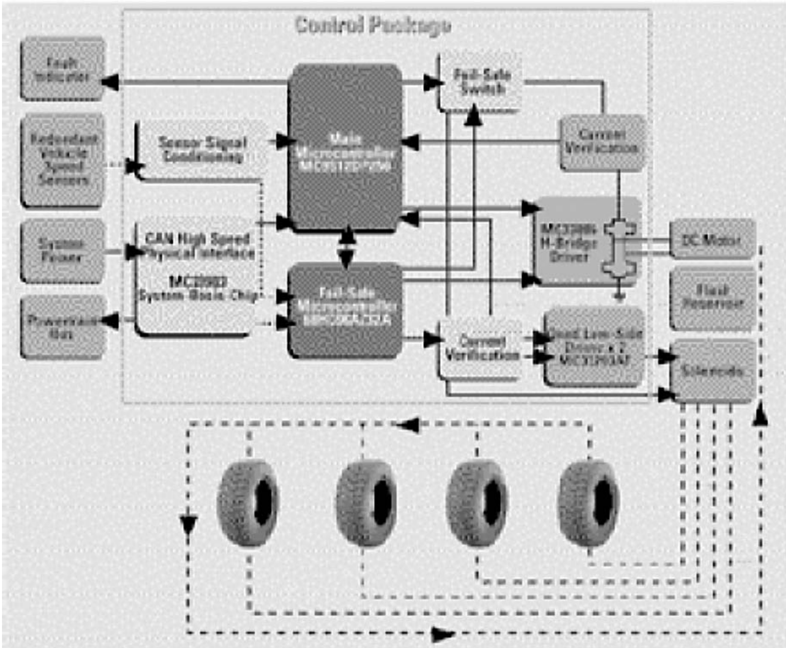


Fig. 3.23 An exemplary anti-lock BBW AWB dispulsion mechatronic control system [ANDERSON 2003].

In many ABSs, a 16-bit microcontroller is used for main application processing with an eight-bit microcontroller functioning as an asymmetrical watchdog processor [ANDERSON 2003]. Both of these incorporate **controller area network** (CAN) communications modules engineered to allow the ABS ECU to communicate with other vehicle mechatronic control systems.

More advanced anti-lock BBW AWB dispulsion mechatronic control systems are now appearing in higher-end modules in the automotive world. These **brake-assist systems** (BAS) are E-F-M or E-P-M based and they are designed to provide more efficient and intelligent braking.

Tests have shown that while drivers tend to step on the brake very quickly, they often fail to apply enough braking fluid or air pressure. With brake assistants the BAS can detect that a rapid brake action requires an emergency response and can automatically apply more braking force [ANDERSON 2003].

EFMB or EPMB is based on existing ABSs with the addition of several enhancements. The inclusion of analogue electrically controlled fluidical valves requires closed-loop, electric current-controlled PWM outputs from the ECU.

An EFMB or EPMB BBW AWB dispulsion mechatronic control system is required to incorporate a fail-safe state in the event of a fault occurring. To correctly initiate the fail-safe state, the system relies on electronic sensors to provide a high level of operational fault coverage so that brakes may be controlled through a back-up conventional fluidic circuit.

EMB BBW AWB dispulsion mechatronic control systems may replace conventional fluidic braking systems with a completely *'dry'* electrical component system that replaces conventional actuators with E-M motor-driven units. This move to mechatronic control virtually eliminates many of the manufacturing, maintenance, and environmental concerns associated with fluidical braking systems. EMB is designed to improve connectivity with other automotive vehicle mechatronic control systems, thus enabling simpler integration of higher-level functions such as TCS and VSC. The integration may vary from embedding the function within the EMB BBW AWB dispulsion mechatronic control system, as with ABS, to interfacing to these additional systems using communication links such as CAN or the FlexRay™ protocol that is designed for high levels of communication bandwidth and deterministic fault tolerant data transmission.

Increasingly, automotive mechatronics is moving towards a systems solution approach where integrated components reduce the cost and part count for adding new features, allowing manufacturers to deliver *'luxury class'*, advanced-safety features to more drivers on a cost-effective basis. Advanced microcontroller, sophisticated sensor and imaging technology, and advanced networking protocols are embodying a new generation of automotive mechatronic systems that offer enhanced safety, better performance, and new conveniences that are expected to continue to generate consumer demand [ANDERSON 2003].

So how does SCS differ from the TCSs currently on the market? Essentially, traction control acts on an automotive vehicle's drive wheels to prevent unwanted wheel spin under acceleration. While this helps in low-traction situations such as snow or rain, traction control's ability to assist in more extreme emergency situations is limited.

An SCS, on the other hand, goes one step further by actually detecting when a driver has lost some degree of control. It then automatically stabilises the vehicle to help the driver regain control.

The SCS of this scenario is a complex system of sensors and microprocessors that continually monitors the vehicle for any signs of instability. Once detected (usually in the form of a slide or skid), the SCS automatically applies selective braking to specific wheels thereby stabilising the vehicle. This split-second intervention often happens so quickly that it's over before drivers even realise they were in danger of losing control.

ESP is applicable for FWD, RWD and AWD vehicles. For instance, FWD vehicles may commonly encounter understeering in cornering at high values of vehicle velocity or in emergency steering manoeuvres to avoid accidents.

In the understeering, the front wheels push the vehicle toward the outer edge of a turn.

In contrast, at higher values of vehicle velocity, RWD vehicles typically may be oversteered that means the vehicle responds to the driver's steering and the rear wheels slide outward.

With ESP, sensor control braking, separately at all the wheels, may also reduce ECE or ICE torque to lower the vehicle velocity and help maintain stability.

For example, if the driver oversteers and the rear wheels begin to slide outward, the ESP's microcomputer counteracts by braking the outer front wheel, creating an opposing and stabilising yaw force and by reducing ECE or ICE power, if necessary.

If the driver has already applied the brakes while cornering, the ESP control microcomputer may boost the brake fluid or air pressure at the front wheel that is on the outside of the turn and reduce brake fluid or air pressure on the inner front wheel.

If the driver encounters understeer, ESP brakes the rear wheel on the inside and helps bring the vehicle onto the required course.

All the enhanced SCSs currently being promoted by vehicle manufacturers may approach vehicle stability in similar ways. The heart of all these SCSs is a central processor that takes information from a number of sensors and then determines whether the vehicle is in a stable or unstable state.

By combining the data from ABS sensors (for wheel angular velocity), steering angle sensors, yaw sensors (measuring the amount a vehicle fishtails, or rotates around its vertical centre axis), and lateral force sensors (measuring the amount of sideways G-force generated by the automotive vehicle), the central processing unit may actually detect when a vehicle is behaving in a way contrary to how the driver intends.

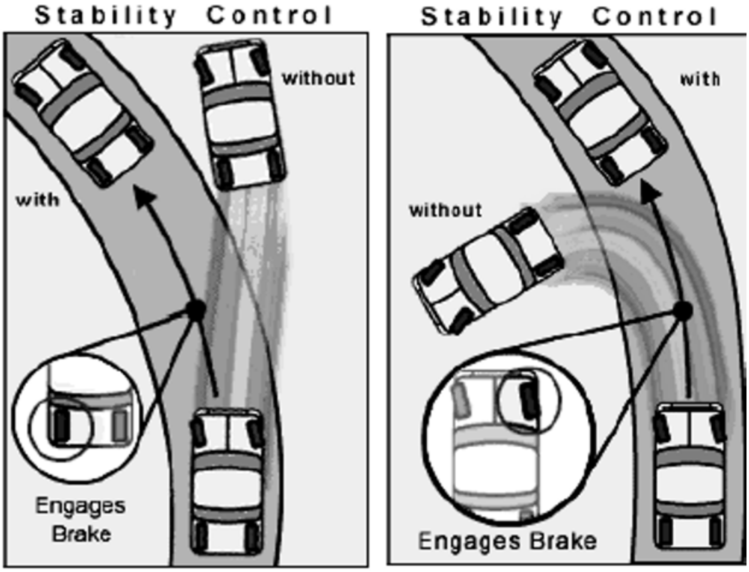
If the processor does detect instability such as a slide produced by a sudden swerve, it automatically applies light brake fluidical or pneumatical pressure to selected wheels to maintain or restore control.

On some SCSs, ECE or ICE torque is also automatically decreased to aid in the stabilising process.

The most common types of slides are referred to as understeer and oversteer. In an understeer situation, the front of the automotive vehicle plods toward the outside of a turn without following the curve of the turn.

When the SCS detects understeer, it applies light brake fluid or air pressure to the inside rear wheel. This helps *'tug'* the front of the automotive vehicle back onto the intended line (see Fig. 3.24a).

In an oversteer situation, the rear of the vehicle fishtails towards the outside of a turn, increasing the chance of a spin. To counteract such a situation, the SCS applies braking to the outside front wheel, bringing the rear end back into line (see Fig. 3.24b).



(a) **(b)**

Fig. 3.24 The stability control system (SCS) at work [ROMANO 2000].

On most automotive vehicle, a warning light on the dashboard illuminates, and a subtle audio signal also sounds, when the SCS is operating [ROMANO 2000].

Like the safety systems that preceded it, stability control is designed to step up the driver input and is incapable of effectively controlling the automotive vehicle. In most cases, critical situations are the result of driver error in the first place – driving too quickly for conditions, inattention, and misjudgement or simply panicking in an emergency situation. But no matter how advanced the safety aid, never forget that the ultimate fate of an automotive vehicle and its occupants remains in the hands of the driver. No safety system should ever be expected to protect unconditionally. So while the latest generation of SCSs offer drivers increased protection from both themselves and the unexpected, they may never overcome poor judgement or laws of physics. The next step is a pure anti-lock and anti-skid AWD DBW dispulsion mechatronic control system and the future is now. Modern vehicles have a mechatronic control system where the brake pedal is a switch with no direct connection to the brake system. In a *'panic-assist feature'* what it does is measure the velocity of brake pedal travel by using either a sensor on the brake pedal or in the brake booster.

If a certain threshold is met, then the brake booster (if it is a mechatronic brake booster) or the **dynamic stability control** (DSC) E-M-F pump apply maximum fluid or air pressure. It doesn't actually stop the vehicle in any shorter distance than you could.

The reason for **dynamic brake control** (DBC) is that it's been established that when emergency braking many people may ease off the brake pedal a little after the initial stab. DBC keeps the fluid or air pressure up even if the driver let off. This may be a real pain when trying to modulate the brakes as most systems have a pretty low threshold and just aggressive braking is seen as a *'panic stop'*. This feature also requires a functioning ABS. The expensive systems are mechatronic so if the ABS fails, the feature is disabled, but some cheaper vehicles have a purely mechanical system and a failed ABS is not detected. Drivers may imagine what happens when they have maximum brake power and no ABS [ROMANO 2000].

An easy way is to replace the input from the brake pedal with a mechatronically controlled actuator. This could be an EFMB or EPMB BBW AWB dispulsion mechatronic control system where mechatronic control is achieved by operating the M-F pump or M-P compressor and various control fluidic valves (see Fig. 3.25) [JB 2004].

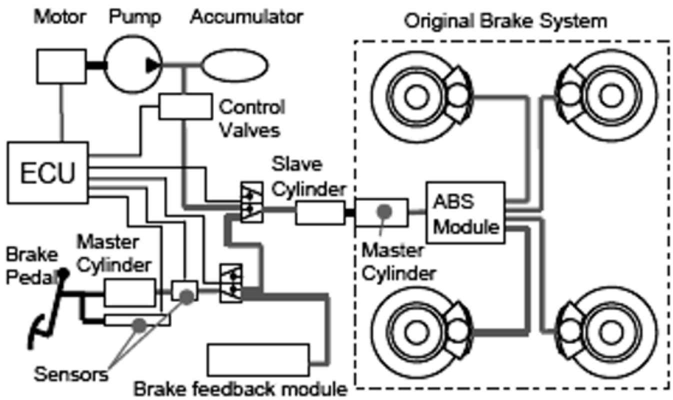


Fig. 3.25 EFMB BBW AWB dispulsion mechatronic control system [JB 2004].

The input from the driver would come from a sensor that could take any form required (for example, conventional brake pedal or even a joystick). With the original EFMB or EPMB BBW AWB dispulsion mechatronic control system intact, this architecture allows for the possibility of a fail-safe state where the control fluidics may be mechanically by-passed [JB 2004].

Figure 3.26 shows a high level overview of control strategies intended for the EFMB BBW AWB dispulsion mechatronic control system [JB 2004].
This structural and functional diagram is meant to give a basic understanding of the control strategy and therefore does not include safety monitors, diagnostics, fallback mechanisms, as well as redundancy, and so on.

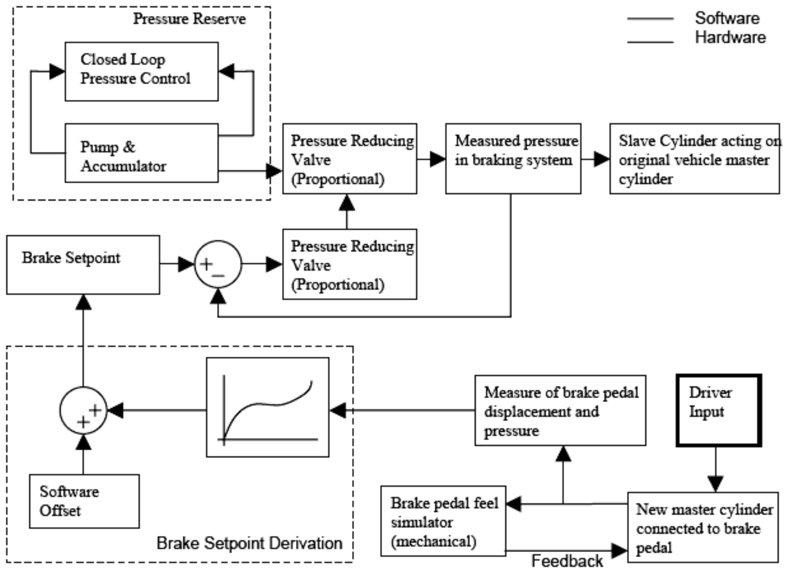


Fig. 3.26 EFMB BBW AWB dispulsion mechatronic control strategy overview [JB 2004].

The alternative to the EFMB BBW AWB dispulsion mechatronic control system is the E-M implementation (see Fig. 3.27) [JB 2004].

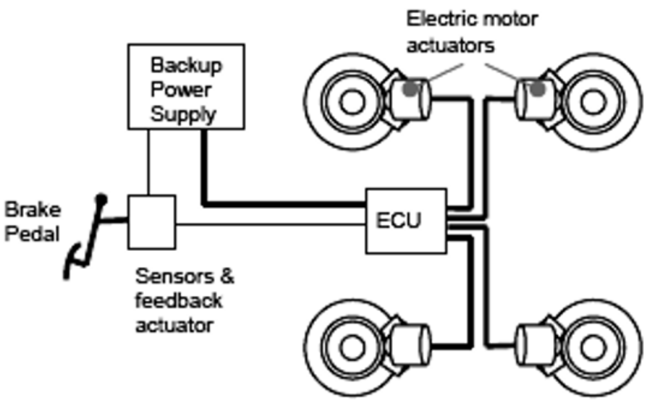


Fig. 3.27 EMB BBW AWB dispulsion mechatronic control system [JB 2004].

Here the EFMB BBW AWB dispulsion mechatronic control system is removed completely. Instead, high-power rotary or linear tubular E-M motors at each wheel generate the braking force. These are controlled from an ECU where the driver input would again be from a suitable sensor similar to an EFMB BBW AWB dispulsion mechatronic control system.

In addition, an actuator at the input (for example, the brake pedal) may be supplementary to the driver. Once again the safety case dictates that the mechatronic control is fail-safe and therefore must have some level of redundancy. For instance, as developed from a *Markov* model [HAMMETT AND BABCOCK 2003], this could be a dual-dual or triplex system.

An important factor is determining the mechatronic control system is not only the ability to detect failures but also to determine what the failure is. For example, if there are two sensors in the system and one fails, it could be obvious that they are different but how do drivers tell that one is correct? The EMB BBW AWB dispulsion mechatronic control system requires measurements of traditional inputs of the wheel angular velocity along with a suitable brake activation sensor that is likely to be a position sensor of some kind (for example, three-track resistive sensor) but could easily be a pressure sensor.

On the information such as yaw rate and lateral acceleration, additional features may be possible such as stability control and steering correction. These signals must be accurate and have good resolution to allow the mechatronic control system to perform well.

These sensors must also be dependable (not affected by their age or environment), reliable and conform to the usual package, cost considerations, and so on. Suitable sensors are likely to be of the non-contact variety with optical and magnetoresistive sensors providing good performance and reliability. The exact sensor and technology, though, is likely to rely on many factors depending on the specific application.

The EFMB, EPMB or EMB BBW AWB dispulsion mechatronic control sys-tem requires actuation for the braking force. This may be through either a secondary F-M or P-M control system acting on the original control system or rotary or linear tubular E-M motors at each wheel operating the brake callipers.

These E-M motors may need to be powerful enough to achieve enough braking force for the vehicle's application. There are two main requirements for an EMB BBW AWB power supply: sufficient power for the braking actuators and redundancy. This may require dual power systems (two brushless AC-DC macrocommutator generators, two CH-E/E-CH storage batteries, two looms, and so on).

The main power system may have to be of a voltage higher than the standard 12 V_{DC} **energy-and-information network** (E&IN) in order to provide the required performance (for instance, 24 or 42 V_{DC}, or even higher). With the necessity for a 12 V_{DC} E&IN for the main power system, this could then provide the required redundancy (albeit at a reduced level of performance). The power wiring may have to be protected against single-point failure. This may require multiple wires from the power supplies to the critical components; wires routed separately, independent protection for the separate wires and switching the utilisation of the separate wires.

CHEN AND LIAO [2000] address the design and performance of non-linear controllers for ABSs. The controllers, based on a non-linear feedback linearisation scheme and **fuzzy logic** (FL) control strategies, may be designed to solve the wheel-slip-ratio tracking problem of a simplified ABS quarter-vehicle physical model.

Given the desired (optimal) wheel-slip ratio, the feedback-linearising controller cancels all non-linear dynamics and imposes an appropriate linear behaviour on the wheel-slip ratio such that it may track in a desired way. Utilising the slip-ratio error and the change-in-error measurements, fuzzy logic controllers have also been developed to resolve the wheel slip-tracking problem. In contrast to conventional FL control systems, a **genetic algorithm** (GA) controller, i.e., GA-based FL controller may be proposed to solve the same problem in which an explicit knowledge of the parameters for the membership functions is deemed unnecessary.

Numerical simulations demonstrate the performance of the proposed control schemes subjected to different road conditions and in the presence of variations in system parameters and a bounded control input. The results indicate that superior performance can be obtained using the GA-based FL controller when compared with the feedback linearising controller and the conventional FL controller [CHEN AND LIAO 2000].

There is a strong parallel between automotive and military mechatronic systems. Driven by the safety-critical requirements of automotive vehicle ECUs, the internationally developed *OSEK/VDX* operating system standard promises reliability, upgradeability and, best of all, open compatibility between hardware and software vendors.

By using an *OSEK/VDX*-compliant **real-time operating system** (RTOS), developers may greatly improve productivity and deliver reliable automotive (and other) systems to the market much faster [BOURDON 2002].

The *OSEK* standard came about as an initiative from the automotive industry to create an open-ended architecture for distributed control units in vehicles. *OSEK* is an abbreviation for the German term *"Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug"*, which translates in English as *"Open Systems and the Corresponding Interfaces for Automotive Electronics"* and includes standardised RTOS, software interfaces, and functions for communication and network management tasks [PATERNOTTE 2002]. *VDX* is an abbreviation for the English term *"Vehicle Distributed eXecutive"*; *OSEK*™ is a registered trademark of Siemens AG.

Because of its standardised, hardware-independent specifications, *OSEK*-based applications enjoy portability across microcontroller architectures, interchangeability at the module (ECU) level, and broad tools support.

Dozens of 8-, 16-, 32- and *64*-bit microcontrollers are supported by nearly 10 different *OSEK* RTOS vendors, reducing the porting effort involved in a technology upgrade to an absolute minimum.

With this level playing field and the strong competition between vendors from the API perspective, one-to-one interchange-able *OSEK* products keep vendors alert and prepared to offer the best possible solutions.

Notably, one-to-one interchangeability is not limited to the RTOS itself. If an ECU is designed to fit in a well-defined, modular system, it opens up possibilities for alternative modules coming from different suppliers or based upon different technologies. The *OSEK* standard always ensures a second source for an application development [PATERNOTTE 2002].

The broad availability of software development tools is probably the greatest benefit of using an *OSEK*-compliant RTOS. Thanks to the *OSEK* standard, companies are able to eliminate two man months of porting time from their application development cycle. They may mix and match different tool solutions throughout the complete software development chain, gaining exceptional flexibility to choose (or rechoose) the most efficient system modelling and simulation tools, compiler, debugger, and emulator for an application [PATTEMOTTE 2002].

At the highest level, system modelling and simulation tools such as *MATLAB®/Simulink®* and *dSPACE/TargetLink* fully support *OSEK* and allow generations of *OSEK* RTOS configuration files and application codes ready to build with the OSEK libraries.

Close cooperation between *OSEK* RTOS vendors and independent compiler tool vendors ensures that incorporating the RTOS libraries into an embedded application – whether generated by modelling tools or propriety – is a well-trodden path. *OSEK*-compliance ensures that integration is automatic and seamless. Further down the embedded software development cycle, a host of in-circuit-emulators and source-level software debuggers offer *OSEK* kernel-aware debugging [PATERNOTTE 2002].

Up till now, typical mechatronic control systems within automotive vehicles consist of many devices connected through various buses. In addition, manufacturers are now linking the safe-critical ECUs found *'under-the-hood'* with these infotainment systems through *'gateway'* devices [BOURDON 2002].

Figure 3.28 outlines these networks along with typical RTOSes and applications found on each [BOURDON 2002].

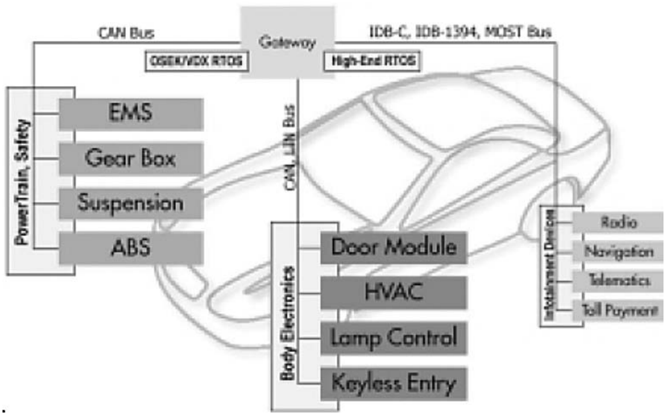


Fig. 3.28 Automotive vehicle networks and embedded applications [BOURDON 2002].

An infotainment bus connects subsystems such as radios, telephone, and navigation, while other buses connect ECUs that control the automatic BBW AWB dispulsion and AWD DBW propulsion mechatronic control systems.

Buses include the CAN bus under-the-hood connectivity, the MOST bus for real-time audio and compressed video, and the IDB-C and IDB-1394 buses for the development of aftermarket and portable devices.

High-end vehicles may have 50 ECUs connected via multiple networks or buses [BOURDON 2002].

ECUs are typically designed and developed by OEMs to meet vehicle manufacturers' requirements, including a detailed description of all data messages transmitted over the connecting networks.

Until recently, OEMs had total freedom in the design of ECUs; including the processor architectures network protocols and the RTOS software. However, this incompatibility between ECUs made by different manufacturers, locked automotive vehicle manufacturers into buying components from particular suppliers [BOURDON 2003].

In addition, the cost of developing and managing non-application-related ECU software for vehicles was high.

Many OEMs found it increasingly difficult to maintain and extend their in-house RTOS solutions. As they looked to refocus on core competencies, the significant and recurring investment in time and money to port the in-house RTOS to new processors, became more difficult to manage.

In an effort to deal with these problems, manufacturers developed *OSEK/VDX*, an open-ended architecture for distributed control units in automotive vehicles. There are also additional specifications emerging under the *OSEK/VDX* umbrella – *OSEKtime* and **fault-tolerant COM** (FTCOM). Both of these standards are targeted at future safety-critical under-the-hood applications including AWD DBW propulsion and BBW AWB dispulsion.

High-level objectives of the EMB BBW AWB dispulsion mechatronic control system are as follows [CADENCE 2003]:

- ❖ Distributing automotive vehicle mechatronic control over multiple systems from different vendors;
- ❖ Enabling automotive vehicle mechatronic control by defining open interfaces between chassis mechatronic control systems;
- ❖ Providing a **fault-tolerant** (FT) safety architecture based on system distribution;
- ❖ Enhancing the *OSEK/VDX* – compliant operating system from different vendors to create a distributed operating system;
- ❖ Distributed approach is focused on the base brake function: most critical for a safe and reliable braking system;
- ❖ Shift from fail-safe to fail-silent:
  - ➢ Fail-safe: in the case of an error within the mechatronic control, the performance of the mechanical system is reduced while still providing minimum functionality;
  - ➢ Fail-silent: when one task or node fails another is already running and the system employs the alternative.

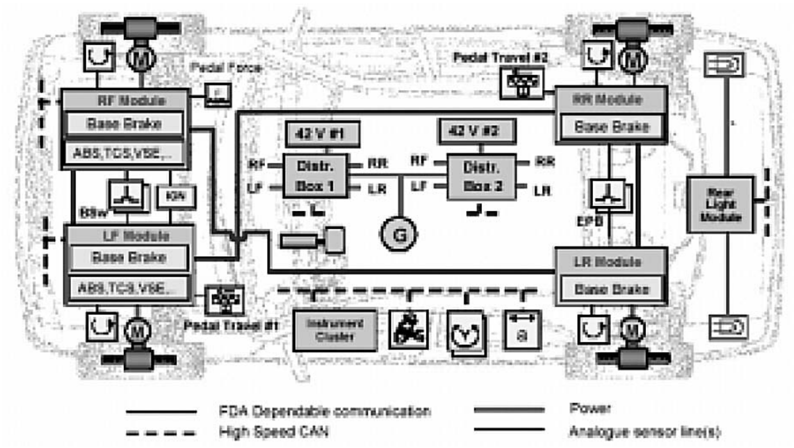


Fig. 3.29 Actual implementation of the EMB BBW AWB dispulsion mechatronic control system - variant of the direction unisensual redundant ring structure [Infineon – Delphi – Volvo – WindRiver; CADENCE 2003].

In Figure 3.29 is shown an actual implementation of the EMB AWD DBW dispulsion mechatronic control system with the single-sense of a direction vector redundant ring structure that contains the following components and/or responsibilities [CADENCE 2003]:

- ❖ Two travel sensors and one force sensor to determine driver intent (each sensor connected to a different wheel node);
- ❖ Sensor values communicated over the network → consistency checks;
- ❖ Wheel node calculates the actuation commands for all four wheels;
- ❖ Commands communicated by means of network → each of the four wheel nodes compares its own actuation commands with those calculated by the other wheel nodes;
- ❖ Voting mechanism in the network layer of each wheel node can then disable the power to individual actuators in the case of a fault;
- ❖ If a node needs to be shut down, the brake force is redistributed to prevent the ehicle from yawing;
- ❖ The advanced brake functions (ABS) are executed in two front-wheel nodes;
- ❖ If the front-wheel nodes do not calculate the same output commands for these advanced brake functions, the function may be deactivated; this provides fail-safe operation; redundant power supply.

In Figure 3.30, as an example solution, a Robert Bosch Corporation ESP system is shown [ROMANO 2000].

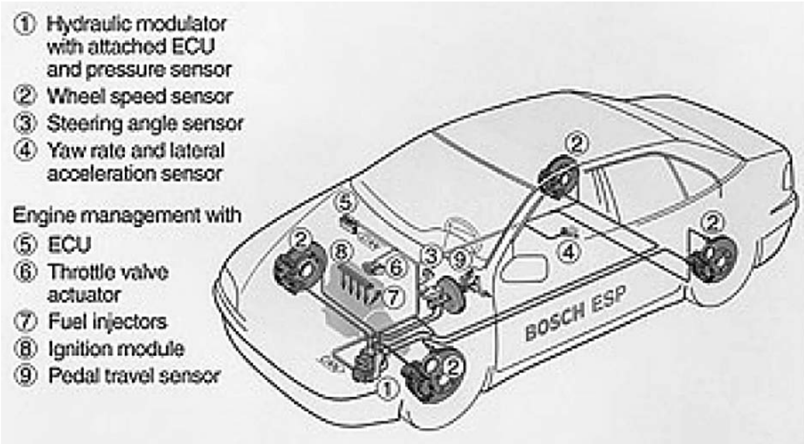


Fig. 3.30 Robert Bosch Corporation ESP system [ROMANO 2000].

In Figure 3.31 the components in the Robert Bosch Corporation ESP system are presented. They include (A) active wheel angular velocity (speed) sensors; (B) steering angle sensor; (C) combined yaw rate sensor/lateral accelerometer; (D) attached ECU; (E) E-M motor; (F) pressure sensor, and (G) fluidical (hydraulical) unit. Some ESP system use ride height sensors [ROMANO 2000].

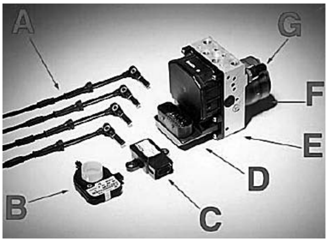


Fig. 3.31: Components in the Robert Bosch Corporation ESP system [Robert Bosh Corporation; ROMANO 2000].

3.5.4 Objectives of Anti-lock BBW AWB Dispulsion Mechatronic Control Systems

The objectives of anti-lock BBW AWB dispulsion mechatronic control systems are three fold:

- ❖ To reduce stopping distances;
- ❖ To better stability in automotive vehicle handling; ;
- ❖ To better steerability during braking.

Stopping Distance - As shown in Eq. (3.4), the distance to stop (v_f = 0) is a function of the initial vehicle velocity, the mass of the automotive vehicle, and the longitudinal frictional braking force.

From this equation it can be seen that by maximising the longitudinal frictional braking force, the stopping distance may be minimised, all other factors remaining constant.

From Figure 3.5, it is evident that on all types of on/off-road surfaces, to a greater or lesser extent, there exists a peak value of frictional braking force. It follows that by keeping all of the wheels of an automotive vehicle near the peak value, an anti-lock BBW AWB dispulsion mechatronic control system may attain maximum value of longitudinal frictional braking force and, therefore, minimum value of stopping distance. This is an objective of anti-lock BBW AWB dispulsion mechatronic control systems. However, it is tempered by the need for vehicle handling stability and steerability.

Vehicle Ride Comfort and Handling Stability - Although decelerating and stopping automotive vehicles constitutes a fundamental purpose of BBW AWB dispulsion mechatronic control systems, a maximum value of longitudinal frictional braking force may not be desirable in all cases. For instance, if a vehicle is on a split-coefficient surface (for example, asphalt and ice), such that significantly more frictional braking force is obtainable on one side of the vehicle than on the other side, applying the maximum value of longitudinal frictional braking force on both sides may result in a yaw moment that will tend to pull the vehicle to the high-coefficient side and contribute to vehicle handling instability.

Typically on short-wheelbase automotive vehicles, a control strategy is employed to control the fluid or air pressure in the rear wheels together to better stability. Similarly, it is common for a front-wheel strategyto be employed to limit the initial side-to-side fluid or air pressure difference so as to not induce excessive yaw moment changes in the steering wheel and force the driver to make excessive steering corrections to counteract the yaw moment.

If an anti-lock BBW AWB dispulsion mechatronic control system can keep the vehicle wheels near the peak value of the longitudinal frictional braking force range, then lateral frictional braking *OSEK*^{TM} force is reasonably high, although not minimised. This contributes to stability and is an objective of anti-lock BBW 4WB dispulsion mechatronic control systems.

Steerability - Steerability depends on high lateral force. A good peak value of longitudinal frictional braking force control is necessary in order to achieve satisfactory lateral frictional braking force and, therefore, satisfactory steerability.

Steerability while braking is important not only for minor course corrections but also for the possibility of steering around an obstacle. Anti-lock BBW AWB dispulsion mechatronic control systems provide this feature through control to the peak value of the longitudinal frictional force range.

3.5.5 Anti-lock BBW AWB Dispulsion Mechatronic Control System Components

The components of an anti-lock BBW AWB dispulsion mechatronic control system are the wheel angular velocity sensors; the fluidical modulator; the fluidical (hydraulical) or pneumatical power source, usually an **electro-mechano-fluidical** (E-M-F) pump or **electro-mechano-pneumatical** (E-M-P) compressor; and the ECU.

***Wheel Angular-Velocity Sensors* -** Due to the simplicity and proven reliability, variable reluctance wheel angular-velocity sensors typically are used in anti-lock BBW AWB dispulsion mechatronic control systems.

Utilised in conjunction with exciter rings, this type of sensor produces a sinusoidal output that is directly proportional in frequency and amplitude to the angular velocity of the sensed wheel.

Depending on the design of the sensor and exciter ring and the gap between them, the sensor output amplitude may be as low as 100 mV_{DC} at very low values of the vehicle velocity and over 100 V_{DC} at high values.

Both single-magnetic-pole and dual-magnetic-pole variable reluctance sensors are used, depending on the application. Single-magnetic-pole sensors tend to have higher outputs and dual-pole sensors tend to have better immunity to some types of noise.

A limitation of this technology is that the very low angular velocity output tends to be too low to be reliably sensed by the ECU, given the electrically noisy environment typical of automotive vehicles.

This may result in errors below 1 to 3 km/h and cumulative inaccuracies if this sensor is used in conjunction with an odometer function; normally, the anti-lock function is inhibited at very low values of vehicle velocity.

Both single-ended and balanced inputs are used in ECUs to receive wheel angular velocity signals.

A variety of active sensor technologies, including the *Hall or Wiegand* effect and magnetoresistive, may be used in applications requiring very low angular velocity sensing and in applications where an appropriate signal level cannot be achieved with conventional variable reluctance sensors.

***Anti-lock Fluidic or Pneumatic Modulators* -** Anti-lock fluidic modulators typically take two forms in production anti-lock BBW AWB dispulsion mechatronic control systems: solenoid fluidical valves and E-M motors.

A simplified solenoid fluidical valve anti-lock BBW AWB dispulsion mechatronic control system's principle layout and schematic diagram are shown in Figure 3.32 [CAGE 1994; AMISEMICONDUCTOR 2004].

In this BBW AWB dispulsion system, if the solenoid fluidical valves are de-energised, fluid or air is free to flow between the master cylinder and the brakes.

If too much fluid or air pressure is presented to the brakes and wheel lock is imminent, the anti-lock BBW AWB dispulsion mechatronic control system may actuate a solenoid fluidical valve and energise the E-M-F pump or E-M-P compressor.

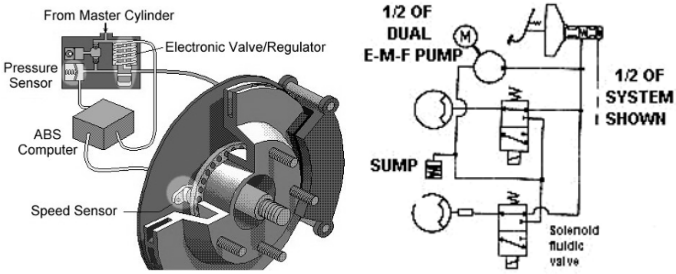


Fig. 3.32 Simplified solenoid fluidic valve anti-lock 4WB BBW dispulsion mechatronic control system's principle layout and schematic diagram [AMISEMICONDUCTOR 2004 – left image; CAGE 1994 – right image].

Actuation of the solenoid fluidic valve allows fluid or air pressure to decrease from the brake through the fluidical valve to a low-pressure fluidical accumulator/sump. The fluid or air is temporarily stored in the sump prior for being pumped or compressed back, respectively, into the BBW AWB dispulsion system by the E-M-F pump or E-M-P compressor. Through repetitive energisation/de-energisation cycles, average fluid or air pressure to a given wheel may be regulated to the level necessary to achieve the desired braking force. Typical brake fluid or air pressure and resulting wheel angular velocity cycling is shown in Figure 3.33 [CAGE 1994].

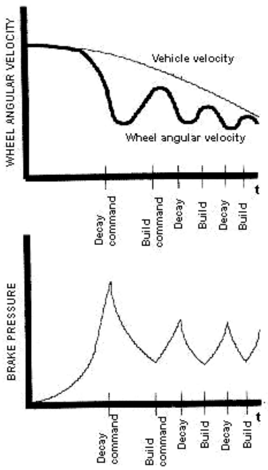


Fig. 3.33 Typical anti-lock braking cycle [CAGE 1994].

Electro-Mechano-Fluidic (E-M-F) Pump or Electro-Mechano-Pneumatic (E-M-P) Compressor - Although some anti-lock BBW AWB dispulsion systems use multiple E-M motors driving fluidical pistons to provide multiple-channel oily-fluid or air (gas) pressure reduction and rebuild, usually an E-M motor-driven M-F pump or M-P compressor is used in conjunction with solenoid fluidical valves, respectively, to achieve individual brake or brake channel oily-fluid or air (gas) pressure reduction and rebuild. A dual E-M-F pump or E-M-P compressor is often used to maintain a complete fluidical or pneumatical separation of the two channels of the BBW 4WB dispulsion mechatronic control system. This is done to ensure that failure in one channel of the BBW 4WB dispulsion mechatronic control system will not affect the operation of the other channel.

Electronic Control Unit (ECU) - Control of the fluidic modulator and E-M-F pump or E-M-P compressor is performed by the ECU. Modern customer expectations coupled with decreasing single-chip microcomputer costs, have made microcomputer-based ECUs the norm rather than the exception. Although the control units can be either engine compartment-mounted or passenger compartment-mounted, reduced wiring costs favour the former. Also, for enhanced reliability, ECUs may be either attached to or integrated with the fluidical or pneumatical modulator.

3.5.6 Safety Considerations of ABW BBW Dispulsion Mechatronic Control Systems

A growing number of automotive vehicles today use mechatronic **brake assist** (BA) to decrease braking reaction times and reduce stopping distances in emergency situations. These systems still use a conventional vacuum booster, but add sensors to the brake pedal and/or throttle pedal to detect panic braking situations. This same type of BA may also be provided by mechanical mechatronic controls at less cost and complexity. A mechanical actuator inside the booster detects the vehicle velocity at which the driver is applying the brakes. If it *'feels'* like a panic stop, the booster goes to full boost and slams on the brakes.

Though BA is not the same as BBW AWB dispulsion, it is a step in the same sense of direction. The last thing any motorist wants is a refined hi-tech BBW AWB dispulsion mechatronic control system that goes off-line while they are driving in heavy traffic. The BBW AWB dispulsion mechatronic control system must be dependable and have backup redundancy in the case of a failure, otherwise there's no way to stop the vehicle [CARLEY 1994].

One of the primary goals of automotive scientists and engineers who are developing the innovative BBW AWB dispulsion mechatronic control systems, therefore, is to make mechatronic E-M braking safe and reliable, if not more so than conventional F-M braking systems.

In this respect, an E-M braking system with redundant computer controls and a voltage supply would probably be safer than a conventional F-M braking system. Why? Because each wheel is on its own separate electrical circuit, if one EMB calliper or circuit fails, it should not affect the other three wheels. This means the vehicle could still have three operational brakes (as opposed to two with contemporary F-M braking systems) in the event of a brake failure at one wheel. The biggest gains in safety, though, are made possible when BBW AWB dispulsion allows ABS, TCS, and VSC to be taken to the next level.

BBW AWB dispulsion mechatronic control systems may be easily combined with ACC to provide automatic braking if a vehicle ahead suddenly stops and the driver fails to react quickly enough. It may also be combined with some type of crash-avoidance system that is capable of detecting objects in the road ahead or an oncoming automotive vehicle to apply the brakes before the driver may react. The same vehicle manufacturers that are developing BBW AWB dispulsion mechatronic control systems have also developed **electronic parking brake (**EPB) systems to replace cable-operated disc, ring, or drum brakes. Pressing a button, the driver sets the parking brake, instead of pushing a pedal or yanking on a handle to set the brake (that few drivers seem to utilise anyway) [CARLEY 2004].

With EPB BBW AWB dispulsion technology, the automotive vehicle's driver may be able to actuate the parking brake using a switch in the vehicle. The switch may allow for either progressive application of the parking brake or simple *'ON'* or *'OFF'*. An electrical signal from the switching arrangement is sent to the smart E-M actuating unit. This unit then applies force and travels to each disc, ring, or drum brake mechanism user continuous mechatronic control using the smart elements of the integrated sensors and mechatronics. EPB BBW AWB dispulsion mechatronic control may also facilitate the automation of the parking brake function, assisting the driver in hill starts or traffic light starts [PACIFICA 2002].

Standard automotive BBW AWB dispulsion mechatronic control systems have been developed and refined over the years to be highly reliable and safe. Because of its ability to decrease fluid or air pressure in FMBs or PMBs, an anti-lock BBW AWB dispulsion mechatronic control system must be designed using a disciplined methodology and must be rigorously tested prior to release for manufacture. One thing is certain,: hi-tech never stands still and BBW AWB dispulsion is no exception. It may take awhile, maybe a decade or more. But sooner or later, BBW AWB dispulsion mechatronic control systems may become as common as ABS is today.

Failure Mode and Effects Analyses/Fault Free Analyses - Failure mode and effects analyses or fault-free analyses are essential to the proper design of anti-lock BBW AWB dispulsion mechatronic control systems. Both system- and hyposystem-level analyses need to be performed and fault effects and detection assumption must be tested.

No single failure may result in an unsafe condition and, if a fault is undetectable in the field, that fault in conjunction with any other fault must not result in an unsafe condition. Because of the sophistication of the ECUs, simulation techniques are used to test those faults effects in which bench or field testing is impractical.

***Common Design Techniques to Improve Safety* -** One of the most common techniques used to improve safety in anti-lock BBW AWB dispulsion mecha+tronic control systems is to include extensive built-in tests within the ECU. Typically, all inputs to the ECU and outputs to the other components of the anti-lock BBW AWB dispulsion mechatronic control system are tested for proper signals and loads, respectively, and all internal functions to the ECU are extensively tested. In addition, redundant processing is commonly used to insure the proper internal working of a single-chip microcontroller. This may take the form either of identical single-chip microcontrollers or of a main and watchdog microcontroller that may inhibit operation. In order to ensure inhibition of faulty anti-lock operation, anti-lock BBW AWB dispulsion mechatronic control systems employ a relay function to remove actuation power from the output actuators. This function may take the form of a discrete relay or it may be an electronics circuit. This relay function is a key element of the design since it affords a secondary method in which to inhibit the energising of fluidical valves or the E-M-F pump or E-M-P compressor and, therefore, a second level of safety relative to improper anti-lock operation. Figure 3.34 is a typical ECU structural and functional block diagram [CAGE 1990, 1994].

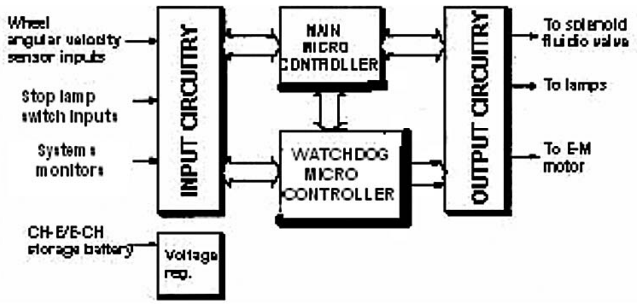


Fig. 3.34 Typical electronic control unit (ECU) structural and functional block diagram [CAGE 1994].

Inputs are filtered and buffered prior to being presented to the single-chip microcontrollers for processing. Likewise, the single-chip microcontroller outputs are buffered/amplified and filtered prior to exiting the ECU. In the block diagram shown, the main microcontroller is responsible for the majority of processing and control of the outputs; the watcdriverog microcontroller, as its name implies, is responsible for monitoring for proper operation and inhibiting anti-lock if faults are indicated.

A characteristic of modern anti-lock ECUs is bi-lateral communication between functional blocks. This is a result of the high level of built-in tests designed into the ECUs. For instance, the output circuitry may be commanded to test the solenoid fluidic valves for proper current draw and convey the test results to the single-chip microcontrollers. Similarly, the input circuitry may be commanded to perform tests on the sensors and other anti-lock components external to the ECU and convey the test results to the single-chip micro-controllers.

3.5.7 Basics of the Anti-lock Control Logic

Due to the sophistication of the anti-lock BBW AWB dispulsion mechatronic control system and the requirements of vehicle ride handling stability and steerability as well as good stopping distance, the brake control algorithm is more easily represented as a state-space block diagram than as a classical **proportional-integrative-derivative** (PID) control system.

A simplified state-space block diagram for a single-channel anti-lock BBW AWB dispulsion mechatronic control system is shown in Figure 3.35 [CAGE 1994].

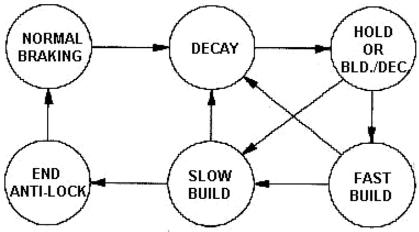


Fig. 3.35 Simplified single-channel state-space block diagram [CAGE 1994].

In this structural and functional block diagram, an automotive vehicle not braking or decelerating would be in the *NORMAL BRAKING* state. If anti-lock action is warranted, it is because the brake fluid or air pressure on a given channel has caused the wheel to begin to lock; the first action would be to decrease the brake oily-fluid or air (gas) pressure or even electrical voltage (*DECAY* state) in an effort to permit the locking wheel to re-accelerate. Fine control of the brake fluid or air pressure, or even electrical voltage, is indicated by the states labelled *HOLD* or *BUILD/DECAY* and *SLOW BUILD* and course control is indicated by the *FAST BUILD* state. The course control is typically used during rapidly changing road surface conditions such as ice-to-asphalt transitions. During the anti-lock cycle, the state may change, as needed, to attain the type of brake fluid or air pressure or even electrical voltage, and resulting wheel angular-velocity activity as shown in Figure 3.35 [CAGE 1994].

Once the need for the anti-lock action has ended, the *END ANTILOCK* state is entered, E-M-F pump or E-M-P compressor is de-energised, the fluidical or pneumatical valves are de-energised, and the BBW 4WB dispulsion mechatronic system can return to the original *NORMAL BRAKING* state [CAGE 1991, 1994]. How this state-space approach is integrated into a typical microcontroller flowchart is shown in Figure 3.36 [CAGE 1994].

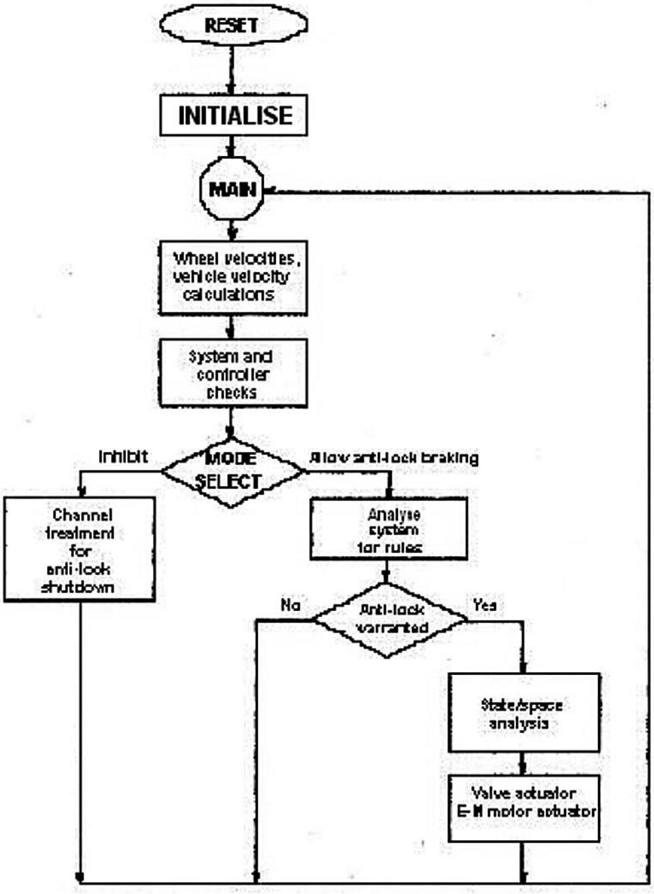


Fig. 3.36 Simplified anti-lock flowchart [CAGE 1994].

After *RESET* and *INITIALISATION*, a single-chip microcomputer enters into a *MAIN* loop that includes extensive control system and ECU checks as well as calculations of values of the wheel angular velocity, prediction of value of the vehicle velocity, analysis of conditions warranting anti-lock action/state-space control law, and fluidical or pneumatical valve and E-M-F pump or E-M-P compressor actuations, respectively.

Calculations of values of the wheel angular velocity consists of scaling the wheel angular velocity sensor inputs to a more usable form and possibly filtering noise due to axle deflection (if any), brake squeal, other electrical/electronic systems, and so on. A consideration is that the bandwidth of wheel acceleration and deceleration is large -- 50 *G* may be attainable [CAGE 1994].

The vehicle velocity prediction is critical to many control systems because wheel angular velocity relative to vehicle velocity, as well as wheel slip, may be used as a factor in determining appropriate fluidic valve action. Vehicle velocity prediction becomes difficult once the wheels begin to lock because the sensors may no longer be reliable indicators of vehicle velocity. The methods used to predict vehicle velocity once the wheels have begun to lock consist of a set of rules that have been developed by anti-lock manufacturers through years of experience to ensure a prediction that has a high degree of accuracy to true vehicle velocity.

The anti-lock BBW AWB dispulsion mechatronic control system checks typically consist of sensor and fluidic valve/E-M-F pump or pneumatic valve/E-M-P compressor continuity tests and electro-energetic system voltage range tests. In addition, the checks normally include tests internal to the ECU, such as inter-microcontroller communication. Once it is determined that conditions are such that anti-lock action can be safely invoked if necessary, the wheel angular velocity conditions are analysed to establish the appropriate state for that channel. Primary indicators for most anti-lock control systems are wheel slip and wheel deceleration. Another factor considered is the effect on vehicle handling stability if a particular state is commanded. Actuation of the fluidical valves or E-M motor actuators is a direct result of the decisions made in the analysis/state-space logic. Other than actuators requiring **pulse-width modulation** (PWM) drives, the actuators will normally remain in the commanded state until the single-chip microcontroller loops back through the code, usually a few milliseconds.

3.5.8 Testing of the Anti-lock BBW AWB Dispulsion Mechatronic Control System

Anti-lock BBW AWB dispulsion mechatronic control system testing has evolved over the years to include the following most common tests [CAGE 1994]:

- Straight-line stopping;
- Braking in a turn;
- Split coefficient stopping with associated stability criteria;
- Transitional road-surface testing including checkerboard and long/high and high/low coefficient surfaces;
- Lane change manoeuvres.

All of these tests may be performed on a variety of surfaces, at a variety of values of vehicle velocity, and with lightly and/or heavily loaded vehicles.

3.6 Enhanced Anti-Lock and Anti-Spin BBW AWB Dispulsion Mechatronic Control Systems

In the nearest future, automotive vehicle manufacturers may be compelled to manufacture **ultra-low-emission vehicles** (ULEV) and **virtual-zero-emission vehicles** (VZEV) for the global market that offer emission-free and moderate vehicle velocity in certain areas [FIJALKOWSKI AND KROSNICKI 1994, 1997; FIJALKOWSKI 1995].

For instance, an ultralight (600 kg), 4 -- 5 passenger, high-performance, all-round energy-efficient, HEV termed a *Poly-Supercar* with the series **hybrid-electric** (HE) AWD DBW propulsion, enhanced anti-lock and/or anti-spin BBW AWB dispulsion, predictive and adaptive ABW AWA suspension and dual-mode hybrid SBW AWS conversion mechatronic control systems and simplified design, may achieve 1.5 -- 4.5 l/100 km.

Automotive E-M components for full-time AWD DBW propulsion, BBW AWB dispulsion, ABW AWA suspension and SBW AWS conversion mechatronic control systems of the *Poly-Supercar* that is a VZEV, as shown in Figure 3.37, may be well suited to help reduce local air pollution emissions.

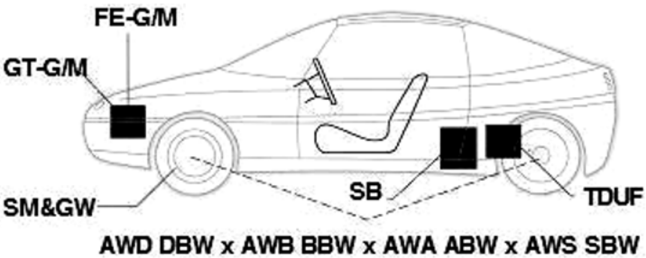


Fig. 3.37 Series HE AWD DBW × BBW AWB × AWA ABW × AWS SBW HEV termed a *Poly-Supercar* [FIJALKOWSKI 2000B].

Automotive E-M components for full-time DBW AWD propulsion, BBW AWB dispulsion, ABW AWA suspension, and SBW AWS conversion mechatronic control systems of the *Poly-Supercar* that is a VZEV, as shown in Figure 3.35, may be well-suited to help reduce local air pollution emissions. The electrical energy required to dispel such VZEV is generated by the clean-burning, hydrogen fuelled **gas turbine-generator/motor** (GT-G/M) that is based on the **Fijalkowski turbine boosting** (FTB) system or the **Fijalkowski engine –generator/motor** (FE-G/M) with the brushless AC-DC/ DC-AC macrocommutator flywheel-disc generator/motor that directly converts into electrical energy the mechanical energy supplied to the pistons by the combustion of gaseous hydrogen, installed on board a VZEV.

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_31, © Springer Science+Business Media B.V. 2011

At the VZEV user end, the energy may be stored in **chemo-electrical/electro-chemical** CH-E/E-CH **storage batteries** (SB), **super-conductor magnetic-field energy storage** (SMES) ultrainductors, **super-insulator electric-field energy storage** (SEES) ultracapacitors and **inertial mechanical energy storage** (IMES) ultraflywheels such as the **twin-disc ultraflywheel** (TDUF).

The core of the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system may be not only four E-M friction disc, ring, and drum brakes with the short-stroke linear tubular brushless DC-AC macrocommutator **interior permanent magnet** (IPM) brake-actuator E-M motors, single smart reciprocating **electro-mechanical brake** (EMB) pedal actuator, driven by the short-stroke linear tubular brushless DC-AC macrocommutator brake-pedal-actuator motor for the left-foot brake pedal (normal braking), but also four independently-suspended front and rear **electro-mechanical/mechano-electrical** (E-M/M-E) **steered, motorised and/or generatorised wheels** (SM&GW) with the brushless DC-AC/AC-DC macrocommutator IPM magnetoelectrically-excited wheel-hub motors/generators (regenerative braking).

E-M friction disc, ring and drum brakes for SM&GWs may provide improved default modes compared to conventional F-M or P-M friction disc, ring, and drum brakes for conventional all-mechanically ECE or ICE-driven wheels plus significantly improved serviceability. Increased diagnostic capabilities may be available through the use of mechatronics.

Automotive developers expect to use a spring-damper to give *'pedal feel'* to a brake pedal that may push against a mechatronic movement-sensing device. The sensor may signal an ECU. For instance, for hybrid anti-lock BBW AWB dispulsion mechatronic control systems, electrical energy for rear SM&GWs may be generated by a brushless AC-DC macrocommutator electromagnetically-excited generator and stored in a DC CH-E/E-CH storage battery and, oily-fluid or air (gas) pressure for front SM&GWs may be generated by a M-F pump or M-P compressor and stored in a fluidic accumulator [WELLS AND MILLER 1993].

The ECU may direct it to apply E-M friction drum brakes for **rear-wheel drive** (RWD) and F-M friction disc brakes for **front-wheel drive** (FWD) as required. If the mechatronics fail, pushing harder on the brake pedal may work a back-up emergency F-M braking system.

AN enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system may eliminate fluidics (hydraulics and/or pneumatics). Electrical energy may work, for instance, the brake callipers. Less brake bulk in front helps better crash deceleration for lower occupant injury.

Other advantages are reduced mass, better brake control in anti-lock and/or anti-spin braking accident situations, more accurate brake force distribution, and potentially better reliability, as well as better pedal feel.

Rather than attempt to adjust the proportioning directly, enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control systems sense the SM&GW lockup occurs, release the E-M friction disc, ring, or drum brakes momentarily on locked SM&GWs, and reapply them when the SM&GW spins up again. It seems that everything is electrically wired in recent times.

Enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control systems are capable of releasing the E-M friction disc, ring, or drum brakes before the SM&GW goes to lock-up, and modulating the level brake application voltage on reapplication to just hold the SM&GW near peak slip conditions. An enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system consists of an ECU, rotating brushed DC-AC mechanocommutator electromagnetically-excited brake-force-actuator motors, or short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically-excited brake-force-actuator motors for releasing and reapplying brake application voltages to disc, ring, or drum-brake force actuators, and a SM&GW angular-velocity sensors. Short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically excited brake-force-actuator motors have translational instead of rotary motion. They may be applied to the drive of a disc- or ring-brake callipers or a drum-brake application levers. The ECU normally monitors vehicle velocity through the SM&GW angular-speed sensors, and upon E-M friction disc, ring, or drum-brake application begins to compute an estimate of the diminishing vehicle velocity.

Actual (measured) values of SM&GW angular speeds may be compared against their computed reference values to determine whether a SM&GW is slipping excessively, or the deceleration rate of a SM&GW may be monitored to determine when the SM&GW is advancing toward lockup. Different anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system designs use different combinations of these physical variables to determine when locking or spinning is imminent and E-M friction disc, ring, or drum-brake release is warranted. At that point, a command reference signal is sent to the rotating brushed DC-AC mechanocommutator electromagnetically-excited brake-force-actuator motor or short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically-excited brake-force-actuator motor to release the brake application voltage, allowing the SM&GW to spin back up. Once the SM&GW regains its angular speed, the brake application voltage is increased again. Depending on the refinement of the control algorithms, the brake application voltage rise rate and the final value of a brake application voltage may be controlled to minimise cycling of the E-M friction disc, ring or, drum brakes. During the stopping of an automotive vehicle with the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system, when the E-M friction disc, ring, or drum brakes are first applied, actual values of SM&GW angular speeds diminish more or less in accordance with the actual value of a supercar velocity. If the E-M friction disc, ring, or drum brakes are applied to a high adhesion coefficient SM&GW level, or the road surface is slippery, the actual values of angular speeds of one or more SM&GWs begins to drop rapidly, indicating that the SM&GW's tyre has gone through the peak value of the friction-slip curve and is heading toward lockup.

At this instant the enhanced anti-lock and/or anti-slip BBW AWB dispulsion mechatronic control system intervenes and releases the brakes on those SM&GWs before lockup occurs. Once the actual value of a SM&GW angular speed picks up again, the brakes are reapplied.

The objective of the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system is to keep each SM&GW's tyre on the vehicle operating near the peak value of the friction-slip curve. In the latest automotive vehicles, braking is achieved with the assistance of SM&GWs with brushless DC-AC/AC-DC or AC-AC macrocommutator IPM magnetoelectricall-excited wheel-hub motors/generators. The driver selects a level of braking effort and this is transmitted to the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control systems. Initially, the E-M friction disc, ring, or drum brakes are operated, while the brushless DC-AC/AC-DC or AC-AC macrocommutator IPM magnetoelectrically-excited wheel-hub motors/generators are configured into brushless AC-DC or AC-AC macrocommutator IPM magnetoelectrically-excited wheel-hub generators, thus developing braking forces. Once developed, regenerative braking is normally sufficient, the E-M friction disc, ring, or drum brakes are not required and are *'blended'* out.

In theory, an enhanced DBW AWD propulsion mechatronic control system can brake right down to zero speed, though the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system is not fail safe as a *'brake'*. Losing the DBW AWD propulsion mechatronic control system may mean losing all braking.

The enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system may quickly intervene and is capable of braking a supercar without a DBW AWD propulsion mechatronic control system. Nevertheless, for complete safety at slow speeds, the DBW AWD propulsion mechatronic control system is faded out (not to be confused, for instance, with pad/disc fade) and the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system brings the automotive vehicle to a halt. This *'blended BBW AWB'* approach, for instance, has the advantage of reducing pad wear significantly and, in many cases, the regenerated electrical energy from the brushless AC-DC or AC-AC macrocommutator IPM magnetoelectrically-excited wheel-hub generators may be put back into the DC CH-E/E-CH storage battery and/or IMES ultraflywheel for use during fast-acceleration starting, hill climbing and high-speed passing, thus saving energy. When this is not possible, the electrical energy may be dissipated across a braking resistor located on the vehicle for heating in the winter (known as rheostat braking). A trend that may impact enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control systems is the automotive industry's desire to reduce vehicle wiring through the use of multiplexing techniques. As increasing numbers of emerging automotive vehicles are outlined with anti-lock and/or anti-spin, this trend is expected to result in an increased number of conventional anti-lock BBW AWB dispulsion mechatronic control systems communi cating with other automotive vehicle mechatronic control systems (for example, DBW AWD propulsion, ABW AWB dispulsion, ABW AWA suspension, and SBW AWS conversion mechatronic control systems) through a multiplex link.

In addition to the wheel angular speed/vehicle velocity data available from the anti-lock BBW AWB dispulsion mechatronic control system, the anti-lock ECU could benefit from this technology by being able to receive engine, transmission, SM&GW, steering angle, and other data. Another trend in advanced mechatronically-controlled enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control systems is supercar dynamics control during propel-ling (non-braking manoeuvres) as well as during dispelling (braking). This is ac-accomplished through use of the AWD DBW propulsion mechatronic control ECU normally integrated in enhanced anti-lock and/or anti-spin electric modulators that are ASIM DC-AC macrocommutators, the addition of sensors to more accurately determine the dynamic state of the vehicle, and communication links with the AWD DBW propulsion mechatronic control.

Automotive **vehicle dynamics control** (VDC) holds the promise of safer vehicle operation through improved stability in all manoeuvres. Vehicle behaviour during braking in a hard turn includes spin and drift-out phenomena. The former may be effectively controlled by independently distributing the braking forces to the left and right rear SM&GWs; the latter can be controlled by adopting a method for preventing SM&GW lockup.

This chapter presents a novel enhanced anti-lock/or and anti-spin BBW AWB dispulsion mechatronic control system for also controlling the braking forces between the inner and outer SM&GWs independently in a hard turn.

Significant bettering has been seen in cornering performances in recent years as a result of advances achieved in tyre and AWA ABW suspension technology. Due to these improvements, *Poly-Supercar* (see Fig. 3.37) handling characteristics during braking has taken on an added importance. The analytical results show that decreasing the yaw moment before SM&GW locking or spinning occurs is effective in achieving stable handling. An effective approach to decreasing the yaw moment is to control the braking forces between the inner and outer SM&GWs. An independent braking force control subsystem for regulating the distribution of brake application voltages to the left and right rear SM&GWs include examples that combine linkage load-sensing input and a lateral acceleration-sensitive input. Currently, for example the Robert Bosch Corporation is developing a mechatronic yaw rate sensor for use in enhanced anti-lock and/or anti-spin ABW BBW dispulsion mechatronic control systems. It is three times lighter than considered yaw rate sensors (only 70 G against 210 G).

For instance, the automotive mechatronic control system used in the *Poly-Supercar* [FIJALKOWSKI 1995] incorporates two linkage load-sensing inputs installed at the back of the rear suspension member.

These provide independent control over the brake application voltage distribution to the left and right rear SM&GWs. The reason for configurating the control subsystem in this way are explained below: it facilitates easy adjustment of the brake application voltage applied to the left and right rear SM&GWs to maintain good supercar stability when braking in a hard turn; the brake application voltage characteristic is tuned to match the load at each rear SM&GW. By combining this control subsystem with the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system at all four SM&GWs, it is possible to lower the yaw acceleration forces causing both the drift-out and spin moments.

The operation performed in braking (decelerating) is the reverse of that carried out in driving (accelerating). In the latter, the thermal energy of the fuel is converted into the mechanic energy and, the mechanical energy of the prime mover is converted into the kinetic mechanical energy of the vehicle, whereas in the former the kinetic mechanical energy of the automotive vehicle is converted into thermal energy. Again, when driving the supercar the torques of SM&GWs produce tractive efforts at the peripheries of the driving SM&GWs, so when the brakes are applied, the braking torques introduced at the brake discs, rings, or drums produce negative tractive efforts or retarding efforts at the peripheries of the braking SM&GWs. As the possible acceleration is limited by the adhesion available between the driving SM&GWs and the ground, so the possible deceleration is also limited. Even so, when braking from a high vehicle velocity to a halt, the rate of retardation is considerably greater than that of full-ahead booster-induction-adjuster (*induction throttle*) acceleration.

Consequently, the friction mechanical energy dissipated by the brakes, and therefore the thermal energy generated, is correspondingly large. When E-M friction brakes are applied to SM&GWs on an automotive vehicle, forces are immediately introduced between the SM&GWs and the road, tending to make the SM&GWs keep turning. The decelerations are proportional to the braking forces, the limiting values of which depend on the normal forces between the SM&GWs and the road, and on the coefficients of frictions, or of adhesion, as they are called. Since the braking forces do not act along a line of action passing through the barycentre (the centre of gravity) of the vehicle, there is a tendency for a supercar to turn so that the rear SM&GWs rise into the air.

The inertia of the vehicle introduces internal inertia force acting at the barycentre in the opposite sense of direction to the braking forces. The magnitude of the inertia force is equal to that of the braking force. The two forces constitute a couple tending to make the rear SM&GWs rise, as stated. Since the rear SM&GWs actually remain on the ground, an equal and opposite couple must act on the vehicle somewhere so as to balance the overturning couple. A need to measure in some way a quantity that is poorly understood (adhesion or creep) and the use of that measurement to control an enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system, that has some uncertainty associated with it, may be identified.

It appears that **neural networks** (NN) may offer some advantages in mapping the adhesion/creep characteristics and for generating an estimation of the current adhesion level. Given this estimate, that has a tendency to some uncertainty in its own right, and the uncertainty in the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system, then the **application specific integrated circuit** *(*ASIC) **neuro-fuzzy** (NF) microcontroller may be used to control SM&GW slip and slide.

The AWD DBW propulsion and BBW AWB dispulsion mechatronic control systems are still mechatronically-controlled by their respective automotive mechatronic control systems, but the driver-demand signal passes through the slip/slide ASIC NF microcontroller before reaching the former. In this way, the slip/slide ASIC NF microcontroller acts to optimise, where possible, the performance of the supercar. The effects of the NN adhesion estimator and **fuzzy logic** (FL) slip/slide ASIC NF microcontroller when compared with a conventional ABS (anti-lock brake system), for the case of AWD DBW propulsion mechatronic control, are interesting.

There is little difference for reasonable adhesion conditions as expected, but for oil on the road surface, the innovative control system performs better with the effects of overspeed much reduced and a corresponding improvement in acceleration. In an enhanced anti-lock and/or anti-spin ABW BBW dispulsion mechatronic control system, an **in-vehicle sensor** (IVS) ought to be applied to sense not only the actual (measured) values of vehicle acceleration but also its jerk (the time rate of change of acceleration of a vehicle's body), and emulate responses of well-skilled and experienced driver.

3.7 Enhanced Adaptive Cruise BBW AWB Dispulsion Mechatronic Control Systems

The number of automotive vehicles travelling world's roads and highways are still increasing on a daily basis. Unfortunately, traffic congestion and the number of road accidents are also increasing. There is an ever-pressing necessity to regulate traffic flow and make driving much safer [RILEY ET AL. 2000].

Automotive vehicle manufacturers develop more intelligent vehicles every year. These enhancements allow many people to foresee a completely autonomous vehicle in the not-so-distant future. There are several organisations in the world that promote the development of safer, more intelligent vehicles. For instance, the US Government's support of the development of more intelligent automotive vehicles is evident from the **Surface Transportation Act** (STA) passed recently. The STA may provide direction, stability, and growth for **Intelligent Transportation Systems** (ITS) that save lives, time, and money in the 21st century. ITSs include advanced technologies that help drivers avoid accidents, reduce traffic jams, and improve traffic flow. One particular topic of ITS may be an intelligent cruise control termed **adaptive cruise control** (ACC). In the meantime, more and more sensors are being scattered throughout automotive vehicles, especially sensors that look outside: at street surfaces, and at obstacles in front, alongside, and behind the vehicle. These sensors include video cameras, radar and photoelectric, those capture and transmit a colossal amount of data in real time for the ECUs within the vehicle. In addition to the now familiar ABS, sensors may also adjust the vehicle's ride and traction mechatronic control. Another innovative technology is the ACC. A pulse *Doppler* radar system scans the road ahead and reduces the vehicle velocity as the vehicle approaches the one in front in order to modulate the preset distance between them. Even wheel-tyre pressure monitoring system may be in place to warn of unsafe wheel-tyre pressure [CROFT 2000].

An exemplary **adaptive cruise** (AC) BBW AWB dispulsion mechatronic control systems is shown in Figures 3.38 and 3.39 [CADENCE 2003].

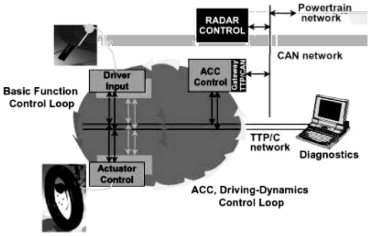


Fig. 3.38 AC BBW AWB dispulsion mechatronic control system [Renault; CADENCE 2003].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_32, © Springer Science+Business Media B.V. 2011

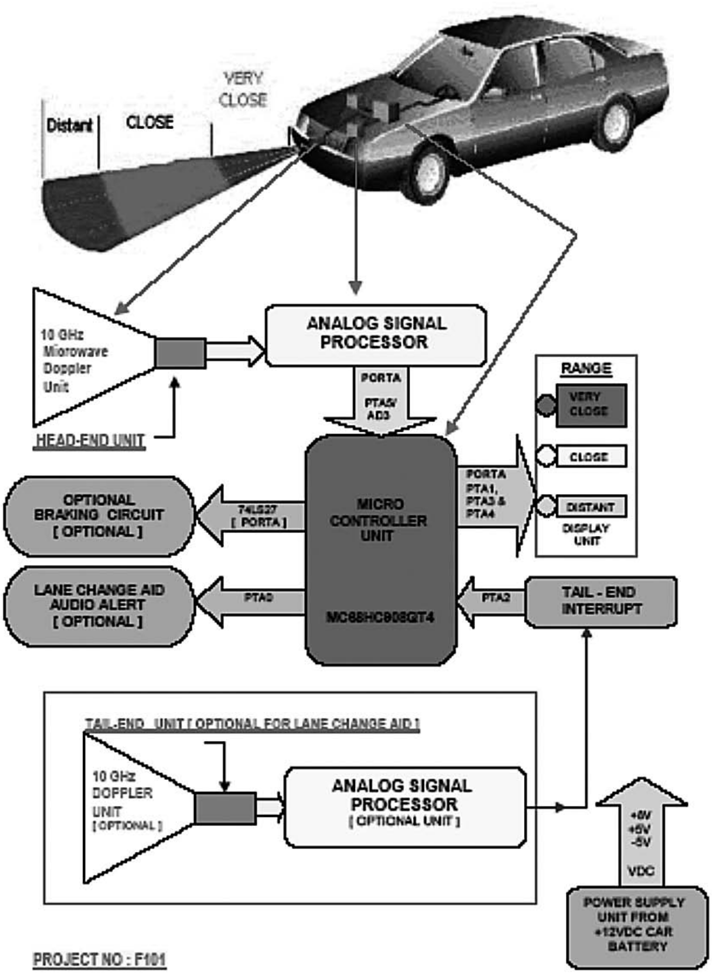


Fig. 3.39 AC BBW AWB dispulsion mechatronic control system [MOTOROLA 2003].

ACC is an extension of the existing cruise control feature that links together a forward obstacle detection system for monitoring traffic directly in front of the vehicle, the cruise control system (throttle valve), the braking system, and the driver's input as to the desired cruise-control set vehicle velocity. Identical criteria are used to determine the distance to the preceding vehicle.

The key objectives of ACC are improved traffic flow and increased driver comfort while reducing the driver's workload. Figure 3.40 shows the components and subsystems used to achieve ACC on a host vehicle [RILEY ET AL. 2000].

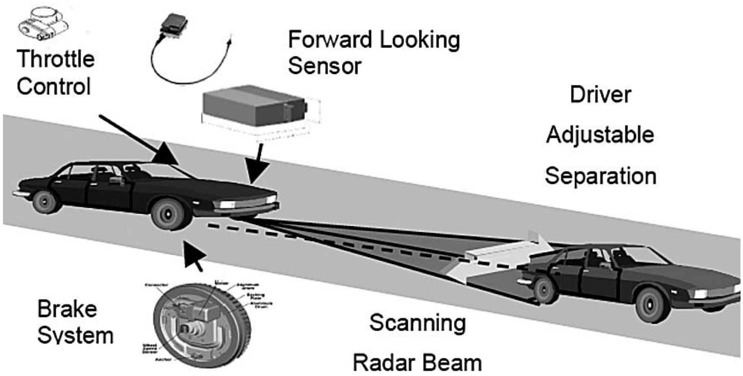


Fig. 3.40 The components and subsystems of the enhanced ACC BBW AWB dispulsion mechatronic control system [RILEY ET AL. 2000].

ACC technology is on the horizon as a convenience function especially intended to reduce the driver's workload. Considerations of moding ABS with ACC and TCS may be applied at the automotive vehicle level.

3.7.1 Fluidical Mechanisation

Figure 3.41 depicts the fluidical mechanisation of a mechatronically controlled AC BBW AWB dispulsion mechatronic control system capable of ABS, TCS and **vehicle stability enhancement** (VSE).

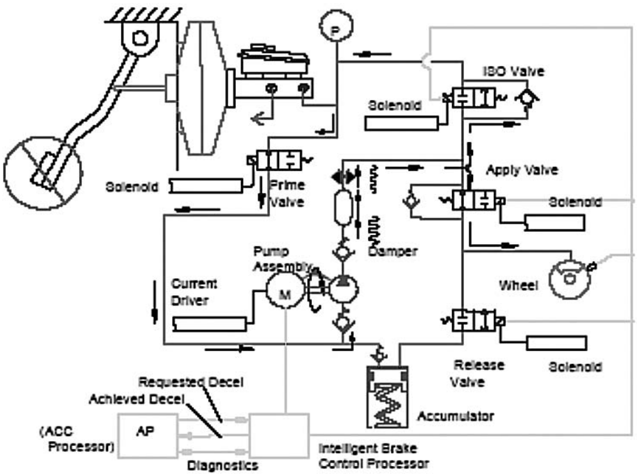


Fig. 3.41 Fluidical mechanisation [RILEY ET AL. 2000].

The system performs ACC auto-braking without driver input on the braking pedal. The ABS controller signals the E-M motor in the modulator to M-F pump brake fluid or air (gas) from the master cylinder into the wheel-braking fluidical lines through the prime solenoid fluidical valves that are opened by energising their electromagnet coils [RILEY ET AL. 2000]. The result is smooth and quiet vehicle deceleration. ACC auto-braking uses PWM-driven **variable isolation valves** (VIV) to regulate the brake fluid or air (gas) pressure level on the fluidical lines between the wheel brake corners and VIVs.

VIV technology provides the characteristic of throttling the braking flow or air through the orifice of the solenoid fluidic or pneumatic valve with extremely low-pressure jumps. The VIV provides an attractive alternative to the control of the solenoid fluidic valves where the applied voltage is proportional to fluid or air-flow. Secondly, VIV technology overcomes the limitations of conventional *'ON/OFF'*-style solenoid fluidic valves available in the current industrial market. Additional key features of the VIV hardware are to match the deceleration control requirements on quiet, smooth, and uniform auto-braking for ACC, conventional TCS, and CA.

3.7.2 Fundamental ACC Functionality and Implementation

ACC requires driver input such as the desired cruising vehicle velocity and the desired following distance in terms of timed headway. Once the cruising vehicle velocity is selected and the trailing time (that is, low, medium, and high) is entered, the driver's input is complete.

The AC BBW AWB dispulsion mechatronic control system performs throttle-valve control that allows the vehicle to travel at a constant set value of vehicle velocity until one of three things occurs.

The three inputs that disrupt the AC BBW AWB dispulsion mechatronic control system are:

- ❖ Thr driver applies the brake pedal – ACC is deactivated;
- ❖ The driver increases vehicle velocity – ACC remains active, but the system may return to the previous (slower) set value of the vehicle velocity if a new cruising velocity is not set once the driver ceases to accelerate;
- ❖ The forward obstacle detection system senses a slower vehicle in the path of the host vehicle.

Input number three poses a challenge to the AC BBW AWB dispulsion mechatronic control system to maintain the desired following distance.

When a slower automotive vehicle is detected, the AC BBW AWB dispulsion mechatronic control system evaluates the velocity of the leading vehicle through issuing throttle valve and/or brake commands.

Throttle-valve control for deceleration is typically performed when deceleration commands from the ACC processor are less than 0.1 *G*, but this is heavily dependent upon the size of the host vehicle and the type of ECE or ICE.

Once the slower moving vehicle is detected and a deceleration command is sent from the ACC processor to the AC BBW AWB dispulsion mechatronic control system via a CAN bus, the latter attempts to achieve the commanded deceleration.

The AC BBW AWB dispulsion mechatronic control system's reaction to the deceleration command is dependent upon the mechatronic control algorithm used and the vehicle hardware used for implementation.

Deceleration control for ACC braking is typically performed using *'smart'* booster, BBW AWB dispulsion, or an ABS modulator.

Deceleration control using a *'smart'* booster is performed, thereby regulating the vacuum inside the booster.

Sending a brake command to the actuator at each wheel that applies braking to the wheels, it performs deceleration control by implementing ABW BBW dispulsion.

Deceleration control using the modulator is done by regulation of wheel fluid or air pressure through solenoid fluidical valves within the modulator.

Modulator-based deceleration control may be selected because of the VIV technology. Smooth and quiet vehicle deceleration is achieved as a result of successful VIV control.

The metrics of success may be the cost of implementing the AC BBW AWB dispulsion mechatronic control system, the vibration that the steering wheel and body of the automotive vehicle may be subject to when performing deceleration, and the noise level of the system when performing deceleration.

Using VIV results in a very quiet system because the fluid or air pressure may be built-up and released in a gradual manner.

Large, abrupt fluid or air pressure changes may cause vibration of the brake fluidical lines that may ultimately cause vibration in the steering column and the vehicle's body. Such vibrations cause the system to be noisy. And most importantly, if the vehicle to be equipped with ACC already has an ABS modulator, then the modulator-based deceleration control comes at the cost of no additional hardware when the ABS modulator is equipped with vies.

Replacement or the addition of hardware in order to implement other methods is very costly [RILEY ET AL. 2000].

3.7.3 Stop-and-Go

The **stop-and-go** (S&G) features added to the basic ACC algorithm address traffic jam situations that require low-velocity cruising, braking to a stop; and gradual release of brakes once the traffic flow resumes.

The original ACC control area encompasses vehicle control over the conventional cruise control values of the vehicle velocity.

Figure 3.42 shows the additional vehicle velocity (speed) ranges required for S&G functionality [RILEY ET AL. 2000].

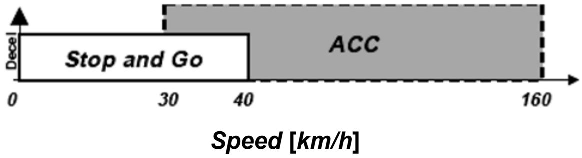


Fig. 3.42 Vehicle velocity (speed) ranges required for stop-and-go functionality [RILEY ET AL. 2000].

Some overlap in functionality is expected to provide a seamless S&G AC BBW AWB dispulsion mechatronic control system.

The features associated with the use of ACC in traffic jams requires closed loop control of the actual values of the vehicle velocity down to 0 km/h, zero vehicle velocity brake application (brake hold), and smooth fluid or air pressure release for transitions from stop to go.

Rapid development and verification of the additional control algorithm are required for use of a **rapid prototyping system** (RPS). The RPS allows for **hardware-in-the-loop simulation** (HILS) with real S&G AC BBW AWB dispulsion mechatronic control system and hardware on the vehicle [RILEY ET AL. 2000].

The addition of S&G to the ACC control algorithm is a step closer to the vision of an autonomous vehicle. While the features of S&G increase driver convenience and reduce the work-load, they are not a suitable for an attentive driver.

3.8 BBW AWB Advanced Technology

Taking advanced braking systems to the next level, some automotive R&D institutions have announced production contracts with major automotive vehicle manufacturers for **electro-fluido-mechanical braking** (EFMB) and **electro-pneumo-mechanical braking** (EPMB).

Additionally, some automotive R&D institutions have development contracts with leading vehicle manufacturers to develop regenerative braking based on an EFMB or EPMB BBW AWB dispulsion mechatronic control system. At the forefront of these dispulsion mechatronic control systems development, some automotive R&D institutions are keen to demonstrate its substantial capability in the field.

To RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis mechatronic control advanced technology forward, it is essential that organisations have expertise in braking mechatronics, in three areas: braking mechanics, electronics, and software development. Automotive R&D institutions are strong in braking mechatronics, in each of these areas and are able to take the knowledge of conventional braking systems and apply it to BBW AWB dispulsion technology development. This technology improves stopping distances by up to 5% and delivers significant improvements in the comfort of brake pedal feel. Moreover, it opens up possibilities in terms of VSC (Fig. 3.43), **integrated vehicle control** (IVC) systems, and the next generation of **adaptive cruise control** (ACC) features [TÖRNGREN 2005].

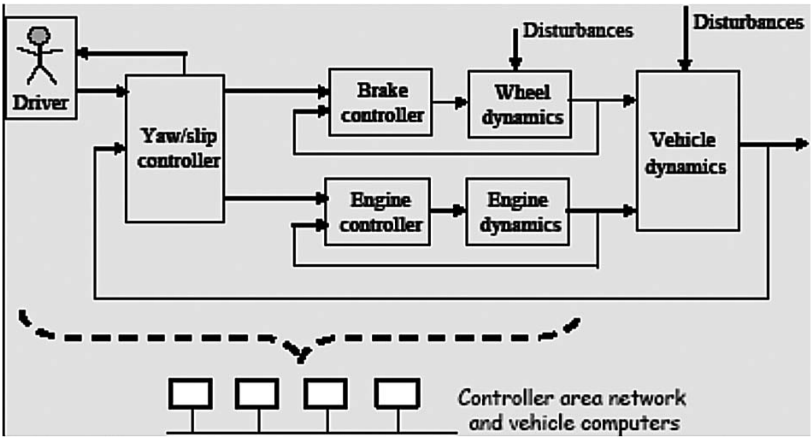


Fig. 3.43 An exemplary application of the vehicle stability control (VSC) [TÖRNGREN 2005].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_33, © Springer Science+Business Media B.V. 2011

Beyond EFMB or EPMB, the introduction of EMB may deliver additional substantial environmental benefits due to the elimination of brake fluid or air as well as other inherent benefits for vehicle manufacturers and customers. In its first generation, BBW AWB dispulsion may complement today FMB systems.

Considered as EFMB or EPMB, the conventional **brake booster** (BB) is replaced with a BPU simulator and the ECE or ICE compartment contains an EFM ECU that generates the required braking energy. The **pedal simulator** (PS) communicates the driver's braking demand to the modulator and a closed-loop fluid or air pressure control measures the pressure at the wheels every millisecond. All brake applications are carried out by the system and not by the pressure of the driver's foot on the pedal. In case of electrical failure, the system is equipped with a secondary FMB mode that functions in the same manner as today conventional FMB or PMB systems. Some automotive R&D institutions introduced this technology to its first customer in 2003 [TRW INC. 2004].

Looking further ahead, the final generation of BBW AWB dispulsion, in the form of EMB, sees the end of F-M (H-M and/or P-M) links. These fluidical links are replaced by a central, **fault-tolerant** (FT) ECU connected to actuators on each wheel that are controlled by the BPU. The driver's brake foot-pedal effort no longer affects brake performance.

The BPU measures the pedal position, calculates brake demand, and applies it to each wheel actuator. This next step in BBW AWB dispulsion technology, to have a system with no F-M (H-M and/or P-M) backup, may require a higher level of integrity than contemporary 12 V_{DC} **energy-and-information networks** (E&IN).

Forty-two volt (42 V_{DC}) E&IN architecture with FT networks is the key to delivering automotive manufacturers' long-term goal of complete BBW AWB dispulsion mechatronic control systems. It is anticipated that production of an EMB system would not be before 2015 in the automotive industry. As well as development of BBW AWB dispulsion mechatronic control systems for the mass automotive vehicle market, automotive scientists and engineers are making substantial progress in developing EFMB applications for HEVs to support measures to reduce emissions and support vehicle makers in meeting the **North American Corporate Average Fuel Economy** (CAFE) regulations. CAFE standards require each vehicle manufacturer to meet a sales-weighted average fuel economy level for the fleets of new automotive vehicles and light trucks it sells each year. A regenerative braking system has already been used for a breakthrough proof-of-concept automotive vehicle for major vehicle manufacturers, and some automotive R&D institutions have another development contract with some vehicle manufacturers for a regenerative EFMB or EPMB BBW AWB dispulsion mechatronic control system. Regenerative braking involves energy being captured during the braking process that is used to recharge the vehicle's energy storage devices.

With the introduction of EFMB or EPMB, there may be communication between the generator and the brake system to ensure the most efficient application of energy for the braking process.

With a complete portfolio of competencies in EFMB, EPMB, and EMB, some automotive R&D institutions are well placed to support vehicle manufacturers with exciting innovative technologies.

In an E-M BBW AWB dispulsion mechatronic control system, the EMB replaces the conventional fluidical linkage between the brake foot pedal and the wheels with an ECU interface.

It is composed of mechanically decoupled sets of E-M actuators and controllers connected through multiplexed in-vehicle computer E&INs, which are normally TTP or FlexRay™ bus systems. To achieve the required level of fault tolerance, an E-M BBW AWB dispulsion mechatronic control system must be designed as a redundant, distributed system composed of a number of **fault-tolerant** (FT) units connected by a reliable real time communication system. It does not require oily-fluid or air (gas) to store or load at the assembly plant and permits more modular assembly, thus reducing the number of parts used during production.

Figure 3.44 shows the three major parts of such a mechatronic control system: the foot pedal with its force emulator, the controller, and the wheel together with the brake actuator [LANGENWALTER AND KELLY 2003].

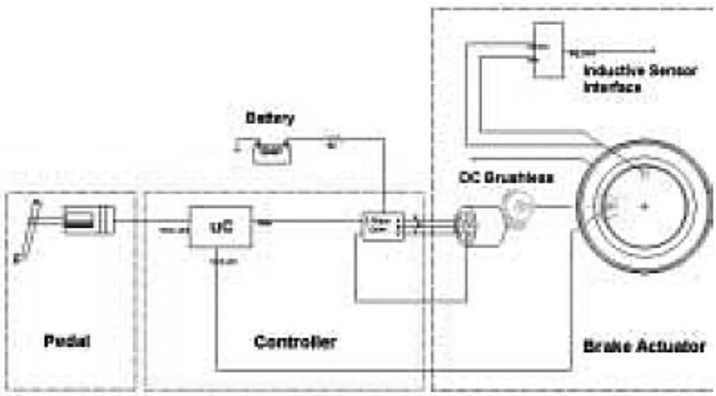


Fig. 3.44 Three major parts of the EMB system [LANGENWALTER AND KELLY 2003].

The brake foot pedal contains sensors to provide information about the requested brake force. Depending on the current state of the vehicle and wheel, the controller determines the actual brake force at the wheel. A rotary brushless AC-DC-AC macrocommutator brake-force-actuator motor may be regulated by the controller and is driven by a three-phase drive.

The E-M motor shaft is then connected via a worm gear/rack and pinion combination or a lead screw drive to the brake piston and calliper assembly. Piezoelectric force and inductive sensors, respectively, provide feedback of the actual brake force and wheel velocity to the controller. Often referred to as an E-M BBW AWB dispulsion mechatronic control system, it enables many innovative driver interfaces and performance enhancements. Overall, it offers a wide flexibility in the tuning of automotive vehicles for safety and performance. While it promises many benefits, they must be carefully designed, analysed, and verified for their functionality. While design variations affect performance attributes, costs, etc., classic architectures of E-M BBW AWB dispulsion mechatronic control systems have been proposed for either single or dual voltage E&INs.

Figure 3.45 illustrates 'BBW AWB' architecture with redundant CH-E/ E-CH storage batteries for the EMBs [LANGENWALTER AND KELLY 2003].

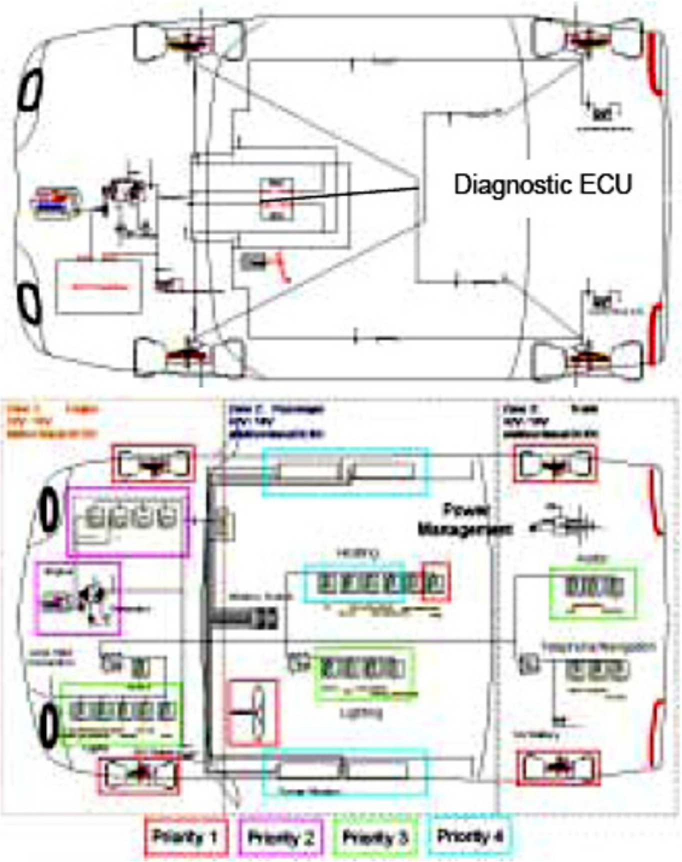


Fig. 3.45 EMB architecture and redundant power distribution system with load priorities [LANGENWALTER AND KELLY 2003].

The dual voltage bus shows both 42 V_{DC} and 14 V_{DC} bus implementation. The electrical housekeeping on the busses includes, among other things, various heaters and fans, lights, an audio system, navigation, EMB, and vehicle velocity dependent loads such as **electro-mechanical valve train** (EMVT) and ignition. Note in this particular application, the CH-E/E-CH storage battery, fuses, wires, and M-E generators are physically modelled with dynamic thermal effects. For optimal load management, it is important to test different power management algorithms to ensure that the essential loads get sufficient power in the event of a low state of charge of the CH-E/E-CH storage batteries. To prevent this, the loads are grouped into different priorities as illustrated in Figure 3.45. Depending on their priority, the loads get reduced or switched off completely by the power management to maintain essential functionality such as braking the vehicle. For the proof-of-concept BBW AWB dispulsion development, automotive scientists and engineers are using, for example, one and only one **micro-auto-box** (MAB) per wheel as a wheel ECU and an **auto-box** (AB) as the central ECU, as shown in Figure 3.46 [TRW INC. 2004]. For instance, the DSPACE architecture makes it easy to observe all the system components, using standardised software under real-time conditions on a central system PC.

(a)
(b)
(c)

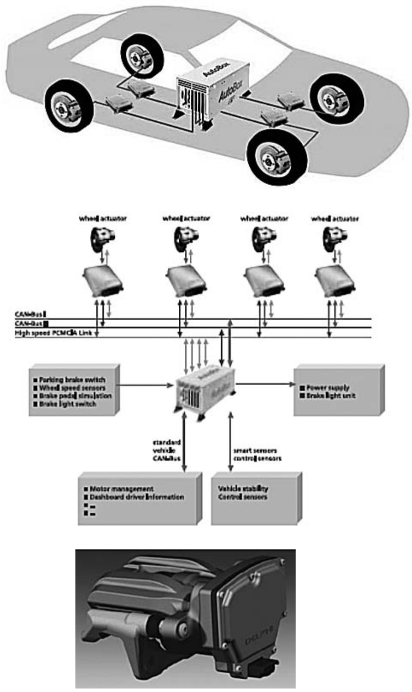


Fig. 3.46 One MAB per wheel and an AB as the central ECU (a), as well as the set-up in detail of the second-generation BBW AWB dispulsion mechatronic control system (b), and an outlook of the EMB (c) [TRW INC. – DSPACE GMBH]

In view of the facts that function development is carried out exclusively, for example by Matlab/Simulink/Stateflow and the DSPACE hardware platform, code generation may be automated. This considerably speeds up function development.

The integration of simulation blocks (simulation of the remaining function components and the actuator/sensor units) in the Simulink/Stateflow models makes start-up easy to perform.

As a result, most of the everyday start-up problems can be detected early on, and putting the vehicle into operation is astonishingly uncomplicated and speedy.

Because only a reduced number of test vehicles are necessary, a huge cost reduction is possible and one can concentrate on the main task, control design.

The work is well accepted by automotive customers, since they are familiar with the EMB assemblies and software tools used [TRW INC. 2004].

EMB BBW AWB dispulsion mechatronic control systems, replace conventional *'wet'* FMB or *'dry'* PMB systems with a completely *'dry'* EMB system. This occurs by replacing conventional FM or PM actuators with E-M motor-driven units. This move to mechatronic control eliminates many of the manufacturing, maintenance, and environmental concerns associated with FMB or PMB systems.

Because there is no M-M, F-M (H-M and/or P-M) back-up system, reliability is critical and the EMB system must be fault-tolerant. Implementing EMB requires features such as a dependable power supply, **fault-tolerant** (FT) communication protocols, for example TTCAN and FlexRay™, and some level of hardware redundancy.

As in EFB BBW AWB dispulsion mechatronic control systems, EMB one is designed to improve connectivity with other vehicle systems, thus enabling simpler integration of such higher-level functions as TCS and VSC systems. This integration may vary from embedding the function within the EMB system, as with ABS, to interfacing to these additional systems utilising communication links.

Both EFMB and EMB BBW AWB dispulsion mechatronic control systems offer the advantage of eliminating the large vacuum booster found in conventional FMB or PMB systems.

Along with reducing the dilemma of working with increasingly tighter space in the engine bay, this elimination helps simplify production of right- and left-hand drive vehicle variants.

When compared to those of EFMB, EMB systems offer decreased flexibility for the placement of components by totally eliminating the FMB system.

EMB systems represent a complete change in requirements from previous FMB and EFMB braking systems. The processing components must be networked using high-reliability bus protocols that ensure comprehensive fault tolerance as a major aspect of system design.

The application of E-M actuators means additional requirements that include E-M motor control operation within an onboard 42 V_{DC} **electrical energy source** (EES) and high temperature and high density to the mechatronic components.

In addition to supporting existing communications standards such as CAN and K-line, EMB systems require the implementation of deterministic, **time-triggered communications** (TTC), for example such as those available with FlexRay, to assist in providing the required system fault tolerance.

The EMB nodes may not need to be individually fault tolerant, but they help to provide fail-safe operation and rely on a high level of fault detection by the electronic components.

These innovative system requirements must be met by using high-end components at very competitive prices to replace established, cost-effective technology, while maintaining strict adherence to the automotive qualification.

Delivering large current requirements to stop a large **smart utility vehicle** (SUV) may cause limited adoption at first. The first implementation may be on small automotive vehicle platforms.

A multiple **micro-controller unit** (MCU) EMB system requires components such as high-performance MCUs (for example, from the MPC500 family) for the vehicle control node, mid-range performance **digital signal processors** (DSP) or MPC500 microcontrollers for the wheel nodes, and HCS12 devices for brake pedal nodes.

MCU manufacturers have vast experience in developing many of the specific aspects required for the implementation of EMB systems. They have a strong background in **fault-tolerant** (FT) communications from the previous development of fail-safe microcontrollers, braking specific modules such as the wheel speed timer, a dedicated E-M motor control lab, and a software centre that develops drivers, tools, and operating systems. They are also core team members in the FlexRay consortium and have been instrumental in the development of this protocol. With this strong foundation, they have the knowledge to develop the right solutions in partnership with customers.

A BBW AWB dispulsion mechatronic control system uses electrical connections to connect the four braking '*corners*' to the brake-pedal and to each other. This system provides better control of brake pedal stiffness, traction control, vehicle stability, and brake-force distribution.

A BBW AWB dispulsion mechatronic control system requires high-performance control architecture, for example, such as the one offered by the MPC500/MPC5500 microcontroller family from Freescale Semiconductor Inc., shown in Figure 3.47 [FREESCALE 2004, 2005A].

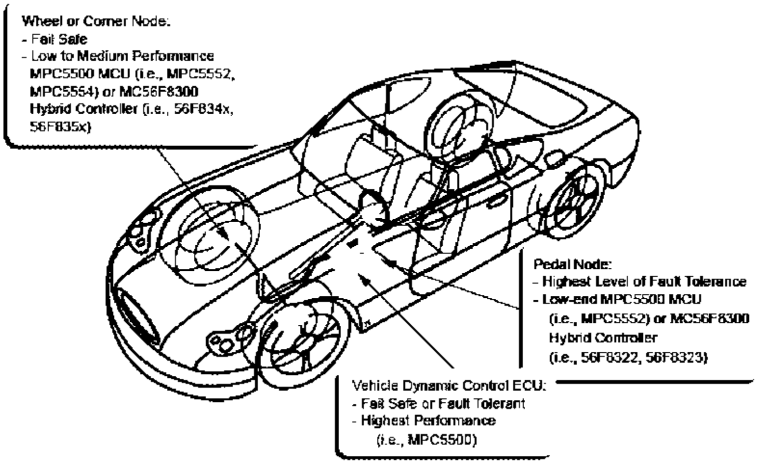


Fig. 3.47 Structural and functional block diagram
of the BBW AWB dispulsion mechatronic control system
[Freescale Semiconductor Inc. – Flex Ray™; FREESCALE 2004, 2005B].

Furthermore, high-speed protocol networks that are deterministic, fault-tolerant, and capable of supporting distributed control systems are necessary. FlexRay provides these capabilities and more [FREESCALE 2004, 2005A].

Consequently, a change is afoot, and the FlexRay is an innovative communications protocol designed for the high data transmission rates required by advanced automotive mechatronic control systems. These are the same mechatronic control systems that, in the next few years, are expected to replace nearly every fluidical or pneumatical line and mechanical cable in most recent automotive vehicles with electrical or optical wire-based networks, sensors, and actuators [FREESCALE 2004, 2005A].

Most recently, braking systems have evolved from FMB or PMB systems to hybrid EFMB or EPMB BBW AWB dispulsion mechatronic control systems. Actually, current braking systems are mostly *'wet'* EFMB or EPMB BBW AWB dispulsion mechatronic control systems, slowly evolving into *'dry'* EMB BBW AWB dispulsion mechatronic control systems. These systems consist of three communications *'protocol'*: F-M or E-M (sensors on each wheel for ABS or ESP), and in at least 80% of automotive vehicles, M-M (a parking brake cable).

In the not-too-distant future, sensors on the vehicle might detect a panic situation – a stopped object, whether another vehicle, a tree, or a person – approaching at a rapid rate while drivers are twiddling with the radio.

Intelligent, mechatronically based *'anticipatory braking'* might *'decide'* to initiate a 0.2 G stop to get the driver's attention – and to help stave off a major collision. Doing this is difficult.

Keeping brake pressure balanced on all brake pads in an automotive vehicle is so much easier in a system of sensors, actuators, servo, mechatronic control, and software [FLEXRAY™ 2003].

Basic features of the FlexRay:

- ❖ Scalable synchronous and asynchronous data transmission;
- ❖ High net data rate of 5 Mbit/s; gross data rate approximately 10 Mbit/s;
- ❖ Deterministic data transmission, guaranteed message latency and message jitter;
- ❖ Support of redundant transmission channels;
- ❖ Flexible allocation of bandwidth to individual nodes;
- ❖ Configurable number of sending slots per node and cycle;
- ❖ Fault-tolerant and time triggered service implemented in hardware;
- ❖ Fast error detection and signalling;
- ❖ Support of a fault-tolerant synchronised global time base;
- ❖ Error containment on the physical layer through an independent *'Bus Guardian'*;
- ❖ Arbitration-free transmission;
- ❖ Support of optical and electrical physical layer;
- ❖ Support for bus, star, and multiple star topologies.

Summing up, FlexRay is an open, common, scalable electronic architecture for automotive applications. An example of backbone architecture with FlexRay is shown in Figure 3.48 [FLEXRAY™ 2003]. It may operate in single- or dual-channel mode, providing redundancy where necessary. It allows both synchronous and asynchronous data transmissions.

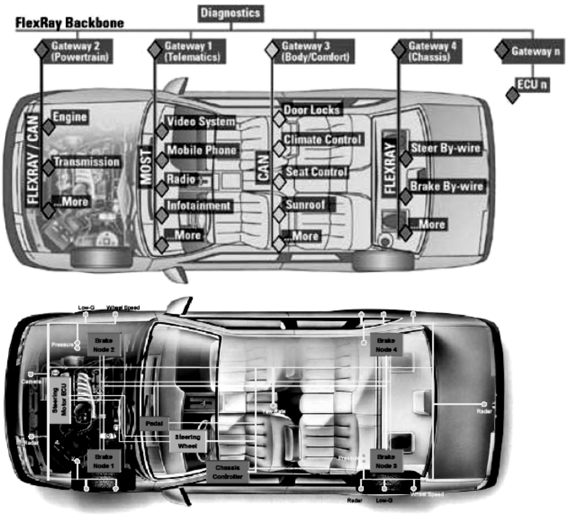


Fig. 3.48 Example of backbone architecture with FlexRay™ [FlexRay™ Consortium; FLEXRAY™ 2003].

With the former, other nodes on the network receive time-triggered messages in a predefined latency time.

With the latter, messages get to their destinations quickly or slowly, depending on their priority.

Currently, FlexRay™ may handle communications at 10 Mbit/s [FLEXRAY™ 2003].

For instance, the physical system that may be modelled is a simple five-node BBW AWB propulsion mechatronic control system. It contains a brake pedal node that outputs, for example, a single value from 1 to 255, linearly correlated to the position of the brake pedal [FRANCE AND CURTIS 1998].

This value is propagated to the four brake nodes that then calculate the required force and apply it to the wheel under their control.

The brake nodes also output the current value of the brake force being applied to the wheel.

A value of 0 is used to indicate a failure mode within the brake node, and that no brake force is being applied to the wheel.

Figure 3.49 depicts a structural and functional block diagram of the simple five nodes BBW AWB propulsion mechatronic control system that may be simulated [FRANCE AND CURTIS 1998].

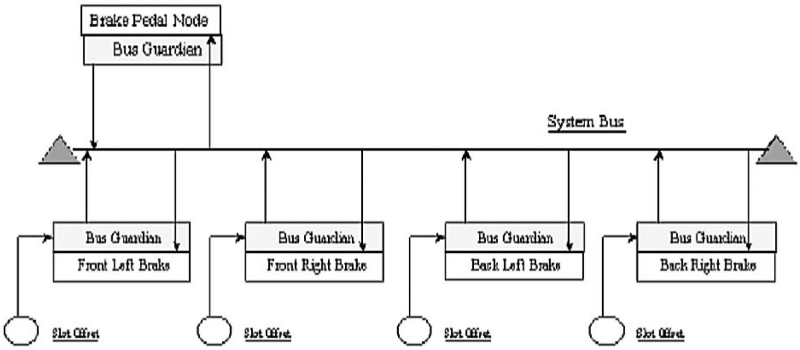


Fig. 3.49 Structural and functional block diagram depicting a physical model of the TTP/C-based simple five node BBW AWB dispulsion mechatronic control system [FRANCE AND CURTIS 1998].

The semantics used are as usual, objects represented by blocks, arrows depict methods, and so on.

The physical model of the simple five-node BBW AWB dispulsion mechatronic control system may be designed to accurately model the operating characteristics of the physical system.

Figure 3.50 depicts the order of the nodes' respective message slots as implemented in the simple five-node BBW AWB dispulsion mechatronic control system [FRANCE AND CURTIS 1998].

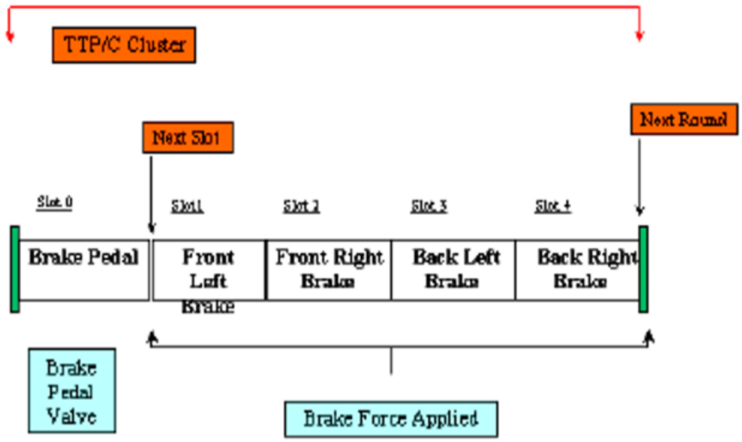


Fig. 3.50 Order of TTP message slots in the simulation of a TTP/C-based simple five-node BBW AWB dispulsion mechatronic control system [FRANCE AND CURTIS 1998].

The time-physical model used in a simulation is discrete time, where each unit of advancement is a single message slot in the cluster cycle. Because the time-slot management is done only in the schedule, each of the nodes run once during each slot and is not allowed to advance time. However, only the node assigned to a given time slot is allowed to send a value, a characteristic enforced by each node's **bus guardian** (BG). This performs management of schedules and data independently from the **communication controller** (CC).

Additionally, the sending node is scheduled first, as the physical model is faithful to the concept of state variables used in the TTP/C communication physical model.

The only major departure from a TTP/C actual, simple five-node BBW AWB dispulsion mechatronic control system that may be identified is that the physical model is single-threaded.

In a real, simple five-node BBW AWB dispulsion mechatronic control system, each node would be running simultaneously. It results in variance, which is how some faults would manifest if the TPP/C hardware failed.

In particular, a babbling idiot node would deadlock a single-threaded system if the bus guardian logic failed. One is chosen to create an incorrect time slot transmission as an application flaw, perhaps by a discrepancy between the **message description list** (MEDL) values and the nodes' perceived current time slot value. This fault is modelled correctly at the bus level.

The result of simulation experiment is that the physical model performed as expected in both the normal and error cases.

The error case result is shown in Figure 3.51, as it is the more interesting of the two [FRANCE AND CURTIS 1998].

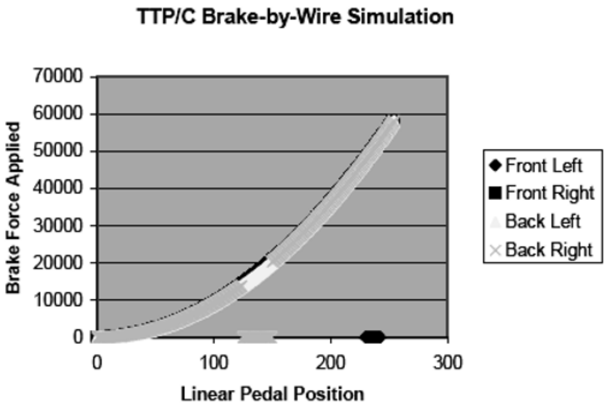


Fig. 3.51 Results of brake fault injection for back right and front right wheels [FRANCE AND CURTIS 1998].

Observe that when the time slot comparison is corrupted by introducing a static offset, the bus guardian in the disturbed node does not allow transmission outside of its retime slot. This error may be introduced in the back right wheel during time slots 125 – 149, and in the front left wheel during time slots 230 –242 [FRANCE AND CURTIS 1998].

Hardware-in-the-loop simulation (HILS) is a scheme that incorporates hardware components of primary concern in the numerical simulation environment. Due to its advantages over actual vehicle test and pure simulation, HILS is being widely accepted in the automotive industry as a test bench for designing, evaluating, and benchmarking vehicle control units. Developed in this study is a HILS system for the EFMB BBW AWB dispulsion mechatronic control system. The system includes a high-pressure generator and a fluidical valve mechatronic control system that independently modulates the brake pressures at four wheels. EFMB control logic and VDC logic were tested in the HILS system. Test results under various driving conditions are presented in [PARK AND HEO 2004].

AIDERMARK ET AL. 2002 present an experimental evaluation of a BBW AWB application that tolerates transient faults by temporal error masking. A specially designed real-time kernel that masks errors by triple time-redundant execution and voting executes the application on a fail-stop computer node. The objective is to reduce the number of node failures by masking errors at the computer node level. The real-time kernel always executes the application twice to detect errors and ensures that a fail-stop failure occurs if there is not enough CPU time available for a third execution and voting.

Fault injection experiments show that temporal error masking reduced the number of fail-stop failures by 42% compared to executing the brake-by-wire task without time redundancy.

BBW AWB dispulsion mechatronic control systems partly or completely replace the FMB system in an automotive vehicle with a mechatronic EMB system. These systems are safety critical. They must also be fault tolerant and have a dependable real-time performance. One communication protocol that is developed to meet these requirements is termed **time triggered protocol class C** (TTP/C). It is a protocol where all operations are initiated and scheduled in advance.

AIDERMARK ET AL. 2002 concentrate on the fault tolerant and the fault detection aspects. Also the TTP/C concept with its software development environment has been evaluated. Using TTP/C as effectively as possible requires that the developer has carefully planned the implementation of the system. R&D work with the TTP/C software development tools may be made easier when more that is known in advance about the system. A more detailed documentation than presently available of how to use the TTP/C tools would also facilitate the work.

LEY AND GRÜNBACHER 2002 describe the design of a **very large scale integration** (VLSI) communication controller for the TTP/C. It is an emerging communication protocol for **fault-tolerant** (FT) real-time systems. Classic applications are safety-critical digital control systems such as RBW or XBW (DBW, BBW, ABW and SBW) as well as FBW. They applied a VdriverL-based design flow to implement digital standard cell logic, RAMs, flash memory and analogue cells into a 27 mm² chip using a 0.35µ CMOS technology. First fully tested manufacture samples are available and proved the design to be right thefirst time. At the 2004 **Society of Automotive Engineers** (SAE) World Congress in Detroit, out of more than 5000 innovations presented, the TTP controller IC was nominated as '*Top Product of the Year*'.

LYE AND. GRENACHE 2002 described the development and verification of software for an automotive BBW AWB dispulsion mechatronic control system. This is an innovative braking system without mechanical or fluidical (hydraulical) backup. The system is based on time-triggered communication architecture. The central control computer in this distributed system, called BBW manager is designed to tolerate any single failure. The software of this computer is subject to a set of safety-related requirements that must be verified.

Automotive scientists and engineers have developed the software using synchronous software components based on the synchronous language *ESTEREL*. Many safety properties have been verified successfully and the software has been integrated in a prototype BBW AWB dispulsion mechatronic control system in a proof-of-concept research automotive vehicle. Most serial communications protocols used in real-time embedded systems are based on an event-triggered method.

Research suggests that when highly dependable system operation is required, a time-triggered, **time-division multiple accesses** (TDMA) approach is a better solution.

Automotive scientists and engineers may discuss the differences between event-triggered and time-triggered systems, and may even explain the principles and architecture of the class C serial communications protocol, TTP/C.

The BBW AWB dispulsion mechatronic control system demands an exceptionally high level of fault-tolerance. As no M-M/F-M/P-M '*backup*' system is available in the event of a fault, the emphasis lies entirely on the distributed embedded system. The BBW ABW dispulsion mechatronic control system is used as an example to exemplify the concepts and principles of the serial communications system [LEY AND GRÜNBACHER 2002].

The protocol control data is stored in the TTP controller. The TTP system generates a global time base using common knowledge about when a node is supposed to send a message. The media access is based on a TDMA scheme and error detection is available at the receiver, based on the common knowledge of sending a message. Fault-tolerance is supported by means of active replication. For nodes that are required to have guaranteed continuous operation in the presence of a fault, the node is replicated with an identical node. The redundant node can also transmit information on the bus in a different time slot. TTP/C also supports different modes of operation.

In many systems, different operating modes are often required to support functions like start-up, diagnostics, normal system behaviour, and maintenance. The packet includes bits to specify the operating mode and it may support sporadic messaging that could be required in the event of an emergency shutdown.

Time-versus event-triggered communication -- Time- and event-triggered systems operate very differently. For a time-triggered system, control signals are derived from the progression of time, whereas in event-triggered systems, control signals are derived from the occurrence of an event (an interruption). Time-triggered systems use state information that is obtained from the condition that exists for a defined period of time, like the value of a sensor reading. This differs from event information in that the event is an occurrence such as a sensor being triggered above or below a predefined threshold. Usually, state information is transmitted to several recipients who do not take in the message received. Event messages are usually deposited at a recipient who may store the information or may activate an interrupt service routine to take the appropriate action that is merited by the occurrence of the event.

In summary, time-triggered communication offers high predictability and easier testing for timeliness but it is inflexible in that additional nodes cannot be added to the system after it has been defined without '*apriori*' knowledge. Event-triggered communication systems are much more flexible with regard to adding nodes but are more unpredictable and require thorough testing to ensure that an overload condition does not occur when many events occur and the bus bandwidth is assaulted. For instance, TTP/C may be well suited for ABW BBW dispulsion mechatronic control systems. An example of BBW AWB dispulsion architecture is given in Figure 3.52 [BANNATYNE 1999B].

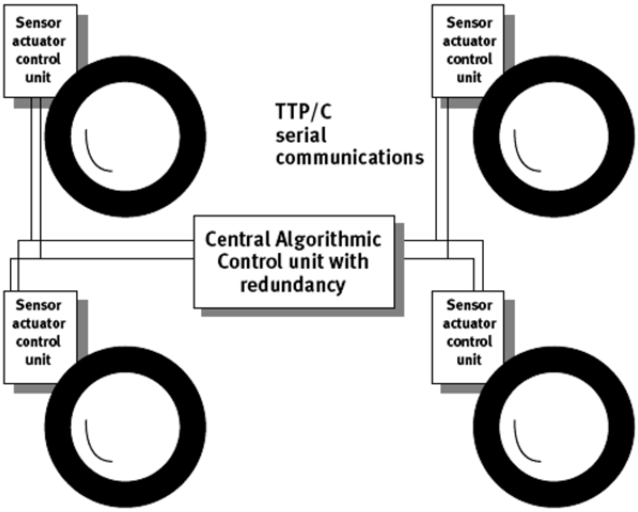


Fig. 3.52 EMB BBW AWB dispulsion mechatronic control system may one day replace today's standard FMB system [BANNATYNE 1999B].

There is little doubt that today's standard FMB system that uses fluidics may one day be replaced by fully EMB systems in the future, as the EMB BBW AWB dispulsion mechatronic control system's implementation has the following advantages [BANNATYNE 1999B]:

- ❖ No brake fluid or air, and so is ecologically friendly and has reduced maintenance;
- ❖ Lighter mass;
- ❖ Increased performance (brakes respond more quickly);
- ❖ Minimised brake wear (spreads load across wheels more evenly);
- ❖ More simplistic/faster assembly and testing (modular structure);
- ❖ More robust electrical interfacing;
- ❖ No mechanical linkages through bulkhead;
- ❖ Further mechatronically-controlled functions could be added with very little complexity;
- ❖ Consistent characteristics of pedal, constant travel;
- ❖ When a trailer is involved, brakes may respond simultaneously on both carriage and trailer;
- ❖ Significantly fewer parts than a fluidic (hydraulic) based system.

The system exemplifies wheel nodes that control actuation of braking E-M motors as well as providing the interface with the wheel speed sensors.

If an individual wheel unit was to fail, the vehicle could still be braked to a stop using the remaining three wheel units.

As a failure of this type would not be catastrophic, the wheel units would not be required to be replicated. The central control unit which runs the main control software has been replicated however, as has the brake pedal position sensor. TTP/C was not developed to compete with existing serial communications protocols, but to address a new category of systems that may emerge and have characteristics that cannot be satisfied by today's **event-triggered protocols/class-B** (ETP/B).

Both class B and class C systems may coexist in modern automotive vehicles with a communications gateway that may allow them to share information. As with other popular serial communications protocols, the TTP/C controller module is planned to be integrated along with other functions on microcontrollers or as a standalone entity that can be designed into nodes in a particular system. The required ECUs must be available and safe.

HEDENTZ AND BELSCHNER 1998 addressed a new automotive architecture approach using the **fault-tolerant** (FT) **time triggered protocol** (TTP) that has been designed for class C safety-related control applications, like BBW AWB dispulsion, due to the SAE classification [SAE J2056/1].

As an example, automotive scientists and engineers present this approach within a proof-of-concept BBW AWB automotive vehicle (case study) without mechanical backup. The intention of this architecture is to tolerate one arbitrary fault -- excepting faults of actuators -- without any effects of the brake performance. For this purpose, they use redundancy in communication (TTP) and electric components like sensors, actuators, and power supply [HEDENTZ AND BELSCHNER 1998].

In an automotive vehicle, a single fault means danger to the vehicle occupants. TTP/C detects communication errors by way of having a '*membership service*'. Every transmitting node sends, as part of its packet, this membership service information.

All other nodes in the system can check this information, ensuring that each node is functioning correctly. The basic principle of operation of the TTP/C system is very straightforward. TTP nodes exchange messages.

An embedded BBW AWB dispulsion mechatronic control system has to be exceptionally fault-tolerant. With the time-triggered method, automotive scientists and engineers can design such an innovative emerging category of systems, having demands that cannot be met using today's event-triggered class B communication protocols.

An automotive vehicle equipped with E-M disc brake actuators and a BBW AWB dispulsion mechatronic control system is shown in Figure 3.53 [HEDENETZ AND BELSCHNER 1998; SCHWARZ 1999; JOHANSEN ET AL. 2001A].

The mechatronic control system consists of five ECUs, one for each actuator with individual torque servo controllers and one central ECU where the four wheel-slip controllers run.

The BBW AWB dispulsion mechatronic control system is based on **time-triggered protocol** (TTP) communication between sensors, ECUs, and actuators. TTP is a synchronous communication protocol with high reliability [HEDENETZ AND BELSCHNER 1998; KOPETZ AND GRÜNSTEIDL 1994; JOHANSEN ET AL. 2001A].

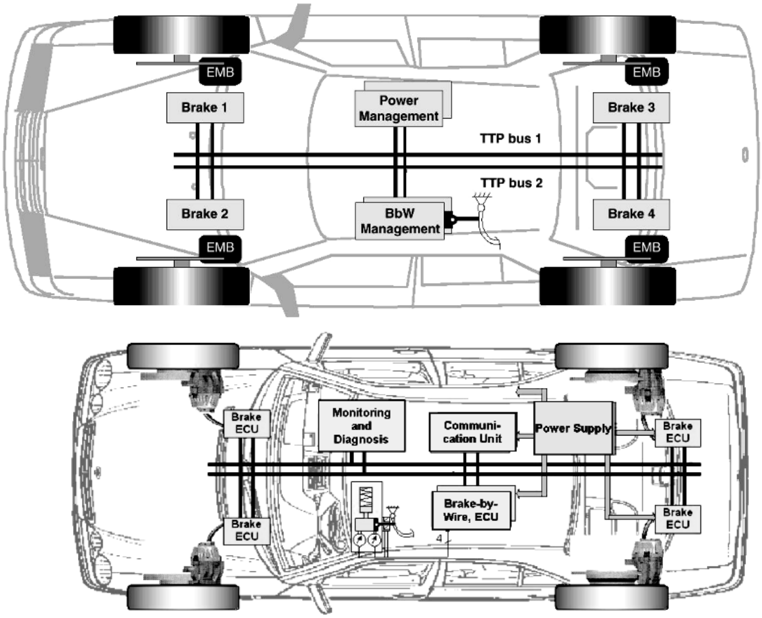


Fig. 3.53 Principle layouts of automotive vehicles
with a BBW AWB dispulsion mechatronic control system
[HEDENETZ AND BELSCHNER 1998 – Top image; JOHANSEN ET AL. 2001A – Bottom image].

The wheel-slip controllers are executed with sampling interval of T_s = 7 ms. The torque controllers on each wheel runs at a 2.33 ms sampling interval and the total delay due to synchronous communication is 7 ms on the actuator side. In addition, the E-M actuator has its internal dynamics that may be aproximated to sufficient accuracy for control design by the following first-order discrete-time linear model.

Both the actuator dynamics and the communications delays introduce fundamental limitations on the achievable performance and the minimum gain that may be tolerated. This section explains mechatronically-controlled BBW AWB dispulsion mechatronic control systems by first considering basic vehicle braking, as well as the wheel-tyre to on/off-road interface, vehicle dynamics, and conventional **fluido-mechanical brake** (FMB), **pneumo-mechanical brake** (PMB) or **electro-mechanical brake** (EMB) BBW AWB dispulsion mechatronic control system components, safety study, mechatronic control logic, and testing.

The section closes with a description of emerging BBW AWB dispulsion mechatronic control systems. Without difficulty and owing to applicability to the middle-of-the-road of automotive vehicles, FMB, PMB or EMB BBW AWB dispulsion mechatronic control systems as used on multi-axle or axle-less, non-articulated vehicles are fully described.

An exemplary structural and functional diagram of the BBW 4WB dispulsion mechatronic control system that is based on TTP is depicted in Figure 3.54 [HANSEN 2005].

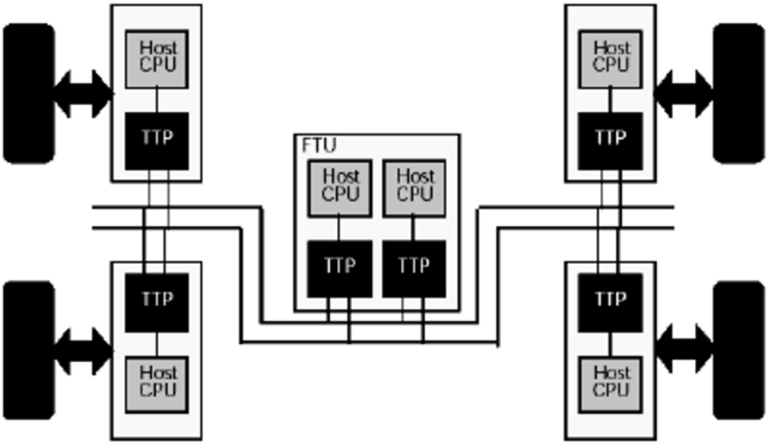


Fig. 3.54 Structural and functional diagram of a BBW 4WB dispulsion mechatronic control system that is based on TTP [HANSEN 2005].

These categories of BBW AWB dispulsion mechatronic control systems are used on passenger vehicles, and on light and medium trucks. It has been exposed that a driver's reaction to an emergency is to hit the brakes hard initially and then dwell before applying full brake force.

3.9 Electro-Mechanical Friction Disc, Ring and Drum Brakes

In an E-M BBW AWB conversion mechatronic control system, **electronic control units** (ECU) and electrical wiring replace fluidical lines and equipment and E-M actuators replace fluidic pistons. When the driver steps on the brake foot pedal, a computer sends information to a control box, which converts the electrical signals into an electrical command: the E-M actuators on the brake disc, ring or drum, replacing the fluidic pistons, press the discs against each other as in a conventional F-M BBW AWB conversion mechatronic control system. An *'EMB'* automotive vehicle simply means one that uses electricity to replace all other forms of onboard energy, especially fluidical. This offers a host of advantages in terms of size, mass, reliability, safety (by eliminating the risk of oily-fluid or air leaks and associated fire hazards), and operating/ maintenance costs (Fig. 3.55).

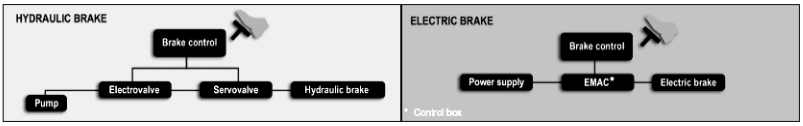


Fig. 3.55 Comparison between fluido-mechanical brake (FMB) and electro-mechanical brake (EMB) [MESSIER-BUGATTI 2005].

EMB technology enhances the efficiency of braking in general and of each individual brake, through faster response, simpler installation and easier diagnostics and maintenance. E-M friction disc, ring and drum brake mechatronic control technologies are gradually being developed and applied in **stability control systems** (SCS) systems and BBW AWB dispulsion mechatronic control systems based on the ABSs, and scientists and engineers have been working to develop an E-M friction disc, ring and drum brake mechatronic control system in terms of future BBW AWB dispulsion, to the practical application phase. Since the ABS entered the practical application phase in 1978, E-M friction disc, ring and drum brake mechatronic control functions have been expanding [FUJINAMI 2003].

Recently, many functions have been used in popular automotive vehicles, and some vehicle manufacturers have already started mass-producing ABSs and SCSs [UEKI ET AL. 2004]. Automotive scientists and engineers are working to develop high-performance and high-functioning mechatronic control systems for the future, and they expect these systems may lead to an RBW or XBW integrated unibody, space-chassis, skate-board-chassis or body-over -chassis mechatronic control system (see Fig. 3.56). The aim of this proof-of -concept automotive vehicle is to improve dynamics and layout [UEKI ET AL. 2004].

B.T. Fijalkowski, *Automotive Mechatronics: Operational and Practical Issues*,
Intelligent Systems, Control and Automation: Science and Engineering 47,
DOI 10.1007/978-94-007-0409-1_34,

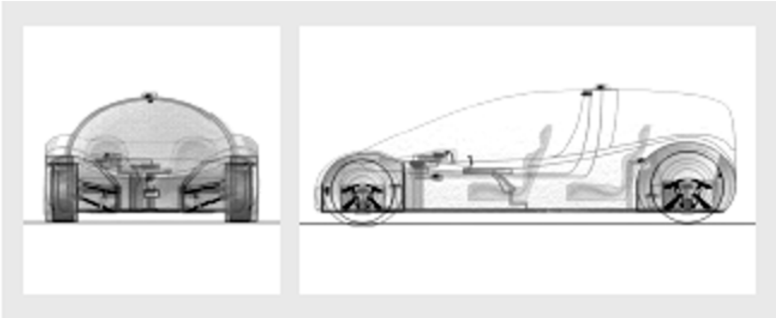


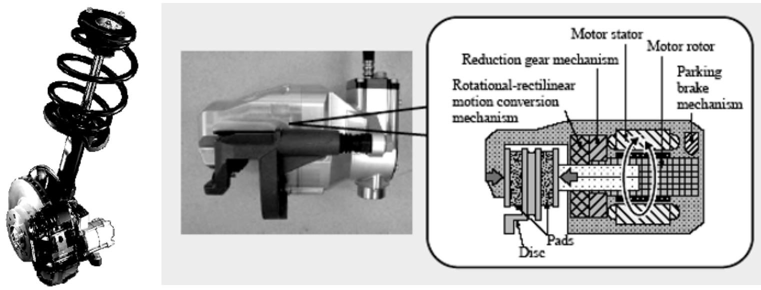
Fig. 3.56 Image of a proof-of-concept automotive vehicle equipped with the RBW or XBW integrated automotive vehicle's chassis-motion mechatronic control hypersystem and ITS [Hitachi Ltd.; UEKI ET AL. 2004].

Stability Control Systems (SCS) – SCSs have appeared as the next-generation ABSs. These are designed to control vehicle dynamics by regulating the brake force on each wheel and are the basis of RBW or XBW, in terms of future chassis technologies. Automotive vehicle manufacturers have developed master cylinder pressure sensorless systems that estimate fluid or air pressure by controlling vehicle dynamics through vehicle deceleration and wheel angular velocity. This reduces the size and cost of the SCSs [UEKI ET AL. 2004].

Electro-Mechanical (E-M) Braking Systems – Recently, vacuums generated in the ECE or ICE have been lacking or have been insufficient for improved fuel efficiency, typically in HEVs. For this reason, conventional braking systems using ECE or ICE vacuums are having difficulty in meeting the brake regulations. To overcome this problem, EFMB BBW AWB dispulsion mechatronic control systems are used as conventional brake functions along with all the brake control functions, including ABS, ESP, BA and autonomous intelligent ACC. It may also be possible to have additional functions such as electric parking braking. There are many other advantages to the innovative system:

- ❖ Less space is required in the ECE or ICE and the driver's compartment;
- ❖ It is more environmentally-friendly because no brake fluid or air is needed;
- ❖ It has a potentially better pedal feel;
- ❖ It can be operated by means of a joystick [HONDA 2001].

Recently, all the necessary technologies for the E-M braking system, as the example shown in Figure 3.57, namely conventional disc brake technologies, electrical and electronic technologies, communication technologies, and wire-harness technologies are available [ARNILD 2001; UEKI ET AL. 2004].



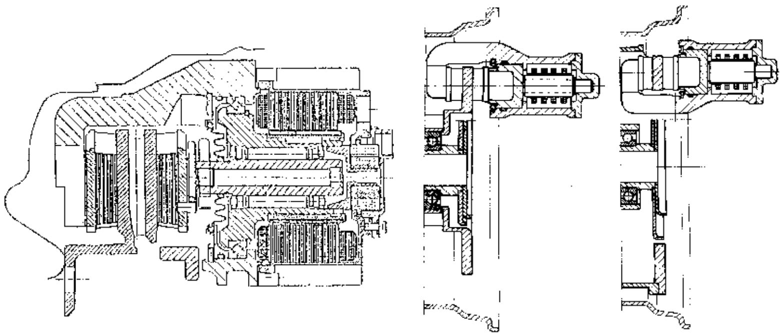
(a) (b)

Fig. 3.57 Outlook of the EMB (a) and EMB calliper (b)
[Siemens VDO Automotive (a), ARNOLD 2001; HITACHI LTD (B), UEKI ET AL. 2004].

A calliper regulates the deceleration of the disc fixed to the wheel by adjusting the thrust force acting on the pads via the reduction gear mechanism and the rotational-rectilinear motion conversion mechanism by controlling the current of the E-M motor stator and then the rotation of the E-M motor rotor. Considering manually-operated (muscular-energy) friction brakes, the brake pedal or lever may be connected to the actual brake either all-mechanically, by means of rods or wires, or electromechanically, by means of an electric current in a wire. Before considering these connections, however, one must deal with the E-M friction brake. The lower brake factor (that is a mechanical advantage that can be used in brakes to minimise the actuation effort required) of the E-M friction disc and ring brakes need a higher actuation effort, and development of integral parking brake features is required before friction disc and ring brakes can be used for all wheel positions. Automotive F-M, P-M and E-M friction drum brakes have seen common usage throughout the world [CHEW 1996], because of their high brake factor and easy incorporation of parking brake features. On the negative side, drum brakes may not be as consistent in torque performance as disc or ring brakes. The E-M friction disc, ring or drum brake is operated by direct current from a maintenance-free **application specific integrated matrixer** (ASIM) DC-DC or DC-AC macrocommutator in the rotary brushed DC-AC mechanocom-mutator IPM brake-force-actuator motor or short-stroke linear tubular brush-less DC-AC macrocommutator IPM brake-force-actuator motor's terminal box, respectively. DC and/or AC **pulse-width modulation** (PWM) operation provides smooth braking, a low closing brake application armature current, and the opportunity to vary the actuating time of the brake. Since braking takes place with runner displacement, the type of transmission may be selected at will, so that gearless runner, for example, can be used, and then may be set up in an arbitrary position without affecting the braking. For instance, easily replaceable long-life brake linings of sintered material permit a high operating intensity, limited only by the performance of the rotating brushed DC-AC mechanocommutator IPM brake-force-actuator motor [BALZ ET AL. 1996; WELLS AND MILLER 1993] or the short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically-excited brake-force-actuator motor [FIJALKOWSKI AND KROSNICKI 1994]. The braking torque is constantly adjustable and independent of wear. The braking effect is not diminished by water or dust. The E-M friction disc, ring or drum brake is free from oil and the operating brake-force-actuator motor's armature winding is not affected by moisture or vibration. A major advantage could also be in reducing the mass of the E-M friction brakes: discs, rings and drums can be made of silicon-carbide-reinforced aluminium instead of cast iron. Disengagement of the E-M friction disc, ring or drum brakes may be easily arranged electrically by connecting the brake's ASIM DC-AC macrocommutators to the automotive vehicles'onboard mains in front of the brake-force-actuator E-M motors.

3.9.1 Friction Disc and Ring Electro-Mechanical Brakes

With the friction disc or ring **electro-mechanical brake** (EMB), a silicon-carbide-reinforced aluminium disc, instead of a cast iron disc rotating with the wheel, is braked by indirect brake application voltage acting on a pair of self-adjusting friction pads lined with a friction material.



(a) (b) (c)

Fig. 3.58 Cross-section diagrams of a friction (a) disc EMB with a conventional rotary brushed DC-AC mechanocommutator brake-force-actuator motor, designed by *ITT Automotive* as well as (b) disc EMB and (c) ring EMB with the short-stroke linear tubular brushless DC-AC macrocommuator IPM brake-force-actuator motor, conceived and developed by the Cracow University of Technology's Automotive Mechatronics Institution, Poland [BALZ ET AL. 1996] -- (a); [FIJALKOWSKI AND KROSNICKI 1994] -- (b) and (c).

Figure 3.58 shows the layout of a friction (a) disc EMB with the conventional rotary brushed DC-AC mechanocommutator brake-force-actuator motor [BALZ ET AL. 1996], designed by ITT Automotive, as well as (b) disc EMB and (c) ring EMB with the short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically-excited brake-force-actuator motor [FIJALKOWSKI AND KROSNICKI 1994].

In these types of EMB, force is applied equally to both sides of the disc or ring rotor and braking action is achieved through the frictional action of in-board and outboard brake friction pads against the disc or ring rotor. The pads are contained within a calliper, shown in Figure 3.57, as is the wheel brake actuator. Although not a high-gain type of friction EMBs, disc or ring EMBs have the advantage of providing relatively linear braking with lower susceptibility to fading than friction drum EMBs. The E-M actuator is a disk EMB working on the calliper-principle. The E-M actuator's housing is connected firmly to the vehicle's steering knuckle. Both brake pads are fixed to the fist with one degree of freedom towards the active line of the clamping force.

Figure 3.59 shows an example of a prototype of an EMB and its mounting in the vehicle [PETERSEN 2003].

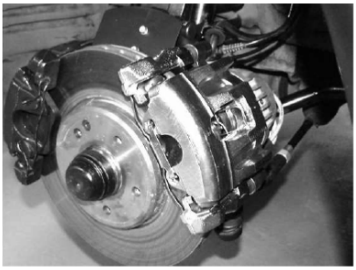


Fig. 3.59 Outlook of the exemplary EMB [PETERSEN 2003].

Figures 3.58a and 3.60 show a cross-section diagram of an example of a prototype of the EMB actuator E-M motor.

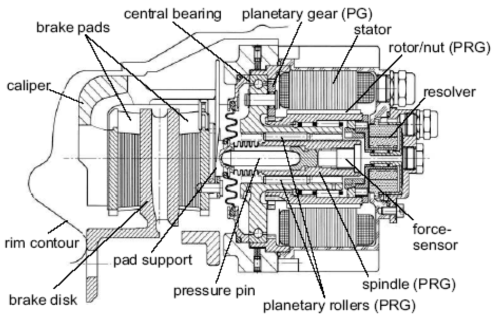


Fig. 3.60 Cross-section diagram of electro-mechanical brake (EMB) [LŰDEMANN 2002].

The E-M actuator is a conventional rotary brushless DC-AC mechano-commutator brake-force-actuator motor. The rotor gear forms the sun wheel of the planetary gear at the pad-sided end. The planet wheels of the planetary gear are in mesh with the internal-geared wheel, bolted in the brake cabinet, and power the planet carrier.

A planetary roller gear transforms the rotary motion into a translatory motion. The gear's spindle is hollow and contains a force measurement device as well as a pressure pin for the decoupling of rotary movements acting on the spindle. When activating the brake, the drive end brakepad may be moved through the pad support, whereas the pressure pin and the force sensor may be shifted towards the brake disc, caused by the spindle's motion [LŰDEMANN 2002].

The physical model of the EMB consists of a model of an E-M motor and a gearbox that transforms the rotary movement into a translatory movement. A non-linear characteristic for the conversion of the movement into a force, as well a linear friction physical model, is taken into account.

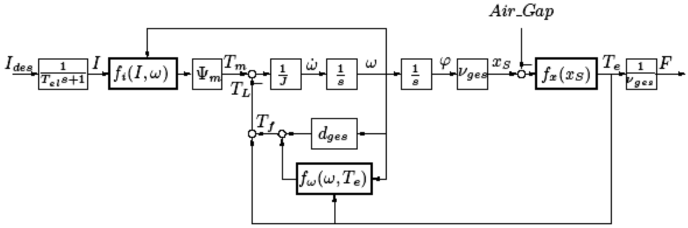


Fig. 3.61 Strutural and functional block diagram of the EMB physical model [LŰDEMANN 2002].

Figure 3.61 shows the structure of the physical model of the EMB where the symbols have the following meanings:

Air_Gap	:	Air gap between brake disc and brake pads;
d_{ges}	:	Overall viscous friction;
$f_i(I,\omega)$	:	Feedback of the E-M motor on the current;
$f_x(x_S)$	:	Transfer function between spindle position and clamping force;
$f_\omega(\omega,T_e)$	:	Transfer function between angular velocity and friction torque;
F	:	Clamping force;
I	:	E-M motor armature current;
J	:	Overall inertia;
T_e	:	Available torque;
T_f	:	Friction torque;
T_L	:	Available load torque; $T_L = T_e + T_f$;
T_m	:	Electromagnetic torque;
T_{el}	:	Electric time constant of the E-M motor;
x_S	:	Spindle position;
Vges		Transmission factor;
Φ	:	Rotation angle;
Ψ_m	:	Magnetic flux;
Ω	:	Angular velocity.

The EMB is servo-controlled by a cascade PID controller that consists of a current controller, an angular velocity controller, and a force controller, as shown in Figure 3.62.

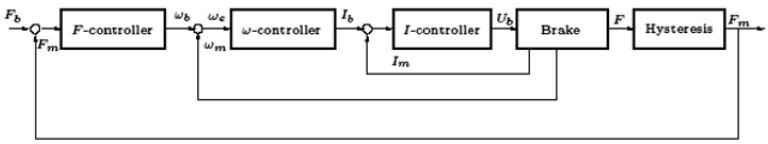


Fig. 3.62 Cascade structural and functional block diagram of the EMB servo controller [SCHWARZ 1999; LÜDEMANN 2002].

The index m denotes the measured values of the clamping force F_m, ω denotes the angular velocity, and I the current. Index b indicates the reference signal. From the brake-pedal measurements (brake-wish) the BBW AWB conversion mechatronic control system computes the desired clamping force (F_d) for each brake E-M actuator. After F_d has passed through an anti-windup routine, the slip-controller output F_b is passed to the EMB servo controller. Thus, the control output F_b cannot become larger than the desired clamping force F_d. F_b is the reference clamping force signal provided to the brake servo controllers of each wheel [SCHWARZ 1999; LÜDEMANN 2002].

The static brake torque T can be calculated using the following equation:

$$T = k\, i\, E\, R \tag{3.30}$$

where k - constant coefficient, depending on a construction of the short-stroke linear tubular brushless DC-AC macrocommutator IPM brake-force-actuator motor;

i - brake application armature current of the short-stroke linear tubular brushless DC-AC macrocommutator IPM magneto-electrically-excited brake-force-actuator motor;

E - effectiveness factor (ratio of the disc or ring rubbing surface to the input force on the shoes);

R - brake radius.

Brake force applied to the disc rotor by the pads is a function of the brake application armature current in the BBW dispulsion sphere and the constant coefficient of the wheel brake-force-actuator E-M motor.

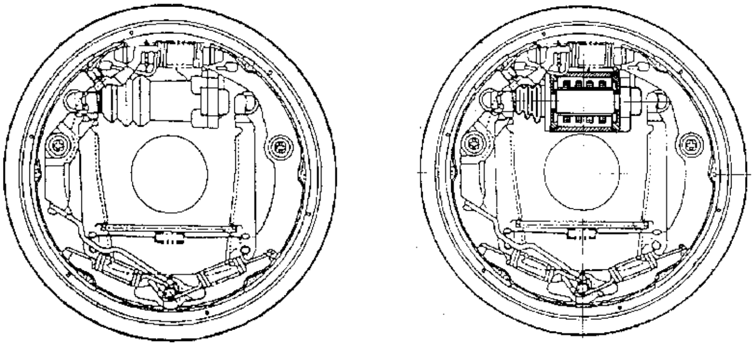
The static brake force F_{can} is calculated with the following relationship:

$$F = T/r,$$

where r is the wheel-tyre rolling radius.

3.9.2 Electro-Mechanical Friction Drum Brakes

With the E-M friction drum brake, a brake drum rotating with the wheel is braked by application of a voltage that is indirectly acting on a pair of curved shoes lined with a friction material. Pull-off springs retract the shoes and the E-M brake-force-actuator runner when brake-pedal application voltage is released. Shoe adjusters can be fitted to compensate for lining wear.



(a) (b)

Fig. 3.63 Cross-section diagrams of a friction drum EMB (a) with the conventional rotating brushed DC-AC mechanocommutator electromagnetically-excited brake-force-actuator motor, developed by Delphi for the BBW AWB dispulsion mechatronic control system known as *Galileo* and (b) with a novel short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically-excited brake-force-actuator motor, which have been conceived and developed by the Cracow University of Technology's Automotive Mechatronics Institution, Poland [(a) WELLS AND MILLER 1993; (b) FIJALKOWSKI AND KROSNICKI 1994]

Figure 3.63 depicts the layout of a friction drum EMB: (a) with a conventional rotating brushed DC-AC mechanocommutator electromagnetically-excited brake-force-actuator motor, developed by Delphi Corporation for the BBW AWB dispulsion mechatronic control system known as *Galileo* [WELLS AND MILLER 1993, SCARLETT 1996] and (b) with a novel short-stroke linear tubular brushless DC-AC macrocommutator IPM electromagnetically-excited brake-force-actuator motor [FIJALKOWSKI AND KROSNICKI 1994].

In friction drum EMBs, force is applied to a pair of brake shoes in a variety of configurations, including leading trailing shoe (simplex), duo-duplex, and duo-servo.

The short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically excited brake-force-actuator motor can be applied to the traversing of a drum brake application lever, replacing the conventional brushed DC-AC mechanocommutator brake-force-actuator motor, gearing drive-shaft, and control equipment.

Maintenance is simplified and as the short-stroke linear motor is unaffected by atmospheric conditions, the like-hood of breakdown is reduced.

E-M friction drum brakes feature high gains relative to friction disc or ring EMBs, but some configurations tend to be more non-linear and sensitive to fading and other brake lining coefficient-of-friction changes.

The static brake torque equation previously presented for friction disc or ring EMBs, Eq. (3.30), is equally applicable to E-M friction drum brakes with design-specific changes for brake radius and effectiveness.

By design, the brake radius for a friction drum EMB is one-half of the drum diameter. The effectiveness factor represents the major functional difference between disc and ring EMBs; the geometry of friction drum EMBs may allow a static brake torque to be produced by the friction force on the shoe in such manner as to rotate it against the drum and increase the friction force developed. The action can yield a mechanic advantage that significantly increases the gain of the brake and the effectiveness factor as compared with friction disc or ring EMBs.

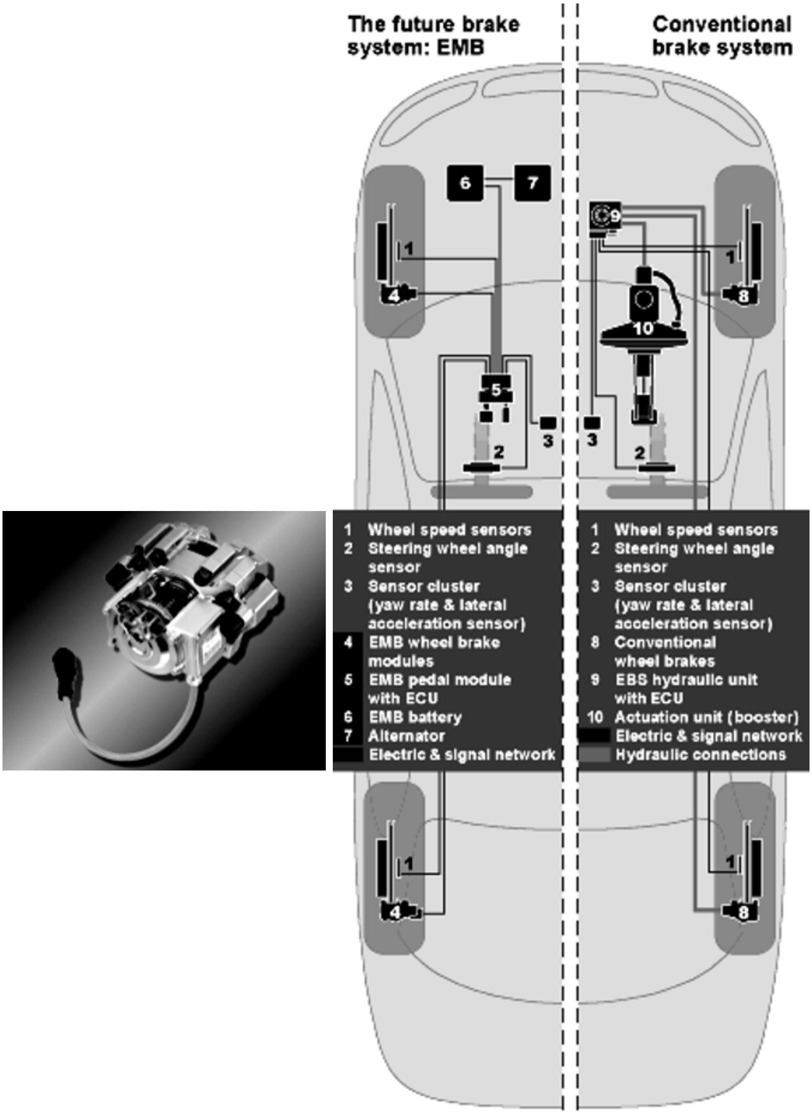
The dynamic brake force calculation for friction drum EMBs is more complex since the brake-lining coefficient of friction is a function of temperature; as the lining heats during a braking manoeuvre, the effective coefficient of friction increases and less brake application voltage/current is needed to maintain a constant brake torque. High-gain friction drum EMBs maximise the torque capability and minimise electrical energy requirements. High gain is achieved through use of mechanical self-energisation. Dynamic stability of the gain is achieved by closed-loop control technology.

For instance, at an operating torque of 0.5 kNm each friction drum EMB responds in a closed-loop control mode at rates up to 5 kNm/s to continuously adjusting dynamic brake output [WELLS AND MILLER 1993].

Integral to the drum EMB is a rotating brushed DC-AC mechanocommutator electromagnetically-excited brake-force-actuator motor, gear train, and ball screw/nut mechanism [CHEW 1996] or a short-stroke linear tubular brushless DC-AC macrocommutator IPM magnetoelectrically-excited brake-force-actuator motor only [FIJALKOWSKI AND KROSNICKI 1994].

In the first case, the ball-screw converts rotary-motion torque to linear-motion force. This in turn actuates a conventional friction surface drum EMB mechanism through a system of apply and motionless levers.

The friction drum EMB, as shown in Figure 3.59, must have the ability to mechanically reduce braking to an acceptable level upon the withdrawal of electrical energy. It must not remain energised in cases of electrical energy interruption during braking. This requires a highly efficient system with a return spring mechanism to *'astern-drive'* the friction drum EMBs without the assistance of electrical energy. The *'astern-drive'* capability needs a separate parking-brake latch mechanism. Thus, the ability to automatically release the braking torque during an electrical energy interruption demands the use of a highly efficient brake-apply-lever actuator and separate parking brake-holding latch. No electrical energy is required to continue application.



(a) (b)

Fig. 3.64 Outlook of the EMB (a) as well as comparison between the innovative EMB and the conventional EFMB systems (b) [Continental Teves Inc. 2004].

With the EMB researchers are getting involved in pure EMB BBW AWB dispulsion technology that eliminates brake fluids and fluidic lines entirely. The braking force is generated directly at each wheel by high performance E-M motors; which are controlled by an ECU and actuated by signals from an EMB pedal module.

The EMB includes all brake and stability functions. It is virtually noiseless, even in ABS mode.

A comparison between the innovative EMB and the conventional EFMB systems is presented in Figure 3.64 [CONTINENTAL TEVES INC. 2004].

Advantages of the EMB are as follows:

- More precise mechatronic control;
- Reduced mass;
- Improved automotive vehicle dispatch rates;
- Higher reliability;
- Shorter stopping distances and optimised stability;
- More comfort and safety due to adjustable brake pedals;
- No brake pedal vibration in ABS mode;
- Virtually silent;
- Environmentally friendly no brake oily-fluid or air (gas);
- Improved crash worthiness;
- Space saving, using fewer parts;
- Easier assembly;
- Capable of analysing all required braking and stability functions;
- May be easily networked with future traffic management systems;
- Additional functions such as an electric parking brake (EPB) may be integrated easily;
- Improved maintenance through information digital monitoring of brake wear and other key characteristics.

Components of the EMB are as follows:

- Four wheel EMB modules;
- Microelectronic controller;
- Microelectronic brake foot-pedal modules with pedal-feel simulator and sensors for monitoring driver settings.

3.10 Future Automotive BBW AWB Dispulsion Systems

So what is the future of the BBW AWB dispulsion mechatronic control system? Some vehicle manufacturers and other OEM supplyr companies have all developed next-generation BBW AWB dispulsion mechatronic control systems for potential use on future automotive vehicles. Innovative BBW AWB dispulsion mechatronic control systems that have been developed to date, essentially fall into one of two categories: **electro-fluido-mechanical brake** (EFMB) or **electro-pneumo-mechanical brake** (EPMB) and **electro-mechanical brake** (EMB).

BBW AWB dispulsion mechatronic control systems still use conventional **fluido-mechanical brake** (FMB) or **pneumo-mechanical brake** (PMB) callipers at each wheel, but a microcomputer-controlled high-pressure E-M-F pump or E-M-P compressor and E-M actuator solenoids apply pressure. These kinds of BBW AWB dispulsion mechatronic control systems use inputs from a brake pedal position sensor (that works much like a throttle position sensor), wheel angular velocity (speed) sensors, a steering angle sensor, yaw rate, and lateral acceleration sensors to determine the optimum amount of brake oily-fluid or air (gas) pressure to apply at each wheel.

With EMB BBW AWB dispulsion mechatronic control systems, there is no fluidics (hydraulics and/or pneumatics) whatsoever. Braking force is generated at each wheel by a fully electronic EMB calliper. Inside is a small, but powerful E-M motor that pushes the pads against the rotor. Many of these systems work best with higher voltages (such as 42 V_{DC}) which means EMB BBW AWB dispulsion mechatronic control systems may probably remain on the shelf until automotive vehicle manufacturers decide whether or not to change to 42 V_{DC}.

The benefits of EMB BBW AWB dispulsion mechatronic control systems are essentially the same as EFMB and EPMB BBW AWB dispulsion mechatronic control systems, plus elimination of brake fluid or air, hoses and lines, the need for a high-pressure M-F pump or M-P compressor and accumulator, and provide improved braking safety by keeping three brakes operational should one calliper fail.

Being able to precisely control the amount of braking force at each wheel electronically also means a BBW AWB dispulsion mechatronic control system may shift more braking effort to the rear brakes during normal braking. This, in turn, may reduce front pad wear while reducing the forward mass shift and nose drive that normally occurs when the brakes are applied.

A trend that may impact BBW AWB dispulsion mechatronic control systems is the automotive industry's desire to reduce vehicle wiring through the use of multiplexing techniques. As increasing numbers of vehicles are fitted with anti-lock, this trend is expected to result in an increased number of anti

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-lock BBW AWB dispulsion mechatronic control systems communicating with other structural and functional systems through a multiplex link.

In addition to the wheel angular velocity/vehicle velocity information (data) available from the anti-lock BBW AWB dispulsion mechatronic control system, the anti-lock ECU could benefit from this technology by being able to receive engine, transmission, steering angle, and other structural and functional subsystems information.

Another trend in advanced mechatronically-controlled BBW AWB dispulsion mechatronic control systems is vehicle dynamics control during non-braking manoeuvres as well as during braking. This is accomplished through use of the traction control actuators normally integrated in anti-lock fluidic or pneumatic modulators, the addition of sensors to more accurately determine the dynamic state of the automotive vehicle, and communication links with the DBW **four-wheel-driven** (4WD) propulsion mechatronic control system, the ABW **four-wheel-absorbed** (4WA) suspension mechatronic control system and, the SBW **four-wheel-steered** (4WS) diversion mechatronic control system ECUs. Vehicle dynamic control holds the promise of safer vehicle operation through improved handling stability in all manoeuvres.

The automotive 4WB BBW dispulsion mechatronic control systems engineering community is also investigating the addition of laser radar to individual vehicles. This addition could lead to semi- or fully-automatic braking in emergency situations as the 4WB BBW dispulsion mechatronic control system anticipates the potential problem and aids the driver in safely applying the vehicle brakes in time to avoid a collision, This concept also lends itself to automatic braking in non-emergency situations to maintain safe distances between vehicles at high values of the vehicle velocity.

Continuing interest in AEVs and HEVs and the need for regenerative braking in these automotive vehicles may significantly impact on future BBW AWB dispulsion mechatronic control systems. It is expected that the regenerative braking function will not be sufficient to provide adequate braking deceleration under all conditions and to provide drivers with the comfort and safety obtainable from conventional friction brake dispulsion mechatronic control systems augmented by anti-lock BBW AWB dispulsion mechatronic control systems. It is expected that a more sophisticated ECU may be used in conjunction with AEVs and HEVs to afford optimum power regeneration without sacrificing braking stopping distance, vehicle handling stability, or steerability. These trends point to the continued use of friction brake dispulsion mechatronic control systems through the next century and significant expansion of the role of automotive mechatronics in these structural and functional systems.

BBW AWB vehicles are to become a fundamental part of the automotive industry within the next decade. The state-of-the-art technology replaces F-M (H-M and/or P-M) components with E-M ones. There are three types of BBW AWB dispulsion mechatronic control systems.

These are EFMB, EPMB and EMB. An EFMB system contains an F (H) or P back-up for the brake system, and in the case of an electrical failure, this F-M (H-M and/or P-M) system takes over and allows the driver to have some limited control of the braking system. EMB has no F-M (H-M and/or P-M) backup system, and is totally realised by electrical and E-M components. Automotive vehicle manufacturers are planning to use EFMB or EPMB as a bridge to EMB that may become an automotive industry standard. As EMB has no F-M (H-M and/or P-M) backup components, safety and fault tolerance is of the utmost importance in an EMB system.

BBW AWB dispulsion is implemented through the application of sensors, E-M actuators, microcontrollers, wires, and communication networks. To power this, a 42 V_{DC} CH-E/E-CH storage battery may be introduced as standard, either stand-alone or in parallel with the existing (12 V_{DC}) CH-E /E-CH storage battery. When the brake is pressed, an electronic signal may be passed from the sensor to the electrical network. Microcontrollers may process this signal and send information out to the E-M actuators, causing the callipers to apply a brake force.

The communication system can process and send signals from the pedal to the brakes in 100 ms, twice as quick as the FMB system, where the calliper may apply a force of a maximum value of 3 Mg, i.e. 30 kN. The application of brake-by-wire requires a real-time distributed system that is safety critical in nature and fault tolerant. In order to apply the fault tolerant nature required, the network's communication is handled by **time-triggered architecture** (TTA). The three major time triggered-architectures are TTP/C, for instance FlexRay™ (developed by BMW and DaimlerChrysler), and TT-CAN. There are many important issues raised with this technology. BBW AWB reduces the risk of physical components injuring the passengers in an accident but problems raises of what happens when the electronic system fails. Although the chance of this is small, black boxes are to be introduced into vehicles, and legislation is set to change. Manufacturing plants and assembly lines may also have to change their business focus, shifting from fluidical as well as mechanical components to mechatronic ones.

Most vehicle manufacturers believe, however, that the benefits of BBW AWB dispulsion far outweigh any initial hurdles, and that BBW AWB technology is the way of the future.

Automotive vehicles have already been constructed with BBW AWB dispulsion, and the first commercially available mass-produced unit was released in 2002. With BBW AWB dispulsion, the vehicle may adapt to situations and determine the optimum force to apply to each different wheel, regardless of user input, to reduce the risk of injury in dangerous situations. The BBW AWB dispulsion mechatronic control system has ABS and TCS fully integrated into it, and performs these functions more efficiently and effectively.

By fully integrating BBW AWB dispulsion with SBW AWS conversion and DBW AWD propulsion (where the steering and drive mechanics are replaced respectively), it is possible to produce safer, more efficient vehicles that can find the optimum way to react to a situation if drivers are putting themselves at risk.

It is also possible that, in the near future, a fully integrated by-wire automotive vehicle may obey velocity (speed) signs and eventually drive itself.

Many in the automotive industry see the EMB BBW AWB dispulsion mechatronic system as the ultimate solution. It is said to offer a range of consumer, industrial, and environmental benefits such as elimination of brake fluid or air, increased fuel economy through automotive vehicle mass reduction, quieter braking, reduced maintenance costs, and the ability to tailor brake response to driver preferences. *EBRAKE*® [US PATENT 6,318,513; GERMAN PATENT 19819564] – an innovative *'BBW AWB'* technology, was developed at the German Aerospace Centre, DLR e.V. This technology is based on an electrically powered and mechatronically controlled friction disc brake with high self-reinforcement capability. Whenever automotive scientists and engineers deploy existing forces, normally the unsophisticated concept is the most convincing. By intelligently controlling a brake wedge, the kinetic mechanical energy (momentum) of an automotive vehicle is transformed into braking power. As it can be seen from a physical model of the electrically powered and mechatronically controlled friction disc brake with high self-reinforcement capability, shown in Figure 3.65, the brake lining is equipped with a wedge on its backside which rests on an abutment, for example, a bolt [HARTMANN ET AL. 2002].

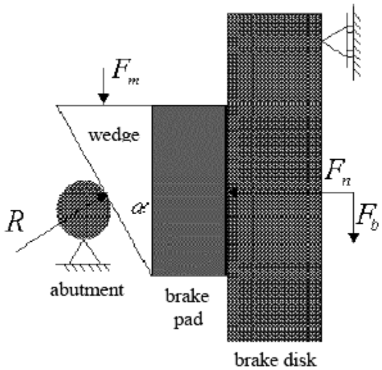


Fig. 3.65 Physical model of the friction disc brake with high self-reinforcement capability [HARTMANN ET AL. 2002].

The E-M actuator presses the brake lining in between the abutment and the brake disc with the E-M motor force F_m.

The braking force F_b resulting from the contact between the brake disc and the brake lining acts in the same direction as the E-M motor force that results in the anticipated self-reinforcement.

From the force balance

$$F_m = F_b \frac{\tan\alpha - \mu}{\mu} \tag{3.31}$$

may be derived.

For the characteristic brake factor C* then applies:

$$C^* = \frac{F_b}{F_m} = \frac{2\mu}{\tan\alpha - \mu}\ , \tag{3.32}$$

where F_m : E-M motor force;
F_n : normal force;
F_{aux} : auxiliary force;
F_b : braking force;
$F_{b,ma}$: maximum braking force (nominal value);
R : reaction force;
α : wedge angle;
μ : friction;
c : calliper stiffness;
x : wedge position/deflection.

From this equation (3.32), it can be seen that for low coefficients of friction, C* is positive, so a steady pushing force is necessary to uphold the braking force. When the coefficient of friction is greater than the tangent of the wedge angle, then a steady pulling force is necessitated from the E-M actuator to stop the wedge being pulled further in. For optimum performance, it is best to operate around the point at which the characteristic brake factor is infinite, since this minimises the necessary control forces. From a control standpoint, this may be thought of as a point of neutral stability, since any small perturbation in the wedge position may result in it remaining in another position (and generating the corresponding braking moment). When the coefficient of friction rises, the wedge position becomes unstable and requires to be controlled to stop the wheel jamming.

In Figure 3.66 a structural and functional block diagram of the mechatronic control system for an electrically powered and mechatronically controlled friction disc brake with high self-reinforcement capability is shown [HARTMANN ET AL. 2002].

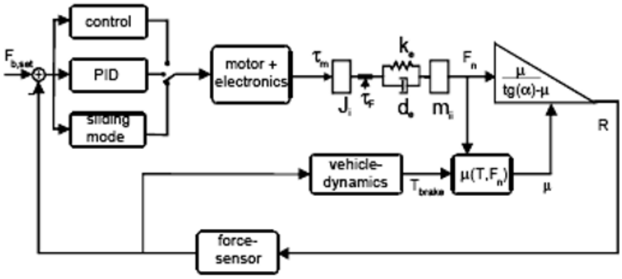
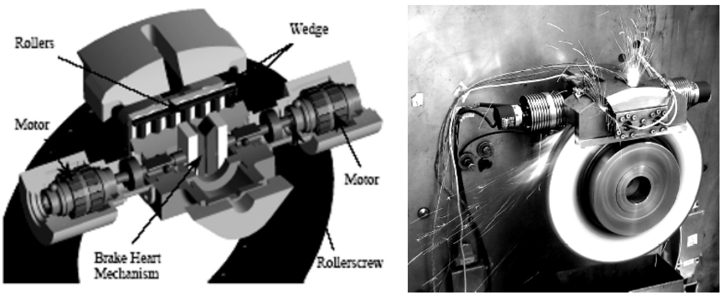


Fig. 3.66 Structural and functional block diagram of the mechatronic control system for an electrically powered and mechatronically controlled friction disc brake with high self-reinforcement capability [HARTMANN ET AL. 2002].

The essential problem with this simple but very efficient method of braking was to find a technique to prevent the jamming of the brake or, better said, to *'control'* this jamming satisfactorily. The German Aerospace Centre, DLR e.V. was successful in solving this problem. A special mechatronic control technology developed under Matlab/Simulink and DSPACE stops the wedge from getting stuck.

In an attempt to prove the general concept of a controlled wedge brake, a prototype of *DLR EBRAKE*® EMB was built (Fig. 3.67).



(a) (b)

Fig. 3.67 Cross-section of the *EBRAKE*® EMB (a) and its high temperature test (b) [HARTMANN ET AL. 2004].

Despite the fact that the principle of a controlled wedge brake is relatively simple, the mechanical implementation is critical to its realisation.
Key factors that need to be taken into account are

- ❖ Removal of free-play within the drivetrain, regardless of component wear;
- ❖ Minimisation of friction in the sense of the wedge travel direction;
- ❖ Action in both senses of direction.

The prototype EMB is best explicated by means of a cross section through the EMB that is presented in Figure 3.65 (a).

The design is based around a modular concept suitable for laboratory testing, rather than being optimised for minimum size and mass, and uses off-the-shelf industrial components wherever achievable. The EMB is driven by two rotary brushless DC-AC mechanocommutator brake-force-actuator motors [DLR ROBO DRIVE] mounted at either end of the assembly. Commutation and current control are realised using conventional E-M motor drives with an incremental encoder on each E-M motor shaft. For controlled braking, a moment sensor provides the feedback to the moment controller. On the other hand, the encoder may be used to provide E-M motor position control. E-M motor rotation is transformed to axial motion by means of roller-screws which are mounted within the rotors on pre-loaded angular thrust ball bearings. The roller-screws drive the so-termed brake heart, which contains the wedge mechanism. Within this component, forces are only transmitted by compression between neighbouring surfaces. This allows the E-M motors to either work together or to preload the system and so remove free-play [ESTOP GMBH].

Backlash is inevitable, both as an effect of construction tolerances and because of wear, predominantly in the bearing surface that allows the wedge to slide outwards from the E-M motor axis. If they are working together, then one roller-screw pulls the wedge in the appropriate sense of direction while the other one pushes against the first roller-screw. This reduces the E-M motor loads when the coefficient of friction is not near the optimum value. For a preload to be introduced, both roller-screws pull against their respective sides of the wedge. The wedge is actually composed of two ground *'W'* surfaces. The inner one relative to the E-M motors is static, while the outer one moves both axially and in translation. This construction spreads the loads and may generate self-reinforcement in both directions of travel. Between these surfaces, there is a series of rollers which minimise the sliding friction from the high calliper forces. The outer part of the wedge, to which the brake pad is attached, is held against the static one by a preloaded spring. It is axially actuated by means of a bearing surface that allows it to move laterally away from the E-M motor centreline.

The automotive industry is expected to move to the first stage of the adoption of BBW AWB dispulsion around 2010 through the introduction of electrically actuated rear brakes and then followed by full DBW AWB dispulsion around 2020. EFMB or EPMB is a BBW AWB dispulsion mechatronic control system that eliminates the physical connection between the brake pedal and brake fluidics.

The brake booster and master cylinder are replaced with a PS and failsafe F-M (H-M and/or P-M) manifold to actuate the brakes through the EFMB or EPMB unit. It may be offered in 2012 on certain luxury models, but probably won't be offered on other vehicles because of its high cost. It may also require special OEM dealer tools and training to service this system because of its complexity [CARLEY 2004].

Further down the road, EMB that uses no fluidics at all may probably find its way onto automotive vehicles. But don't look for this new technology to go into manufacture until the end of the next decade.

Some vehicle manufacturers are using an innovative type of brake rotor made of ceramics on certain models (for example like the one on the Porsche *911*). The ceramic rotor is very light mass and does not conduct heat into the hub, but it's also extremely expensive. It wears very little, but if it is damaged, it can't be resurfaced and must be replaced. It also requires a special type of high temperature friction material to withstand the heat.

Some manufacturers are also using drilled and slotted rotors on their high performance models. The automotive scientists and engineers have indicated that they don't offer a significant improvement in cooling compared to a standard rotor and are used primarily to enhance the '*racing mage*' of the vehicle. On the issue of brake life, premature pad wear and rotor wear are major customer issues with all vehicle manufacturers. The latest approach is to make the design of the brake system more robust so that the brakes last longer and run quieter.

3.11 Discussion and Conclusions

The present power braking systems are bulky and complex. They rely on **mechano-mechanical** (M-M) linkages, airtight vacuum seals, and fluidics (hydraulics and/or pneumatics). When the brake pedal is pressed, the force is amplified using a lever. From there, a vacuum generated from the ECE or ICE is used to assist the brake pedal motion. That motion is transferred through oily-fluid or air (gas) in all senses of flow direction until it reaches the braking unit on each wheel. This complex configuration may be simplified and improved using BBW AWB dispulsion [TREVETT 2002].

Three levels of BBW AWB dispulsion exist. The first is called EFMB. In the EFMB BBW AWB dispulsion mechatronic control system, E-M-F pumps and fluidical valves are used to power and control the fluidic elements. The second is termed EPMB. In EPMB BBW AWB dispulsion mechatronic control system E-M-F compressors and pneumatical valves are used to power and control the pneumatical elements. This reduces the power draw on the ECE or ICE and eliminates some of the large cumbersome interfaces. In EFMB or EPMB, driver input is interpreted electronically allowing computer-controlled coordination between the braking and other systems. Another advantage of EFMB or EPMB is the possibility of mechanical backup [TREVETT 2002].

Since fluidics is ultimately responsible for stopping the vehicle, they can be configured to apply a braking force in the case of electrical failure [HEDENETZ AND BELSCHNER 1998].

The third level of BBW AWB dispulsion is called EMB. It consists of sensors on the brake pedal, an ECU, and E-M actuators at each wheel. This system holds the greatest potential for control and variability. It would also be a fraction of the cost of the current design. Regenerative braking would be easier to develop and implement. Maintenance would be reduced because of the elimination of brake fluid and M linkages. Using EMB, a mechanical backup cannot be realised. The electrical components must be designed fail safe. Electrical redundant methods are being developed. One promising approach to be failsafe electronics is known as **time triggered protocol** (TTP) [HEDENTZ AND BELSCHNER 1998]. This approach is being developed for use with BBW AWB dispulsion and AWS SBW conversion mechatronic control systems [TREVETT 2002].

EFMB or EPMB BBW AWB dispulsion mechatronic control systems do everything: the anti-lock and traction-control functions of contemporary ABSs plus brake power assist, vehicle stability enhancement control, parking brake control, and tuneable pedal feel, all in single, modular automotive system [BRETZ 2001].

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With contemporary anti-lock brakes, the mechatronics do the brake-pedal pumping instead of the driver, but otherwise they are still mechanical systems. Pressing the brake pedal produces fluidical or pneumatical pressure on the brake pads that squeeze the brake disc or ring to produce friction and stop the vehicle.

Compare that to the conventional disc or ring brakes on a vehicle today. Pressing the brake pedal applies fluidic or pneumatic pressure (via fluid or air) to force the pads in the calliper assembly against the spinning brake disc or ring on each wheel. The friction between disc or ring and pads slows the vehicle.

A EFMB BBW AWB dispulsion mechatronic control system may fall somewhere between conventional F-M or P-M braking systems and E-M braking systems. Though each wheel is assigned a conventional F-M or P-M calliper, a mechatronically controlled fluidic or pneumatic valve controls the actual braking force (the pressure of the fluid or air it releases).

Instead of the brake pedal directly pushing the F-M or P-M servo, an E-M-F pump or E-M-P compressor, connected to the brake pedal by electrical or optical wires, governs brake oily-fluid or air (gas) pressure. Press the brake pedal, activate the E-M-F pump or E-M-P compressor, and brake the vehicle.

Beyond just working out the technical kinks, winning over the driving public to BBW AWB dispulsion may be crucial.

When ABS first came out, for example, high accident rates for vehicles equipped with ABS made consumers sceptical.

In addition, ABS cost more and requires a different approach. Once drivers learned to apply steady pressure and not pump the brake pedal themselves, wariness gave way to acceptance.

In fact, nearly a decade after their introduction, as anti-lock brakes are considered, standard equipment by most vehicle owners, or at least as an option worth the purchase price.

Vehicle manufacturers hope drivers may come to find BBW AWB dispulsion equally desirable. They are introducing BBW AWB dispulsion mechatronic control systems slowly, initially making ABW BBW dispulsion transparent to the customer.

Then, as incremental improvements are made and fluidics eliminated from even backup roles, public confidence in the BBW AWB dispulsion technology may increase [BRETZ 2001].

The EMB BBW AWB dispulsion mechatronic control system is considered to be *'true'* because it does away with the F-M (H-E and/or P-M) link between the brake pedal and brake pads and E-M braking puts an E-M motor-driven calliper supplied by $42\ V_{DC}$ power to each wheel. Mechatronic control operates the E-M calliper through a multiplexed signal sent by sensor in the brake pedal.

Microcontrollers on each wheel are connected to a master controller with the ability to interrupt the signal between the brake pedal and calliper. The E-M calliper is basically the mechanism that squeezes the brake pads against the brake disc or ring to produce friction that slows down the vehicle.

Safety and stability are at the heart of the push to develop BBW AWB dispulsion technology, especially for a combination of braking and steering. [BRETZ 2001].

The goal is to make the average driver as skilled as a professional test driver in bringing the vehicle back to a safe and stable condition from an unsafe one. Controlling the brakes at each wheel individually, as is done in BBW AWB dispulsion, and helping the driver steer through a skid may prevent an accident. There are vehicle stability systems, also termed yaw control packages by manufacturers, in vehicles that do similar things. They too are primarily focused on braking. The systems mechatronically control the brake F-M (H-M and/or P-M) pressure applied separately to each wheel that therefore gets the amount of braking it needs to help guide the vehicle out of a skid, for instance. Vehicles with EMB BBW AWB dispulsion could soon be using microcomputer control to adjust the steering by braking each wheel individually on the basis of input from collision avoidance radar, yaw rate sensors at each wheel, and lateral acceleration sensors. But even when BBW AWB dispulsion and AWS SBW conversion mechatronic control systems start appearing on automotive vehicles, the automotive industry may not consider it *'true'* EMB BBW AWB dispulsion technology since F-M (H-M and/or P-M) backup systems may be in place, just in case.

EMB BBW AWB dispulsion mechatronic control systems also have manufacturing and design advantages. BBW AWB modules would plug into the corners of a vehicle, near each wheel, connected by electrical wires to an AI NF microcontroller connected by electrical wires to the brake pedal, making vehicle assembly easier and faster than putting a plumbing system into a vehicle. Plus, things may not be quite so rigidly aligned with AWD DBW. Also, no F-M (H-M and/or P-M) lines as well as fluid or air, means that there is no fluid or air to renew.

The two leading **time-triggered architecture** (TTA) candidates are **time-triggered protocol** (TTP) and FlexRay. A third protocol candidate – **time-triggered controller area network** (TTCAN) – is considered a remote possibility because its development is just beginning. Still, it cannot be ruled out because it reduces the protocol governing the networks that control such systems as power windows and door locks in today's automotive vehicles. BBW AWB dispulsion applications necessitating high availability, such as an E-M BBW AWB dispulsion mechatronic control system, imposes stringent reliability and performance demands upon the underlying communication systems.

M-M and F-M BBW AWB dispulsion mechatronic control systems in vehicles may be replaced by fault-tolerant, time-triggered microelectronic and software systems that may recover from failures under certain circumstances. For example, the FlexRay *AS8202* processor is the first time-triggered chip to fulfil the extreme demands that are necessary for such applications.

At first glance, FlexRay and TTP seem almost identical. Both are TTAs but have different data rates and transmission media.

FlexRay is designed for optical fibre for a 10 Mb/s data transmission rate; but it can also run on copper. TTP uses copper only 2 Mb/s, though developers at the University of Vienna are exploring fibre.

FlexRay first appeared on copper and is today's state-of-the-art in automotive vehicles. But fibre is likely to be the future state of the art. It offers speedy data transmission plus weight and electromagnetic compatibility (EMC) advantages over copper, but bending fibre to run throughout a vehicle is not yet practical. Interestingly enough, FlexRay was designed for both copper and fibre because some vehicle manufacturers backed different options.

The thinking behind FlexRay goes something like this: the electrical or optical wires must provide the same safety as a mechanical system. So what is safeguarded in a mechanical system? The fluid or air (gas) which subsequently has to be protected. The protocol controls and organises the information. The information must arrive at a clearly *'deterministic'* point in time – that is to say, at the correct time. To avoid an indeterministic point in time requires predictability.

'Deterministic' simply means that data is sent at a predetermined time (time-triggered) in contrast to any time (event-triggered). In terms of FlexRay and TTP, the data messages to and from each node on the network are scheduled against the network's global clock.

Thus synchronisation and periodical resynchronisation are required to keep all network nodes to the same schedule and in the same time frame. TTP and FlexRay have built-in mechanisms for clock synchronisation.

The AWD DBW protocol must also be fault tolerant. A vehicle operates in a rugged environment. Electrical or optical wires run from a very hot ECE or ICE compartment to an icy-cold trunk. And as the vehicle moves, things shift, including electrical or optical wires and connectors. So both the bus system (that is, the electrical or optical wires) and the protocol must safeguard against wire breaks, corrosion at connectors, and short-circuits. It does so with redundant systems.

The dark horse protocol candidate is TT-CAN. Basic CAN (without the time trigger) is used in automotive vehicles now for control and communication at up to 1 Mb/s by way of serial data transmission. But it is an event-triggered protocol, meaning that it processes commands, as they occur, not by priority.

Because of its slow speed and inability to prioritise, automotive vehicle manufacturers think CAN is not suited for safety-critical applications like mechatronically controlled braking or steering.

Whether TT-CAN developers are able to overcome these problems is unknown. It's always difficult to expand a protocol to something it wasn't originally designed for.

Whether vehicle manufacturers prefer FlexRay or TTA, a safety-critical communications network is an essential ingredient in BBW AWB dispulsion and SBW AWS conversion mechatronic control systems, which remove all fluidical components.

The first of these mechatronic control systems to come on the market may probably be EMBs, which may not appear in passenger vehicles until 2020, at the earliest. EMBs remove fluidics and power the brakes with powerful, quick-response rotary or linear E-M motors.

Compared with conventional FMBs, EMBs are far easier to build, are more serviceable, more reliable, and the response time between the driver's brake foot-pedal and the EMBs is faster. The response time is better by one or two orders of magnitude, and that enormously enhances the link between the driver's intentions and the braking manoeuvre.

Another benefit of EMBs is that they are much easier to integrate with other RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis motion mechatronic control hypersystems. And since with EMBs there is no direct link between the brake foot-pedal and the brakes, the unacceptable feedback experienced on the brake foot-pedal when ABS pulses during emergency braking may not be an issue. As with any innovative technology, cost is a major problem in bringing EMBs to the automotive market. All but the smallest number of automotive vehicles may necessitate 42 V_{DC} E&INs that actuate the brakes with high-quality dynamics. These are costly and may stay the use of that technique at least until 2020. Another major cost factor comes with the redundancy necessary with EMB BBW AWB dispulsion mechatronic control systems. Supplementary components need to be included to the mechatronic control system so it may function 100% of the time, with no preference of failure.

Fundamentally, in the case of BBW AWB the *Poly-Supercar* [FIJALKOWSKI 1995, 1997, 2000B], the front SM&GWs must lock earlier than the rear ones. Otherwise, the vehicle stability is dangerously lost and the vehicle would skid because the locked SM&GW tyres cannot contribute to side stability. Thus, yaw torques cannot be balanced. Consequently, in vehicles without an enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system, the braking force between front and rear SM&GWs is distributed in a relation of approximately 0.7 to 0.3.

The enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system is continuously monitored for faults such as open- and short-circuits. Precise knowledge of such faults allows instant reconfiguration of the mechatronic control system for well managed stability, that is not only three-wheel diagonal or front/ rear wheel split braking but also inner/outer wheel split braking independently.

Enhanced anti-lock and/or anti-spin BBW AWB dispulsion control delivers improvement in performance, driver convenience, automotive vehicle design and assembly flexibility, mass reduction, and default mode operation.

E-M friction disc, ring and drum brakes provides improved default modes compared to F-M brakes plus significantly increased diagnostic capabilities, proactive default mode management, and improved serviceability. Increased diagnostic capabilities are available through the use of mechatronics.

Many drivers of enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system-equipped automotive vehicles, faced with an emergency stop, do not sustain the initial panic-strength brake-pedal voltage through-out the stopping, so that maximum anti-lock and/or anti-spin braking ceases when it is still very much needed. The simplest to be fitted as standard to automotive vehicles, is the electronic actuation system (EAS) which recognises the fact that the driver is panic braking by sensing the rate at which the brake pedal is pushed, and that the driver then subconsciously eases off. By harnessing the help of the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system's booster induction adjuster and master ASIC NF microcontroller, it automatically keeps the brake application voltage at an anti-lock and/or anti-spin braking-operating level until the vehicle stops.

Electronic stability system (ESS) is another handling product that uses the enhanced anti-lock and/or anti-spin BBW AWB dispulsion mechatronic control system. To help correct an under-steering or oversteering skid, the sphere momentarily applies E-M friction disc, ring or drum brakes to an individual SM&GW. Robert Bosch GmbH first developed ESS for a conventional ABS, and Mercedes-Benz was the first vehicle manufacturer to adopt it. It is currently found on the *S*- and *E*-class Mercedes.

The Cracow University of Technology's Automotive Mechatronics Institution has already started on a version of **vehicle disabling system** (VDS) capable of immobilising supercars. The VDS only works if the vehicle is fitted with novel enhanced anti-lock and/or anti-spin BBW AWB propulsion mechatronic control systems. VDS works by releasing the brake application voltages in a supercar's E-M friction disc, ring or drum brakes, thus immobilising it. The VDS may operate with either paging or cellular connections. As with more conventional stolen vehicle warning systems, it is possible to negotiate reductions in insurance premiums for automotive vehicles fitted with a VDS.

Automotive vehicle developers explain that most vehicle theft involves moving the supercar onto a transporter. But, if they cannot get the E-M friction disc, ring or drum brakes off, the vehicle is difficult to move. Further R&D work is required in several areas before these techniques are applied to a real AWD DBW propulsion and BBW AWB dispulsion as well as AWA ABW suspension and AWS SBW conversion mechatronic control systems, although R&D work to date demonstrates some of the benefits that can be had by applying these methods to a RBW or XBW integrated unibody, space-chassis, skateboard-chassis, or body-over-chassis mechatronic control hypersystem.

Imagine an automotive vehicle that senses when its brakes are wearing thin and can alert the driver turns on parking brake as soon as the key is withdrawn from the ignition; and that has no need for fluid.

Such a vehicle is not far away, judging by the pace of R&D among global automotive developers. In a BBW AWB dispulsion mechatronic control system, the brake pedal may be attached to a system of computers and wiring connected to small E-M motors controlling the callipers and may ultimately make the pedal and handbrake redundant.

The technology is likely to considerably improve safety and performance, as well as enabling data to be gathered to allow real-time adjustment of the brakes, minimising wear and providing service diagnostics. In the future, it may also radically redefine the design of vehicle interiors. BBW AWB dispulsion is defined as a next-generation braking system that may stop an automotive vehicle by electrical signals versus conventional fluidics braking systems in vehicles today.

Summing up, a revolutionary brake arrangement suited to automotive vehicles is termed *'BBW AWB'*. BBW AWB dispulsion is a method of braking where the primary braking circuit is mechanically isolated from the brake foot-pedal. BBW AWB conversion provides an efficient, direct means of converting electrical energy into mechanical energy in the form of a braking torque. BBW AWB dispulsion mechatronic control systems also allow faster response times, easily implemented ABSs and TCSs. Independently controlled F-M, P-M or E-M actuators create a multi-redundant mechatronic control system. They also have the advantage of reduced mass and fewer moving components.

For instance, an E-M BBW AWB dispulsion mechatronic control system shows advantages compared to an F-M BBW AWB dispulsion mechatronic control system in terms of comfort, safety, and environment. But due to the different setting elements it is necessary to develop adapted mechatronic control algorithms. This may be done by a physical model-based approach using measured values of the individual wheel velocity and the clamping forces as input values. It is shown that despite of the slower E-M actuator response, it is possible to achieve at least the braking performance of nowadays fluidical ABS systems.

Glossary

Anti-lock braking system (ABS) is a system on automotive vehicles which prevents the wheels from locking while braking; the purpose of this is to allow the driver to maintain steering control under heavy braking and, in some situations, to shorten braking distances (by allowing the driver to hit the brake fully without the fear of skidding or loss of control); disadvantages of the system include increased braking distances under certain circumstances and the creation of a *'false sense of security'* among drivers who do not understand the operation and limitations of ABS.

***ABS return M-F pump* -** A piston M-F pump that returns the brake's oily fluid to the master cylinder.

***ABS return M-P compressor* -** A piston M-P compressor that returns the brake's air to the master cylinder.

***AC-DC commutator* -** The commutator is a mechanical AC-DC rectifier; for a rotary DC-AC commutator generators, the commutator mechanically switches the armature windings so that the resultant induced source AC armature voltages always act with the same sense of voltage polarisation; this requires a reversal of the armature winding connection every π rad; the induced source AC armature voltages are mechanically rectified to the induced source DC armature voltage via commutator segments that contact the carbon brushes.

***AC-DC macrocommutator* -** The macrocommutator is an application specific integrated matrixer (ASIM) AC-DC rectifier; for a rotary DC-AC commutator generators, the macrocommutator electronically switches the armature windings so that the resultant induced source AC armature voltages always act with the same sense of voltage polarisation; this requires a reversal of the armature winding connection every π rad; the induced source AC armature voltages are electronically rectified to induced source DC armature voltage via inputs of the ASIM that contact the output of the ASIM via bipolar electrical valves.

***Actuator* -** The component of an open-loop or closed-loop mechatronic control system that connects the electronic control unit (ECU) with the process; the actuator consists of a commutator and a final-control element; positioning electrical signals are converted to mechanical output.

Algorithm **-** A set of software instructions causing a computer to go through a prescribed routine; because embedded computer ECE or ICE controls have become so common, the algorithm has become essentially synonymous with the control law for automotive scientists and engineers.

Analog input **-** Sensors usually generate electrical signals that are directly proportional to the mechanism being sensed; the signal is, therefore, analog signal or may vary from a minimum to a maximum limit.

Analog signal **-** A signal in which the information of interest is communicated in the form of a continuous signal; the magnitude of this signal is proportional (or analogous) to the actual quantity of interest.

Analog-to-digital (A/D) converter **-** An electronic device that produces a digital result that is proportional to the analog input voltage.

Anti-lock all-wheel-braked (AWB) brake-by-wire (BBW) dispulsion system (or antiskid or ABS) **-** A structural and functional automotive vehicle chassis-motion mechatronic control system which prevents wheel lock during overbraking.

Anti-lock fluidic or pneumatic modulator **-** A fluidical or pneumatical brake oily-fluid or air (gas) pressure modulation actuator used in anti-lock BBW AWB dispulsion systems.

ASIC **-** Application-specific integrated circuit, an integrated circuit (IC) designed for a custom requirement, frequently a gate array, single-chip micro-processor or programmable logic device.

ASIM **-** Application-specific integrated matrixer, an integrated matrixer (IM) designed for a custom requirement, frequently a gate array or single-chip macrocommutator.

ASR deactivation switch **-** A device to switch off ASR on sand and loose gravel that realises maximum traction on these on/off road surfaces.

Automatic throttle valve actuator **-** An actuator for automatic reduction of the throttle angle in circumstances of extreme acceleration slip.

Braking intervention **-** Automatic brake action at drive wheels in circumstances of extreme acceleration slip.

***Booster* -** A brake pedal force amplifier, typically vacuum or fluidically powered.

***Booster crack point* -** The brake pedal/push rod travel point initiating booster force amplification.

***Booster run-out* -** A condition in which the brake booster can no longer provide the required gaion due to high input forces and the input force/output force slope becomes less positive.

***Brake calliper* -** A part of a disc or ring brake that contains the brake pads and the brake cylinder.

***Braking force* -** A force tending to stop a moving vehicle; usually applied to the force resulting from brake torque being applied to a wheel of a moving vehicle.

***Braking manoeuvre* -** Any automotive vehicle braking action intended to decelerate a moving vehicle, including partial as well as full stops.

***Bus* -** Topology of a communications network where all nodes are reached by links that allow transmission in both senses of direction.

***Capacity* -** Energy storage capability of the CH-E/E-CH storage battery, ultracapacitor, ultrainductor or ultraflywheel.

***Central processing unit (CPU)* -** The portion of a computer system or microcontroller that controls the interpretation and execution of instructions and includes arithmetic capability.

***CH-E/E-CH storage battery* -** Self-contained CH-E/E-CH cell/cells or system that converts chemical energy to electrical energy in a reversible process.

***Closed-loop mechatronic control* -** A process by which a variable is continuously measured, compared with a reference variable, and changes as a result of this comparison in such a manner that the deviation from the reference variable is reduced; the purpose of closed-loop mechatronic control is to bring the value of the output variable as close as possible to the value specified by the reference variable in spite of disturbances; in contrast to open-loop mechatronic control, a closed-loop mechatronic control system acts to offset the effect of all disturbances.

DC-AC commutator **-** The commutator is a mechanical DC-AC inverter; for a rotary DC-AC commutator motors or actuators, the commutator mechanically switches the armature windings so that the resultant force always acts in the same sense of rotary direction; this requires a reversal of the armature winding connection every π rad; the DC supply to the armature is via carbon brushes that contact the commutator segments.

DC-AC macrocommutator **-** The macrocommutator is an ASIM DC-AC inverter; for a rotary DC-AC commutator motors or actuators, the macrocommutator electronically switches the armature windings so that the resultant force always acts in the same sense of rotary direction; this requires a reversal of the armature winding connection every π rad*;* the DC supply to the armature is via an input of the ASIM that contact the ASIM outputs via bipolar electrical valves.

Defuzzification **-** The process of translating output grades to analog output values.

Depth of discharge (DoD) **-** Percentage of electrical energy capacity [*Ah*] that has been removed from the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel.

Diagonal split four-wheel-braked (4WB) BBW dispulsion mechatronic control system **-** A 4WB BBW dispulsion mechatronic control system configura-tion in which a front brake and its opposing rear brake are included in the same brake channel; this technique is used to allow braking on one front wheel in the case of catastrophic failure of the other brake channel.

Digital signal **-** A signal in which the information of interest is communicated in the form of a number; the magnitude of this number is proportional to (within the limitations of the resolution of the number) the actual quatity of interest.

Digital signal processor (DSP) **-** A monolithic integrated circuit (IC) optimised for digital signal-processing applications; portions of device are similar to a conventional microprocessor; the architecture is highly optimised for the rapid, repeated additions and multiplications required for digital signal processing; digital signal processors may be implemented as programmable devices or may be realised as dedicated high-speed logic.

***Disc brake* -** A type of brake characterized by force being applied to both sides of a disc rotor, thereby creating braking torque.

***Driver* -** A solid-state device used to transfer electrical energy to the next stage that may be another driver, an electrical load (power driver), a wire or cable (line driver), a display (display driver), etc.

***Drum brake* -** A type of brake characterized by brake force being applied to the inner surface of a drum, thereby creating braking torque.

***Dynamic load transfer (DLT)* -** The characteristic of mass shift during deceleration that places more mass on the front wheels and reduces mass on the rear wheels.

***ECE or ICE torque control* -** An actuator for ECE or ICE torque modulation in circumstances of extreme acceleration slip.

***Electro-mechano-fluidic (E-M-F) pump* -** The typical fluidic power source used in anti-lock 4WB BBW dispulsion mechatronic control systems; an electro-mechanical (E-M) motor driving a mechano-fluidical (M-F) pump.

***Electro-mechano-pneumatic (E-M-P) compressor* -** The typical pneumatic power source used in anti-lock 4WB BBW dispulsion mechatronic control systems; an electro-mechanical (E-M) motor driving a mechano-pneumatical (M-P) compressor.

***Electronic performance (EPC)* -** Electronic acceleration control.

***Final-control element* -** The second or last stage of an actuator to control mech-anical output.

***Fuzzification* -** The process of translating analog input variables to input member-ships or labels.

***Fuzzy logic (FL)* -** Software design based upon a reasoning model rather than fixed mathematical algorithms; a fuzzy logic design allows the automotive system engineer to participate in the software design because the fuzzy language is linguistic and built upon easy-to-comprehend fundamentals.

***Inference engine* -** The internal software program that produces output values through fuzzy rules for given input values; the inference process involves three steps: fuzzification, rule evaluation, and defuzzification.

***Input memberships* -** The input signal or sensor range is divided into degrees of membership, i.e., low, medium, high or cold, cool, comfortable, warm, hot; each of these membership levels is assigned numerical values or grades.

***Longitudinal frictional braking force* -** Force to the direction of travel.

***Lateral frictional braking force* -** Force perpendicular to the direction of travel.

***Longitudinal slip* -** Relative slip between the wheels and the road surface in the direction of travel.

***Master cylinder* -** A two-chambered fluidic or pneumatic cylinder operated by the driver through actuation of the brake pedal.

***Microcontroller unit (MCU)* -** A semiconductor device that has a central processing unit (CPU), memory, and input output (I/O) capability on the same chip.

***Open-loop mechatronic control* -** A process within a mechatronic control system in which one or more input variables act on output variables based on the inherent characteristics of the mechatronic control system; an open loop is a series of elements that act on one another as links in a chain; in an open loop, only disturbances that are measured by the control unit can be addressed; the open loop has no effect on other disturbances.

***Output memberships* -** The output signal is divided into grades such as off, slow, medium, fast, and full-on; numerical values are assigned to each grade; grades can be either singleton (one value) or *Mandani* (a range of values per grade).

***Proportioning fluidic valve* -** A fluidic valve designed to reduce oily-fluid pressure to the rear brakes relative to the front brakes once a crack point is reached; the fluidic valve may be fixed or mass-sensing.

Proportioning pneumatic valve **-** A pneumatic valve designed to reduce air (gas) pressure to the rear brakes relative to the front brakes once a crack point is reached; the pneumatical valve may be fixed or mass-sensing.

Protocol **-** The rules governing the exchange of information (data) between networked elements.

Pulse-width modulation (PWM) **-** The precise and timely creation of negative and positive waveform edges to achieve a waveform with a specific frequency and duty cycle.

Regenerative braking **-** Capability of an E-M propulsion acting as an M-E dis-pulsion to return the kinetic mechanical energy, stored in the vehicle velocity of the AEV or HEV body, to the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel during braking; a type of braking used in all-electric vehicles (AEV) and hybrid-electric vehicles (HEV) in which the drive electro-mechanical (E-M) motor(s) is used as a mechano-electrical (M-E) generator(s) during braking, and it serves as the load to brake the vehicle; this technique is used to reclaim a portion of the energy expended during a vehicle's motion.

Ring brake **-** A type of brake characterised by force being applied to both sides of a ring rotor, thereby creating braking torque.

Robust **-** Able to survive and operate properly in a severe environment.

Rule evaluation **-** Output values are computed per the input memberships and their relationship to the output memberships; the number of rules is usually set by the total number of input memberships and the total number of output memberships; the rules consist of *IF inputvarA* is *x*, *AND inputvarB* is *y*, *THEN outvar* is *z*.

Semicustom MCU **-** An microcontroller unit (MCU) that incorporates normal MCU elements plus application-specified peripheral devices such as higher-power port outputs, special timer units, etc.; mixed semiconductor technologies, such as high-density CMOS (HCMOS) and bipolar analog, are available in a semicustom MCU; generally, HCMOS is limited to 10 V_{DC}, whereas bipolar-analog is suitable to 60 V_{DC}.

Slip threshold switch **-** A switch for escalation of indispensable slip threshold on sand and loose gravel that realise maximum traction on these on-off road surfaces.

***Specific energy (energy density)* -** Energy storage capability per unit mass of the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel [Wh/kg].

***Specific power (power density)* -** Power delivery capability per unit mass of the CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel [W/kg].

***State of charge (SoC)* -** The CH-E/E-CH storage battery, ultracapacitor, ultrainductor, or ultraflywheel level of charge can be stated as either DoD or SOC.

***Switchover valve* -** A valve to switch over of the fluidic performance from normal braking to ASR performance.

***Throttle valve control (TVC)* -** An ASR actuator for modulation of the throttle angle.

***Vertical split 4WB BBW dispulsion system* -** AWB dispulsion system configura-tion in which both front brakes are on one channel and both rear brakes are on an other channel.

***Wheel slip* -** The difference between tangential wheel velocity and vehicle velocity; a rolling wheel-tyre with no braking torque on it exhibits null percent (0%) slip; a non-rotating wheel-tyre on a moving vehicle exhibits full percent (100%) slip.

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Acronyms

AB	Auto-box
ABS	Anti-lock braking system; anti-locking brake system
ABW	Absorb-by-wire
AC	Adaptive cruise
ACC	Adaptive cruise control
ACMC	Adaptive cruise mechatronic control
ADA	Active driving assist
ADAMS	Automatic dynamics analysis of mechanical systems
A/D	Analog-to-digital
AE	All-electric
AEMC	Active engine management control
AEV	All-electric vehicle
AF	All-fluidical
AFC	Alkaline fuel cell
AFR	Air-fuel-ratio
AFV	All-fluidic vehicle
AGT	Automotive gas turbine
AH	All-hydraulic
AHED	Advanced hybrid-electric wheel drive
AHV	All-hydraulic vehicle
AI	Artificial intelligence
ALD	Active-brake limited-slip differential
A-MT	Automatic manual transmission
AP	All-pneumatic
APT	Automatic power-shift transmission
APU	Auxiliary power unit
APUT	Axleless progressively-variable transmission
APV	All-pneumatic vehicle
AR&BC	Active roll and body control
ARC	Active roll control
ARP	Active rollover protection
ARS	Active roll stabilisation
ASIC	Application specific integrated circuit
ASIM	Application specific integrated matrixer
ASR	Automatic slip regulation; anti-spin regulation
AT	Automatic transmission
ATC	Automatic traction control
ATF	Automatic transmission fluid
ATMC	Adaptive traction mechatronic control
AWA	All-wheel absorbed; all-wheel-absorb

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AWB	All-wheel braked; all-wheel-brake
AWD	All-wheel driven; all-wheel-drive
AWS	All-wheel steered; all-wheel-steer
AYC	Active yaw control
BA	Brake assists; brake assistance
BAC	Brake assist control
BAS	Brake assists system
BB	Brake booster
BBW	Brake-by-wire
BCC	Body-centred cubic
BDC	Bottom dead centre
BEV	Battery-electric vehicle
BFD	Brake force distribution
BM	Brake master
BPSU	Brake pedal sensor unit
BPU	Brake pedal unit
BSP	Bit stream processor
BTT	Bottom-to-top
CA	Collision avoidance
CAD	Computer-aided design
CAE	Computer-aided engineering
CAFE	North American Corporate Average Fuel Economy
CAN	Controller area network
CARB	California Air Resource Board
CCP	Cold-combustion process
CDC	Continuous damping control
CH-E	Chemo-electrical
CH-TH-F-M	Chemo-thermo-fluido-mechanical
CH-TH-F-M-E	Chemo-thermo-fluido-mechano-electrical
CH-TH-F-M-E-M	Chemo-thermo-fluido-mechano-electro-mechanical
CIL	CPU interface logic
CIM	Column integration module
CLUS	Cluster
CMT	Constant-mesh manual transmission
CNG	Compressed natural gas
CNI	Communication network interface
CoG	Centre-of-gravity
CPC	Central powertrain controller
CPU	Central processing unit
CSMA/CR	Carrier sense multiple access/collision resolution
CSMD/CD	Carrier sense multiple access collision detection
CSR	Control and status register; Cambridge silicon radio
CSV	Critical sliding velocity
CVJ	Constant-velocity joint

CVT	Continuously variable transmission
CWD	Centre-wheel-drive
D	Derivate
DBL	Dynamic bending light
DBW	Drive-by-wire
DE	Distributed embedded
DI	Direct injection
DLL	Data link layer
DLT	Dynamic load transfer
DMC	Driveline mechatronic control
DMFC	Direct methanol fuel cell
DoE	U.S. Department of Energy
DoF	Degrees-of-freedom
DSC	Dynamic stability control
DSP	Digital signal processor
DSTC	Dynamic stability traction control
DYC	Direct yaw-moment control
EAS	Electronic actuation system; electronic air suspension
EBD	Electronic brake-force distribution
ECB	Electronic control bit
ECD	Electronic control device
ECE	External combustion engine
ECI	Electronic control instrument
ECU	Electronic control unit
ED&MC	Emergency disconnect-and-main contactors
EEB	Electrical energy booster
EEC	Electrical energy charger
EED	Electrical energy distribution
EES	Electrical energy source
EGR	Exhaust gas re-circulation
EFMB	Electro-fluido-mechanical braking; electro-fluido-mechanical brake
ELV	End of life vehicle
EMB	Electro-mechanical brake
EMC	Engine management control; electromagnetic compatibility
EMF	Explicit model following
EMI	Electromagnetic interference
EML	Error management logic
EMVT	Electro-mechanical valve train
EPAS	Electric power assisted steering
EPB	Electric parking brake
EPC	Engine performance control

EPMB	Electro-pneumo-mechanical braking; electro-pneumo-mech-anical brake
EPS	Electric power steering
ER	Electro-rhlogical
ERF	Electro-rheological fluid
ESAS	Electric steer-assisted steering
ESD	Energy store device
ESP	Electronic stability programme
ESS	Electronic stability system
ESU	Energy supply unit
ET	Electro-mechanical transmission
ETC	Electronic throttle control
ETP	Eventitriggered protocol
ETP/A	Event-triggered protocol class A
ETP/B	Event-triggered protocol class B
ETP/C	Event-triggered protocol class C
E&IN	Energy-and-information network
E&PF	Engined and/or pumped flywheel
E-CH	Electro-chemical
E-F	Electro-fluidical
E-M	Electro-mechanical
E-M-F	Electro-mechano-fluidical
E-M-P	Electro-mechano-pneumatical
E-TMC	Engine-transmission management controller
FA	Full authority
FADEC	Full-authority digital engine control
FAT	Fully-automatic transmission
FBL	Fixed bending light
FBW	Fly-by-wire
FC	Fuel cell
FCEV	Fuel cell-electric vehicle
FD	Fluido-dynamic
FDI	Fault detectionand isolation
FE	Fijalkowski engine
FES	Fluidical energy store
FE-G/M	Fijalkowski engine-generator/motor
FIFO	First-in-first-out
FJ	Flexible joint
FL	Fuzzy logic
FMB	Fluido-mechanical brake
FO	Fibre optic
FS	Fluido-static
FT	Fault-tolerant
FTB	Fijalkowski turbine boosting

FTCOM	Fault-tolerant COM
FWD	Front-wheel driven; front-wheel-drive
FWS	Front-wheel steering
F-F	Fluido-fluidical
F-M	Fluido-mechanical
GA	Genetic algorithm
GCC	Global chassis control
GERF	Giant-electro-rheological fluid
GTC	Gear-shifting transmission control
GTMC	Gear-shifting transmission mechatronic control
GT-G/M	Gas turbine-generator/motor
HCC	Highway cruise control
HD	Human driver
HE	Hybrid-electric
HES	Hydraulical energy store
HEV	Hybrid-electric vehicle
HF	Hydro-fluidic
HFC	Hydro-fluorine-carbons
HFV	Hybrid-fluidic vehicle
HHV	Hybrid-hydraulic vehicle
HILS	Hardware-in-the-loop simulation
HMB	Hydro-mechanical brake
HMI	Human-machine interface
HP	Hydro-pneumatical; human pilot
HPS	Hybrid power system
HPV	Hybrid-pneumatic vehicle
HW	Hand wheel
H&TD	Human and/or telerobotic driver
IA	Inter-axle
ICE	Internal combustion engine
IEMC	Ion exchange membrane fuel cell
IFSC	Integrated front steering control
IFW	Inner-front wheel
ILC	Intelligent lighting control
IMES	Inertial mechanical energy storage
I/O	Input/output
IPC	Integrated powertrain control
IPM	Interior permanent magnet
IPMC	Integrated mechatronic control
IRW	Inner-rear wheel
ISS	Integrated safety system
ITS	Intelligent transport system
IVC	Integrated vehicle control
IVCS	Integrated vehicle control system

IVS	In-vehicle sensor
IWD	Inter-wheel drive
LAC	Lane-keeping assist control
LAN	Local area network
LEP	Light-emitting diode
LEV	Low-emission vehicle
LiIon	Lithium ion
LIN	Local interconnect network
LiPolymer	Lithium polymer
LMC	Lane-keeping monitoring control
LQFP	Low-profile quad flat package
LQR	Linear quadratic regulator
LSC	Lane-keeping support control
LTR	Load transfer ratio
LVC	Low-voltage cut-off
LWC	Lane-keeping warning control
MAB	Micro-auto-box
MBM	Message buffer memory
MBT	Main battle tank
MCFC	Molten carbonate fuel cell
MCU	Microprocessor unit
MEDL	Message descriptor language
MEMS	Micro-electro-mechanical system
MES	Mechanical energy store
MOST	Media oriented systems transport
MGV	Manned ground vehicle
min BSFC	min best SFC
MMB	Mechano-mechanical brake
MMD	Magneto-mechano-dynamical
MMU	Memory management unit
MR	Magneto-rheological
MRF	Magneto-rheological fluid
MSC	Message state counter
MSI	Mild-soft iron
MT	Manual transmission
M&GF	Motorised and/or generatorised flywheel\
M-E	Mechano-electrical
M-F	Mechano-fluidical
M-H	Mechano-hydraulical
M-M	Mechano-mechanical
M-P	Mechano-pneumatical
NaS	Sodium-sulphur
NF	Neuro-fuzzy
NHTSA	National Highway Traffic Safety Administration

NiCd	Nickel-cadmium
NI	Network infrastructure
NiMH	Nickel-metal hydride
NMRF	Nano-magneto-rheological fluid
NN	Neural network
NTU	Network time unit
OEM	Original equipment manfacture
OF	Optical fibre
OS	Operating system
PAC	Parking assist control
PAFC	Phosphoric acid fuel cell
PB	Pedal box
PbAcid	Lead acid
PBI	Pre-crash brake force intervention
PCS	Polymer clad silica
PDC	Preview distance control
PEC	Pollutant emission capability
PEFC	Polymer electrolyte fuel cell
PEIT	Powertrain equipped with intelligent technology
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PES	Primary energy source; pneumatical energy store
PFS	Pedal feel simulator
PI	Proportional-integral
PID	Proportional-integral-derivative
PLL	Phase-locked loop
PMB	Pneumo-mechanical brake
PMC	Powertrain mechatronic control
PPS	Pedal position sensor
PS	Pedal simulator
PSM	Porsche stability management
PTC	Powertrain controller
PWM	Pulse width modulation
P&P	Plug-and-play
P-M	Pneumo-mechanical
P2P	Pear-to-pear
RBW	Ride-by-wire
RCC	Radar cruise control
RFI	Radio frequency interference
RT	Real-time
RPM	Rollover prevention metric
RPS	Rapid prototyping system
RTOS	Real-time operating system
RWD	Rear-wheel driven; rear-wheel-drive

RWS	Rear-wheel steering
RZM	Rear zone module
R&D	Research-and-development
R&P	Rack-and-pinion
RH&S	Ride handling and stability
RM-TM	Rotary motion-to-trandlational motion
SAE	Socity of Automotive Engineers
SAT	Semi-automatic transmission
SB	Storage battery
SBC	Sensotronic brake control
SBME	Specific basic mechanical energy
SBW	Steer-by-wire
SCS	Stability control system
SES	Secondary energy store
SEES	Super-insulator electric-field energy storage
SFC	Specific fuel consumption
SIL	Safety integrity level
SKME	Specific kinetic mechanical energy
SLI	Starting, lighting and ignition
SM	Stability margin
SMA	Scalable modulr architecture
SMES	Super-conductor magnetic-field energy storage
SMT	Synchronised manual transmission
SoC	State-of-charge; system-on-chip
SoF	Start-of-frame
SOFC	Solid oxide fuel cell
SoH/SoC	State of health/state of charge
SPEFC	Solid polymer electrolyte fuel cell
SPFC	Solid polymer fuel cell
SPR	Side pull ratio
SS	Start-stop
SSF	Static stability factor
STA	North American Surface Transportation Act
SUV	Smart utility vehicle
S&G	Start-and-stop
SM&GW	Steered, motorised and/or generatorised wheel
SM&PW	Steered, motorised and/or pumped wheel
TC	Traction control; torque converter
TCC	Traction converter clutch
TCL	Transceiver control logic
TCS	Traction control system
TCU	Transmission control unit
TDC	Top dead centre
TDMA	Time-division multiple access

TDUF	Twin-disc ultra-flywheel
TMD	Torque management device
TT	Time-triggered
TTA	Time-triggered architecture
TTC	Time-triggered communications
TT-CAN	Time-triggered controller area network
TTP	Time-triggered protocol
TTP/A	Time-triggered protocol/class A
TTP?B	Time-triggered protocol/class B
TTP/C	Time-triggered protocol/class C
TTR	Through-the-road; tilt table ratio
TVC	Throttle valve control
TVMC	Throttle valne mechatronic control
TWC	Three-way-catalytic
TM-RM	Translational motion-to-rotary motion
TH-M	Thermo-mechanical
T-R	Time-to-rollover
UGV	Unmanned ground vehicle
UJ	Universal joint
ULEV	Ultra-low-emission vehicle
VC	Viscous coupling; vehicular controller
VDC	Vehicle dynamics control
VDS	Vehicle disabling system
VI	Virtual instrument
VIV	Variable isolation valve
VLSI	Very large scale integration
VSC	Vehicle stability control
VSE	Vehicle stability enhancement
VT	Viscous transmission
VVC	Variable valve-timing control
VZEV	Virtual zero-emission vehicle
VS&H	Vehicle stability and handling
WAP	Wireless application protocol
WRC	World Rally Championship
WWC	Windshield washer control
YSC	Yaw stability control
ZEV	Zero-emission vehicle
XBW	X-by-wire
4WA	Four-wheel absorbed four-wheel-absorb
4WB	Four-wheel braked; four-wheel-brake
2WD	Two-wheel driven; two-wheel drive
4WD	Four-wheel driven; four-wheel-drive
2WS	Two-wheel ateered
4WS	Four-wheel steered; four-wheel-steer

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