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09 | September 2009 Volume 111
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Technology Trends at the IAA 2009

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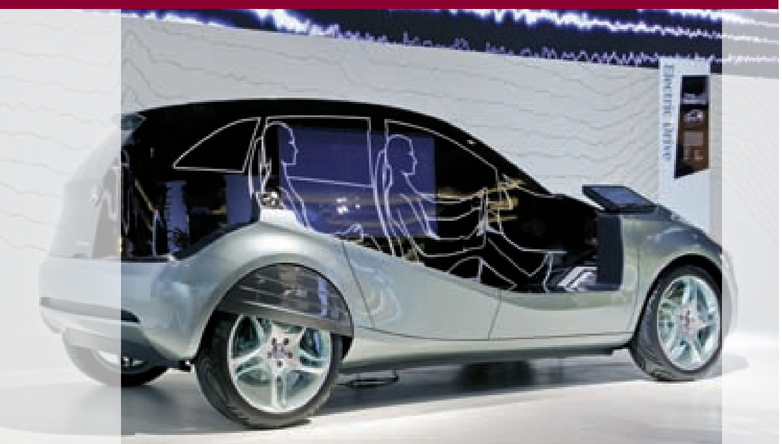
Technology Trends at the IAA 2009



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A total of 700 exhibitors, including more than 60 car makers from all over the world, will be presenting their world premieres at the **63rd IAA Cars** in 2009. In this report, ATZ presents some of the latest technology trends, especially concerning the electrification of the powertrain, lightweight design and innovative safety systems.

COVER STORY

DEVELOPMENT

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Is the IAA Still Worthwhile?

Dear Reader,

Due to the economic crisis, some vehicle manufacturers and many suppliers have decided not to participate in this year's IAA. I assume that the decision not to be part of the automotive industry's leading platform was taken very carefully in each individual case and that no one is making symbolic gestures for political reasons. All the same, it is regrettable and I will miss them at the show. After all, the majority of the industry's leaders will still be present in Frankfurt, also thanks to the clever policy of the VDA to accommodate the wishes of suppliers by offering special opening times for individual halls. As a result, I consider a visit to Frankfurt to be an obligation. I would like to expressly invite you to plan a visit to the IAA regardless of your company's decisions or travel restrictions. In case of doubt, you might simply take a day's holiday. That would be a good signal. No other platform allows you as an engineer to „absorb" the current state of the art in engineering and technology in the space of one or two days. Conversations with colleagues at the exhibits will expand your horizons for future decisions at work.

Three mega issues become apparent this year: the electrification of the powertrain, lightweight design and innovative safety systems. A particularly exciting topic will be powertrain technology. Automobiles with further developed internal combustion engines, hybrid and purely electric cars compete for the public's favour. Some innovations have already been announced in previews (the latest information is always available at ATZonline.com), but there is no doubt that the show will reveal numerous premieres that are still subject to strict secrecy.

For those who are really unable to make it to the show, we will of course be providing detailed reports in ATZ and at our online portal.

I look forward to seeing you in Frankfurt.

Johannes Winterhagen
Würzburg, 6 August 2009

Johannes Winterhagen
Editor-in-Chief

ATZ WORLDWIDE
09|2009

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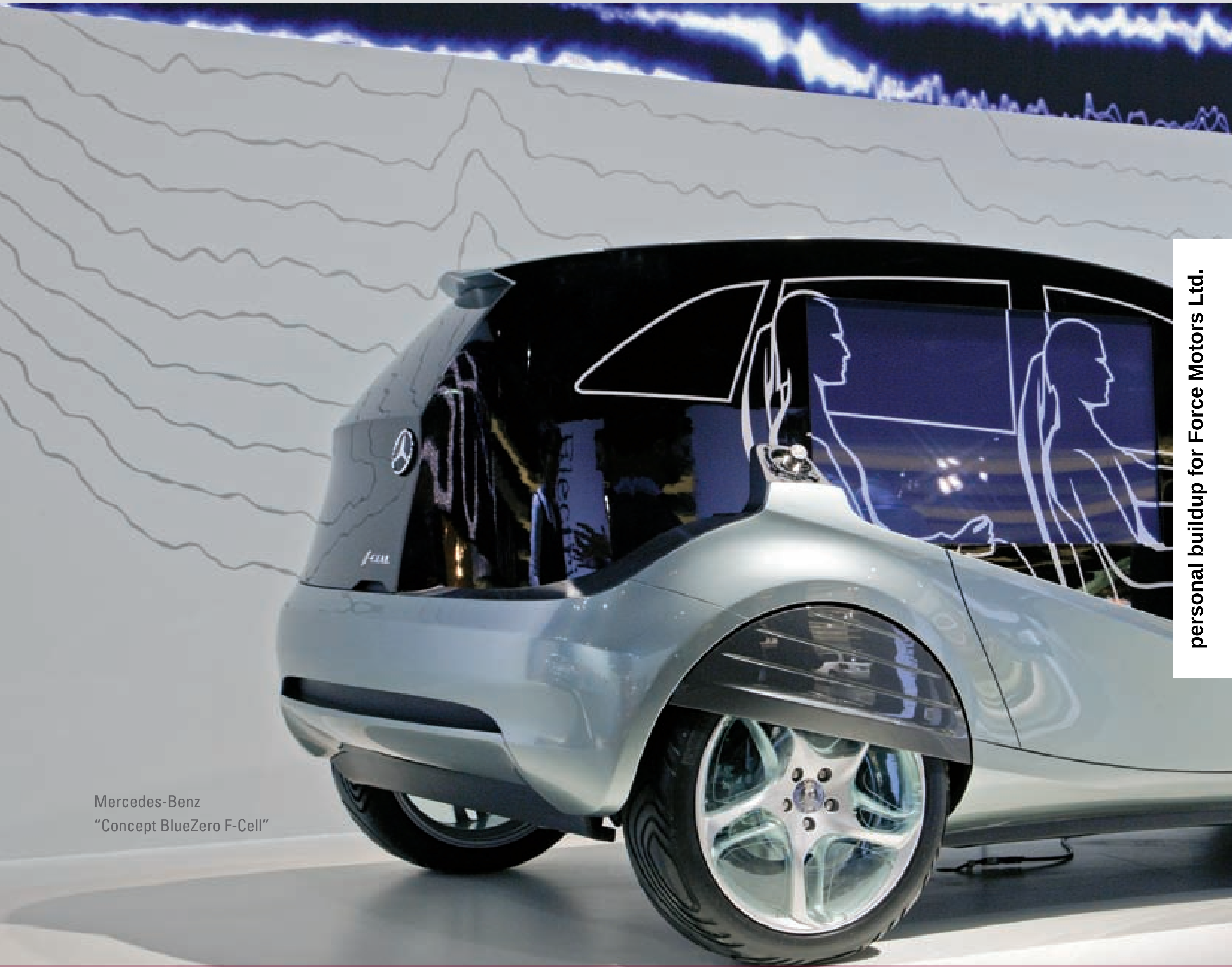
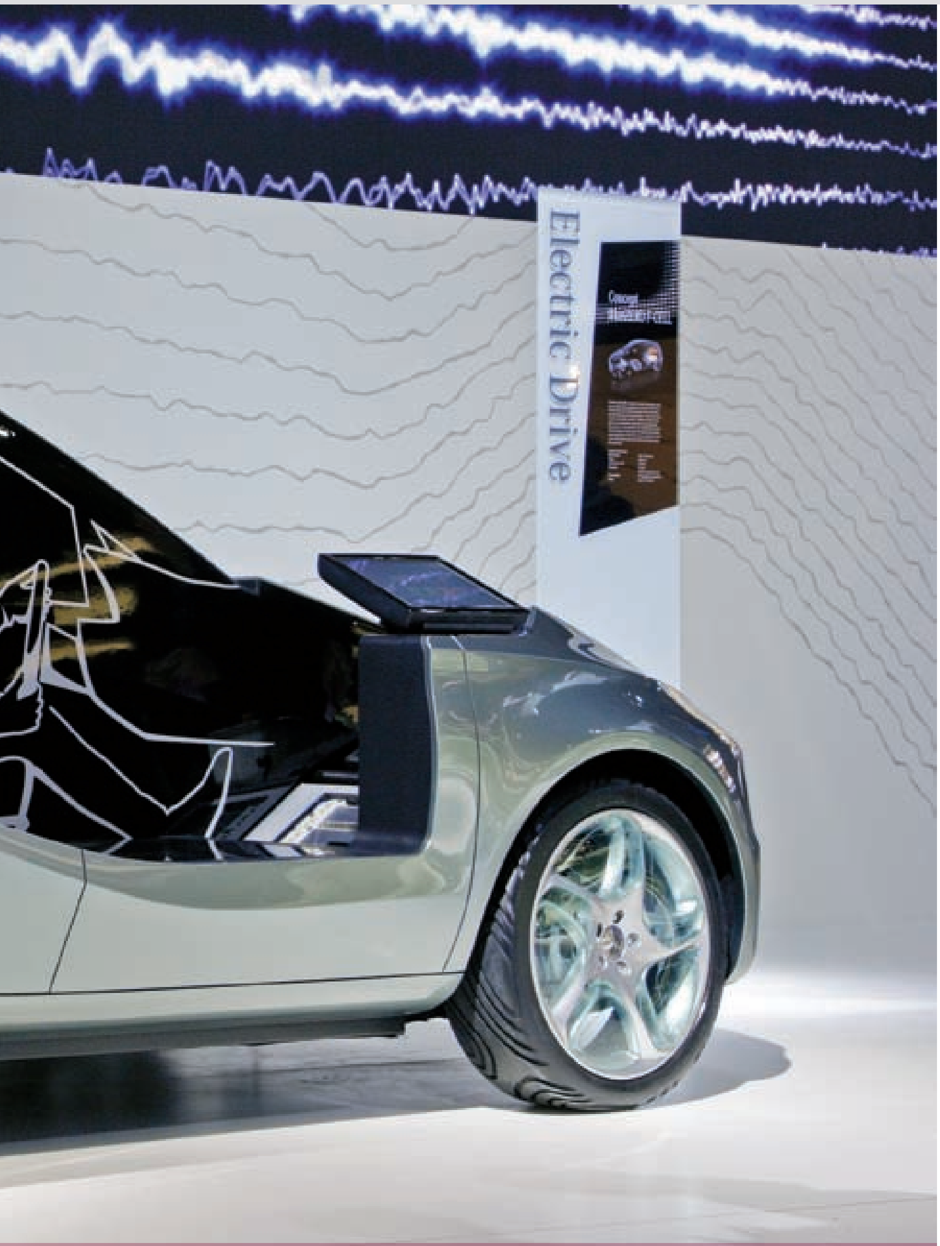


Mercedes-Benz
"Concept BlueZero F-Cell"

Technology Trends at the IAA 2009

A total of 700 exhibitors, including more than 60 car makers from all over the world, will be presenting their latest products at the 63rd IAA Cars from 17 to 27 September 2009. In this report, ATZ covers some of the latest technology trends, with a focus on ongoing reductions in fuel consumption and therefore in CO_2 emissions, as a result of improvements in drive systems and the use of lightweight designs, together with innovative safety systems.



1 Introduction

The slogan of this year‘s exhibition, „A Moving Experience“, continues the IAA‘s central theme of sustainable mobility which began in 2007. The exhibition will showcase further improvements to traditional powertrains, including clean diesels and turbocharged gasoline engines with direct injection, and also progress in vehicle electrification, ranging from mild hybrids to pure electric propulsion systems. Car manufacturers have also found further potential for cutting fuel consumption by using lightweight structures: reducing the weight of a medium-sized car by 100 kg can result in fuel savings of around 0.3 litres per 100 km.

In addition, as in previous years the IAA will be focusing on innovative safety and comfort systems.

2 Drive Systems

Over recent years introducing further reductions in fuel consumption and emissions has become a major concern for car manufacturers throughout the world because, on the one hand, the world‘s reserves of fossil fuels are gradually running out and, on the other hand, cars have to meet increasingly strict environmental regulations.

2.1 Three Cylinders are Conceivable in a Mid-range Car

In good time for the IAA, Mercedes-Benz is introducing onto the European market the diesel versions of the GL, M and R-Class models, which were launched in the USA in 2008, with the clean BlueTec exhaust treatment system. All new BlueTec models already comply with the Euro 6 emissions standard, which is due to come into force in 2014. By the end of this year, the company will be offering 58 environmentally friendly BlueEfficiency models, with this figure increasing to 76 in 2010. Like many other manufacturers, Daimler‘s long-term goal is emission-free driving using electric drive systems. However, instead of choosing a single solution, the company is focusing on three main areas: the optimisation of the internal combustion engine, further efficiency improvements with tailor-made hybridisation and local emission-free driving using fuel-cell and battery-powered vehicles. The company has extensive experience of alternative drive systems. Daimler‘s fleet of fuel-cell vehicles has already covered 4.5 million test kilometres and 100 electric Smart cars have been on the road in London since 2007. This year will see the start of small-scale production of the Smart Fortwo Electric Drive, **Figure 1**, and the B-Class F-Cell with a fuel cell drive system. These will be joined in 2010 by a battery-powered A-Class model.

The BlueZero concept car represents a key trend in the electrification of the powertrain. For this concept, Mercedes-Benz has developed a modular hybrid system that offers various possibilities for increasing the performance and the range of applications of the car. Hybrid modules with different levels of power and batteries with a corresponding capacity can be combined with a variety of gasoline and diesel engines. Like the four- and six-cylinder internal combustion engines, all the hybrid modules are compatible with the 7G-Tronic automatic transmission. According to Mercedes-

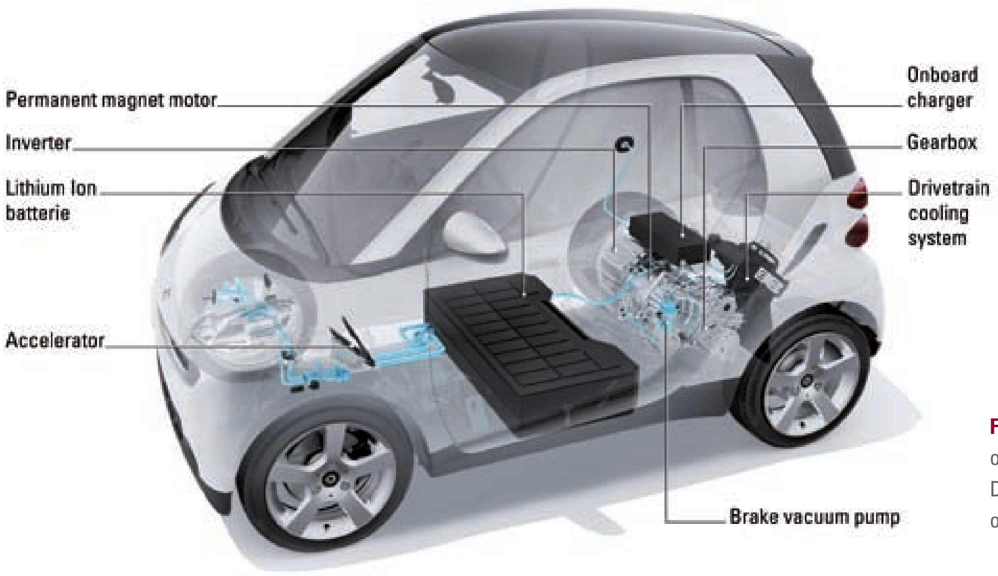


Figure 1: Small-series production of the Smart Fortwo Electric Drive is to start before the end of 2009

Benz, this makes it possible to provide all the variants of hybrid drive systems, from mild hybrids through to full hybrids. A further option is the plug-in hybrid, in which the battery can additionally be recharged from the mains in order to increase the electric driving range.

In common with almost all other manufacturers, Mercedes-Benz is working on downsizing and turbocharging its internal combustion engines, combined with direct fuel injection for the gasoline engines. According to Mercedes-Benz, its new, high-torque, 2.15 litre, four-cylinder diesel engine is ideal for use in the S-Class and is likely to offer fuel consumption of less than 4 litres per 100 km. The company is also of the opinion that a three-cylinder engine in the C-Class is also quite conceivable. More information on this subject is promised for the IAA.

2.2 En Route to 95 Grams of CO_2 Emissions

The world's largest automotive supplier, Bosch, is optimistic when it comes to achieving future CO_2 limits for cars. The company is convinced that the internal combustion engine alone offers around 30 % potential for improvement. According to Bosch, hybridisation and other vehicle-related changes can reduce the diesel consumption of a compact car to as little as 2.6 litres per 100 km.

Bosch highlights the growing significance of electric drive systems in the long term. However, in the short and medium term the optimisation of the internal combustion engine is the most important means of reducing vehicle CO_2 emissions quickly and effectively. For this reason, the company has put together various technology packages to improve fuel consumption in stages.

Bosch bases its demonstration on the example of an imaginary lower mid-range car weighing 1400 kg. The basic vehicle

Not at the IAA, but Trendsetting: Thermomanagement by Behr for Electric Cars

Up to 50 % of the battery capacity might be needed for cooling and heating in an electric car if drivers are not prepared to give up what they are used to. Thermal management in the vehicle will compete with the powertrain for the valuable electric energy available. In order to ease the conflict of distributing the energy between driving the wheels and thermal management, Behr is working on a solution to reduce the requirements regarding climate comfort in certain driving situations. The company is developing an operating strategy to deal with the case of a vehicle that is only able to reach its destination or a charging station by extending its normal driving range. One possibility is to provide the air-conditioning system with different options: a comfort style, a range style and perhaps a third, medium style.

When the range style is selected, the power requirement of the air-conditioning system can be reduced, for example by cooling the interior more slowly, by selecting a higher interior temperature or by reducing the airflow through the interior. To enable drivers to make an optimum decision between the different styles to suit their needs and those of the other vehicle occupants, the battery management system must be able to calculate the effects of the selected style on the range and journey time. The input of the destination and route planning can be achieved by interconnection with the navigation system. This also makes it possible to take traffic reports and traffic jams into consideration.

Due to the high level of complexity involved, future thermal management for the vehicle interior and the lithium ion battery will require close cooperation between OEMs and system suppliers. According to Behr, the issues of battery cooling and electrochemistry have to be addressed in an interdisciplinary manner.

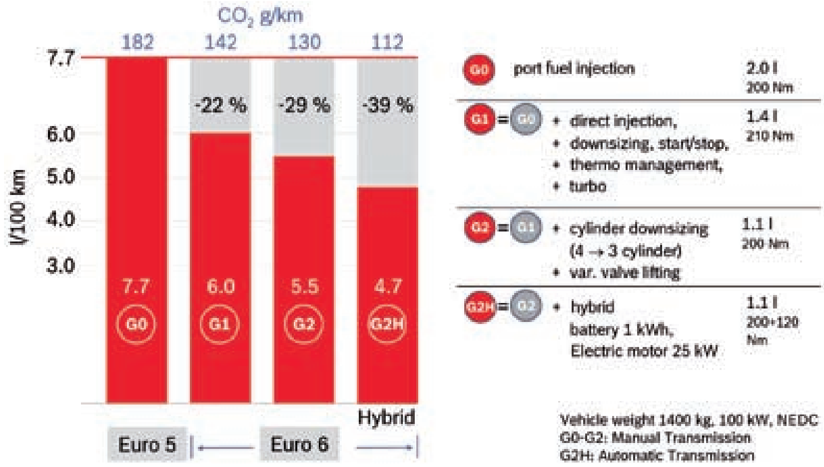


Figure 2: Technology packages from Bosch for CO_2-optimised gasoline engines – advantages in fuel consumption

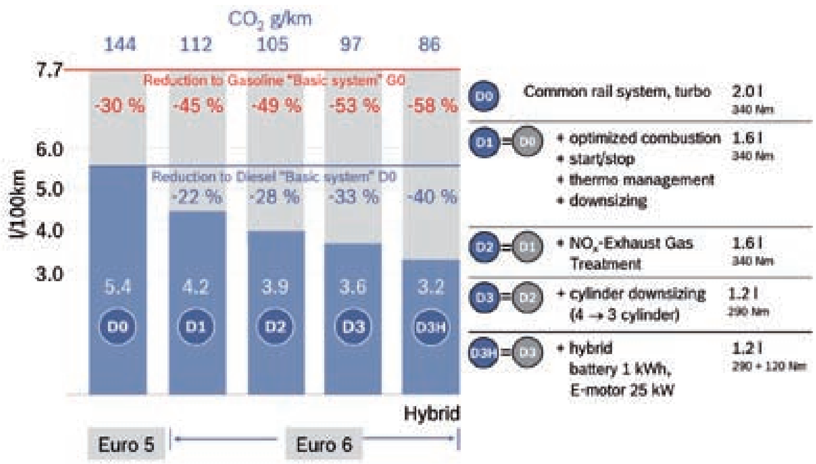


Figure 3: Technology packages from Bosch for CO_2-optimised diesel engines – advantages in fuel consumption

has a 2-litre, four-cylinder gasoline engine with a power output of 100 kW and 200 Nm of torque. The car's emissions levels are 182 g of CO_2 per kilometre.

The first stage of the technology package, **Figure 2**, involves reducing the engine capacity to 1.4 litres and adding direct injection and turbocharging. In addition, a start/stop system is used with a resulting saving of 22 % of CO_2. According to Bosch, if the second technology package is added, a further 7 percentage point cut in emissions is possible. This involves reducing the engine capacity to 1.1 litres by removing one cylinder. An increase in the turbocharger boost pressure from 1.8 to 2.4 bar, together with variable valve timing, ensures that engine continues to produce more than 200 Nm of torque. If all of these measures are not sufficient, Bosch suggests hybridisation using a 25 kW electric machine. This would allow a further reduction of 10 % in CO_2 emissions compared with the basic model. However, whereas the cost of the first two technology packages would be recovered within three years, given an annual mileage of 15,000 km, this would take very much longer in the case of the hybrid version.

The ideal changes are rather different when it comes to the diesel engine, **Figure 3**. Although this engine also has a displacement of 2 litres and produces 340 Nm of torque, the vehicle emits only 144 g of CO_2. In this case, the first step, according to Bosch, would be to reduce the engine's displacement to 1.6 litres. The mean effective pressure could also be at least maintained by using higher injection and charge pressures. The next issue is to decide how to achieve the NO_x limits specified by Euro 6. With higher engine-out emissions and an SCR catalytic converter, it is possible to achieve fuel consumption savings of six percentage points. The next step is more radical: the diesel engine can also be downsized to three cylinders with a resulting displacement of only 1.2 litres.

According to Bosch, the diesel engine can also be hybridised, albeit with a less favourable cost/benefit ratio. With the same electric equipment, an improvement in fuel consumption of seven percentage points is possible, which is a relatively small reduction. The company explains the additional costs not only in terms of the reduced fuel consumption, but also in relation to the added value, such as virtual four-wheel drive.

2.3 Electrifying the Powertrain

Many examples in addition to those of Daimler and Bosch indicate the growing importance of electrifying the powertrain. In a few years' time, there will hardly be any new vehicles without a simple start/stop system and the recuperation of braking energy by the vehicle's electrical system. Hybrid drive systems, from mild hybrids to full hybrids, with or without „plug-in" recharging capability from the mains power supply, are seen by experts as an intermediate step towards the electric vehicle. All car makers and many suppliers and development service providers are working intensively on technically and economically viable solutions. They have presented a number of vehicles that are being gradually introduced onto the market, such as the BMW 750 Hybrid, the new Honda Insight, the Mercedes-Benz S 400 Hybrid and ML 450 Hybrid, the Porsche Cayenne, the Toyota Prius III and the VW Touareg V6 TSI Hybrid, to mention just a few models and manufacturers. Bosch believes that the additional costs of a mild hybrid system for the car maker, including a small lithium-ion battery, will in future be „at the level of a highly efficient diesel powertrain", but its fuel consumption in the NEDC cycle will be up to 15 % lower than that of a direct-injection gasoline engine. The fuel saving offered by a full hybrid system that also allows purely electric driving for a short time is as much as 25 % in the NEDC. However, Bosch puts

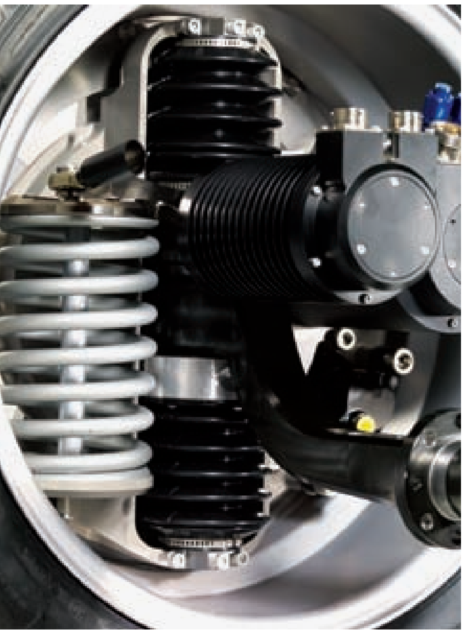


Figure 4: Michelin's market-ready wheel hub motor is scheduled to go into series production as early as 2010

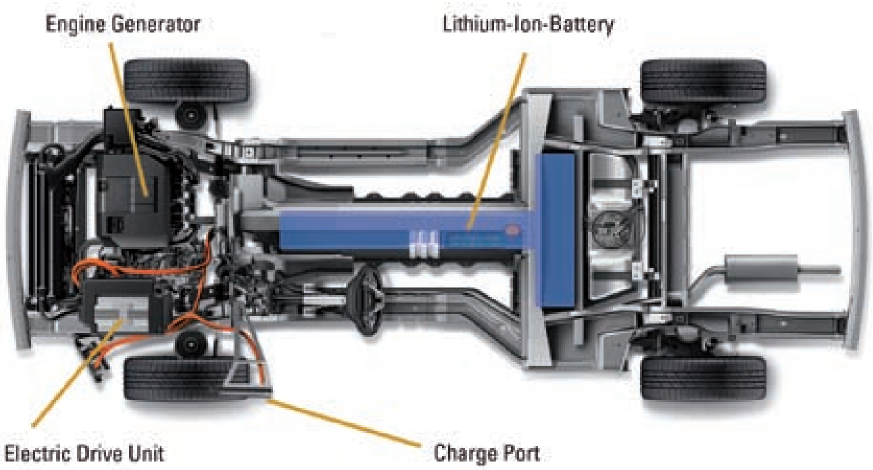


Figure 5: Opel Ampera – the 16 kWh capacity of its lithium ion battery is enough to drive for around 60 km

the additional costs of the system at around one-and-a-half times those of a mild hybrid.

The electric powertrain is a highly efficient concept. One kilowatt hour of energy in a conventional internal combustion engine allows the vehicle to be driven for between 1.5 and 2.5 km. A diesel hybrid will achieve a maximum of 3.2 km. An electric motor converts one kilowatt hour into more than 6.5 km. How quickly electric vehicles become established on the market depends above all on the high-cost battery technology. In terms of drive systems, the next innovative step may well be wheel hub motors. Michelin recently presented a fully developed wheel hub motor that will go into volume production as early as 2010, **Figure 4**. In addition to the electric motors, the Michelin engineers have also succeeded in accommodating the brakes and the springs in the wheel hub.

There has been much talk lately about hybrids with a range extender, that is, with an internal combustion engine that drives a generator to recharge the battery during long journeys, thus supplying energy for the electric motor. The advantages of this include fewer components on the vehicle which reduces costs and weight compared with a parallel hybrid. For example, the transmission of the internal combustion engine and the conventional alternator can be dispensed with. Furthermore, compared with a pure electric vehicle, the battery can be made smaller, which also reduces costs and weight. In principle, the use of a range extender makes it possible to cover distances comparable with those of a conventionally powered vehicle. Chevrolet will start volume production of the first electric vehicle with a range extender, the Volt, in 2010. The 16 kWh output of its lithium-ion battery will be sufficient for a range of around 60 km. After this, a 1.4 litre gasoline engine producing 55 kW starts up and runs at a constant speed of 2000 rpm to power a generator and recharge the battery. The Opel Ampera, **Figure 5**, is based on the Chevrolet Volt. Other concepts use smaller, less powerful but also more economical range extender internal combustion engines with power outputs of up to 28 kW. AVL is working not only on simple four-stroke engines, but also on two-stroke engines and even, like the FEV, on rotary engines as range extenders. Mahle is currently examining the potential of the range extender system in a specially commissioned study.

3 Lightweight Design: Plastic Reduces Weight

The trend towards lightweight design is continuing. ZF Friedrichshafen AG is currently working with various project partners from research and industry on an active lightweight chassis, **Figure 6**, made of fibre composite materials.

The chassis will have driving dynamics, safety and comfort features similar to those of a conventional chassis, but will weigh significantly less and can be produced cost-effectively on a large scale. According to ZF, a lighter chassis not only results in better driving dynamics and improved comfort, it also allows a less powerful engine to be used without compromising on performance.

In addition to improved design and adaptronics, the project will also focus on developing a cost-effective production concept, as attempts to integrate fibre composite materials into the chassis have often failed because of a lack of suitability for volume production. Alongside ZF, the project, which is scheduled for completion in mid-2011, involves other partners from industry and research, including the German Aerospace Centre, the Fraunhofer Institute for Chemical Technology, the Institute of Aircraft Design at Stuttgart University, DSM Composite Resins Deutschland GmbH and 3B Fibreglass.

ContiTech Vibration Control is the first automotive supplier to develop a bush bearing made of particularly high-strength plastic for the transmission mounts of luxury cars. This new plastic transmission mount is one of the first

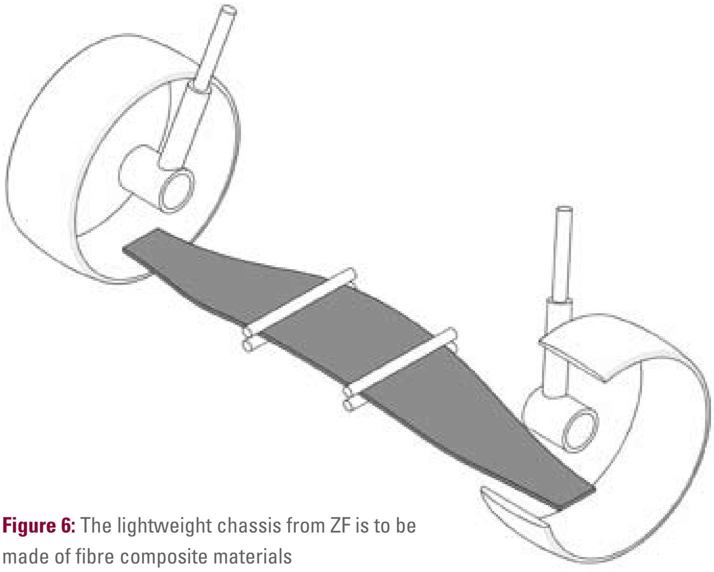


Figure 6: The lightweight chassis from ZF is to be made of fibre composite materials

lightweight load bearing components to be used in the automotive industry. It is fitted as standard in the latest models of the BMW 740i and BMW 750i and will also be introduced into other mid-size and luxury vehicles from BMW.

The innovative bearing is manufactured as a modular system and can be designed as a conventional or hydraulic mount. Depending on the requirements of each application, the damping behaviour and stiffness of the component can be adapted to different engine and transmission combinations. The modular design has made it possible to reduce the number of different parts needed for different versions. Both the conventional and the hydraulic bearing have a plastic housing based on the glass-fibre-reinforced polyamide PA 6.6. This offers a high level of energy absorption and combines high strength with resistance to heat deformation and chemicals.

4 Safety For All

Vehicle manufacturers and automotive industry suppliers are working to introduce modern safety systems into all classes of car. The importance of these measures has increased as a result of the current recession which has caused a growth in demand throughout the world for small and compact cars. In addition, the price-sensitive markets in Eastern Europe and Asia will see the largest increase in new vehicle sales over the next few years. Experts believe that demand in the four BRIC countries alone (Brazil, Russia, India and China) will grow to more than 20 million cars by 2015, which represents a doubling in growth in only ten years.

The key to increased safety in low-cost vehicles lies in the combination of networked components and functions, scalable safety systems and lower costs. For example, the electronic stability program, which is a requirement in all new vehicle models in Europe from November 2011 onwards, offers a range of stability control functions. By networking the system with other components, it can intervene directly, for example, in electric steering systems.

In order to maintain or even improve the efficiency of increasingly complex vehicle architectures, manufacturers are focusing on combining control units. As an example, Continental has developed a second generation of its central control unit, the Chassis and Safety Controller, which can relieve the pressure on the vehicle data architecture and coordinate the safety systems by bundling and analysing all the data, **Figure 7**.

According to Continental, it can be easily adjusted to different model sizes and adapted to suit the manufacturer's requirements. Another example is the integration of longitudinal acceleration and yaw sensors in the airbag or ESP control unit. The resulting system is more compact and has a smaller number of housings and cable and plug connections. Another benefit is the increased reliability of the system as a whole.

The possible extent of system scalability is indicated by the new-generation electronic brake system which Continental aims to launch in 2011. The MK100 will be based on a modular system which can be designed to meet specific requirements. According to Continental, it can be used as a motorcycle ABS system with or without an integral braking function, but can also provide high-end ESC, safety and assistance functions. These include active rollover protection, trailer stabili-

Figure 7: The central „Chassis and Safety Controller" from Continental

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ty assisst, hill start assist and full speed range adaptive cruise control (FSA).

BMW, Bosch, Continental, Daimler and Infineon have launched the „Radar on Chip for Cars“ technology cooperation project to make radar sensors for predictive driver assistance systems available in all classes of car. Scientific support for the project is provided by the universities in the German cities of Bochum, Bremen, Erlangen-Nürnberg, Stuttgart and Ulm, the Technical University in Munich and the University of Applied Sciences in Ulm.

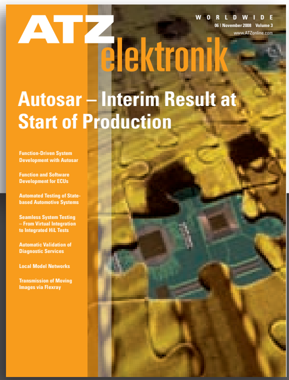
The five companies will work together to develop highly integrated, cost-effective radar sensor systems in the 76 to 81 GHz frequency range for both long-range systems (covering distances of up to 250 m) and short-range systems (covering distances between 5 cm and 20 m).

5 Using the Crisis as an Opportunity

Two years ago the IAA chose the forward-looking slogan „See What‘s Driving the Future“. At that time, no one could have predicted the difficult situation which the automotive industry now finds itself in. The worldwide economic and financial crisis has had a major impact on the industry, affecting jobs, sales, turnover and profits. At this year‘s IAA, despite being faced by serious challenges, car manufacturers and suppliers will be presenting innovative products and services. It will be interesting to see which companies use the crisis as an opportunity to gain a technological advantage over their competitors.

Richard Backhaus, Michael Reichenbach, Johannes Winterhagen

Imagine that
electronics was orange ...



The colour orange stands for creativity and dynamic energy. And because there is hardly any other sector in which development is as active and dynamic as automotive electronics, there is now a specialist e-Magazine in orange: ATZelektronik.

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Active Air Spring Suspension for Greater Range between Adjusting for Comfort and Dynamic Driving

In many cases, adjusting the suspension of powerful vehicles has to remain a compromise between comfort and performance. But with the Panamera, its new Gran Turismo model, Porsche is adopting a new approach whereby the driver himself can choose whether his vehicle is tuned to provide a comfortable, a sporty or a decidedly dynamic ride. The air spring suspension with an adjustable spring rate has been developed and produced for Porsche by Continental.

1 Introduction

The new suspension technology of Continental has produced a significantly wider spread of options for tuning the suspension, from comfort at one end of the range to a dynamic suspension configuration at the other. The rationale for this is that, with powerful vehicles, the characteristics needed to provide ride comfort compete with equally desirable demands for dynamic driving and driving safety. This design conflict is particularly evident in the luxury car class where it greatly influences the development and optimisation of the suspension and its components.

The semi-active suspension, generally achieved by using systems which adjust the damping, has established itself as the current state of the art. Adjusting the spring rate, a measure which goes beyond adjustable and ideally continuous damping, offers great potential for resolving this design conflict. An air spring makes it possible not only to adjust the ride height but also to increase or reduce the spring rate. This can be achieved by simply connecting and disconnecting an extra air volume supply but it poses huge challenges when designing the electronics for controlling the system. The new Porsche Panamera combines performance and comfort to a degree not experienced before by implementing and interlinking a whole series of new suspension technology.

Starting from the basic comfort setting, the driver can change to the sports suspension mode at the touch of a button thanks to Porsche Active Suspension Management (PASM). If desired, both the drive dynamics and comfort can be further enhanced on all Panamera model variants by means of the Porsche Dynamic Chassis Control (PDCC) active roll stabilisation system. The vehicle's sporty performance can be further enhanced, thanks to the integrated design of all the drive and suspension systems, including the Porsche Traction Management (PTM) with electronically-controlled four-wheel drive, by pressing the "Sport Plus" button, **Figure 1**, available in the optional Sport Chrono packages. In addition, adaptive air suspension with its individually selectable additional volume of air in each spring in combination with PASM (features which are normally available as options) is fitted as standard in the Panamera Turbo, producing an even greater and previously unachievably wide range of chassis characteristics.

Figure 1: The selector gate of the Porsche double-clutch transmission PDK in the of the Porsche Panamera with selector buttons for the Sport and Sport Plus modes (bottom left)

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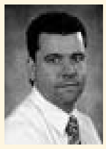

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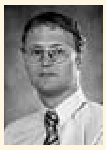

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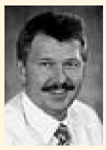

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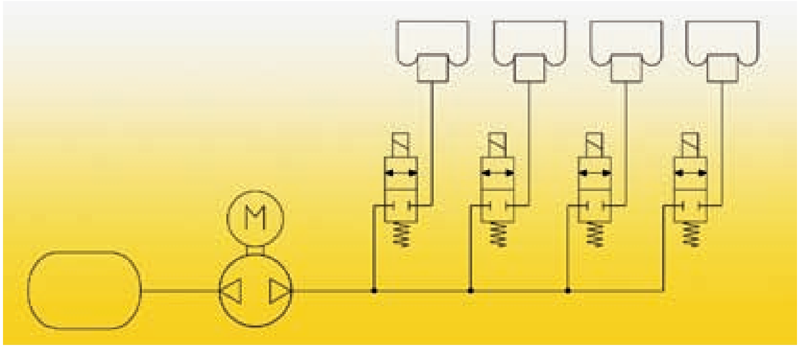


Figure 2: A self-contained air supply system: a solenoid valve releases the air into a reservoir from where it is fed back into the air springs as required; the small pressure differentials ensure great efficiency and rapid air supply control

2 Operation and System Functions

Whilst driving, the driver can select from the following programs to produce the vehicle configurations shown:
- Normal: Comfort damping characteristic, normal ride height, soft suspension
- Sport: Sport 1 damping characteristic, normal ride height, soft suspension
- Sport Plus: Sport 2 damping characteristic, low ride height, hard suspension.

The driver can select these modes using the PASM, the Sport or the Sport Plus button, Figure 1. Pressing the Sport and Sport Plus buttons will simultaneously affect other systems such as the transmission and the engine in addition to the chassis control (PDCC). The low ride height is approximately 25 mm at the wheel. Using the air suspension system to lower the vehicle's center of gravity makes a major contribution to the drive dynamics.

The system also allows the ride height to be manually raised from normal to lift height for approximately 25 mm. This raised ground clearance protects the vehicle from damage when driving over obstacles or when parking and maneuvering. The system automatically cancels lift height at speeds above 30 km/h.

One of the air suspension system's main tasks is automatic load-levelling, which supplements the many other aerodynamic features in the vehicle as a whole. Lowering the body in Sport Plus mode also reduces air drag resistance, resulting in similar reductions in fuel consumption and CO_2 emissions, while increasing the vehicle's maximum speed.

3 The System's Components

The air suspension system consists of four air springs with additional selectable volumes of air, an air supply system with compressor unit, a pressure reservoir and a solenoid valve block. There are also four height sensors, a pressure sensor, a temperature sensor, three body acceleration force sensors and a control unit for the air suspension system and the PASM.

3.1 Self-contained Air Supply System

The compressed air for the air suspension system is provided by an innovative air supply system, unique in that it operates on the self-contained principle, **Figure 2**. Unlike open systems, **Figure 3**, the energy level in the vehicle remains constant, allowing the design's intrinsic advantages to be exploited.

In an open system, air is taken in from outside and stored in a reservoir. This air is then used to fill the air springs when the vehicle is raised or has to carry an additional load. The air is deflated into ambiance when the load is reduced or in order to lower the vehicle's height.

In a self-contained system, the air volume required to control the pressure adjustments is pumped into and out of the air springs from a reservoir. There are only very minor pressure differentials in such a system and this results in a considerably improved efficiency level. Compared with open systems, the self-contained system reduces energy consumption by roughly one third, shortens compressor operating time to about a quarter and, at the same time, provides superior control response speed. Continental's self-contained air supply system and the compressor, **Figure 4**, which has developed especially for this application, are being installed for the first time by a European manufacturer of premium vehicles in a luxury class vehicle.

3.2 Selectable Spring Rates

The central features of the selectable spring rates are the recently-developed valve integrated into the air springs and a control program which has been specially developed and tailored to the requirements of the vehicle. The ability to switch between spring rates demanded that a complex control program be developed because, in addition to spring rate selection by the driver, the driving conditions and vehicle configuration at any given moment also affect the switching process. In addition to horizontal dynamic movements, vertical dynamic module movements have to be taken into

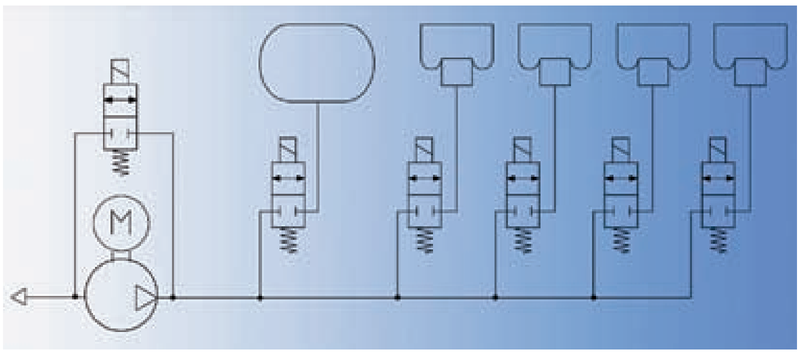


Figure 3: Diagrammatic illustration of an open air supply system: the air needed to inflate the air springs is taken in from the immediate environment and subsequently released again into the open air; this requires longer compressor run times

account in order to determine the optimum switchover moment which will always occur in the desired position for the vehicle's current ride height.

A further requirement is the ability to detect signals emanating from the body and the wheels which, depending on how they occur, will result in different spring rate adjustment strategies. The switching program also needs to account for numerous specific occurrences such as the air volume becoming heated while driving. The purpose of this control mechanism is that, even in the Sport Plus mode, the vehicle should always, from the driver's point of view, exhibit the same familiar and predictable handling characteristics.

3.3 Main Components: Air Spring Struts

The air spring design has made it possible to fit the wide range of spring rates into a compact package. The important factor here was the development of a valve for the additional air volume which, in contrast to the current state of the art, boasts smaller dimensions and less weight. The valve design is further assisted by the design of the air springs which minimizes the volumes of air required.

In addition to their wide spring rate range and low weight, one of the main objectives for this class of vehicle when developing the air springs was to achieve not just very comfortable suspension but, in particular, an excellent initial suspension response, essential for imparting a feeling of comfort, **Figure 5**. This objective was achieved by employing very thin-walled air bellows manufactured from suitable rubber compounds in conjunction with an external guidance arrangement.

The front axle is a double wishbone design, with the air spring including its control valve and additional air volume, forming a compact unit together with the damper, **Figure 6**. In the multilink rear axle, **Figure 7**, the damper and the air spring unit are fitted separately. Despite the restricted installation space, it was possible to develop a free standing air spring (the air spring is not arranged coaxially on the damper) with an integral additional air volume reservoir and control valve, **Figure 8**.

A further feature of the rear axle air spring is that for the first time a free standing air spring with an external guidance

Figure 4: Used for the first time by a European manufacturer: a self-contained air-supply with the Continental CK2.1 compressor

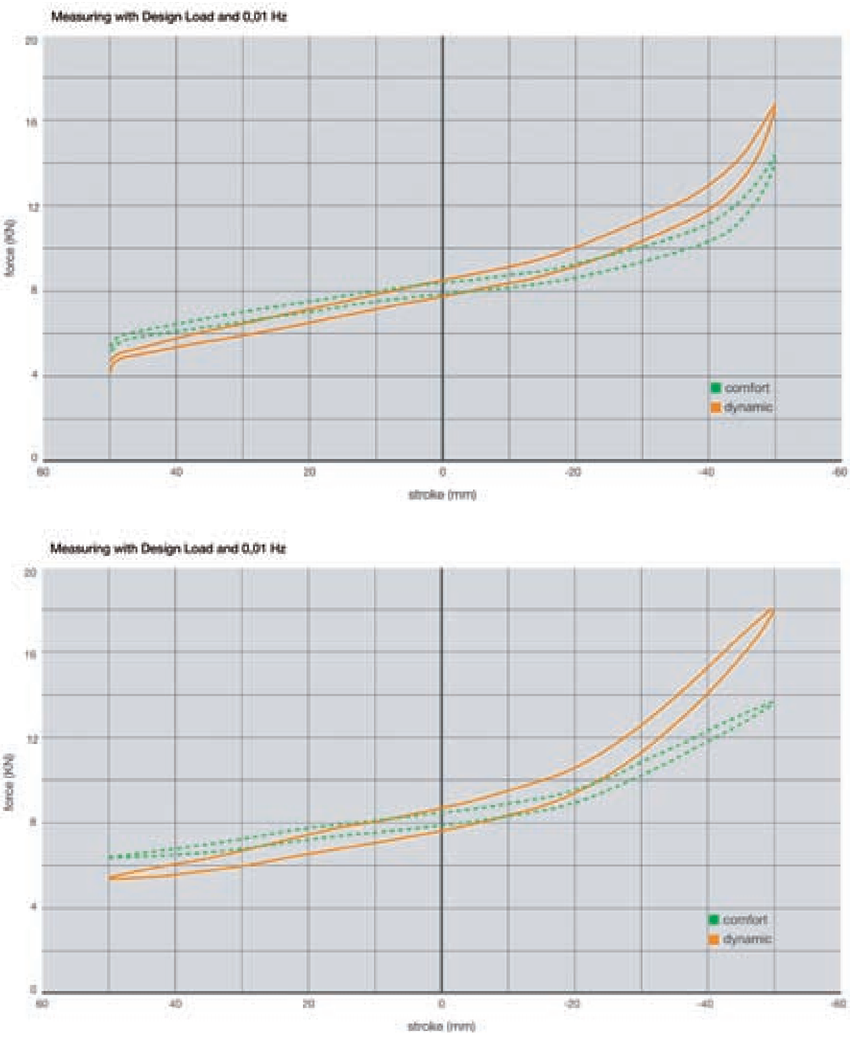
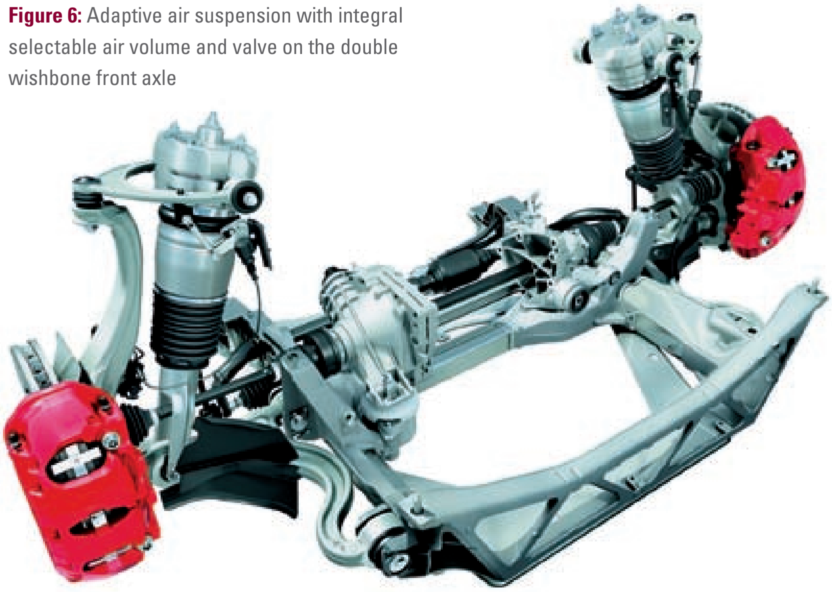


Figure 5: Force/distance characteristics of the air springs in the Comfort and Sport positions for front (top) and rear axle (bottom): Clearly visible is the wide range between soft and hard

Figure 6: Adaptive air suspension with integral selectable air volume and valve on the double wishbone front axle



arrangement has been used to optimize the comfort characteristics. The weight of the air spring module has been significantly reduced by the use of plastic materials.

For coordinating the design of the air springs as part of the overall vehicle development, Continental has a self-contained tool chain consisting of a PC-based design tool, software for data conversion into a machine data record for producing prototype parts on a CNC machine, a mobile servo-hydraulic test rig for design verification and, finally, on-vehicle evaluation. For coordination tasks within Europe, this tool chain is installed in the service truck; a mobile CNC machine is available for use elsewhere in the world. This allows air spring prototypes to be manufactured and modified in close collaboration with the vehicle manufacturers on their own test track.

Continental's Chassis & Safety Division can implement system functionality in accordance with the customer's specification but can also carry out full development. For example, all the functions in connection with the Panamera's self-contained air supply system and ride level control were developed by Continental and coordinated with the customer. In addition to laboratory tests, all the software is subjected to a functional and system verification and qualification by Continental together with Porsche in order to ensure that the electronics meet the high standards for ruggedness in the field.

3.4 Air Supply

The compressor has been specially developed for use in a self-contained air suspension system. The electric motor, compressor unit, drier and reverse switching valves have been integrated within a single module. Compared with other compressors used in open air supply systems, this component reduces weight by approximately one kilogram. The air supply system is waterproof and completely maintenance-free. To compensate for any leakages and temperature fluctuation, air can be filled from ambiance. The development of a sophisticated control program was also required in order for the air to be dried, thus preventing ice from developing.

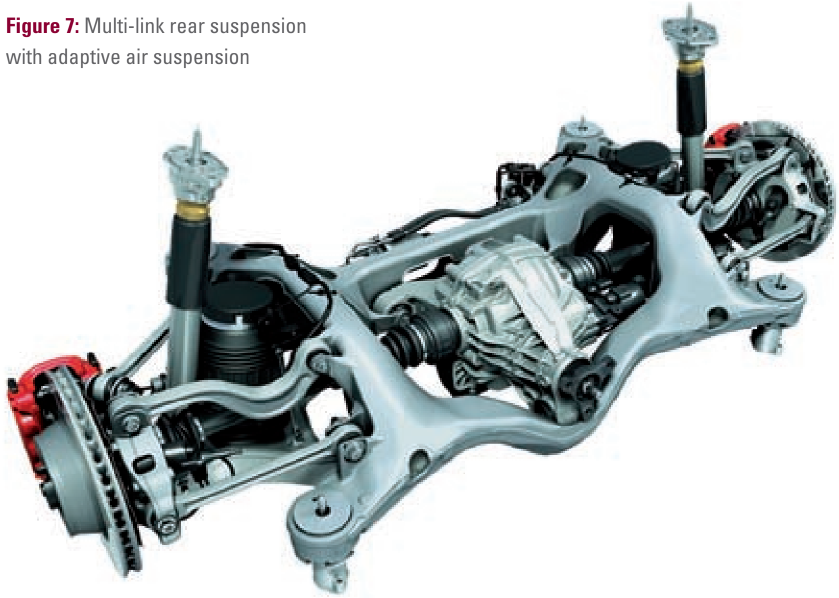
3.5 Control Unit

Because of the size of the system and the variety of power amplifiers in the Panamera's air suspension system, Continental has developed a new control unit hardware platform. A variant of the same control unit is also used for the non-air spring PASM system. Equipped with an Infineon Tricore 1766 processor (32 bit, 66 MHz) and a 1500 kilobyte ROM, both the low level and the high level software are sub-divided into different task disks depending on what is required of them.

The control unit software is made up of components from different manufacturers. For example, Porsche has provided a standard software package for all vehicle control units, consisting of the boot-loader, the CAN driver, the interaction layer and the transport and diagnostic protocol. This reduces the scale of the networking needed between the individual control units responsible for start-up, fault detection and minimization, software updating and maintenance and, at the same time, enhances reliability and ruggedness. A standard operating system, supplied by Vector, has been used as the ECU operating system.

Implementation of the functional elements was carried out by teams based in various locations using the dSpace TargetLink automated code generation sys-

Figure 7: Multi-link rear suspension with adaptive air suspension



tem. Software developers in Hanover, Nuremberg, Sibiu (Romania) and Bangalore (India) worked together on the project. One of the main tasks was to create a multi-user-capable structure for the TargetLink model, to allow both parallel development by a larger group of developers at different sites and to make it easier to carry out software module and component tests. The individual software modules can be used again in subsequent projects.

Before producing any ECU software, the software developer can either simulate the functional availability of his module or component at an early stage on a PC with the help of model in the loop (MIL) or software in the loop (SIL) or can test them directly in the vehicle using hardware like Autobox, without first having to produce a complete ECU software package. This significantly shortens development time and can lead to early detection of programming errors. So as to optimize run time, each function was divided up depending on the processing time it required and was allocated to different task disks.

In addition to providing virtual vehicle simulation, the modular design structure had the advantage that functions which had been developed could be optimized either directly in the vehicle or with the aid of measurement data. This meant that characteristics which were particularly important for this vehicle could be examined on high speed and handling test tracks.

4 Great Complexity Requires a Balance to be Found between Rubber and Electronics

The particular challenge for the project management was that advanced technology was employed in three key components on the Porsche Panamera as shown later. Continental has integrated the functions of these components in the vehicle to produce a complete air suspension system:
- selectable air springs: the volume of air stored in the air springs and, in particular, the new control valve and essential control program developed for this application
- the self-contained air supply, installed for the first time in a vehicle produced by a European manufacturer and the control program developed to meet its requirements
- new control unit platforms (both hardware and software).

Because of the variety and different natures of the system components and individual parts, five teams of engineers were involved: control unit and software experts, the designers of the air springs, the air supply system and the overall integrated system, plus road testing and system trials staff. Quality management, purchasing and the production plant itself were brought into the development project at an early stage and joined the project team. Final assembly of the air suspension systems is carried out at the Gifhorn plant; individual components such as the control units are supplied from Continental's plant in Manila in the Philippines.

At all times, the primary objective was to adhere to the development milestones which had been agreed and laid down together with Porsche and thus to ensure that the customer's schedule would be met. The milestones were the delivery dates for the individual sample phases including the earlier status reviews and sample submission dates and, especially for the software, the regular inspection and qualification deadlines. Against the background of the different development cycles and milestones for the modules and software, all development activity needed to be synchronized so that the components and the software functionalities were compatible with each other. Similarly, of course, the components and software had to match the relevant vehicle status and progress. This systematic approach, which applied both to the basic costs defined at the start of the project as well as to any necessary changes as the project progressed, allowed work on the various development tasks to proceed purposefully and on schedule and also offered sufficient flexibility so that special tasks, such as developing certain new components, could be carried out as part of a series development.

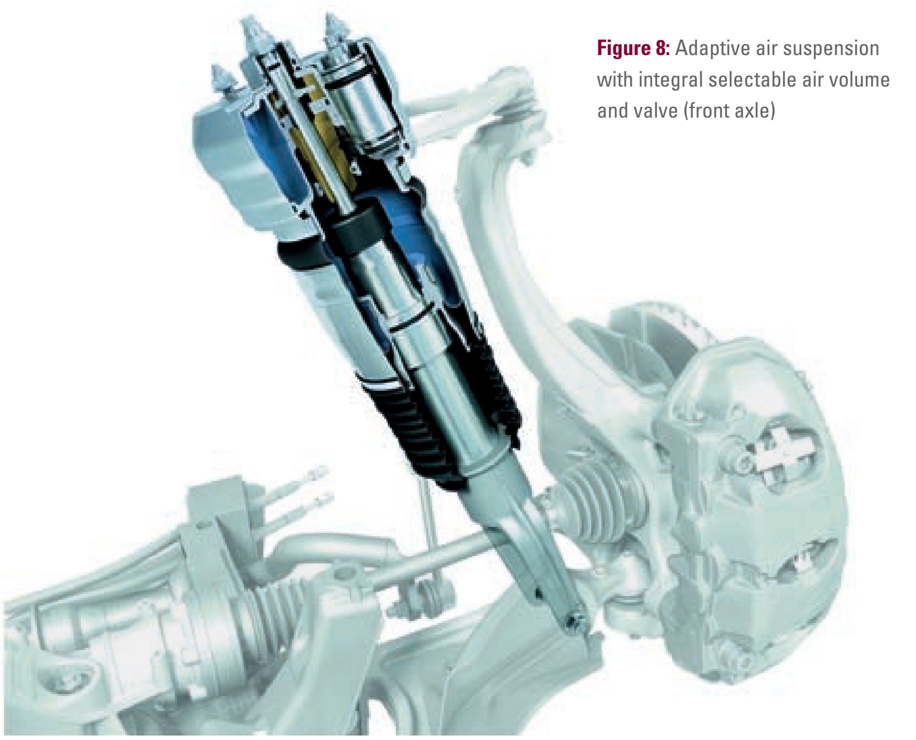


Figure 8: Adaptive air suspension with integral selectable air volume and valve (front axle)

5 Summary

By using spring rates which the driver can select, it has been possible for Continental to produce, within a single system, a suspension for the Porsche Panamera which is both comfortable and sporty and which exceeds the performance of existing systems. Selective tuning can decisively influence both the rigidity of the chassis/bodywork connection and the vehicle's self-steering behavior. By disconnecting the air volumes in Sport mode, the vehicle will handle in a more neutral manner compared with Comfort mode, thus complementing the vehicle's sporty characteristics in the best possible way. ■

Acknowledgements
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The Powertrain of the BMW 535i Gran Turismo

The BMW Group is once again laying the foundation stone for a new segment in the automotive market with the 5-Series Gran Turismo. It heralds the debut of BMW's new six-cylinder TVDI spark-ignition engine, which combines turbocharger, fully variable valve system Valvetronic and direct injection for the very first time. The new eight-speed automatic transmission is an ideal complement to this engine. The powertrain design underlines the Gran Turismo character and permits luxurious and comfortable travelling at outstanding economy.

1 Introduction

BMW is establishing a new segment in the automotive market this year 2009 with the new 5-Series Gran Turismo, which is being launched in the late autumn. The vehicle combines the characteristic features of a classical, stylish Gran Turismo with the luxurious, noble ambience of a prestigious limousine and the versatile utility of a modern sports activity vehicle.

"Sheer driving pleasure thanks to efficient powertrain dynamics", the character of the 5-Series Gran Turismo is impressively highlighted by a newly developed six-cylinder engine combined with a modern eight-speed automatic transmission. The engine lives on the unique combination of TwinPower turbocharger with separate exhaust gas branches, the fully variable intake valve system Valvetronic and the direct injection. This collection of sophisticated engine features TVDI mated with the new eight-speed automatic transmission gives the driver speedy, jerk-free acceleration at low rpm with a minimum of noise and a high degree of efficiency. Apart from a dynamic sporty response, the driver also experiences superior, relaxed driving performance accompanied by low fuel consumption.

2 Powertrain Requirements and Characteristics

Superior driving performance at low rpm requires an engine with a high level of smoothness and refinement as well as a pronounced low-end torque. The in-line six-cylinder engine with no free inertial forces or torques offers ideal prerequisites for this. The turbocharging concept with direct injection offers a means of achieving a very generous torque characteristic with a high torque level at very low engine speed. Combined with Valvetronic technology – the fully variable valve control system for throttle-free load control – this produces extraordinarily direct, highly precise responsiveness of the powertrain, **Table**.

Table: Technical data of the powertrain

Feature	Value	Unit
Engine technology	direct injection with turbocharger (TwinPower Turbo) and fully variable valve control (Valvetronic)	
Style/number of cylinders/of valves	In-line/6/4	
Displacement	2979	cm³
Stroke/bore	89.6/84.0	mm
Compression	10.2:1	
Fuel	over ROZ 91	
Power	225 (306)	kW (PS)
– at speed	5800	min^{-1}
Torque	400	Nm
– at speed	1200 – 5000	min^{-1}
Transmission technology	eight gear stages, automatic transmission with Steptronic function	
Transmission ratio I – VIII	4.714; 3.143; 2.106; 1,667; 1.285; 1.000; 0.839; 0.667	
Fuel consumption	NEDC cycle, Euro-5	
– city	12.3	l per 100 km
– road	6.9	l per 100 km
– over all	8.9	l per 100 km
CO_2 emission in NEDC cycle	209	g/km

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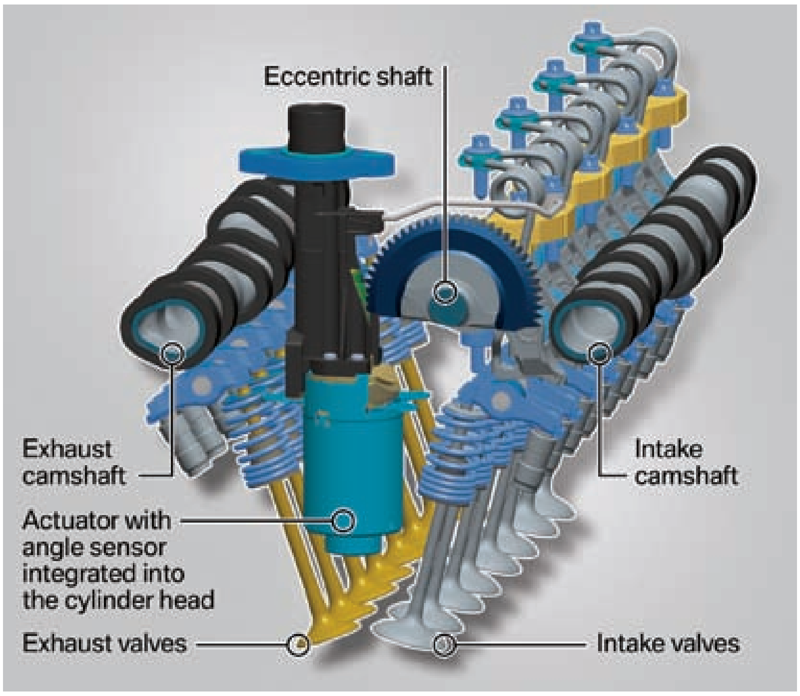

Figure 1: Fully variable valve control Valvetronic with integrated actuator

A completely new automatic transmission was developed to provide optimum utilisation of the generous low-end torque and exceptional smoothness and refinement right through to the highest engine speeds. Relaxed driving at low rpm coupled with excellent driving performance require a broad spread with optimum increments, which are realised by the implementation of eight gear stages.

3 Engine Characteristics

The new turbocharged six-cylinder spark-ignition engine with 2979 cm³ displacement, Valvetronic and direct injection promotes the 535i Gran Turismo driving experience in an ideal manner by consistently pursuing the high low-end torque objective to its logical conclusion without making any sacrifices in terms of dynamic performance or responsiveness. The concept of combining fuel direct injection with a turbocharger has become firmly established in the market for realisation of high-performance spark-ignition engines in recent years and therefore provides the basis for the new engine concept. From a thermodynamic point of view, this is the only way of achieving high specific performance with a high compression ratio and the associated high level of efficiency.

Central positioning of the injectors competes with lateral positioning for the geometric integration of the direct injection system. BMW gives precedence to the central injector position with a correspondingly large combustion chamber diameter, a concept that offers considerable advantages in terms of emissions when combined with Valvetronic. BMW was able to qualify a coil-actuated multi-hole injector for installation in a central position in the combustion chamber for the first time for this engine. This not only includes targeted action to increase ruggedness – such as injector coking prevention measures – but also measures to increase thermodynamic stability. Charge motion optimisation is the most important factor in this respect, to improve mixture preparation in the combustion chamber by the selective use of swirl and tumble flow, realised by phasing the intake valve control times and masking the intake valve seat inserts [1].

The combination of centrally positioned direct injection with Valvetronic constitutes a great challenge for the package design in the cylinder head. Efforts must be concentrated on arranging the components in such a way as to comply with all of the requirements relating to kinematics, mechanical strength, cooling and combustion system. A newly developed actuator, with a much more compact design, gives the redesigned Valvetronic system much higher dynamic performance, as well as enabling complete integration of the actuator into the actual cylinder head. The result is shown in **Figure 1**. Attention must also be drawn to the fact that there is no longer any need for a separate angle sensor as it has been possible to combine this component with the actuator in a single housing [2].

Bank separation is unavoidable in order to achieve a high naturally aspirated and turbocharged full load combined with high specific performance values and direct response from a six-cylinder engine. After considering all of the pertinent aspects, such as low-end torque, responsiveness, maximum output, emissions and costs, a decision was finally made in favour of a TwinPower mono-turbo concept. This operates according to the twin-

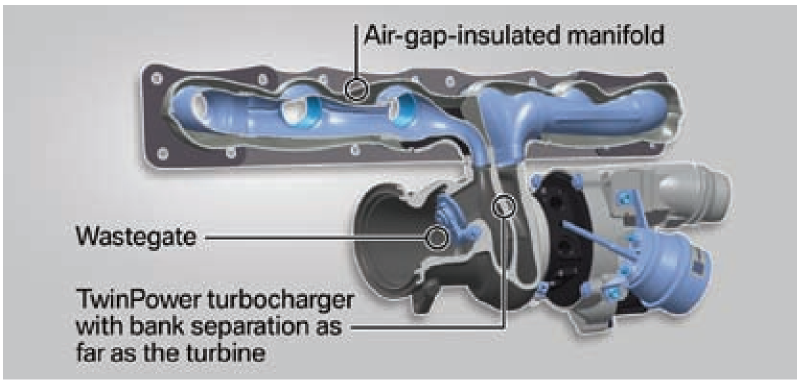

Figure 2: Manifold with TwinPower turbocharger

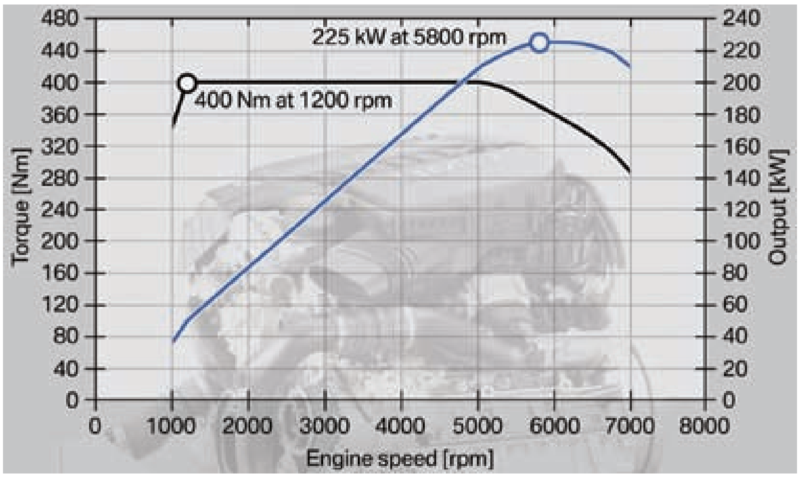

Figure 3: Diagram of torque and output

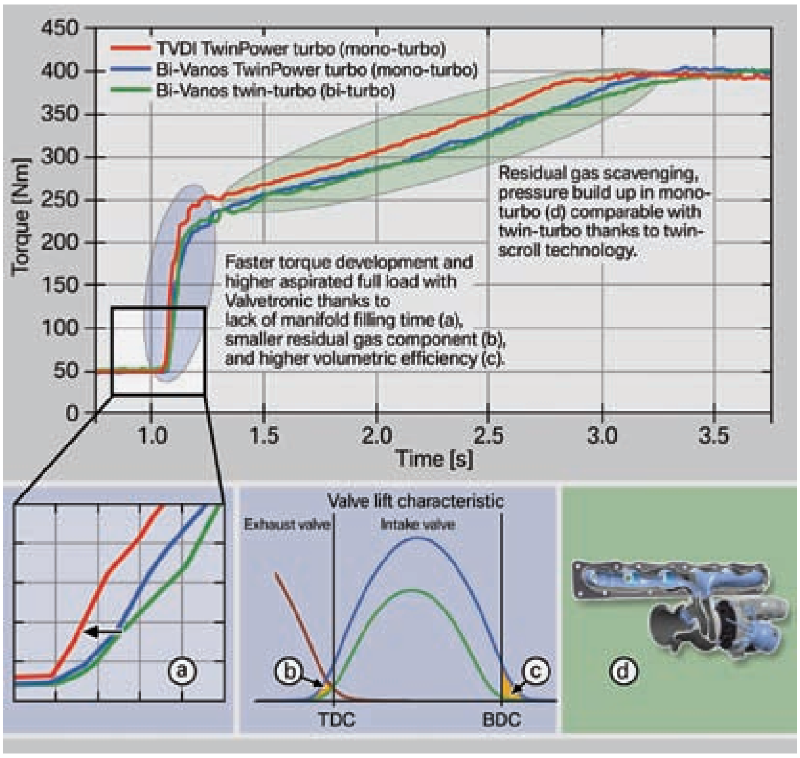

Figure 4: Response at speed of 1500 rpm (TDC = top dead center, BDC = bottom dead center)

scroll principle, whereby the exhaust gases from both cylinder banks are routed separately until just upstream of the turbine but, unlike the twin-turbo concept, drive a common turbine. This provided the basis for the development of a new exhaust manifold with a completely new turbocharger unit, **Figure 2**. This offers a means of achieving 400 Nm low-end torque at an engine speed of just 1200 rpm. The maximum output of 225 kW is produced at 5800 rpm as shown in **Figure 3**.

Figure 4 shows that it has been possible to completely avoid the “turbo lag” that was a known problem in the past. The unusually direct responsiveness is achieved by means of several different measures. The Valvetronic system eliminates the need for the dead time that is usually required to fill the intake manifold in an engine without fully variable valve control system.

The Valvetronic system is responsible for load control – i.e. adjusting the intake valve opening – which means that the cylinder can be filled without any delay and the charge is available for immediate use to increase the torque. It is also thanks to the Valvetronic system that the stroke of the intake valves can be reduced within the naturally aspirated range to such an extent that the residual gas component is reduced to a minimum while maximising the volumetric efficiency, a measure of the fresh charge remaining in the cylinder after charge cycle. In the turbocharged range, the positive scavenging gradient – the pressure in the intake manifold is higher than the exhaust gas backpressure – is used to scavenge residual gas out of the cylinder at low engine speeds by means of expedient positioning of the camshaft actuators. The increased exhaust-gas mass flow rate, for its part, generates a correspondingly high supply of energy for the exhaust-gas turbine, resulting in a high level of motive power for the compressor [3].

The build-up of boost pressure in the mono-turbo engine is comparable to that of a twin-turbo engine by virtue of the twin-scroll principle. The unique combination of torque and power output characteristics, as well as outstandingly smooth running in conjunction with direct responsiveness, make it possible for the new six-cylinder engine to offer superior, relaxed driving at exceptionally low rpm.

4 Transmission Characteristics

The newly developed eight-speed automatic transmission is an ideal complement to the new engine, enabling it to make full use of its potential. The engineers were able to reduce engine speeds significantly by broadening the spread still further, from 6.04 to 7.07, and also achieved improvements with respect to drive-away dynamics and driving performance. An as yet unparalleled standard of sophistication and acoustic comfort has been reached as a result of the low rpm level, which once again underlines the Gran Turismo character of the vehicle.

The lower engine speed makes a major contribution towards reducing the consumption of the eight-speed automatic transmission. This means, for example, that the engine speed at 70 km/h has been decreased from 1400 rpm to 1100 rpm. A logical consequence of the reduction in engine speed is an increase in the torsional vibration in the powertrain by a factor of 5. BMW's answer to this is a further development of the turbine torsion damper (TTD) used in the predecessor transmission, which is integrated into the torque converter. **Figure 5** shows the significant improvement compared with the converter in the six-speed automatic transmission.

In spite of excellent decoupling quality, it has even been possible to reduce the converter inertia by 10 %. In conjunction with the agile responsiveness of the engine, this has made it possible to achieve the dynamic drive-away performance that is typical of BMW. The desired direct engine interfacing is also achieved by driving with the converter lockup clutch closed to a great extent, bringing benefits in terms of agility and precision.

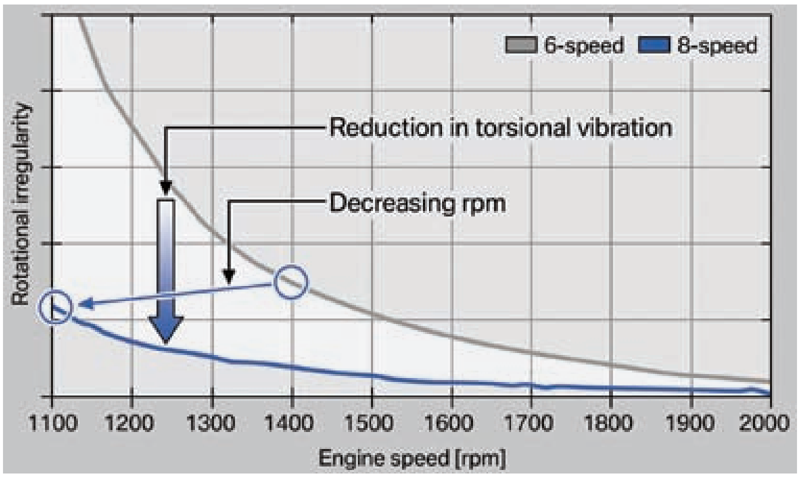

Figure 5: Rotational irregularity of eight and six-speed automatic transmissions in comparison

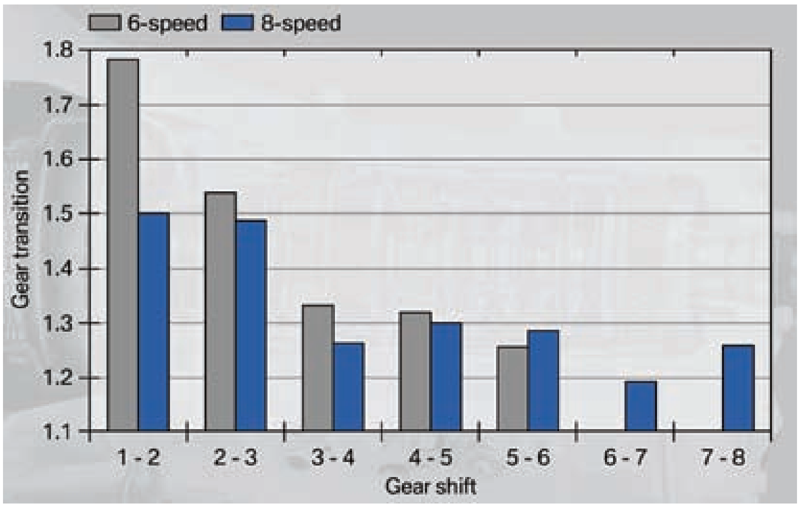

Figure 6: Progressive ratios of eight and six-speed automatic transmissions

The small gear transitions shown in **Figure 6** enable the initiation of partial-load upshifts at low rpm and freewheeling gear shifts at higher engine speeds. In conjunction with the reduction in the engine's re-engagement speed, this leads to a situation in which the engine can remain in fuel cut-off mode for a longer period in order to reduce consumption.

Efforts to lower fuel consumption also focussed on improving transmission efficiency, which can be achieved by reducing the drag torque of the clutches and the oil pump. These measures made it possible to reduce fuel consumption by 6.0 % compared with the six-speed automatic transmission, **Figure 7**.

The dynamic performance that is typical of BMW is assured by leading the engine out of the low rpm range very quickly when required by the driver. When a dynamic response is required, a downshift is triggered as soon as the accelerator pedal is pressed, whereby the actual shift operation is imperceptible with the engine torque at a relatively moderate level. This accentuates the superior driving performance.

The freedom to request different shifting speeds and select steeper accelerator pedal progression with the selector level in the S position allows the driver to choose between a comfortable, relaxed driving style and dynamic, agile performance. This, combined with the smaller gear transitions and the optimised hydraulic selector unit with downsized control volumes, enabled a considerable reduction in the response and contact times, **Figure 8**.

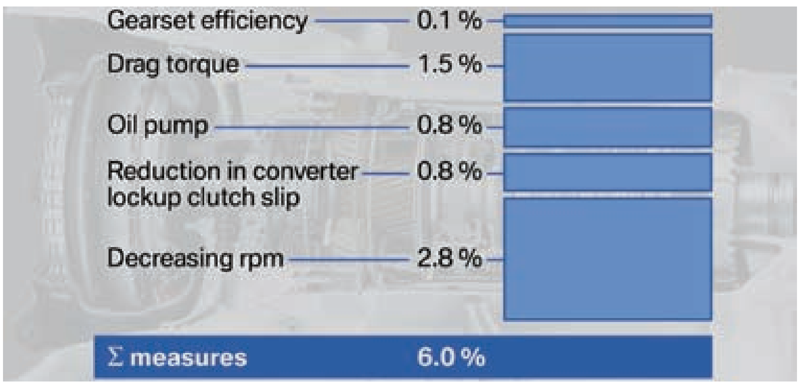

Figure 7: Improved fuel consumption of the eight-speed automatic transmission compared with the six-speed transmission

The improvement in driving performance and dynamics, accompanied by lower fuel consumption, made possible by the eight-speed automatic transmission, has been achieved without increasing the weight of the vehicle and constitutes yet another contribution to the BMW Efficient Dynamics programme.

5 Powertrain Efficiency

The design concept described above is a prerequisite for the special economic efficiency of the new powertrain. **Figure 9** illustrates the effects of the shift in operating point achieved by the engineers when driving at a constant speed by way of an example. By broadening the spread of the eight-speed automatic transmission compared with the six-speed automatic transmission, the operating point can be shifted in the direction of lower rpm and a higher load with a corresponding reduction in the specific consumption. The saving in this case amounts to 3 %.

Numerous different concepts have been developed to reduce fuel consumption and CO_2 emissions at BMW since 2000, within the framework of the Efficient Dynamics strategy. The optimisation potential of the vehicle as a whole is taken into consideration in this respect – from highly efficient engines and weight reducing measures, right through to innovative energy management systems. **Figure 10** gives an overview of the most significant measures included in the innovation package for the 535i Gran Turismo.

One of the central components that contribute towards reducing consumption, the new TVDI combustion system combines a turbocharged, direct-injection engine with the continuously variable intake valve lift control provided by the Valvetronic system. Substantial fuel savings have been achieved in the NEDC test cycle and in customer hands by dethrottling the charge cycle and reducing the effects of frictional forces by shortening the intake valve lift at partial load.

Map-based control of the oil pump was realised in a turbo engine for the first time as a further measure in improving efficiency, whereby the oil pressure can be adjusted as required for every operating point by means of a solenoid valve, thereby reducing the drive power of the oil pump. Optimisation of basic engine and transmission friction, along with the intelligent heat management system with electric water pump and map-controlled thermostat, and the intelligent alternator control – which are both familiar concepts at BMW – add up to a unique combination of performance and efficiency for the powertrain as a whole.

Consistent weight-reducing measures were implemented in the engine in an effort to improve dynamic driving performance and reduce fuel consumption to an even greater extent. The lightweight camshafts manufactured according to the IHU (internal high-pressure forming) principle used in naturally aspirated engines were therefore carried over to the turbo engine, along with the variable camshaft control (Vanos) made from aluminium. Both components are currently the lightest of their kind in the world for comparable engine concepts [4].

The engine, comprising crankshaft, flywheel and vibration dampers, has been optimised and its weight reduced in the same way as the actuator for the Valvetronic system. The engineers were able to achieve a 40 % weight reduction here by changing over to a brushless DC motor, in spite of simultaneously integrating the angle sensor module and creating an opportunity to do away with the separate angle sensor. All in all, these measures made it possible to make the basic engine 1 kg lighter, in spite of adding supplementary Valvetronic functions and components.

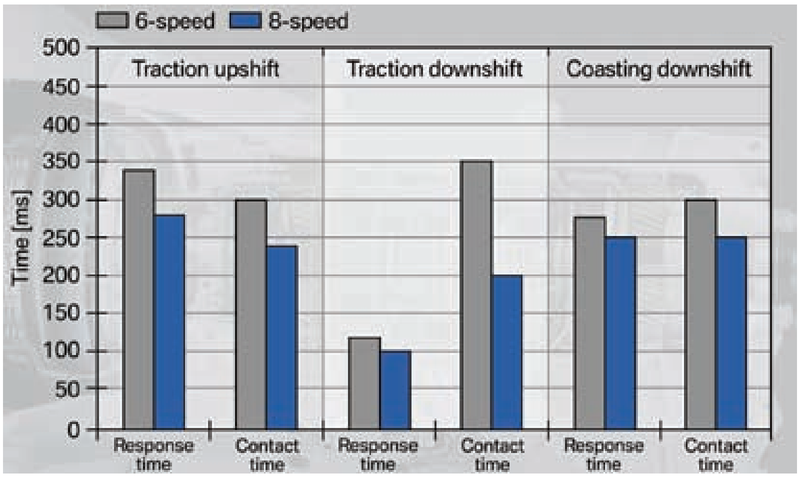

Figure 8: Shifting periods of eight and six-speed automatic transmissions in comparison

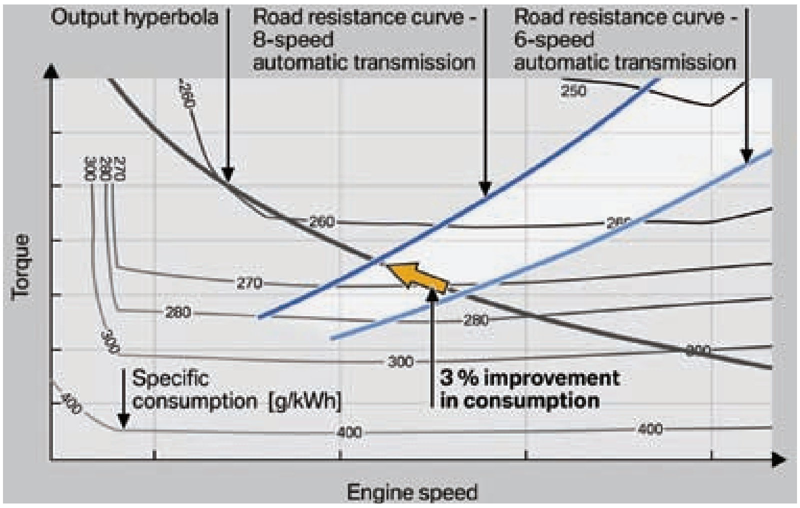

Figure 9: Fuel consumption improved by shifting the operating point

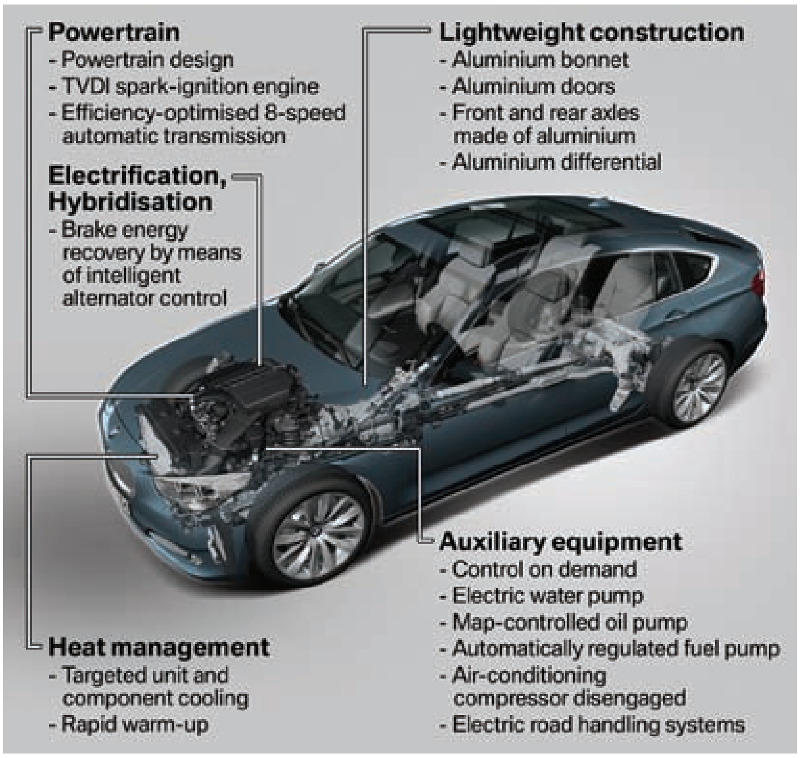

Figure 10: Efficient Dynamics measures

The targeted maximum possible integration is also evident in the digital control unit of the combustion engine (DME), which could be accommodated under the intake manifold, independent of package, where it is cooled by the intake air.

The vacuum tank used to control the wastegate and the internal blow-by line for introduction into the cylinder head are both integrated into the cylinder head cover. Apart from this, the oil intake pipe, oil deflector and oil collector have been combined in a single component.

6 Characteristics of the Vehicle as a Whole

All in all, the implemented measures described above have resulted in an outstanding fuel consumption of 8.9 l per 100 km driving distance in the NEDC test cycle, corresponding to 209 g of CO_2 per km. The consistent implementation of the powertrain design, with a long transmission ratio and optimum shift points enable economic driving by the customer. The driving performance of the new 535i Gran Turismo achieves a very high level, accelerating from 0 to 100 km/h in just 6.3 s, and the vehicle complies with the requirements of exhaust emission standards Euro-5 and Ulev-II.

7 Summary

BMW is defining a new class of vehicle with the 5-Series Gran Turismo. The powertrain with the new six-cylinder TVDI spark-ignition engine with Twin-Power turbocharger, fully variable intake valve system Valvetronic and direct injection, and the new eight-speed automatic transmission, underline the classical character of a Gran Turismo (Italian for "great tourism"): superior, relaxed and comfortable driving performance, smooth running characteristics of a turbine mated with a great deal of power and torque to spare and extraordinary economy.

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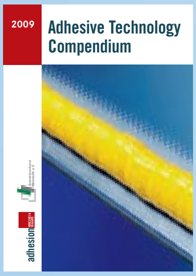

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Exemplary arrangement of an Eco-LED system on reflection basis in the headlamp

Future Developments in LED Headlamps

As a grounding-breaking innovation, LED headlamps are for the time being to be found in the premium segment. In order to transfer LED headlamps to the volume segment, concepts must be developed which are aimed at reducing the currently very high development and parts costs, as well as further increasing the system efficiency. Based on the experience which Hella gained within the framework of the development of the first LED headlamp in the Cadillac Escalade Platinum, concepts and solutions for meeting future requirements in relation to LED headlamps are described here.

1 Introduction

In the field of automotive lighting, LED headlamps mark the current highpoint of a rapid development, which LED technology in the car has followed since the introduction of the first lighting functions in the form of the center high mounted stop lamp at the beginning of the 1990s. Owing to their complexity and the currently high costs in comparison with conventional technologies, LED headlamps currently in development are for the time being to be found in the premium segment. However, the current CO_2 discussion, both on the political side and triggered as a result on the economic and technological side, forces energy-efficient lighting to be placed on the market via the volume segment as well. In relation to this, LED headlamps offer the corresponding potential [1]. In order however to transfer LED headlamps to the volume segment, concepts must be developed which are aimed at reducing the currently very high development and parts costs, as well as further increasing the system efficiency. Based on the experience which was gained within the framework of the development of the first Hella LED headlamp in the Cadillac Escalade Platinum, in the following, concepts and solutions for meeting future requirements in relation to LED headlamps are described.

Even though full-LED headlamps have only been on the market for a short time, no-one doubts anymore that with its advantages the LED light source will gain acceptance in the automotive market – even in the case of the main lighting functions. With the Cadillac Escalade

Platinum (GMT 926), which has been available since January 2009, General Motors has set new standards in lighting technology on the US market [2]. For the US-American market in particular, increasingly lower energy consumption and freedom from maintenance, as well as special styling possibilities thanks to LEDs and their special light color, will be key sales arguments in the future.

Thus both at home and across the globe, social factors, as well as the political general conditions, such as CO_2 taxation for example, are felt to have a strong influence on customer decisions. In the last few years, topics such as energy saving and climate change have been found in the media more and more, and therefore in the consciousness of wide sections of the population. As a result of this, a need related to society as a whole has arisen, with corresponding pressure on politics and the economy.

From the point of view of the consumer, it can be seen that the role of fuel consumption has changed over time under the different prevailing conditions. In the 1970s, it was politically-driven due to the scarcity of oil. In the 1990s, the price rose due to economic developments such as globalization and the related increasing demand from newly industrializing countries. Since the year 2000, a social demand for environmental protection has been discernible, which makes consumers take the criteria of environmental effect and CO_2 emission into consideration more strongly when purchasing a vehicle.

Consequently, the discussion about climate change and greenhouse gasses is developing into an important factor for car buyers, and for the majority today, lower CO_2 emission is an important decision criterion when it comes to the next car purchase. Energy-efficient cars with the necessary energy-efficient components are required. Here, LED headlamps offer corresponding potential for meeting this demand in the field of lighting systems.

2 Special Challenges for Today's LED Headlamps

The history of full-LED headlamps began with the equipment of show-cars, which had virtually nothing to do with real headlamp requirements. When, however, the LED light sources very quickly entered a performance range for main lighting functions, the challenges for such new headlamp systems became clear.

It was a matter of implementing the light distribution, the thermal and climatic management, the electronic control, mechanical strengths and industrialization for higher volumes as well. Key elements in coming up with and safeguarding a concept are the results from the simulations to be carried out. A main focus in the following is the photometric simulation, thermal/climatic simulation, as well as the tolerance and strength simulation. But also design concept and industrialization are discussed.

2.1 Photometric Simulation

For the calculation of the optical elements in the GMT 926, Hella uses its own software, which makes it possible even at an early stage to discuss with the customer light distributions which are close to reality. Even long before the application, the specification and therefore the basis for a new type of LED light source was worked out and implemented together with the supplier Osram.

2.2 Thermal and Climatic Management

On the basis of the results of the lighting simulation and the defined styling of the headlamp, the next step is to simulate the thermal management and the climatic efficiency. The flow simulation (CFD) makes it possible even in the concept phase to design in a thermally stable manner the headlamp components and – with special modeling – the LED assemblies as well, **Figure 1**. Furthermore, this method is the prerequisite for the realization of optimum ventilation and the avoidance of fogging and icing effects. Targeted design of air conduction, coupled with the use of a fan suitable for automotive application, leads to the solution of these climatic problems.

In a joint development with the supplier EBM-Papst, an extremely low-noise and reliable fan has been developed. Through corresponding simulations, the air conduction was designed and constantly optimized based on the air properties and the structural conditions.

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2.3 Tolerance and Strength Simulation

For the first time, a low-beam light distribution is produced in the lighting system of the GMT 926 from five single lenses, which is supplemented by two further lenses for the high-beam distribution. This leads to tolerance specifications – based on the optical simulation

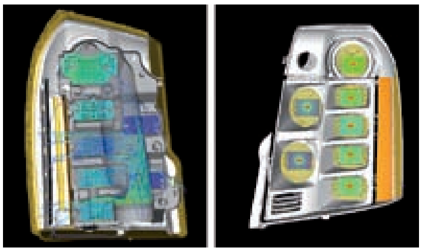

Figure 1: CFD flow simulations for the optimum design of the airflow around the heat sink as well as calculation of mitigation of critical temperatures for LED and headlamp components

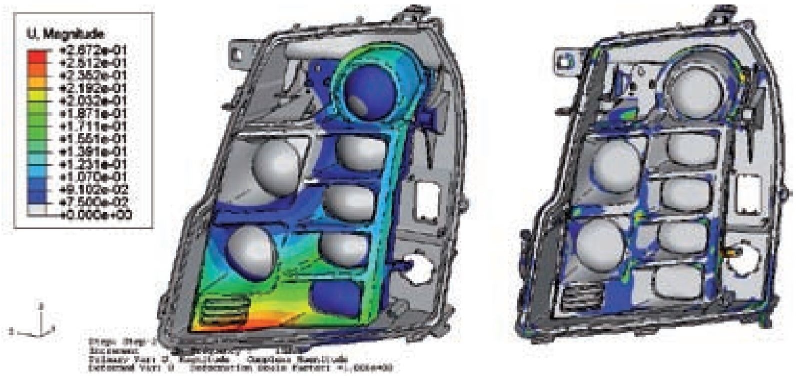

Figure 2: FEA strength calculations for discovering impermissible deformations and material loads

with regard to adjustment system, material selection and mechanical concepts – which require new solutions.

In addition, the use of heat sinks and the number of lens systems result in a higher weight than in the case of previous systems. On the basis of the CAD data, FEA calculation networks are generated for the strength simulations. With these virtual prototypes, **Figure 2**, the dynamic behavior and the vibration resistance are optimized. The aim is to achieve processing times which are as short as possible in the case of the later qualification tests on the test rig, **Figure 3**.

2.4 Design Concept – Safeguarding Through Prototypes

If one looks at the design concept of the GMT headlamp, **Figure 4**, it quickly becomes clear that, in addition to the simulation, testing with a multitude of prototypes is unavoidable. The heart of the system is an diecast aluminum carrier, which receives the individual lens systems. A second assembly is formed by the plastic air ducting with the mounted fan.

A unit consisting of position light, side marker lamp and the headlamp housing with cover lens completes the system. While the signal functions including control electronics can be connected directly to the vehicle electric system, a separate control unit is available for the main lighting functions. This is connected to the headlamp housing via a corresponding interface.

2.5 Industrialization

The GMT 926 headlamp is marketed as hundred-percent standard equipment in the Platinum version of the Cadillac Escalade. This premium equipment of the vehicle is a very popular equipment variant, which achieves mass production volumes. For this reason, reliable industrialization is a compulsory prerequisite and not to be compared with the production of a small amount of exclusive optional equipment. In relation to this – especially for the pre-assembly group of the LED module – Hella has set up a flexible mounting system, two special stations as laser soldering system and photometric test station of which are presented in detail in the following.

2.5.1 Laser Soldering System

There are 16 pads in the overall system of the headlamp. As conventional connector systems often represent a quality risk, the process engineers decided on laser

Figure 3: Vibration test on the test rig for safeguarding the strength simulations

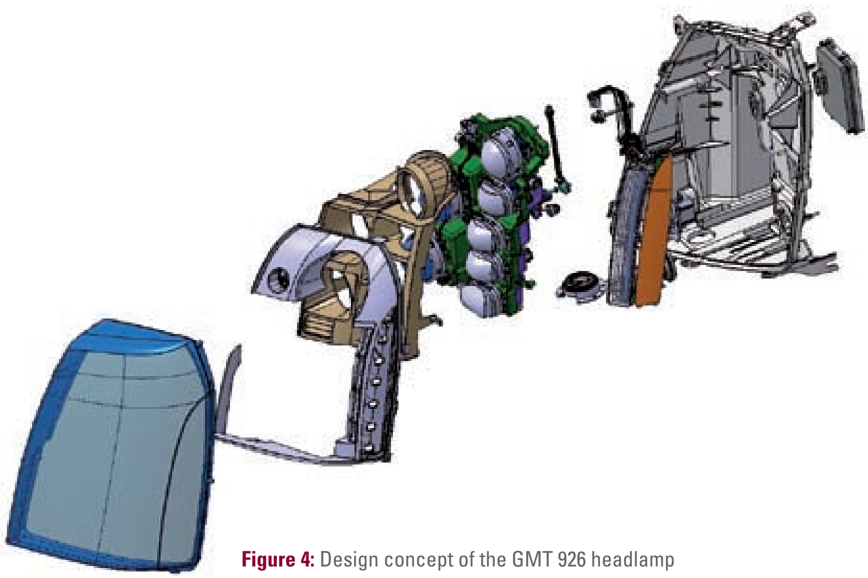

Figure 4: Design concept of the GMT 926 headlamp

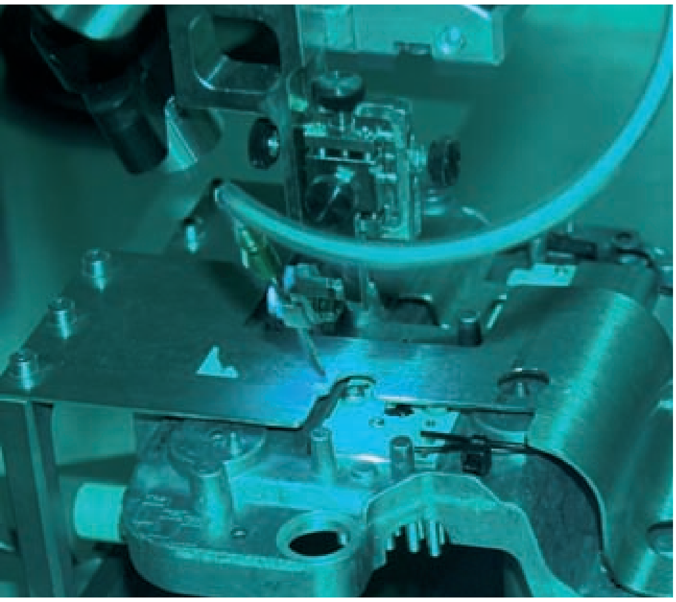

Figure 5: Laser soldering system

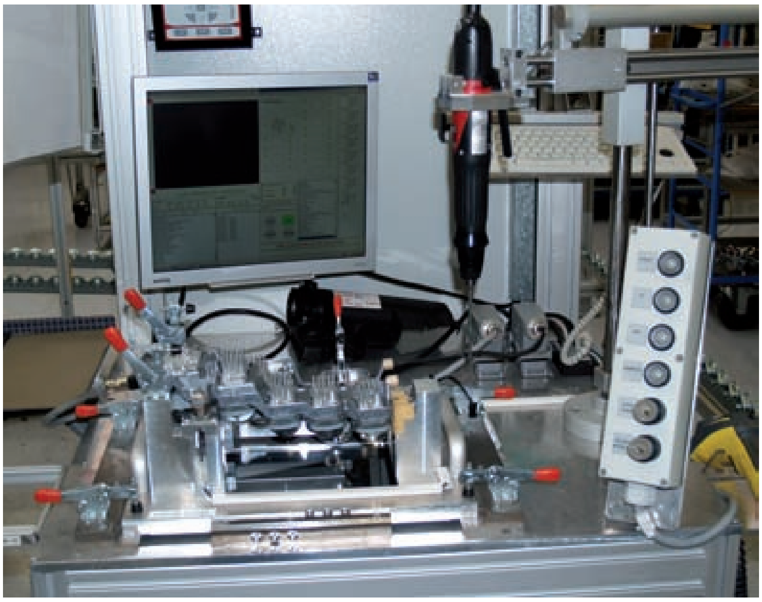

Figure 6: Visicon system for adjusting the optical system

soldering, **Figure 5**, to the seven light sources very early on. This takes place fully automatically and is monitored by a camera system. The preassembled wiring harness is accordingly pre-fixed to the aluminum carrier and held.

2.5.2 Photometric Test Station

A further crucial part of the mounting system is the test station for photometric testing called visicon system, **Figure 6**. Here, trained personnel carry out adjustment of the system until the required light distribution is achieved. Including traceability of component parts and modules, these and further process steps form a reliable mounting system with a high level of quality.

Even if future LED headlamps are not based on exactly the same design principle and many component parts still have to be adapted to the special applications, more and more components will be standardized in the future. With the headlamp for the GMT 926, an extensive know-how basis was created, on the foundations of which the further spread of LED headlamps can take place.

3 Further Development of LED Headlamps

Previous LED headlamp systems available on the market, such as for example for the Cadillac Escalade Platinum described before and the Audi R8, use the possibilities of a compact LED light source in order to produce customer-specific styling with the aid of the main lighting modules [4, 5]. The accompanying increase in attractiveness of the vehicle front represents a significant marketing argument for increasing the acceptance of LED headlamps.

It is however more cost-effective than the implementation of OEM-specific styling features with the aid of the main lighting module to generate the brand-specific recognition value by means of signal functions and – similar to conventional headlamps – to develop main lighting modules which can be used widely. However, the prerequisite for concentration on such main lighting modules is that corresponding target categories are defined. This categorization is oriented toward both the photometric and the functional requirements.

3.1 Highest Functionality and Photometric Performance

For reasons of cost, innovations in the motor-vehicle sector find their way onto the market mainly via the premium vehicle class. This basic rule has proved to be true in the field of full-LED headlamps as well. In order to be able to survive in this premium segment, an LED headlamp must compete with the latest xenon lighting modules both in terms of photometric performance class and functionality.

Luminous fluxes of over 1100 lm in the low beam, homogeneous illumination of the road, dynamic bend lighting functionality, AFS compatibility and, most recently, also the possibility of being able to adapt the range of the low beam to the respective traffic situation, distinguish the current xenon main lighting modules. An LED main lighting module, which shows a corresponding photometric performance and functionality is called „Vario-LED" in the following.

3.2 Low Energy Consumption and Cost Optimization

Increasing energy costs and an increased awareness of the environment are currently leading to an increased demand for energy-saving, low-emission vehicles. Although the LED light source certainly has comparatively low energy consumption, due to its considerably higher efficiency in comparison with halogen light sources, there is still a broad field of further optimization possibilities here. Main lighting modules, the lighting performance of which lies in the range between today's halogen headlamps and xenon headlamps, are called „Eco-LED" in the following. Here, „Eco" stands both for ecology, that means optimized energy consumption, and economy, that means for cost-optimized systems.

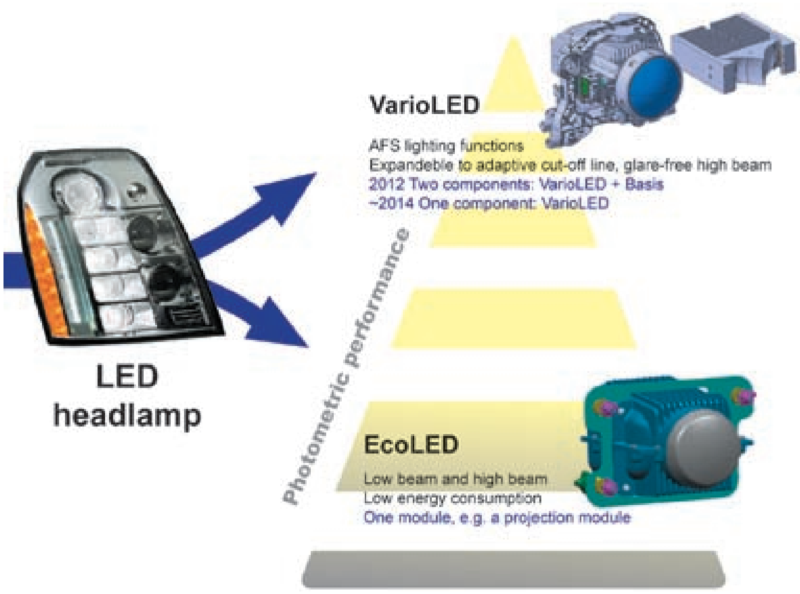

Figure 7: Categorization of future LED headlamps into the two concepts Vario-LED (good photometric performance) and Eco-LED (good energy and cost values)

As shown in **Figure 7**, it can therefore be assumed that the further development of the LED main lighting modules will be divided into two categories: On the one hand in the field of high functionality and photometric performance (Vario-LED), on the other hand in the field of energy and cost-optimized modules, the performance of which will be scalable within certain limits (Eco-LED).

4 Concepts for Future LED Main-light Modules

Here, the concepts for future LED main-light modules as Vario-LED and Eco-LED are described more in detail. The first module represents concerning photometric performance and the second in regard to costs and energy consumption an optimized systems.

4.1 Vario-LED for Good Photometric Performance

An important requirement in relation to the Vario-LED module is the possibility of generating all AFS (advanced front lighting system) functions as well as adaptive cut-off line and glare-free high beam with a photometric performance comparable with a xenon headlamp, using LED light sources.

At Hella, an extremely flexible and reliable AFS projection module, which is based on a cylindrical shutter, has already been developed for xenon light sources. This shutter has different contours on its surface which are moved into the beam path of a projector-type system according to the desired light distribution, **Figure 8**.

This principle, which has already been successfully positioned on the market, is also to be taken over for the Vario-LED module. The advantages are the compact dimensions and the possibility of being able to generate all AFS lighting functions with the aid of a single module. Here, the costly and fault-prone adjustment of individual modules in relation to one another is not applicable.

As, however, the luminous flux emitted by a single LED chip is currently under operating conditions less than that of a xenon arc lamp by more than a magnitude, it is not possible here simply to fall back on an existing concept with an exchanged light source. Instead of this, it is necessary to develop a projector-type system which, with a high level of efficiency, gathers the luminous flux of different multi-chip LED light sources and concentrates this at the shutter level. The light distribution preformed with the aid of the shutter contour is then reproduced in the road space via a projection lens. In this way, it is possible to represent all AFS-relevant partial light distributions in the central area. In the case of the high beam, the cylindrical shutter is rotated to a position which allows the light from LED light sources to be coupled-in via a second reflector and to be directed to the road space via the lens.

Currently it is still necessary to support the Vario-LED projector-type system with a basic light distribution, which is generated with the aid of a second (basic) module. In the case of this second module, it may be a lens or reflector optics. Very high levels of efficiency can be achieved. In addition, the basic lighting module offers the possibility of supporting brand-specific headlamp styling. The rapidly advancing development of LED light sources shows that such a basic lighting module will no longer be necessary by 2015 at the latest.

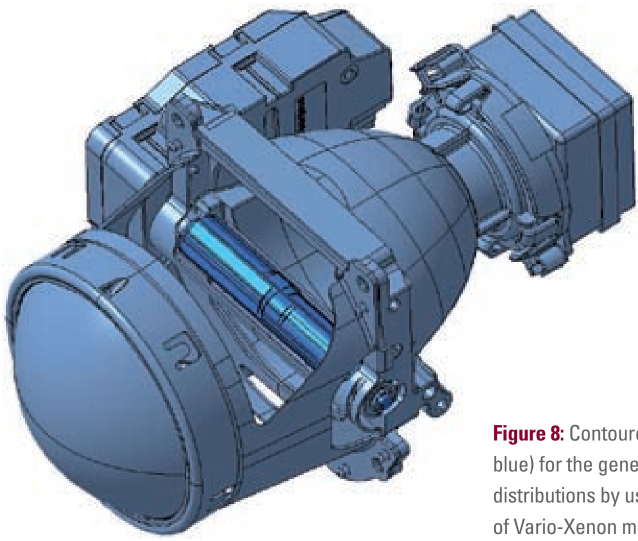

Figure 8: Contoured shutter (light blue) for the generation of AFS light distributions by using the example of Vario-Xenon module

4.2 Eco-LED for Good Eco Values

Both regard to costs and with regard to energy consumption, the Eco-LED concept represents optimized systems. The reduction of the number of LED light sources obviously offers an important change-lever to get closer to both goals simultaneously. The use of efficient optical systems must accompany the reduction of the number of light sources, in order still to be able to represent good lighting performance. A further important point of approach is doing without mechanically moved components, and therefore doing without being able to reproduce full AFS functionalities. Low beam and high beam should nevertheless be producible from one module. In the following, two approaches are shown which meet these requirements.

An Eco-LED module can be implemented technically both on a projection and a reflection basis. Here, implementation by means of a projector is based on the same basic principle as in the case of the Vario-LED module. The luminous flux of different multi-chip LEDs is captured by means of optimized reflectors and reproduced in the area of a shutter. This horizontally-lying shutter is in the focal point of a projection lens, which reproduces the light distribution in the road space. Here, the reflector arrangements are laid out separately for low beam and high beam, such that a changeover between the two light distributions can take place by switching individual LEDs. Through the light color of the white high-performance LEDs, which is similar to daylight, a considerably higher subjective perception of light is generated, which for example significantly surpasses a halogen headlamp of the same performance. The ability of the customer to differentiate between a headlamp equipped with an Eco-LED projector and conventional systems is a given due to the light color of the LED system, which is similar to daylight [3].

As mentioned before, an implementation of an Eco-LED module on the basis of reflection is also possible. Here, the low-beam distribution and high-beam distribution are generated by the coupling-in of separately controllable multi-chip LEDs into the respective reflector body of the system. In the case of the Eco-LED reflector, as is the case with all LED systems, the light color, which is similar to daylight, contributes to improved perception for the driver as well as to easy detection of an LED headlamp. In addition, even in switched-off state, a reflector system offers an easy ability to differentiate in comparison with conventional headlamp systems, as it is shown by way of example in the Title Figure.

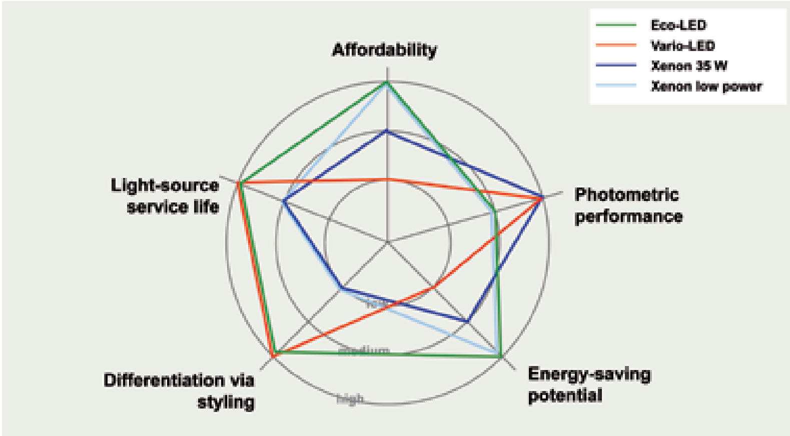

Figure 9: Comparison of xenon and LED systems with their different main focuses

5 Conclusion

Current developments point to the LED headlamp market in future developing in two directions – on the one hand in a premium sector, which demands high functionality coupled with excellent light output, and, on the other hand, in a economically and ecologically motivated sector, which, in addition to low energy consumption, assumes cost-effective solutions. Hella has developed therefore the headlamp modules "Vario-LED" respectively "Eco-LED" as solutions that meet the market.

Through the current endeavors of the automotive industry for the introduction of a low-power xenon light source, which with reduced photometric performance exhibits a similarly reduced energy consumption, the sector described here through ecological and economic drivers is likewise being addressed. The latter can, however, especially profit from the LED light source, since with this new light source, firstly, highly efficient and scalable main lighting modules can be developed and, secondly, the light color of the LED, which, in addition to improved perception at night, allows easy identification of correspondingly equipped vehicles.

To summarize, one can thus see that in the future in the premium segment, in addition to the familiar 35 W xenon systems, Vario-LED modules designed for performance will exist. In the lower volume segments, in which energy-efficient solutions for the reduction of fleet CO_2 emission have particularly great leverage, in addition to the low-power xenon light source, the Eco-LED modules designed for energy efficiency and cost-optimization will be available. A comparison of all systems with their different main focuses regarding

- affordability
- photometric performance
- energy-saving potential
- differentiation via styling
- light-source service life

is shown in **Figure 9** as a summary.

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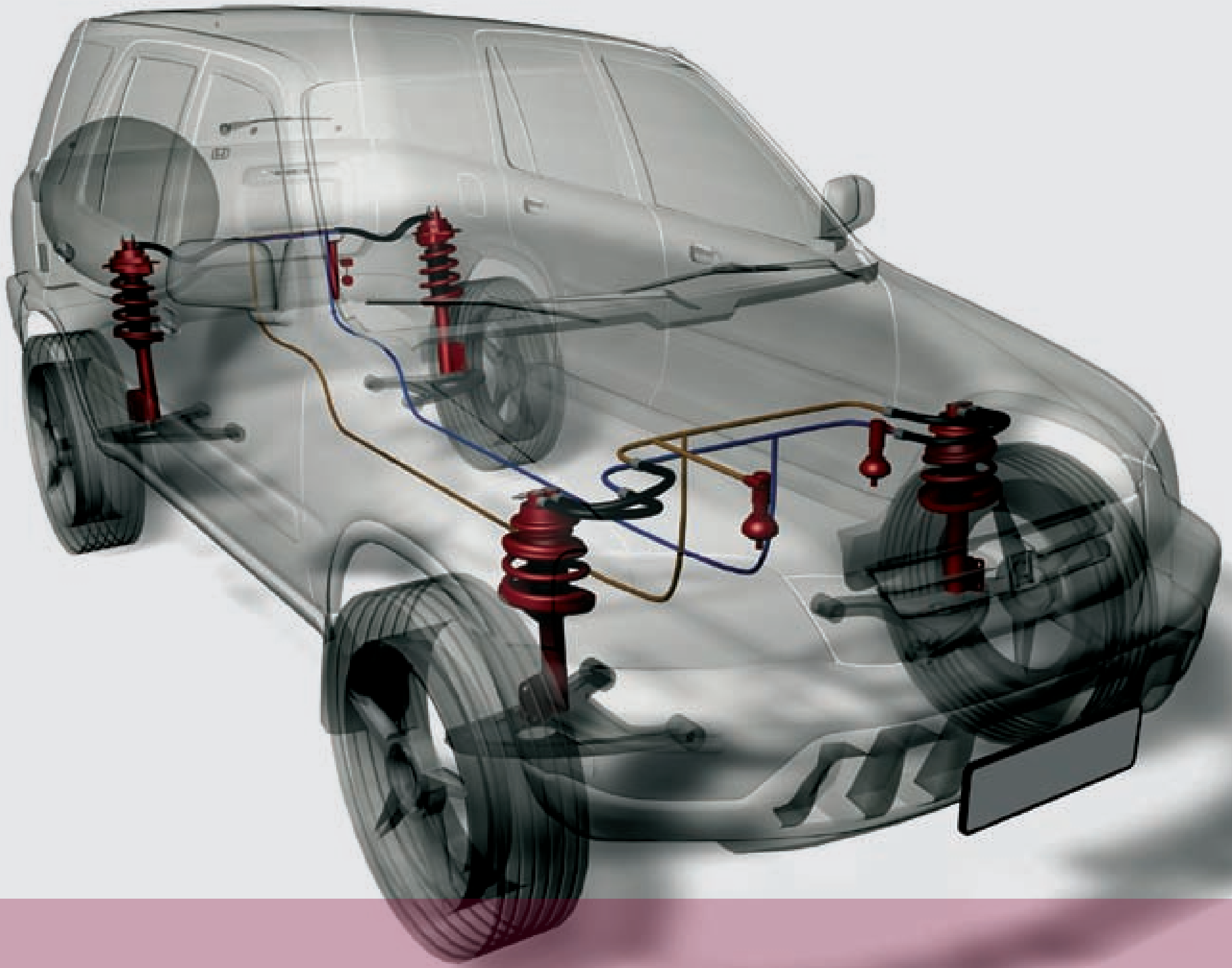

Integration of the "Kinetic" Anti-roll System with Semi-active Damping

Bringing together mechanical and hydraulic systems with the intelligence of electronics leads to new suspension concepts that improve vehicle dynamics. At the same time, they need less energy compared with active anti-roll systems. Tenneco has developed such a system, named Kinetic H2/CES. CES stands for Continuously controlled Electronic Suspension. It combines the features of a passive hydraulic anti-roll system with added electronic intelligence through semi-active damping and adjustable roll stiffness.

1 System Overview

The Kinetic H2/CES system is an advanced suspension system that substitutes the standard dampers and anti-roll bars on the vehicle with actuators linked together by hydraulic lines. The front and rear anti-roll bars and the four shock absorbers have been replaced with four double-acting hydraulic cylinders with two integrated CES damper valves, four roll accumulators, an Automatic Pressure Maintenance Unit (APMU), a comfort valve and interconnecting hydraulic lines, **Figure 1**. Two CES damper valves at each corner restrict the flow between cylinders and accumulators to electronically control roll, bounce and pitch modes, allowing decoupling of transient ride and handling performance.

2 Functioning

The system provides roll stiffness that is decoupled from articulation stiffness. Unlike conventional stabiliser bars, the Kinetic system offers additional roll stiffness only when both axles are rolling in the same direction. **Figure 2** depicts the fluid flow for a roll motion of the body. During a left hand turn, the cylinders on the right side of the car compress while the cylinders on the left side of the car extend.

This motion pushes fluid into the right circuit's accumulator (orange) and takes fluid from the left circuit's accumulator (blue). Pressure then rises in the orange circuit and falls in the blue circuit. The pressure difference results in a force that tries to extend the right side cylinders and compress the left side cylinders thus providing stiffness to roll motions.

The Kinetic system also passively decouples bounce damping from roll damping. Wheel and body damping is provided by CES semi-active damping valves located near the cylinders. The damping valves at the cylinders control both the unsprung mass motions and the body roll, pitch and bounce motion. Optional passive damping valves can be attached to the throats of the accumulators. These valves have a negligible contribution to bounce damping because only rod volume flows through them. During roll, however, the dampers at the throats of the accumulators can add significant damping because of the large flow through them. Therefore, roll motions can be damped differently than bounce motions by the use of this damper valve in combination with the electrical controlled cylinder damper valves. When the axles are rolling in opposite directions, or articulating, a flow of fluid occurs as depicted in **Figure 3**. During articulation, cylinder motion pushes fluid from the front of the vehicle to the back in one circuit and from the back to the front in the other circuit. No fluid enters or exits the accumulators. Therefore,

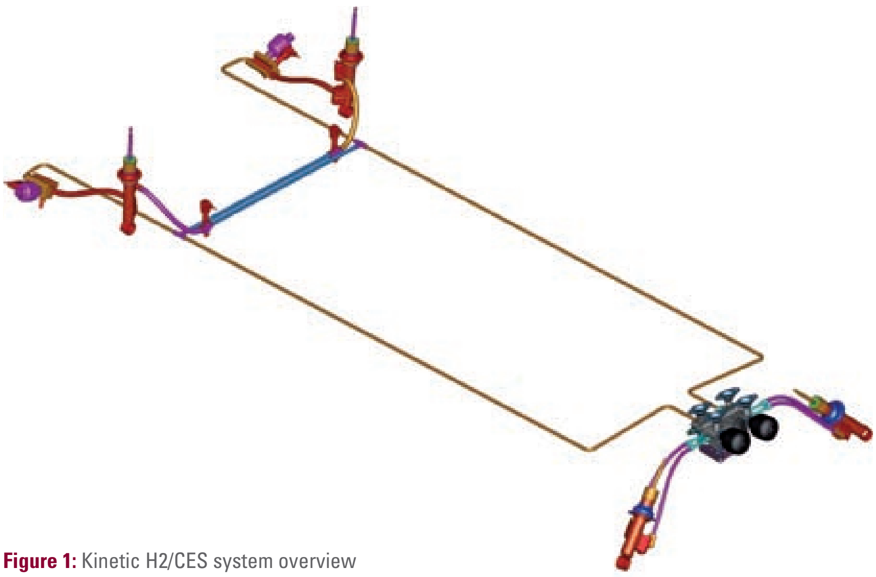

Figure 1: Kinetic H2/CES system overview

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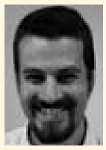

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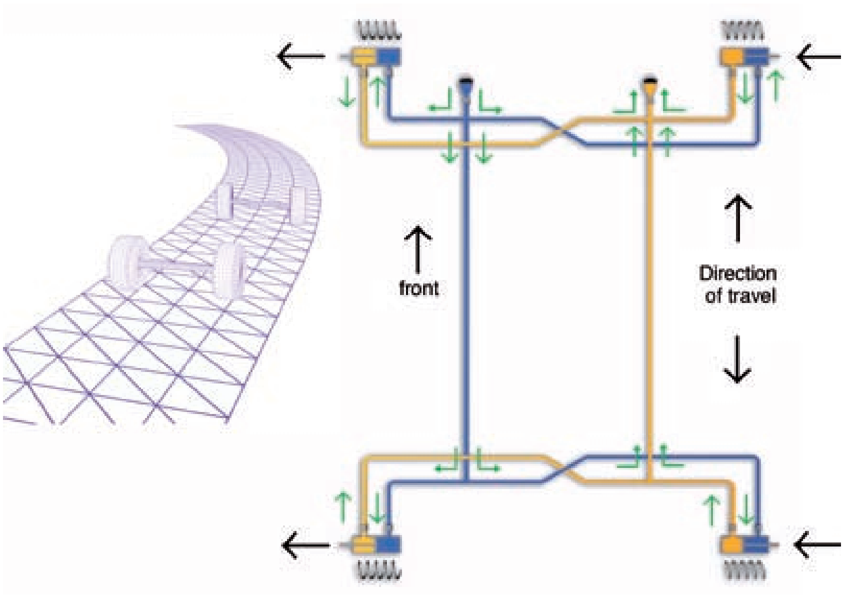

Figure 2: Roll stiffness and damping

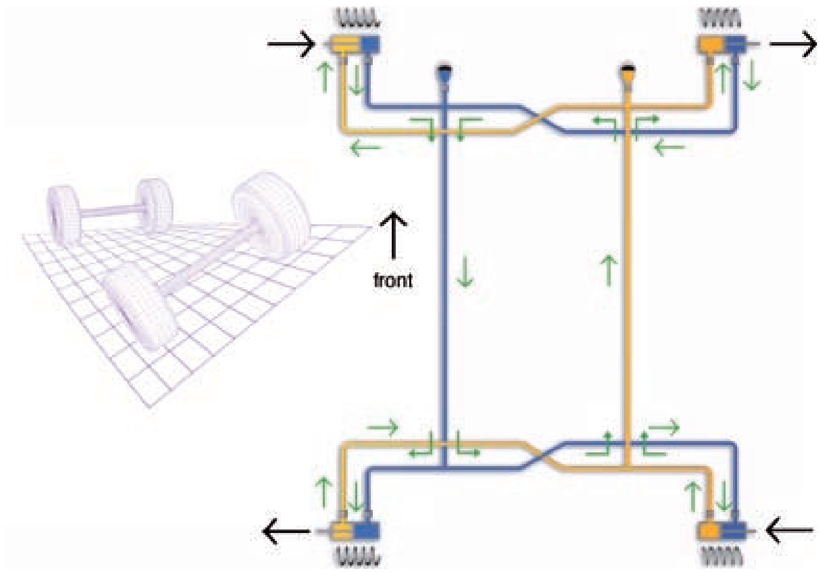

Figure 3: Articulation stiffness and damping

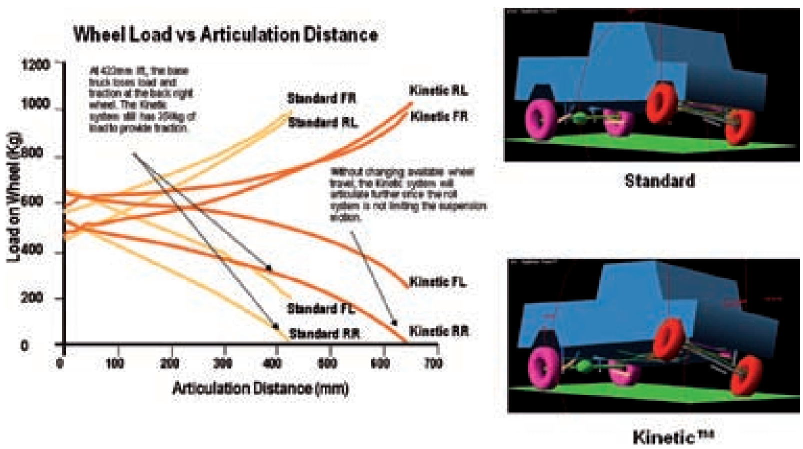

Figure 4: Wheel loading versus articulation distance for off-road application

there is no static pressure change in the circuits and no force is produced at the cylinders thus no articulation stiffness.

As the system has passive decoupled functional modes, it has no problem in combining different modal inputs. It will maintain its high roll stiffness in a corner while at the same time allowing the wheels to travel freely up and down on road induced suspension articulation.

Tyre force variations, and the related changes in vehicle yaw rate, will be greatly reduced on road undulations while very high roll stiffness, even higher than normal sport vehicles, can be maintained. That leads to better steering response, combined with constant steering angles during fast cornering and less ESP activation.

Not only is the vehicle behaviour in fast cornering improved, but also wheel traction becomes better. More engine power can be transferred to the wheels, reducing wheel spin. **Figure 4** shows the effect of articulation travel distance on wheel loading. For this off-road application, the articulation distance before the wheel start to loose contact is increased from 325 mm to 545 mm with a Kinetic system added. This vehicle will be able to cross much rougher terrain compared to the standard vehicle.

3 The Actuators

3.1 Prototype Actuator Design

The actuator design is constructed as a double tube damper, but the functioning is very different, **Figure 5**. It features a closed piston design and high pressure piston rod seals, optimised for friction performance. The damping is generated in valve systems located between the fluid chambers above and below the closed piston and the interconnecting hydraulic lines.

The damping valve systems include a CES valve in parallel with a tunable passive valve to generate damping when the fluid is pushed out of the actuator, and an intake valve to refill the actuator with fluid. The passive valve allows tuning the maximum damping curves and protects the actuator from overloading. Two independent rebound and compression valves are used allowing for fully independent rebound and compression tuning.

3.2 Damping Performance

The damping values of the actuator are dependant on the characteristic of the CES valves, the sizing of the actuator and the passive valve elements in parallel with the CES valve. The CES valve is designed as a continuously variable servo valve and its input is the current from the ECU. In normal operation this current is between 0.29 A (softest damping) and 1.60 A (hardest damping). When no current (0 A) is applied to the CES valve's solenoid coil the valve switches to fail safe. In this mode, the pressure in the servo valve is dependent on a mechanical fail safe valve and the fluid flow through the servo valve, leading finally to a predefined passive damping inside actuator.

A broad range of both the Öhlins CES valves and the passive valving are available for the tuning. They can be freely selected independent for rebound and compression. A normal CES tri-tube damper uses only one CES valve which provides optimal damping both in rebound and compression. It does not only change damping to the optimal value during rebound and compression, but at the transition between rebound and compression the valve setting has to be changed very fast to achieve the right performance. The Öhlins CES valves are originally developed for this application and they are capable of very fast switching. Different to a conventional CES semi-active damper, the Kinetic H2/CES actuator uses two different CES valves for rebound and compression, and thus has less stringent switching time requirements.

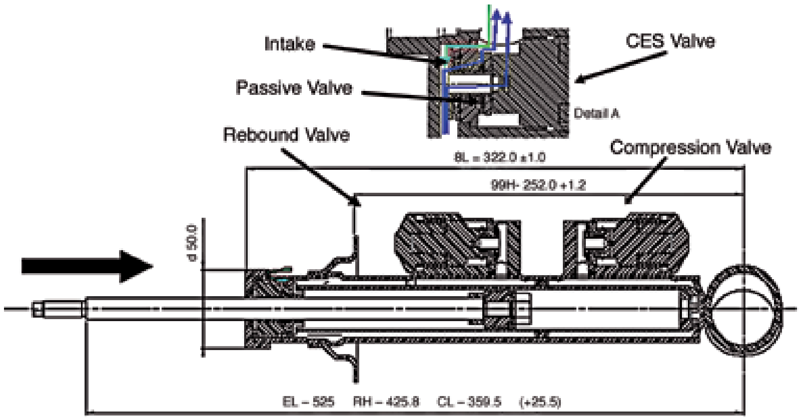

Figure 5: Kinetic H2/CES prototype actuator design

3.3 Actuator Design Proposals

Wherever possible, the preferred construction is to have inverted shocks in the front and the rear, **Figure 6**. This construction concept requires no moving flexible hoses, and will result in less friction generated by these hoses, as only small changes in angle from the shock need to be compensated. There is less construction complexity, better endurance, the unsprung mass is reduced and this concept results in shorter hydraulic lines with less fluid inertia and line restriction. Spring seat units, where springs are mounted around the actuators are possible without problem when the piston rod diameters are less than 14 mm. In the case of a McPherson strut, a reversed monotube type construction is a must, as the Kinetic system does not work well with big piston rods. Big piston rods would result in increased average system pressure in roll, which would consequently lead to roll jacking during cornering.

Package space needs to be made available early in the vehicle development phases, as a different, but not necessarily a larger or more difficult package compared to the standard shocks absorbers and roll bars, is needed.

4 APMU and Comfort Valve

The system pressures are steadily controlled in order to maintain the vehicle behaviour at a predefined target. Pressures require controlling due to temperature changes and small leakage between system circuits.

This pressure maintenance can be achieved through the APMU that comprises of at least a release valve, a check valve, a pump and a tank. An algorithm to measure online and target roll stiffness rather than just static system pressure was developed to anticipate on changing driving conditions (temperature, vehicle weight etc.).

An additional function of the APMU can be the adaptive control on roll stiffness. Increasing the static pressure in the system will lead to a reduction of the gas volumes in the roll accumulators, and thus an increase in roll stiffness. The tuning roll stiffness range of

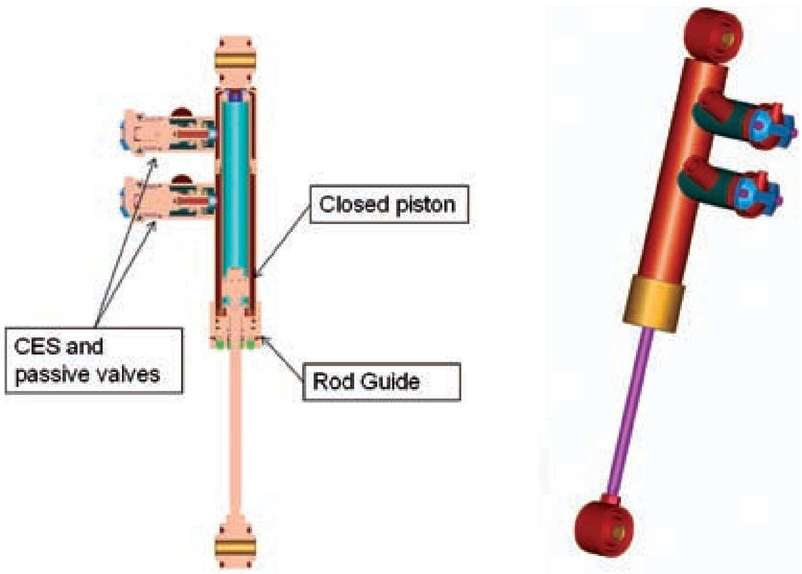

Figure 6: Example of production intendet design for rear actuator

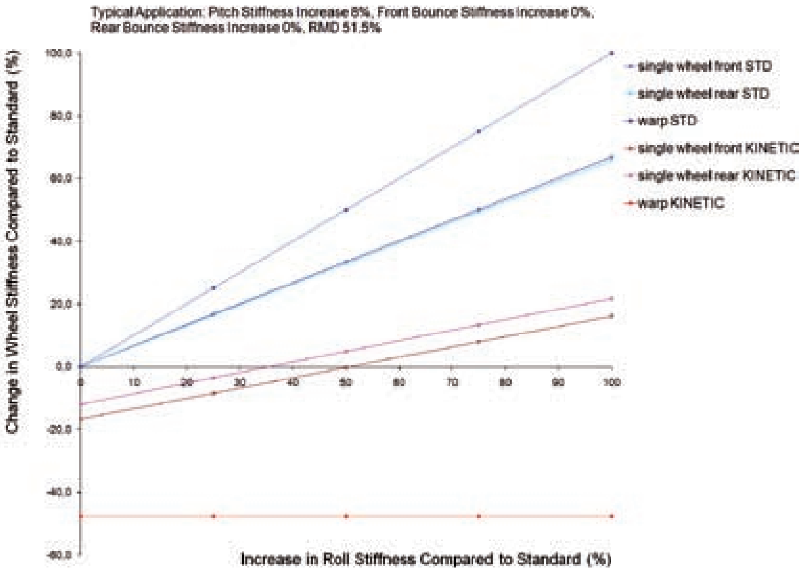

Figure 7: Relative change in stiffness in function of Kinetic roll stiffness increase

the system is determined by the type of settings the customer wants to provide in the vehicle. For comfort benefits the recommendation is for lower single wheel stiffness than standard but if maximum stiffness is required the system pressures could be higher. There are physical limits to the tuning range available, largely based on the accumulator volumes and pre-charges, but in general a design can achieve -5 % to +60 % roll stiffness increase. The Kinetic systems are modelled to match the customer requirements and the optimal tuning range for the target vehicle is selected. **Figure 7** shows the roll stiffness tuning effects.

Current APMU designs also use a comfort or bridge valve to connect the two separated fluid circuits in order to balance or set the pressure as well as to provide lower stiffness for a higher degree of comfort. By connecting the two circuits, the system provides no roll stiffness and the vehicle is able to gently waft for small inputs during straight line driving. Especially head toss and road copying are improved. The control system will determine when the comfort valve may be opened based on the current state of the vehicle taking into account inputs such as steering angle, steering rate, lateral g, long g and speed. The usual switching time of the comfort valve is around 40 ms.

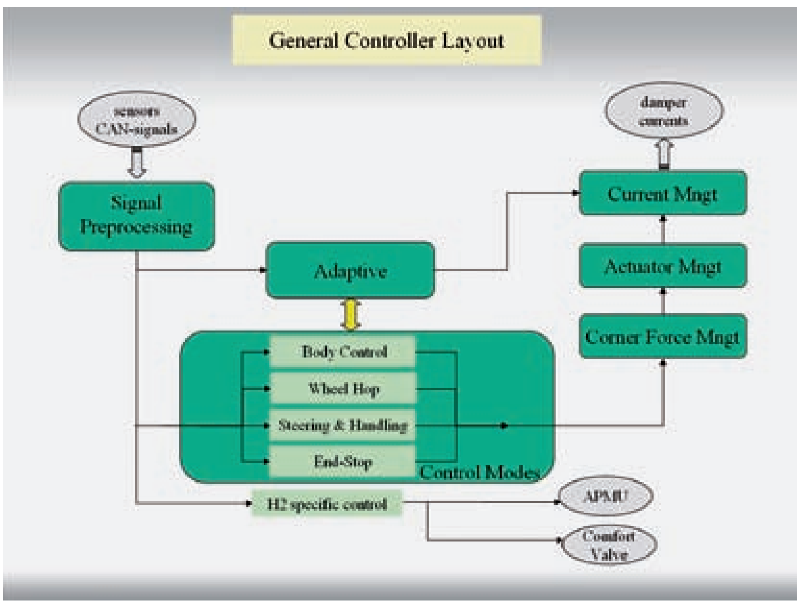

Figure 8: Outline of the CES and Kinetic controller algorithm

5 Control System

5.1 System Hardware

The Kinetic H2/CES suspension provides controllable roll stiffness in combination with semi-active damping. When the road or driving conditions change, the system automatically changes the roll stiffness and, for each corner independently, also the damping. To this end the system comprises besides the actuators and the APMU with comfort valve, also an Electronic Control Unit (ECU) and a set of additional sensors placed at key locations on the vehicle. To exploit the full potential out of the quick switching times of the CES valves, the time delay of all system components is a core characteristic. Therefore, an ECU based upon a high-end 16 bit or 32 bit microcontroller is appropriate, enabling update rates up to 1 ms for the most time-critical tasks.

A set of four height sensors is used to measure the position of each damper. A high resolution (more than 12 bit) and low time delay (less than 1 ms) are prerequisites in order to assure enough accuracy of the derived damper velocity signal (via hardware or software filtering). The CES controller algorithm comprises a Skyhook module to control the body movements. To this end, a set of three body mounted accelerometers is used. Requirement is that they are sensitive for a frequency range around the body eigenfrequencies and have a range of about 20 m/s² upwards and downwards. A last analogue input is required for a pressure sensor to monitor and control the system pressure.

Additionally, by interfacing to the CAN network, the ECU gathers extra driver input information (steering wheel angle, vehicle velocity, brake pressure), as well as other chassis control system information (ABS, ESP, TCS).

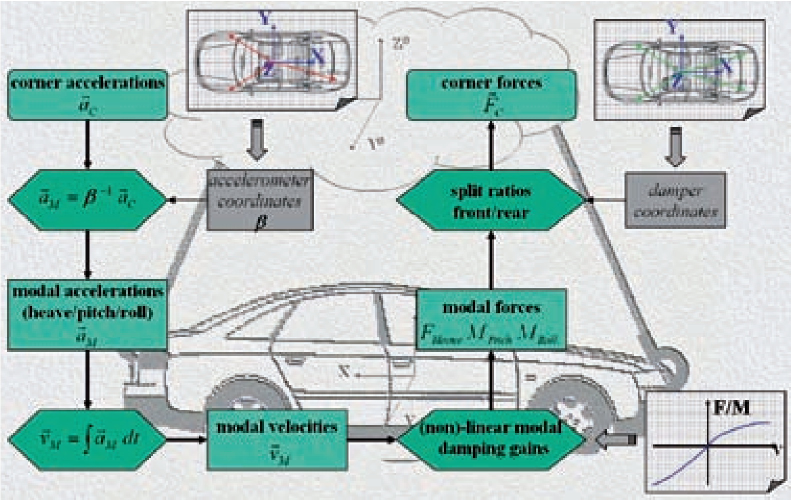

Figure 9: Outline of body control algorithm

As an output, after signal processing and decision making, the ECU sends the appropriate control signal to each of the eight valves in the system individually. The average electrical power consumption is typically less than 10 W per corner. Furthermore, three digital outputs are used to control the comfort valve, the low flow pump and the release valve.

5.2 Control Algorithms

Figure 8 shows the general layout of the CES and Kinetic control algorithms. The CES control algorithm takes care of the semi-active damping (upper, dark green parts), while the Kinetic control algorithm focuses on the roll stiffness control (lower, light green part).

The basic philosophy of the CES control strategy can be stated as: Set the damping levels, which can be adjusted independently and continuously, as soft as possible in order to provide the maximum comfort, while guaranteeing the damping to be quick and high enough to provide the required road holding and handling as dictated by the instantaneous driving conditions.

The upper part of Figure 8 reflects an overview of the CES controller set-up. First of all, a signal pre-processing module makes sure that the input signals are conditioned (unit conversion, filtering). In addition, some derived signals are calculated within this module (damper velocity out of damper position). The main controller algorithm includes a body control module with switchable add-ons to address specific events like wheel hop, handling and end-of-suspension travel.

A supervising adaptive routine, running at a slower sample rate, automatically adjusts the involved parameters of the main algorithm depending upon specific conditions such as braking/accelerating, rough/smooth road, driving style. Furthermore the driver can toggle between different predefined sets of controller settings (comfort to sport). Finally, the actuator management module processes the damping force requirements for each corner and outputs the corresponding signals for the valve current.

The body control module, **Figure 9**, entails a three-modal Skyhook control algorithm, which makes it possible to tune heave, pitch and roll body movements independently. From the body accelerometer signals (and their location with respect to the car's centre of gravity) the modal accelerations are calculated. Integration of these yields the modal velocities, which by an arbitrary tuneable relation establish the corresponding modal force requests. The modal forces are turned into damper forces based upon a tuneable split ratio (spreads modal force over front and rear axle) and the coordinates of points of action of the dampers on the car body.

The wheel hop module increases the damping forces when wheel hop is detected (based upon the frequency content of the damper displacements). It operates for each corner individually. The detection sensitivity is tuneable pro axle. The handling algorithm anticipates roll motions based on information from the steering wheel angle sensor. The end-stop module sets up a variable safety distance (proportional to the actual damper speed) near the extreme damper lengths. The damping is increased gradually when the damper enters this safety zone.

The aim of the Kinetic control algorithm, as shown in the lower part of Figure 8, is twofold: controlling the comfort valve to improve comfort and reduce head toss on straight roads, and maintaining the roll stiffness in the Kinetic H2/CES at the desired level.

To control the comfort valve, the vehicle velocity, steering wheel angle and angle rate and the lateral acceleration are taken into account to check the driving conditions. If the controller detects that the roll stiffness can be lowered safely, the comfort valve opens. As soon as the driving conditions require roll control, the comfort valve will close again. The smoothness of the comfort valve opening and closing can be tuned in the algorithm.

To maintain the roll stiffness constant at the desired level, especially when the temperature changes, the APMU pump and valves are switched on and off, based on the measured system pressure. Accurate pressure control is achieved by taking into account the dynamics of the pump and the hydraulic lines.

6 Conclusion

Kinetic H2/CES system integrates the stiffness mode decoupling of a Kinetic system with all features of semi-active damping control. Doing so, it allows high roll stiffness and damping (for better handling), reduced articulation stiffness (for better traction) and improved wheel control (for better comfort). On the vehicle, the system provides high performance and safety, combined with comfort. Especially gains in traction, stability and head toss are noticeable. The light weight design, easy packaging, low power consumption and interesting cost are advantages of the system, especially in the case of high performance sport cars and SUVs. Prototype and serial development projects are ongoing for several European OEMs. ■

Electromechanical Actuation
Potentials for Rear-axle Kinematics

Initial developments in the field of rear-wheel steering showed the early potentials. Today there are some general grounds on which a fresh appraisal of this technology, for which Active Rear-axle Kinematics (ARAK) has proven to be an appropriate term, is necessary. As far as the actuator is concerned, the use of electromechanical steering assistance on the front axle provides grounds for reappraisal, since there is the potential for cost-effective transfer of this technology to an ARAK, as Schaeffler´s development shows.

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1 Introduction

Since the end of the 1970s, control systems governing driving dynamics improve the longitudinal and transversal handling characteristics and today they are linked up to an ever greater degree [1]. Some systems, such as active steering, torque vectoring and rear-wheel steering – when not mechanically coupled with front-axle steering – occupy a special position. Their functions are not triggered directly by the driver, but rather only indirectly, based on information such as driving speed, transversal acceleration, wheel slip, yaw rate and steering angle. The objective is to implement the driver's intentions intelligently and improve driveability, as well as avert or compensate for any instability in the vehicle.

By using the electromechanical steering assistance for the rear axle there is a cost saving potential as well as an improvement of actuation time in comparison to a hydromechanical solution, and the limits of application are less restricted, particularly at high temperatures. Furthermore, the increased network capacity of the chassis systems and the variety of driving-dynamics-related state variables available contribute to an improvement in the quality of the chassis control [2]. This creates almost good conditions for exploiting to the full possibilities and prospects with regard to driving dynamics offered by an ARAK system, as proven by the recent vehicles fitted with this technology [3]. It is therefore necessary to reassess the potential applications and limitations of ARAK against this new background. The following sets out to present the ARAK system and demonstrates how it differs from other solutions.

2 Requirements and Benefits of ARAK Systems

The requirements for an ARAK system can be summarised in a general way. The system has to feature:

- an adjustment angle on the wheel of +/-3.5°
- an adjustment path on the actuator of 10 mm to 25 mm (depending on the axle)
- a maximum actuation speed of up to 0.1 m/s
- an actuator precision/resolution of approximately 0.1 mm
- an actuation force up to approximately 6 kN and a static overload of 18 kN
- a high level of electromechanical efficiency (maximum battery power more than 40 A with 12 V vehicle electrical system)
- a minimal energy consumption at constant steering angle
- a fail-safe behaviour in event of malfunction (holds position).

The characteristics of the actuator can be adapted to the specific requirements of the OEM if necessary. If the abovementioned requirements are met, the following system advantages can be exploited. For instance it features:

- an optimisation of the transversal acceleration time and yaw velocity in transient driving situations
- direct responsiveness to steering commands
- a less tendency to oversteer (rear end swinging out)
- an improved stability/security, particularly when braking on a bend under µ-split conditions
- a potential to improve straight-line driving by reducing constructive kinematic toe-in changes at the rear axle
- an improved stability when towing a trailer
- a smaller turning circle
- a reduced tyre wear and fuel consumption thanks to the possibility of reducing the initial toe-in.

A wealth of studies attempting to quantify the benefits of the system can be found in the literature on the subject. The improved handling characteristics and increased stability can be recorded and measured thanks to tests such as the 18-m slalom and the ISO lane change. Higher transit speeds can be achieved in these driving manoeuvres with ARAK, a

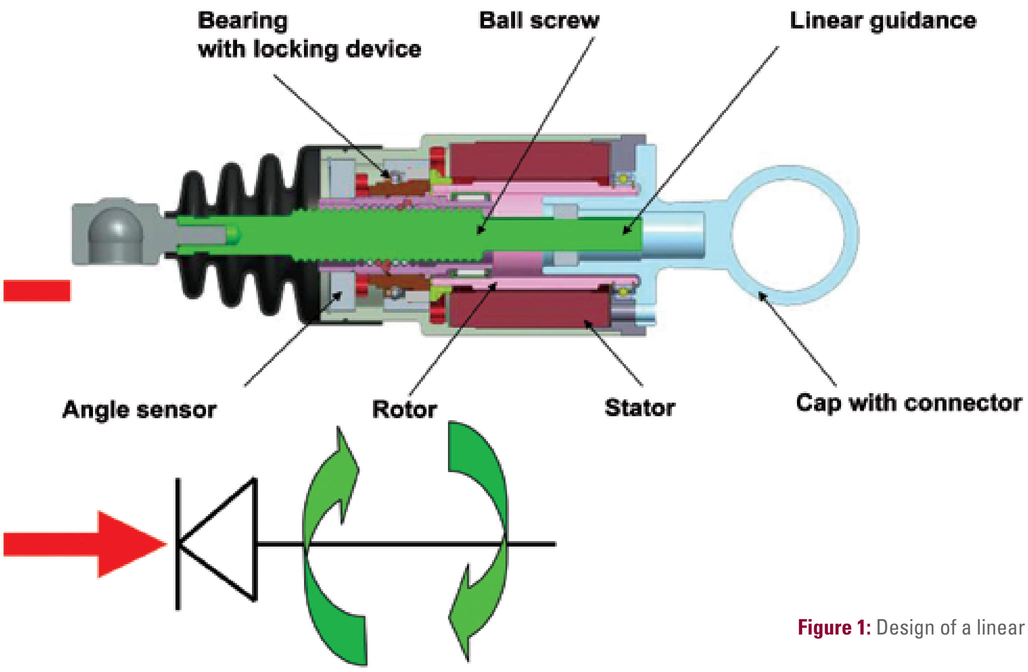

Figure 1: Design of a linear actuator

fact that has been borne out by numerous studies [4, 5]. These researches can also be used to suggest that trailer operation is improved. The amount by which the turning circle is reduced can be calculated by making a simple modification to the Ackermann formula. It also appears that the above-mentioned swivel range of +/-3.50 of an ARAK system is sufficient to achieve a significant reduction in the turning circle [4].

3 ARAK Actuator

Electromechanical actuators are increasingly being used wherever it is necessary to produce linear or rotational actuation without the use of hydraulic power, and for several reasons: they offer advantages in terms of lower fuel consumption and CO_2 emissions, they are simple to use, and they offer fail-safe behaviour. The basic configuration is shown in **Figure 1** and comprises components such as an e-motor with power electronics, a sensor and a gearbox or mechanical actuation element.

3.1 Actuator Design

Gearboxes are generally fitted with a self-locking device, so that no holding forces/currents are required when idling and therefore, in the event of an actuator malfunction, the position of the actuator would not change even if there were no current. However, as the self-locking mechanism reduces efficiency, this leads to significant power consumption on actuation. On the other hand, although optimising the efficiency of the actuator reduces the power consumption and results in improved dynamics, large holding forces/currents are required to maintain the set position under static loads. It is possible to achieve an energy improvement by combining an actuator transmission (ball screw) optimised for efficiency with a locking mechanism that locks the actuator in the set position under load. This method resolves the conflict of objectives between greater efficiency and the self-locking mechanism. Figure 1 shows the structure of one such actuator for linear motion. Aside from the e-motor and a low-friction ball-type linear drive for converting rotation to translation, an overrunning clutch that is switchable in both directions has been integrated into the actuator power flow.

3.2 Actuator Function

The analogy with an electrical diode can help to explain the function of the actuator, although the comparison should only be seen as an aid to understanding due to the various differences that exist between the two. In simplified terms, the energy that enters the actuator from the inside out – induced from the e-motor – gets "out" and is then available for actuation. However, if external forces act on the actuator (red arrow in Figure 1), the switchable overrunning clutch locks the actuator mechanically. The engine is relieved of the load and therefore protected against high current consumption. This mechanical design also fulfils the fail-safe requirement by holding the actuator in position in the event of a loss of current. A separate electromagnetically actuated locking device is not required. The actuators, **Figure 2**, can be designed with either a co-axial or axially parallel architecture depending on the arrangement of the e-motor. They can also be adapted to installation space requirements or other contextual constraints. Primarily for cost reasons, ARAK systems available on the market are fitted with a central actuator that can only actuate toe-in on both wheels synchronically. The gains in driving dynamics that can be achieved by having a wheel-selective ARAK system as opposed to a synchronic one have not been utilised until now, for reasons of cost and weight savings and because of the package situation. Schaeffler has developed actuators with both wheel-selective and centralised designs in order to cater for both possible applications. When constructing the centralised actuators, particular attention was paid

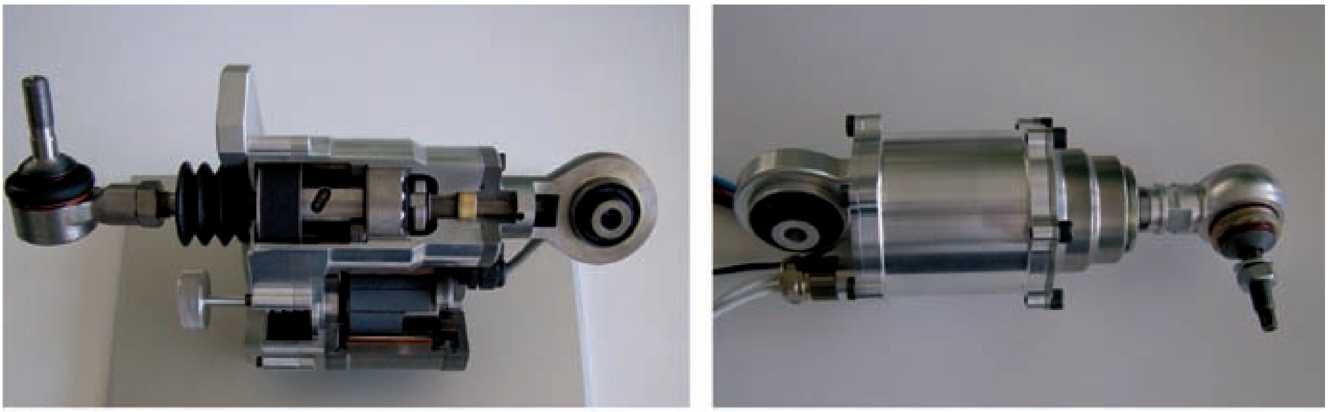

Figure 2: ARAK designs with axially parallel and co-axial e-motor for wheel-selective toe-in actuation

to making the design scalable for the different setting forces used in various model ranges. In addition, an effort was made to use as many common parts as possible for both the wheel-selective and centralised actuators.

In **Figure 3**, only the components highlighted in red must be adapted to change a centralised actuator to an individual actuator for wheel-selective actuation, and these modifications are not excessively costly or time consuming. In future, Smart actuators with localised power electronics will increasingly penetrate the market. Figure 3 shows the configuration of an add-on ECU selected for the ARAK system. When deciding on this configuration, great importance was placed on making the actuator as compact as possible and adapting an available control unit from an existing application. For installation space reasons, the add-on ECU can be made even smaller for use in the synchronic actuator by arranging components in the power unit differently. The programme Bearinx calculates stability and checks loads, enabling all the mechanical actuator components to be configured and optimised with respect to the required service life. The misuse situations required by the OEM are taken into account in this process. The analogous model on which the Bearinx calculation is based is shown on the left-hand side of **Figure 4**. Initially, the rigidity values of the housing are calculated analytically in a simplified fashion as bars and discs. The load distributions for the rolling elements in a ball-type linear drive caused by the external loads indicated are shown on the right-hand side of Figure 4. The depiction of the force application points and the related vectors indicates the Hertz pressure on the rolling elements. This example diagram demonstrates the contribution Bearinx can make when designing actuators. In a second stage, an FE calculation is carried out to check the rigidity of the housing more precisely.

The usual industry process chain, consisting of Matlab-Simulik, Targetlink and Autobox, is used for simulation and developing the functions of the ARAK system. A universal control unit is used, which can be operated with phase currents of up to 120 A.

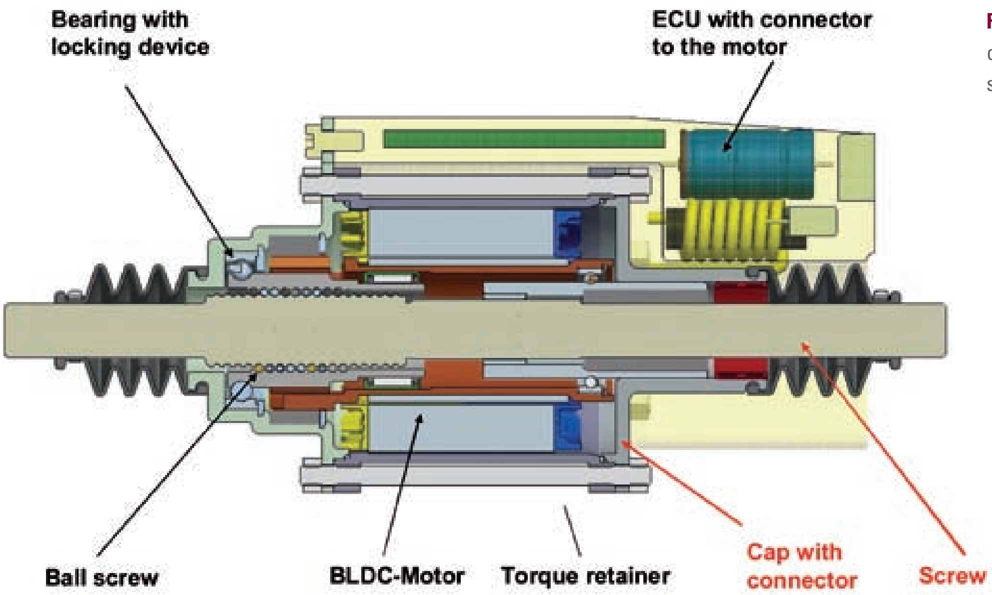

Figure 3: ARAK actuator with co-axial aligned e-motor and synchronic actuation

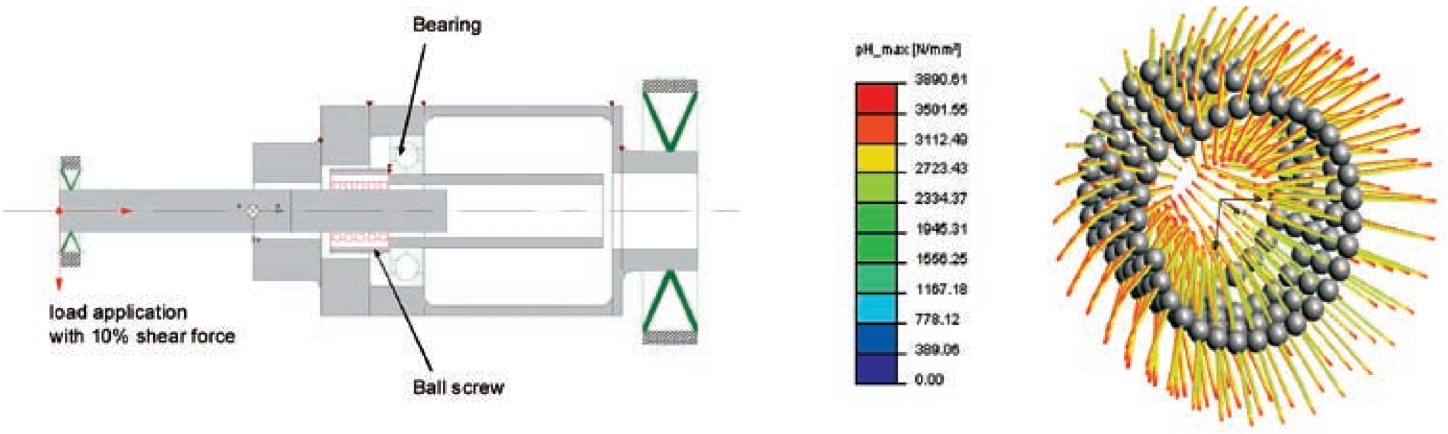

Figure 4: Indication of pressure forces and modelling with the software Bearinx

4 System Performance and Results

In addition to test bench studies, road tests have also been carried out in a demonstration vehicle to verify the performance of the ARAK. The functionality, stability and reliability of the mechanical components, the electrical and electronic components and the system have all been verified in endurance, overload and road tests. A selection of the test results are presented below.

A characteristic feature of ARAK dynamics is the system's step response to a setpoint change. An actuation time of less than 200 ms for a distance of 13 mm is shown in the top part of **Figure 5**. In the bottom part of Figure 5, a power consumption of 30 W is shown for the actuator without the lock applied due to the holding current.

Figure 6 demonstrates the response to the setpoint change with a triangular signal showing the corresponding actual position of the actuator.

Figure 7 compares the power consumption pattern for an actuator with a recirculating-ball drive to one with a trapezoidal thread. The blue line indicates the time-distance-gradient for the actuator. The gradient marked in red is the power required by a trapezoidal drive and the green line indicates the power required by the actuator. The actuator controller design depicted in **Figure 8**, has shown to be robust and reliable and is also used in other chassis applications based on a similar concept.

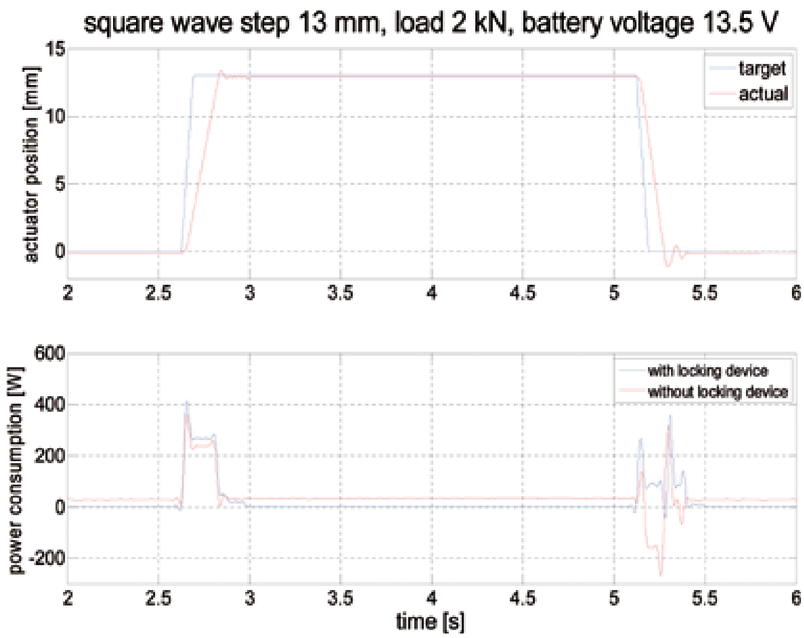

Figure 5: ARAK step response and corresponding power consumption

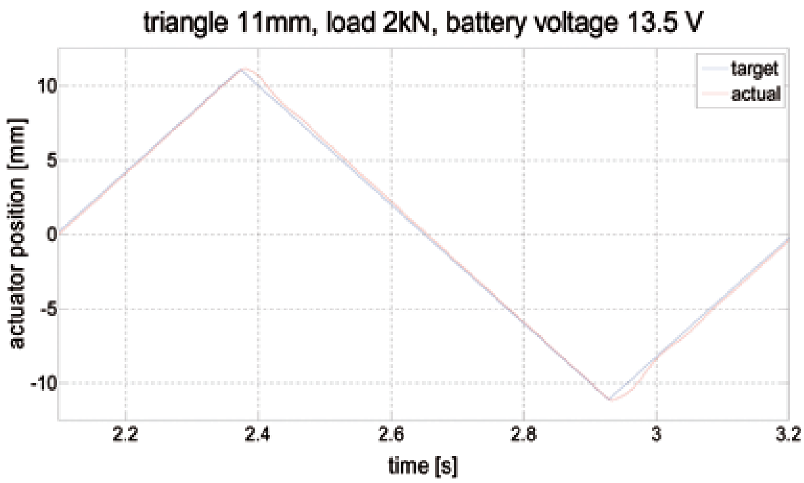

Figure 6: Response of the ARAK to a setpoint change

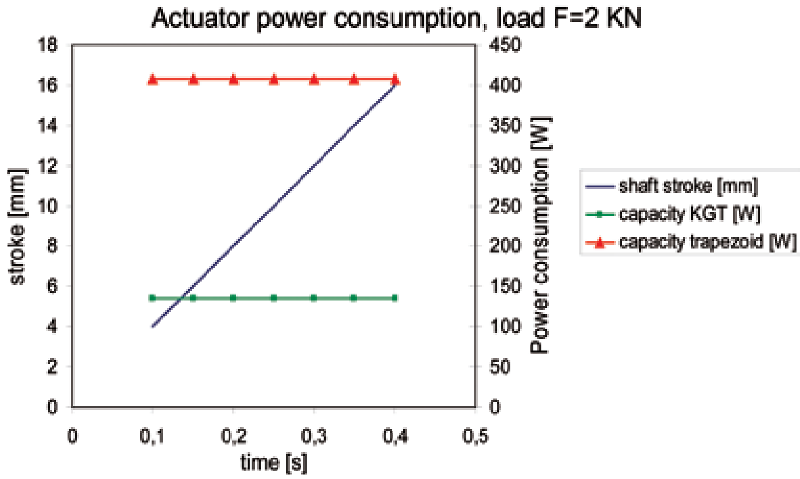

Figure 7: Power consumption pattern for an actuator with a recirculating ball drive and an actuator with a trapezoidal thread

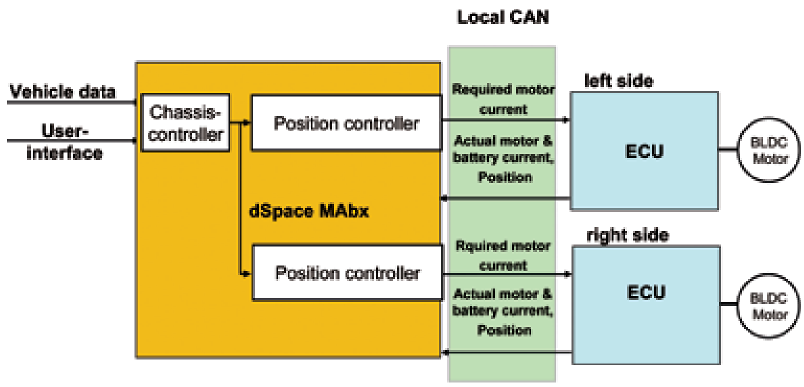

Figure 8: Design of the ARAK controller

5 Functional Safety

Thanks to the mechanical lock integrated into the actuator power flow, the actuator holds its final position in the event of a loss of current. If the sensor malfunctions, other monitoring devices, such as the distance sensor cause the current to be cut from the actuator, and a warning message is triggered in the control unit and displayed to the driver. In such an instance, other vehicle functions can be impaired simultaneously. In addition, plausibility tests are constantly being carried out inside the control unit and a number of monitoring parameters are checked and logged [6, 7]. Furthermore, the multi-layered malfunction monitoring system ensures that in the event of a non-critical malfunction, the actuator is reset in a controlled manner to the zero point in a safe, straight-ahead position.

6 Outlook

Electromechanical actuation technology is on the move. A proposal comprising an e-motor, a sensor and a self-locking gearbox is often not enough to provide a suitable, competitive solution. It is therefore necessary to develop advanced technologies that offer an improved energy balance. Solutions that have already been developed show the new potentials. They are functional, energy focused and ahead of the field in their use of installation space and power density when compared with the state-of-the-art technology. The resulting test phase achieved today equates to that of a prototype. Furthermore, not only can the production technology of the series-production Schaeffler ball-type linear drive for EPS applications be used for ARAK, but a whole host of other geometries and experiences from the same series can also be applied to ARAK in a targeted way. Thus the ARAK system will go into series production within the next two years.

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Electromechanical Active Body Control

Electronic suspension control systems have been established on the market for some years already and thus improved ride comfort and dynamics. Most of the active systems for body control or active roll stabilisation systems use hydraulic actuators. In this context, the high energy demand and assembly costs for the system components have proven disadvantageous. ZF and Volkswagen Group Research have investigated whether such disadvantages can be avoided by using active suspension control systems based on electromechanical actuators.

1 Introduction

Prototypes of an electromechanical active chassis system for vehicle body control were developed. The investigations focused on reducing the energy consumption of the active system while living up to the requirements relating to ride comfort and driving dynamics. This presentation covers the development of the modules – supported by simulations –, measurements at the test rig, integration in a prototype vehicle, and the results from driving tests. In a joint project, ZF was in charge of the development and testing of the actuators with the power electronics as well as actuator control, and Volkswagen Group Research was responsible for integration into the test vehicle, the vehicle controller, and the driving tests [1].

2 Actuator Development

2.1 Main Targets and Basic Conditions

In order to be able to vary vertical forces in push and pull direction between the body and the wheel within milliseconds, the vehicle must be equipped with an individually controllable actuator at each single wheel. Technical requirements result from the application in the specific test vehicle:

- actuator forces and strokes as well as actuating dynamics suitable for an upper class saloon
- installation space comparable to the air spring application
- front and rear axle modules with high percentage of shared components
- 12 V main power supply
- use of passive shock absorbers
- cost advantages compared with hydraulic systems
- minimal energy consumption.

2.2 Actuator Principle

Figure 1 shows the schematic configuration of the actuator with two series-connected springs, the spindle drive, and a parallel hydraulic shock absorber. The suspension spring c1 is deflected by the electric drive in push and pull direction. In order to reduce the electric power demand, the so-called accumulator spring c2 is installed in parallel to the electric motor, which bears the static load.

Since energy is taken from the vehicle electrical system only on demand, this principle requires a considerably lower power input than a hydraulic system. Moreover, when operated in the generator mode, an appreciable share of the energy used can be recovered during rebound and compression phase.

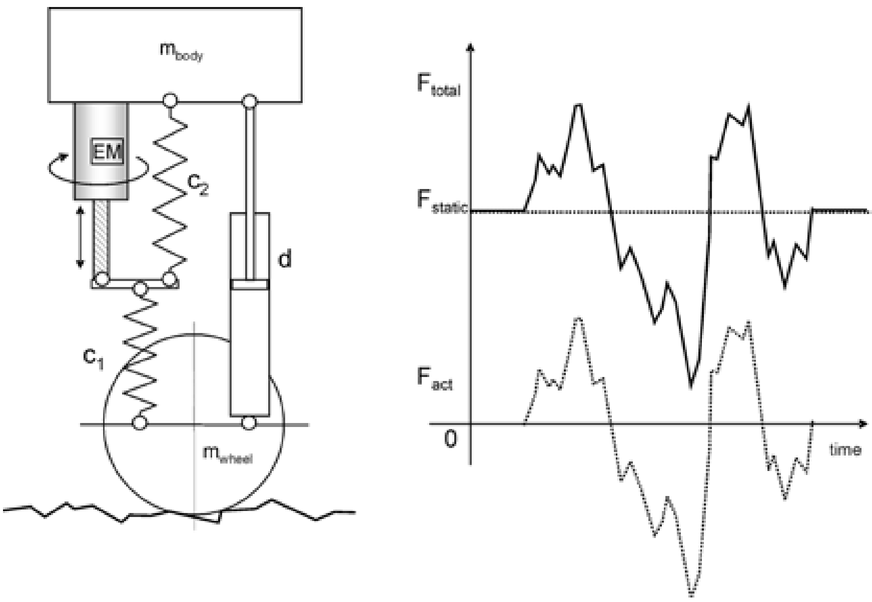

Figure 1: Actuator principle with force compensation, actuating forces with and without accumulator spring

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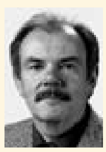
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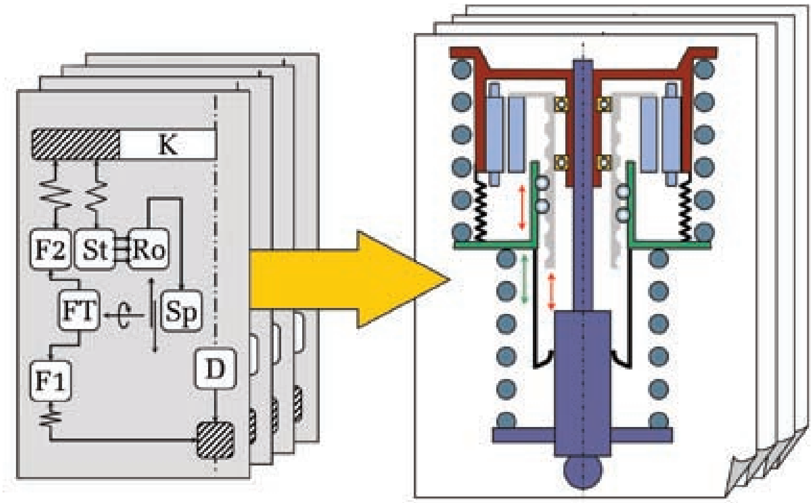

Figure 2: Conceptual design process based on abstract configurations (left) and derived specific layout (right)

2.3 Concept Development

As shown in **Figure 2**, the optimal arrangement of the components was systematically worked out in three steps during the early development phase:

1. synthesis of possible configurations, for example parallel or coaxial allocation to the spring strut
2. component arrangements with due consideration of boundary conditions and functions, for example fastening possibilities, mechanical linkages, free of collisions
3. selection of the optimal configuration after having assessed various criteria such as minimal mass moments of inertia for the rotor and spindle, sealing, heat dissipation etc.

As depicted on the left of Figure 2, different variants of the components and functions are assembled in an abstract illustration and specified in a next step to prove feasibility, Figure 2 right.

2.4 Design of Spring Strut Modules

The main components were dimensioned once the favourite concept had been determined. The major challenge was to attain the required dynamic behaviour while adhering to the specified installation space available and all this with minimum energy requirements.

It was possible to solve the design-related conflict resulting thereof by means of parameter studies and object-oriented simulation. In this context, modelling was done for the electric drive with its thermal and magnetic losses, mass moments of inertia, and the speed-dependent friction, as well as for the springs and the non-linear shock absorber characteristics. For optimal system efficiency, a permanent-magnet synchronous motor was selected as the drive, supplemented by a translation transmission featuring a precise ball screw with low friction.

Figure 3 shows the design of the active spring strut module. In order to ensure cost-efficient production, the electric drive with the motor and the ball screw is identical for both axles. The shock absorbers, springs, housing parts, and top mounts have been engineered in an axle-specific design in order to adapt to the different installation space, load cases, and ratio requirements.

All prototype spring struts were tested on a hydropulse test rig for function and load tests as well as for drive control software development. On this test rig, reality-based depiction of the load direction and the elastokinematics under vehicle installation conditions become possible.

Vehicle measurements provided the basis for the derivation of load cycles for standard manoeuvres and rough track circuits. These test bench excitations were synchronised in real time with simulated target actuating forces for the actuator in order to ensure that realistic loads are generated through time-related exact superimposition. Thus, the dynamic behaviour, power consumption, friction hysteresis, shock absorber character-

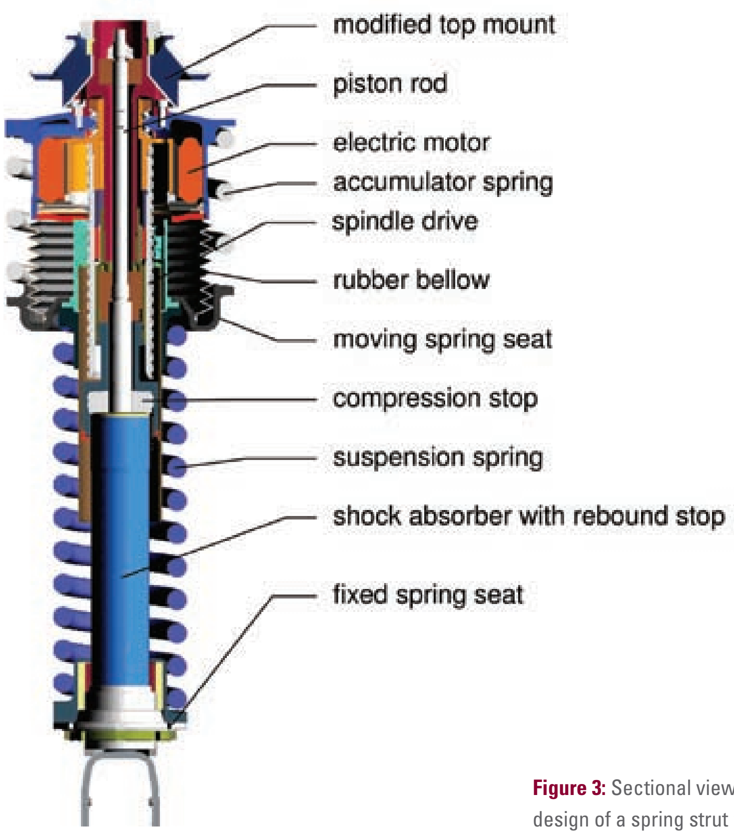

Figure 3: Sectional view on the design of a spring strut module

istics, thermal behaviour of the power electronics, and the durability of the entire unit were tested under worst-case conditions before installation in the test vehicle.

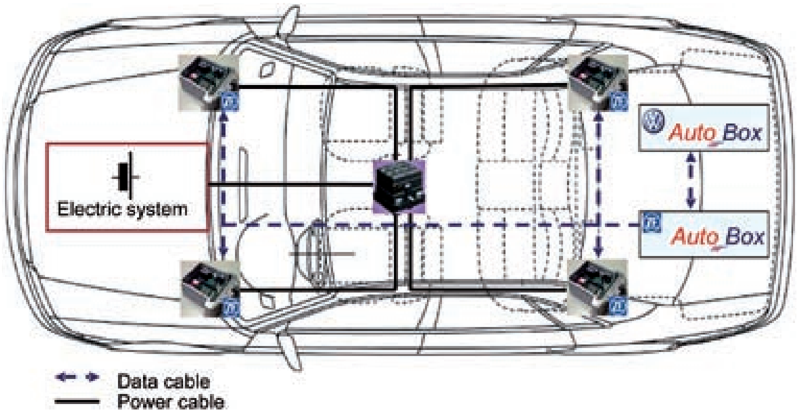

Figure 4: Test vehicle

3 Vehicle Integration and Suspension Control

Figure 4 shows the system setup in the vehicle. The power electronics are supplied by means of a double-layer capacitor (100 F), which is installed in parallel to the vehicle electrical system. Anti-roll bars are not necessary due to the active suspension.

Two vehicle control units are located in the vehicle's rear. These control units are connected to the power electronics, the bus system, and the vehicle sensors by means of signal lines. Vehicle dynamics control is effected by the VW Auto Box.

The overall suspension controller consists of three parts. The lateral dynamics controller calculates the target position of the spindle of each active suspension strut, taking the driver-induced body motions and the requested vehicle height. The four spindle positions ensure that additional forces and torques are provided individually per wheel in order to reduce body movements. Moreover, the torque needed to minimise the roll angle can be distributed to the front or to the rear axle in a targeted manner. This affects the vehicle's self-steering response [2].

The vertical dynamics controller calculates the target spindle positions from the road-induced body vibrations. Main components of the controller are a Skyhook algorithm [3] and an algorithm for tuning the vertical eigenfrequency and damping ratio of the body.

The spindle position controller is in charge of optimally setting the target spindle positions. To this end, the required torques of each electric motor are calculated and passed on to the ZF Auto Box. There, the power electronics are triggered respectively to control the four electric spring strut drives within the desired response time and accuracy.

4 Test Results

4.1 Vertical Dynamics

Figure 5 left shows the comparison between an active and a conventional suspension system in terms of power-density spectra of vertical acceleration at the suspension-strut dome. The level of vertical body acceleration serves as a means for determining vibrational comfort. Here, a reduction of body acceleration up to a frequency of approximately 3 Hz is clearly visible.

The illustrated behaviour is subjectively perceived as being very positive. The vehicle body is highly damped without the high-frequency disruptions of the road becoming strongly noticeable as it would be the case with a conventional, sporty setup.

4.2 Lateral Dynamics

Figure 5 centre reveals that the roll angle during cornering is significantly lower than in the conventional system. In addition to the roll angle reduction, the system ensures a higher roll damping. Subjectively rated, this anti-roll damping is perceived as being particularly comfortable.

The impact of the roll moment distribution among the front and rear axles is shown in Figure 5 right. Roll moment distribution above a 4 m/s² lateral accel-

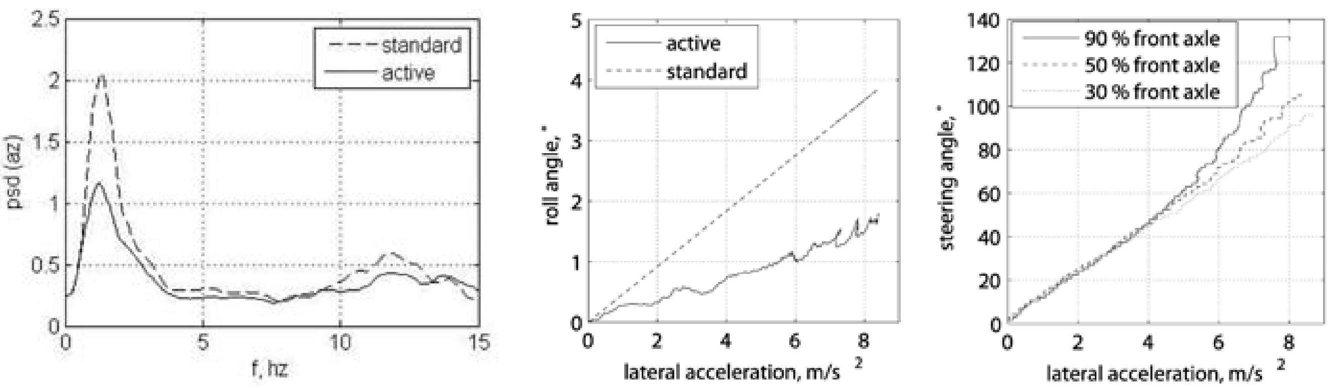

Figure 5: left: power-density spectrum of vertical body acceleration at the suspension-strut dome; centre: roll angle versus lateral acceleration; right: steering wheel angle versus lateral acceleration

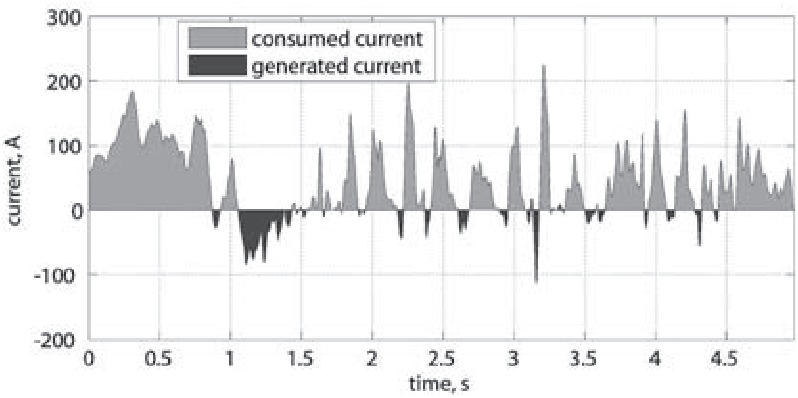

Figure 6: Total current when travelling over a rough, winding country road

eration influences the self-steering response and thus the steering angle requirement. This aspect is due to the non-linear behaviour of the tyres. If the vertical tyre force exceeds a specific threshold, the cornering force no longer increases to the same degree. Agile driving behaviour with concurrent safety reserves is made possible in dynamic driving situations thanks to a targeted distribution of the roll moment [2].

4.3 Energy Requirements

So far, the market almost exclusively offers hydraulic actuators whose permanent power losses are usually much higher than those of comparable electric systems. Moreover, electric systems are capable of regenerating energy or consuming energy or a demand-oriented basis.

Figure 6 illustrates a section of the total Direct Current (DC) over time when travelling over a rough, winding country road. The dark sections indicate the regenerated energy, the light ones the consumed energy for positioning the four spindle drives. The regenerated current reduces the mean total DC current and thus improves the vehicles energy balance.

The **Table** shows the average total DC current needed by the four electric motors and the resulting additional fuel consumption for different road surfaces. In comparison to this scenario, also the measurement results from a similar test vehicle – equipped with a comparable hydraulic system – are shown [4].

The test drives on the track represent extreme chassis loads. The winding sections are crossed at maximum lateral acceleration. At the same time, the road surface is very rough. Thus, strong low and also high-frequency bumpiness occurs.

Good examples for customer-relevant driving situations are the routes on rough, winding country roads and on the highway. In such cases, additional fuel consumption generated by electromechanical systems is below 0.2 l/100 km. The corresponding additional fuel consumption of the hydraulic system is considerably higher with up to 0.6 l/100 km.

Table: Energy consumption on different road surfaces

	Electromechanical system		Hydraulic system
Distance	Ø current (A)	forecasted Ø additional consumption [l /100km]	Ø additional consumption [l /100km]
Rough handling course of the test track	28	0.5	1.0
Rough, winding country road	8	0.2	0.6
Highway (160 km/h	2.5	0.15	0.4

5 Summary

The presented electromechanical suspension system unveils strong potential for improving driving dynamics and ride comfort in the test vehicle. The body movements induced by driver-triggered braking and steering manoeuvres are significantly reduced. Vertical body vibrations caused by road surface excitations are damped at the best possible rate. The lateral dynamics of the vehicle have been improved thanks to the dynamic distribution of the roll moment. Average energy consumption of the electromechanical system is considerably lower than the demand put forward by a comparable hydraulic system. Lower energy consumption leads to decreased additional consumption and consequently to less CO_2 emissions than is the case with a hydraulic system.

6 Outlook

The application of electromechanical chassis systems becomes particularly interesting for future hybrid and electric vehicles. Here, the combustion engine – as the power source – is either eliminated or only temporarily available which makes the use of a hydraulic system extremely difficult and costly. Moreover, higher voltages will be available to supply the electrical spindle drives. Operation at a higher voltage level reduces power demand supplementary and thus also the power losses of the electromechanical suspension system. Therefore, efficiency will be further enhanced.

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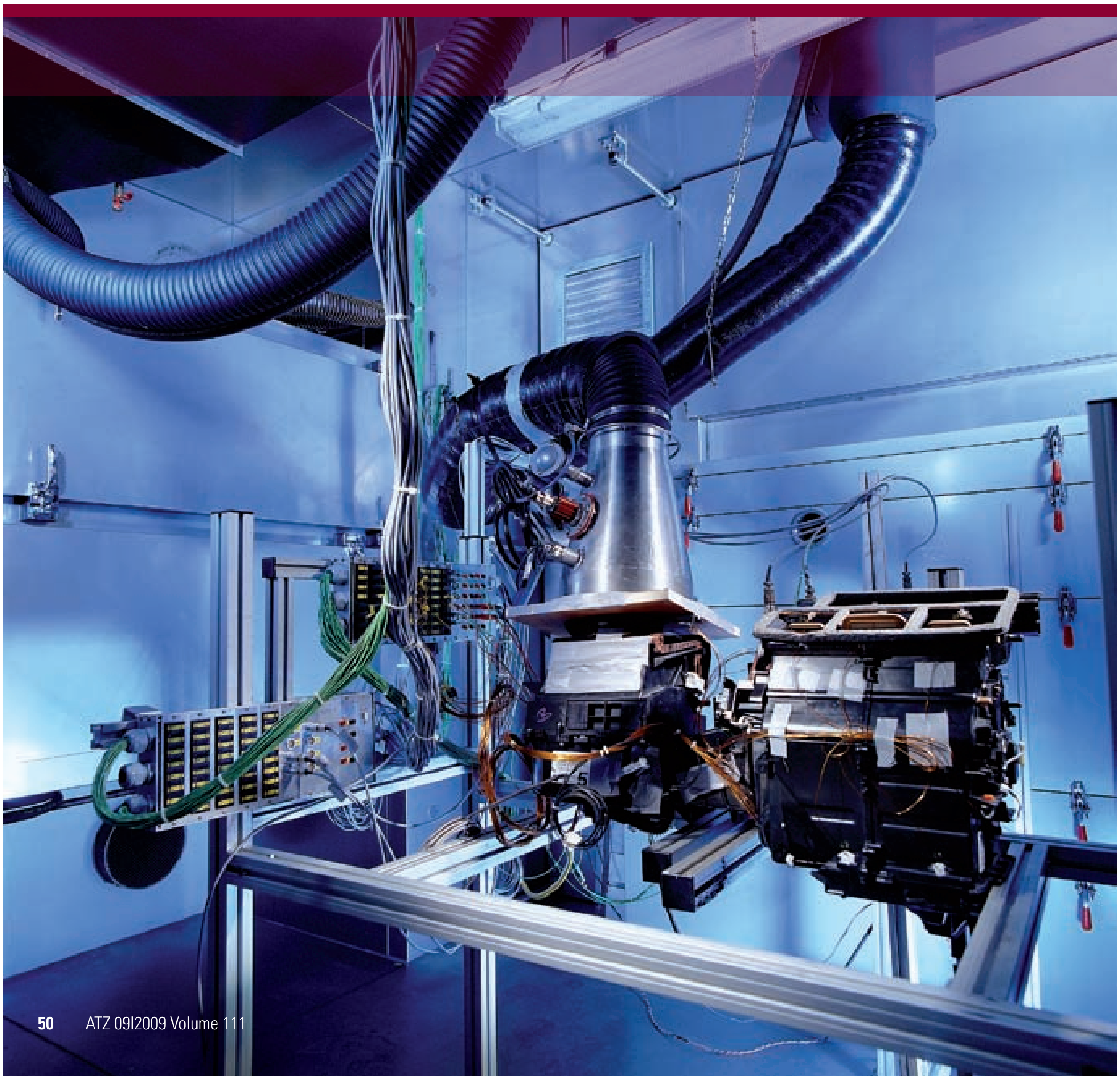
Enhancement of Energy Efficiency in Air-conditioning Systems

As part of efforts limiting carbon dioxide emissions, Behr has conducted a detailed evaluation of the entire refrigerant circuit and its peripheral equipment. It has examined ways of optimizing the circuit of air-conditioning systems, both with regard to the components used and in terms of harmonizing the overall system. Test bench studies show that, with an optimized system, 20 to 50 % of energy requirements can be saved at the full and low load points, depending on the initial system used. A method to evaluate annual fuel consumption and the individual optimization stages are presented.



1 Introduction

Irrespective of the dispute over the scope and timing of the introduction of the planned new EU limit on carbon dioxide emissions of passenger cars, the entire German automotive industry is working on reducing vehicle fuel consumption. When it comes to improving the efficiency of its products, Behr holds a leading-edge position in the automotive industry. Examples of climate control innovations include the sliding evaporator temperature control, high-performance flat-tube evaporators, and a condenser module with an integrated supercooling section. Additionally, we have achieved substantial reductions in the weight and electrical power consumption of air-conditioning (A/C) systems.

These and other improvements helped cut A/C system fuel consumption by 25 % between 1997 and 2008 [1]. As an efficiency target for 2012, we have set ourselves the task of reducing the energy used to operate the refrigerant circuit by over 20 %. This will also encompass current consumption by components such as fans and blowers. This saving roughly corresponds to a reduction in average annual fuel requirements from currently 0.5 down to 0.4 l per 100 km, leading to an associated reduction in CO_2 emissions of around 2.5 g per 100 km. However, automakers and suppliers will need to work closely together in order to achieve this target.

2 Fuel Consumption of the Air-conditioning System

A/C compressor power draw depends almost exclusively on the cooling power required. It, in turn, depends on factors such as the required cabin temperature, outside temperature, humidity, and incoming solar radiation. In turn once more, the latter depend on the size, the angle of inclination, and the transmittance of the window panes.

In contrast, the speed of the vehicle is of only minor importance. Under identical environmental conditions, there is virtually no difference in the fuel consumption of the A/C system whether it is operating at 2 km/h in a traffic jam, or at 120 km/h highway ride. However, the difference is enormous if fuel consumption is expressed in liters per 100 km, because the lower the speed, the higher the fuel consumption for the distance traveled. Stating the fuel consumption in liters per 100 km is informative only if the underlying climate and driving profile from which the average speed is obtained are also specified. A standardized driving profile is appropriate, such as that used for fuel consumption measurements for vehicle registrations, for example.

At present, there is no generally accepted standard or guideline for determining the annual fuel consumption for A/C systems. For that reason, Behr develops load profiles for each country and each major region. With these, the hitherto usual estimates and statistics on the energy consumption of A/C systems derived from extreme situations can be replaced with exact values.

In the first stage of drawing up load profiles at this time, the parameter of outside temperature, which is an important factor for fuel consumption and can be obtained from regional weather services, is represented as a climate profile and then compacted to a temperature record for one year. To arrive at a simple calculation of the fuel requirements for A/C, the temperatures in the climate profile are divided into four categories, and each category is assigned annual frequencies. In turn, the driving profile selected, in this case the New European Driving Cycle (NEDC), is divided into three speed categories, and these are weighted according to the frequency with which they occur. A load profile is drawn up as last stage from the climate profile and the driving cycle that classifies the driving conditions according to temperature and average speed. **Figure 1** shows the climate profile for Frankfurt/Main (Germany) – combined with the NEDC.

Twelve load points are obtained by creating four categories for temperature and three for speed. The size of the circular areas in Figure 1 represents the frequency with which they occur. This clustering allows the annual fuel require-

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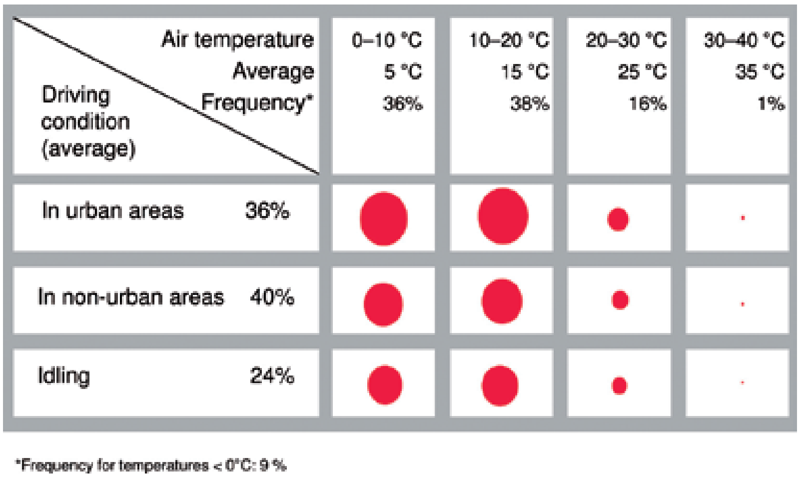


Figure 1: City Frankfurt climate profile and NEDC driving profile

ments to be calculated on a refrigerant circuit test bench, and also in the climatic wind tunnel. Input power to the compressor is measured and weighted for the twelve load points on the test bench. The transferability of the input power for compressor, blower, and fans to fuel consumption in the vehicle can be made using scaling functions [2].

A vehicle is driven in the climatic wind tunnel in the NEDC (average speed 33.6 km/h) in four temperature classes, and fuel consumption by the A/C system is weighted at a cabin temperature set to 22 °C (automatic mode) on the basis of the temperature frequency. In both cases, an average annual fuel requirement for the A/C system is obtained of roughly 0.5 l per 100 km, with an average-sized vehicle (pane size and angle of inclination) in the climate profile for Frankfurt, which is representative for Germany.

In order to reduce this value, we must first identify the operating points that offer the greatest savings potential. The combined temperature and speed frequency values from Figure 1 are therefore multiplied by the power input of the individual load points that were calculated on the test bench. **Figure 2** shows the annual compressor work for the particular temperature cluster in the Frankfurt climate profile, with 15,000 km driven per year and an average speed in the NEDC of 33.6 km/h. The most work is required for the temperature cluster 20 to 29 °C, followed by the cluster 10 to 19 °C.

The situation is rather different for cooling performance; here, the cluster 30 to 39 °C requires the greatest input, but this can be substantially reduced by operation in recirculated air mode. In addition, this cluster is so rare that, as shown in Figure 2, it accounts for only a small amount of the annual compressor work, and therefore of fuel consumption as well. However, this range is extremely important in terms of comfort design.

These operating points are partial load points for the refrigerant circuit, in which the climate compressor is in a governed state, that means working with a reduced delivery volume. Drive torques of between 1 and 10 Nm can occur. At full load, on the other hand (45 °C and maximum air flow), such as is required to rapidly cool down a vehicle that has been parked in the sun, for example, compressor drive torques in the region of 25 to 30 Nm occur.

3 Savings Potentials

The ambitious target of a 20 % reduction in the additional fuel consumption for the A/C system can be achieved only by implementing a large number of detailed improvements in the A/C system. Additionally, unlike in the past, the guiding principle now is that cooling should take place only as much and as often as is required to ensure comfort, driver alertness, and driving safety. Important facts are the right control, the reduction of heat input, current consumption and compressor input power.

3.1 Control

Control of an A/C system should be implemented according to several criteria: evaporator temperature, enthalpy and shutoff are important parameters.

3.1.1 Evaporator Temperatures

By controlling the evaporator temperature, the evaporator can be operated at the upper temperature limit. The higher the discharge temperature at the evaporator, the lower the required cooling power. However, the time that the maximum temperature can be maintained is limited by the risk of evaporator odors originating from moisture and deposits on the evaporator surfaces.

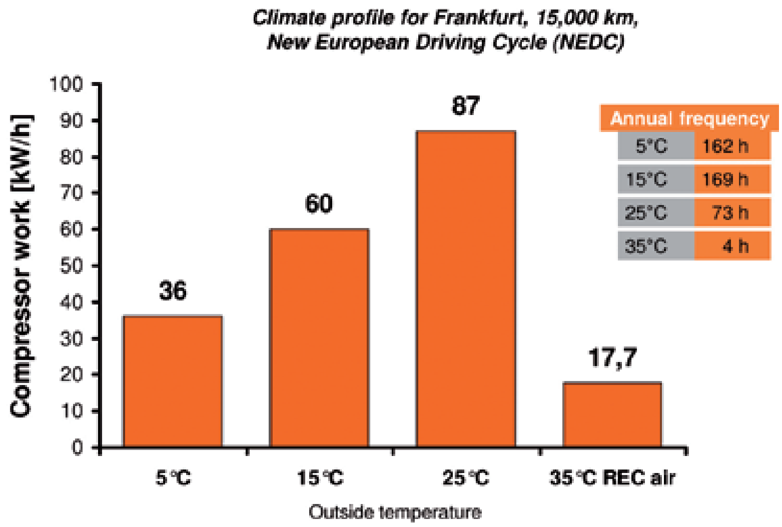


Figure 2: Annual compressor operation of the A/C system in the NEDC

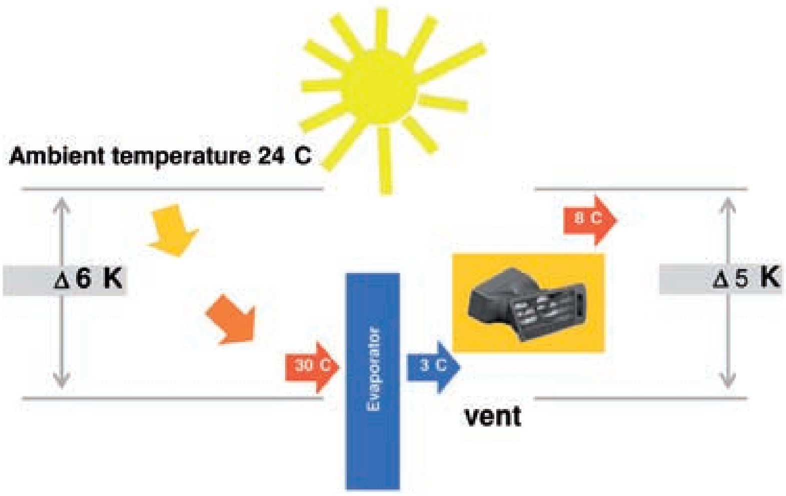


Figure 3: Heat input into the HVAC module and air ducts (wind tunnel measurements with a midrange vehicle)

The new BehrOxal hydrophilic evaporator coating and a new evaporator geometry that improves condensate runoff mean that not only are deposits flushed away more effectively, but also the evaporator dries more quickly after use. Both factors together substantially reduce the probability of odor development. This means that the evaporator temperature control can be used much more frequently than before, while the required cooling power is reduced accordingly.

3.1.2 Enthalpy Control

If the air that is drawn in from outside is cooled in the evaporator, a portion of the moisture in the air condenses. The capacity required for this is known as latent capacity. The evaporator capacity consists of the sensitive portion (for cooling down the air) and the latent portion (condensation of water vapor). A reduction in the latent capacity is desirable on energy grounds.

Depending on external conditions, a controlled recirculated air mode can be more efficient in terms of energy than fresh air mode. But this control function must take into account demisting of the windows and the CO_2 content of the vehicle cabin. Measurements in the wind tunnel with a midrange vehicle at a 28 °C wind tunnel temperature and 40 % relative humidity, and without incoming solar radiation, yielded a reduction in fuel consumption of 35 % in recirculated air mode compared with fresh air mode.

3.1.3 Shutoff Control

The function “Auto AC off” switches off an operating A/C system whenever it is not really required for reasons of comfort, unless there is the risk of window fogging at this time, for example in wet weather with high air humidity. If this risk exists only when the A/C system is switched off, the control system must be able to switch the unit on again. This also applies when there is the risk of odor development, for example because of a rapid rise in temperature and moisture in the evaporator after the unit is switched off. This can be achieved through a delayed, staged shutdown, for example. “Auto AC off” takes into account all of the conditions that affect window fogging, odors, and comfort in the shutdown and (re)start strategy.

Today’s control strategies allow an A/C system to keep operating even when cooling is no longer required to achieve a comfortable ambient climate, for example in the case of a drop in the external temperature, and this increases the additional fuel consumption for A/C accordingly.

3.2 Reduced Heat Input

The heat input can be reduced by optimizing of the HVAC module and the engine cooling module.

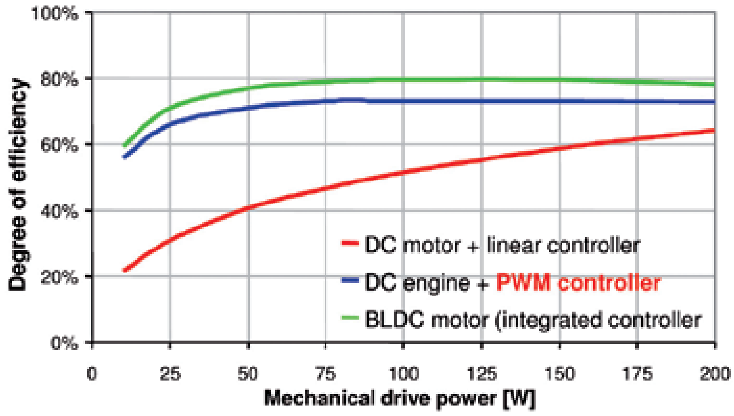
3.2.1 HVAC Module

At an external temperature of 24 °C and 700 W/m^2 solar radiation, the ambient air drawn in by the blower will, in this example, be heated by 6 K by the heated-up vehicle body and by the waste heat from the blower motor and the blower control, **Figure 3**. Once the air has been cooled in the evaporator to approximately 3 °C, the cold air flows through the air ducts into the vehicle’s passenger compartment. On the way, the air is once again heated by up to 5 K. In this two-stage heat input system, a portion of the cooling power provided by the evaporator for conditioning the climate in the passenger compartment is lost.

Using a PWM controller in the blower control system that emits less heat than a linear controller makes it possible to reduce this loss, and the loss can be further reduced through the insulation and shortening of the cold air paths, as well as by sealing off the heater core located downstream of the evaporator in the HVAC module. The sealing off and ducting of the air around the heater core is devised in such a way that only a very small amount of heat from the heater core, through which hot coolant is constantly flowing, can be transferred to the cold air. If the heat input in the supply air is reduced by a total of 4 K, the required cooling power in a midrange vehicle is reduced by approximately 10 %.

3.2.2 Engine Cooling Module

Measurements of the air inlet temperature at the condenser of a stationary small car with the combustion engine idling (idle with wall) yielded mean temperatures of 50 °C and maximum temperatures of up to 65 °C at an outside temperature of 30 °C. This is the result of warm air rising from the road and backflow of hot air from the engine compartment to the front. In order to prevent such backflows, the air must be conducted out of the engine compartment in a



	Upgrade 1: DC motor with PWM control	Upgrade 2: BLDC motor
Reduced current consumption	40 W	46 W

All measurements in the climate profile for Frankfurt

Figure 4: Reduced current consumption through use of PWM controllers in the Frankfurt climate profile (basis: DC motor with linear controller)

more efficient manner. The cooling module in which the condenser sits must be sealed off from the vehicle body in such a way that no hot air from the engine compartment can flow along the side of the module into the front of the vehicle. This makes it possible to reduce the condenser air inlet temperature by an average of 12 K.

3.3 Current Consumption

Blowers, fans, and their control systems have electric power requirements amounting to between 10 and 50 % of the power required for the A/C, depending on the operating point. This electric power is supplied by the generator with an efficiency factor of approximately 0.6. Using PWM controller makes it possible to reduce the current consumption in the Frankfurt load profile by an average of 40 W compared with linear control devices. The use of a brushless motor reduces current consumption by a further 6 W, and this reduces the additional fuel consumption for A/C by approximately 10 % compared with a linear controller with a brush motor, **Figure 4**.

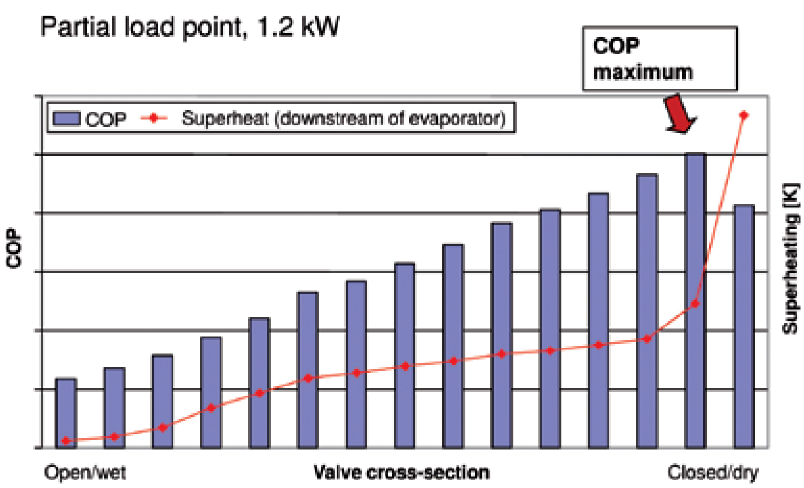


Figure 5: Influence of superheating on the COP when an electrical expansion device (EXV) is used

3.4 Compressor Input Power

The greatest portion of the fuel consumption for the A/C system is required for driving the compressor. A reduction of this input power can be achieved only through optimization of the entire refrigerant circuit: the circuit components, the quantity of oil circulating, the evaporator superheating control – possibly in conjunction with an internal heat exchanger – and the circuit coordination.

Based on current refrigerant circuits, these improvements have the potential to reduce the power draw by at least 10 %. The measurement used here is the COP (Coefficient of Performance), the ratio of cooling capacity to input power. Greater increases in efficiency are also possible depending on the basic circuit used.

3.4.1 Internal Heat Exchanger

The internal heat exchanger (IHX) cools the refrigerant downstream of the condenser in the countercurrent using the refrigerant downstream of the evaporator. The refrigerant on the way to the evaporator is thereby further supercooled; it therefore takes up more heat following expansion in the evaporator. For the same cooling capacity, the refrigerant mass flow can be reduced and the COP of the refrigerant circuit increased by 5 to 10 %, depending on the suction-side pressure loss and the heat exchange capacity of the IHX.

3.4.2 More Efficient Components

A new generation of condensers provides up to 10 % more efficiency compared with series-production models, resulting in an increase in the COP of approximately 6 %. The new compressors also exhibit greatly enhanced efficiency.

3.4.3 Circuit Coordination

The expansion device is particularly important to the circuit coordination, since it controls the superheating downstream of the evaporator. Optimal superheating increases the difference in enthalpy used in the evaporator, and, like an IHX, reduces the required refrigerant mass flow. **Figure 5** demonstrates the influence of superheating downstream of the evaporator on the COP for a load point of 1.2 kW cooling capacity

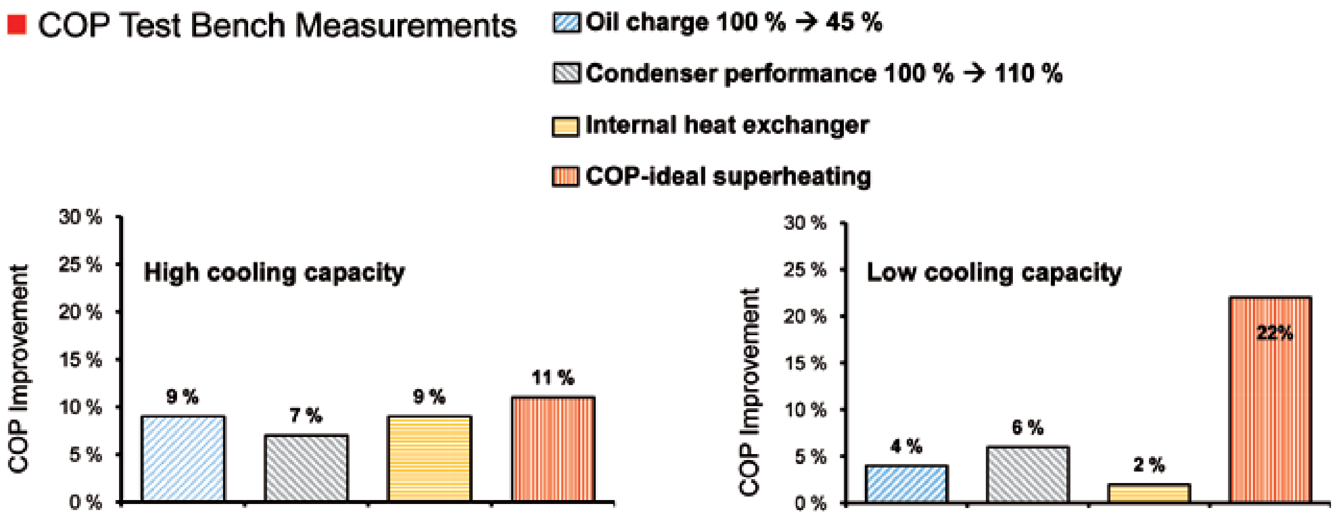


Figure 6: Potential for increase in the COP in the enhanced refrigerant circuit at various cooling capacities

when an electrical expansion device (EXV) is used. With increased superheating, the COP will initially increase, whereas excessive superheating will cause it to drop dramatically.

A thermal expansion device (TXV) does not make it possible to obtain COP-ideal superhating at all operating points [3]. However, selecting an expansion device that is precisely matched to the refrigerant circuit makes it possible to utilize a large part of the superheating potential.

4 Test Bench Results

The improvements in the COP shown in **Figure 6** were determined from measurements from a series-production refrigerant circuit of a midrange vehicle on a system test bench. At a high cooling capacity, the reduced oil charge, increase in condenser performance and the use of the IHX result in an improvement potential amounting to 36 % compared with a series-production circuit. At low cooling capacities, the IHX potential, which is 9 % for high cooling capacities, is reduced to 2 %. In this case, the superheating control is the most significant, with an improvement potential of up to 22 %.

This result was obtained on the test bench using an electric expansion device. It could be argued here that the small improvement in the COP of just 2 % does not really justify the use of an IHX for the very common partial load cases. However, this applies only to optimal superheating, which is never required in practice. For safety and stability reasons, ideal superheating, shown by the peak of the blue curve in **Figure 7**, is not selected, but instead an operating point to the left of it. A comparison of the two curves in Figure 7 shows that with an IHX, that means with an optimized combination of IHX and a suitable TXV, a COP improvement of well over 2 % is obtained.

5 Application in a Series-production Vehicle

The enhanced efficiency refrigerant circuit was installed to measure fuel consumption in the climatic wind tunnel in an upper midrange vehicle. For the purposes of comparison, the additional fuel consumption of the series-production system was calculated beforehand, at an ambient temperature of 28 °C, a relative humidity of 40 %, and a cabin temperature set to 22 °C. The A/C system was switched to external air mode and the

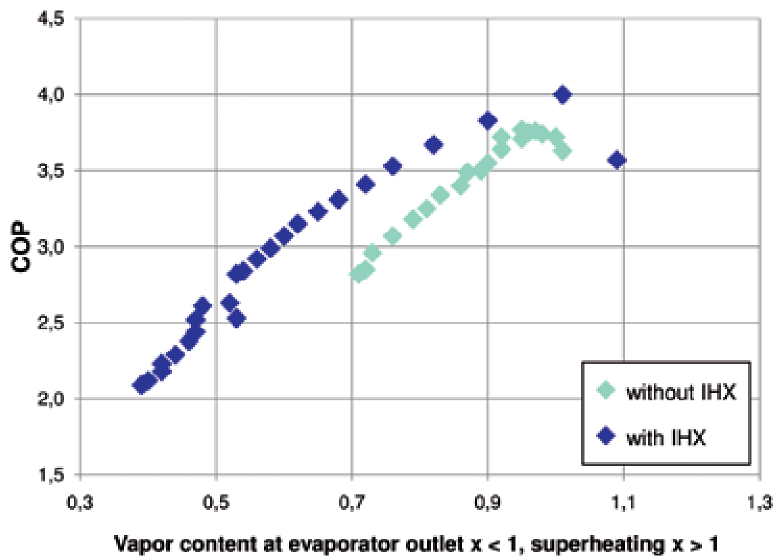


Figure 7: Influence of the evaporator outlet condition on the COP by way of comparison: with and without internal heat exchanger (IHX), at 1.2 kW cooling capacity

temperature downstream of the evaporator had a standard setting of 3 °C. The additional fuel consumption calculated on this basis was defined as 100 %.

Simply by switching to recirculation mode (85 % recirculated air), fuel consumption was reduced to around 65 %. Following installation of the enhanced efficiency refrigerant circuit, but still without a sliding evaporator temperature control, the additional fuel consumption fell to approximately 35 %. With the evaporator temperature control – at a discharge temperature of 8 °C instead of 3 °C – fuel consumption was reduced to only around 20 % of the original value.

6 Measuring Accuracy

The measurement technology used for the COP improvement must be able to accurately determine compressor input power at all load points. However, this is usually not the case, since, in conventional test benches, the average error rate for small measured variables, which are common in partial load operation, is often greater than the value of the respective variables. For example, Figure 7 shows that, for a cooling capacity of 1.4 kW, a maximum COP improvement of approximately 10 % is obtained by using the IHX. However, at this low capacity, the mean error in a conventional cooling capacity test bench is ± 20 %, as the following calculation shows:

$$COP = \frac{\dot{Q}_{evaporator}}{P_{compressor}} \quad \text{Eq. (1)}$$

$$\frac{\Delta_{COP}}{COP} = \sqrt{\left(\frac{\Delta_{\dot{Q}evaporator}}{\dot{Q}_{evaporator}}\right)^2 + \left(\frac{\Delta_{Pcompressor}}{P_{compressor}}\right)^2} = \quad \text{Eq. (2)}$$

$$\sqrt{2{,}9\ \% + 20{,}2\ \%} = \pm\ 20{,}4\ \%$$

The basis for this calculation is the measurement accuracy that can be achieved with the different measurement devices (scales, sensors), namely:

- air inlet temperature at evaporator: ± 1.0 K
- dew point: ± 0.3 K
- air mass flow [kg/s]: ± 2 %
- air output temperature: ± 1.0 K
- mass flow of condensate [k/s]: ± 0.1 %
- compressor speed: ± 15 rpm
- torque: ± 0.50 Nm.

In the case of a partial load, a measurement is practical only if the errors can be reduced to below ± 5 %.

In collaboration with test bench manufacturers, Behr has improved the refrigerant circuit test bench and some measuring methods, with the compressor torque measurement being particularly significant, which meant that the goal of a mean error of less than ± 5 % over all measurement ranges was achieved. With this test bench and a modern climatic wind tunnel, Behr now provides highly sophisticated measurement technology that is recognized by the automotive industry.

7 Summary

Given that a reduction in additional fuel consumption from air-conditioning systems of around 25 % has already been achieved in the last decade, a further reduction of 20 % by 2012 is an ambitious goal. Behr's studies have demonstrated how this goal can be achieved. A method to evaluate the annual fuel consumption with the climate example of the city Frankfurt/Main (Germany) was presented. These studies involve controlling and adjusting the refrigerant circuit, enhancing the efficiency of existing components such as heat exchangers, blowers, and air ducts, and also the use of new components such as the internal heat exchanger and PWM controlled blowers and fans. Fuel consumption calculations in the individual load situations have also shown that, in the partial load situation, a great deal of energy can be saved by means of an optimized superheating control. In future, system settings will therefore need to first give priority to the partial load operating points.

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Special

50th Anniversary of Kistler

From Piezoelectric Sensor to Measuring System

In 1959, Hans Conrad Sonderegger established Kistler Instrumente AG in Switzerland. In 1957, Walter P. Kistler and Hans Conrad Sonderegger had already founded Kistler Instrument Corp. in the USA and Hans Conrad Sonderegger had established Kistler Instruments in Switzerland. In 1958, Kistler launched the first universal miniature pressure sensor. In the years that followed Kistler set milestones in the field of sensor technology with its innovations and expanded its global presence. In 2009, its jubilee year, Kistler is adding the new KiBox, the mobile in-vehicle combustion analysis system, to its range of products.

The Beginnings

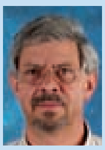
Piezoelectric effects were described for the first time by the brothers Pierre and Jacques Curie in 1880. However, these effects remained little more than a scientific curiosity for more than 30 years. The first publication on piezoelectric pressure measurement in internal combustion engines appeared in 1925, with the first publication on piezoelectric cutting force measurement being issued in Japan in 1927. In addition, forces and pressures were measured with piezoelectric sensors in Germany, France and the USA until the 1940s.

At the end of the 1940s the Schweizerische Lokomotiv- und Maschinenfabrik in Winterthur started developing and manufacturing piezoelectric pressure sensors on a larger scale. Together with the patenting of the charge amplifier by Walter P. Kistler in 1950, this revolutionized piezoelectric measurement technology and opened up undreamt-of opportunities for extremely precise dynamic measurement of mechanical variables. In 1957, Walter P. Kistler and Hans Conrad Sonderegger had established Kistler Instrument Corp. in the USA, and Kistler Instruments had been founded by Hans Conrad Sonderegger in Switzerland. Kistler launched the first miniature pressure sensor as early as 1958. It was universal in application and went on to set a new standard in pressure measurement. Over the next few years the company expanded successfully. In 1966, Kistler moved into its own new company building in Winterthur-Wülflingen. This building still houses the company's headquarters today.

Innovations Extend the Range of Products

The market success of the pressure sensor encouraged Kistler to develop high-quality measurement products for other areas of application as well. As a result, the company launched a number of innovations in close succession. In 1965, Kistler introduced the world's first quartz force sensor in the form of a load washer. The two-wire concept „Piezotron" for piezoelectric sensors with voltage output followed in 1968. From then on it was used, first and foremost, in accelerometers and – to a lesser extent – in pressure sensors. The following year Kistler launched piezoelectric three-component force sensors, a world first, and had them patented. Mounted in dy-

The Author



Bernhard Bill
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namometers they were used all over the world to measure cutting forces. The now legendary Type 5001 charge amplifier („measuring without math") was introduced the same year. The first ultra-sensitive quartz strain sensor, another world first, was launched in 1980. In 1983, the rotating quartz wheel-force dynamometer, which was yet another world first at the time, and was developed for and with VW and BMW, was introduced. In 1988, the first microprocessor-controlled charge amplifier was launched.

However, Kistler also continued to develop pressure measurement technology and, in 1973, introduced sensors using the piezoresistive measurement principle. The patented polystable quartz cut enabled the company to introduce quartz sensors for operating temperatures of up to more than 350 °C in 1974. They were the first uncooled engine pressure sensors. Another milestone was Kistler‘s uncooled high-temperature pressure sensor with a diameter of only 5 mm for use in engine measurement in 1989. In 1998, Kistler commissioned its first in-house crystal growing system. The resulting „PiezoStar“ crystals are particularly outstanding for their extremely stable temperature characteristics. 2002 saw the first M10 measuring spark plugs for use in Formula 1. In general, combustion analysis still plays an important role to this day; measuring spark plugs and glow plug adaptors enable measurement without an additional indicating bore. Thanks to new crystals, Kistler was able to increase the sensitivity of uncooled M5 engine pressure sensors to -45 pC/bar in 2005.

Kistler made the leap from sensor to measuring system manufacturer as long ago as the 1980s. The first step into process monitoring was made in 1987 with the introduction of the „ControlMonitor“ (CoMo). In 1992, Kistler‘s first rotating four-component cutting force dynamometer with integral electronics and telemetric signal transmission was launched. In the same year, the first control monitors with online monitoring functions and display (CoMo II) were introduced. In 2002, the company launched the Internet-compatible ControlMonitor „CoMo Net.“

In 1994, the first WIM station using Kistler Lineas sensors to determine the axle loading of moving vehicles was installed. In the same year, Kistler was accredited as a calibration center for pressure, force, acceleration and electrical charge. In 2004, Kistler built the first „SmartCrash“ barrier. These systems are now an everyday development tool and are used at Audi, BMW, Daimler, Fiat, Hyundai and PSA.

Internationalization

Kistler‘s corporate success is closely linked to the company‘s global orientation. Kistler‘s international expansion started shortly after the establishment of the companies in America and in Switzerland. Thus, in 1963, the Group company in Germany was established and, in 1966, the company in England was founded, followed in 1986 by the subsidiaries in Japan and in 1991 in France. Kistler expanded its presence in Asia with the establishment of Group companies in China and Singapore in 1996 and in Korea in 2000. The subsidiary in India followed in 2003. However, Kistler continued to expand in Europe as well: in 2000, a company was founded in Austria and in 2002 in the Netherlands. The firm set up Group companies in Sweden and Denmark the following year. In 2002, with the integration of IGeL Ingenieurgesellschaft für Leichtbau Kistler expanded the product portfolio of measuring wheels from the 1980s with lightweight measuring wheels. These are based on the strain gage principle and make it possible to measure static components. A strategically logical step was the takeover by Kistler of Velos Messysteme a year later in 2003. In 2006, Kistler acquired the long-established German company Dr. Staiger Mohilo, thereby extending its portfolio with the torque measurand. The Group companies in Australia and the Czech Republic were established in 2007, and the Group company in Spain a year later.

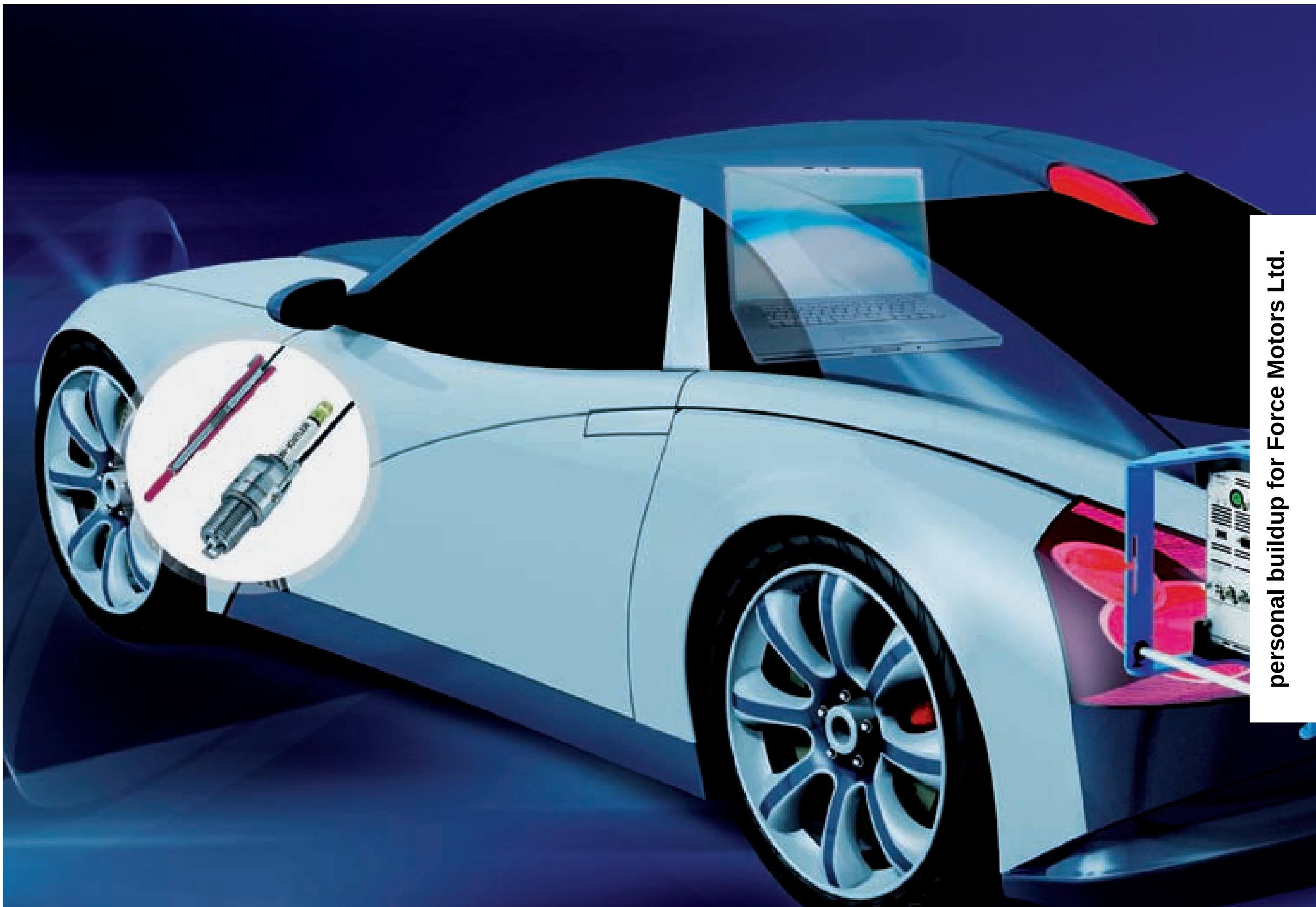
First micro-processor-controlled charge amplifier

2009 – A Jubilee Year Full of Innovations

In 2009, Kistler is celebrating its fifty-year jubilee. Kistler is marking this momentous occasion by the addition of the new KiBox, a mobile in-vehicle combustion analysis system, to its range of products. In addition, the new Type 5018 charge amplifier is being launched. On the product side, optical systems are also helping to round off Kistler‘s portfolio.

In 2009, Kistler also acquired MSC Automotive GmbH, thereby expanding the company‘s portfolio with dummy measurement technology for in-vehicle safety. Together with the SmartCrash barriers, Kistler is now able to offer comprehensive system solutions for safety as well. The acquisition of Corrsys-Datron Sensorsysteme GmbH enables Kistler to perfect its range of measuring systems for dynamic vehicle testing in automotive development. ■

Systems with SmartCrash barriers are now in use at Audi, BMW, Daimler, Fiat, Hyundai and PSA



personal buildup for Force Motors Ltd.

System Capability
A New Era in Dynamic Measurement

The Author

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Over the last 50 years Kistler has developed from a pioneer of piezoelectric measurement to a technology leader and system provider. The sensors and charge amplifiers for measuring the mechanical quantities of pressure, force and acceleration have been perfected over this period. For approximately 20 years Kistler has been increasingly focusing on the development, manufacture, and sale of system solutions for the main application of engine and vehicle development as well as manufacturing process control. A great deal of importance is attached to both system capability and after-sales service.

Evolution of the Lab Charge Amplifier

Charge amplifiers convert the charge output by the piezoelectric sensors into a proportional voltage. To do this, the highest possible insulation values, the smallest possible input currents and a signal bandwidth from 0 to 200 kHz combined with minimum noise are required. The gap between the piezo sensor and the cathode-ray oscilloscope was closed with the invention of Kistler's Type 1 charge amplifier – which at that time was still built with tubes. This opened up the possibility of developing dynamic measurement technology with piezoelectric sensors. This was followed by the era of Types 5001 and 5007 with their integral „slide rule". This made it possible to „measure without math" for the first time. The Type 5011 was the first charge amplifier with a microprocessor which could be remotely controlled via data communication interfaces. The Type 5018 will supersede Type 5011 with even better specifications and new features in 2009.

Universal Measuring Amplifier Platform

The market is increasingly demanding modular, multichannel amplifier systems, especially for combustion analysis of internal combustion engines on test stands. The cost-effective solution is the „Signal Conditioning Platform" (SCP). It can accommodate up to 16 two- or four-channel measuring modules and includes five different rack variants. Measuring modules for piezoelectric and piezoresistive sensors and for strain gages and thermocouples are currently available. Manual configuration of parameters is tedious and prone to errors if there are a large number of measuring channels. Kistler was therefore involved from the outset in a working group in the USA set up to define the 1451.4 IEEE standard for the „Transducer Electronic Data Sheet" (TEDS). The TEDS memory chip is integrated into the connector on the amplifier side and permanently linked to the sensor. The identifying features such as manufacturer, type and serial number as well as individual sensor characteristics and operating time are stored in the TEDS. When a TEDS sensor is connected to the measuring module, the amplifier immediately reads the sensor characteristics and automatically adjusts. This satisfied the desire of many measurement technicians for „plug and measure". The SCP can be readily controlled, for example from the combustion analysis PC, using the graphical user interface.

The „Equipment Database" web application makes it possible to efficiently manage the measuring equipment over its entire life cycle. It provides interfaces with the calibration system, other user applications, and the Kistler web server along with its calibration data. As of recently, customers have been able to call up their sensors' calibration data at any time and from anywhere in PDF and XML format.

Evolution of Kistler's lab charge amplifier

Mobile Combustion Analysis System for Over-the-road Engine Testing

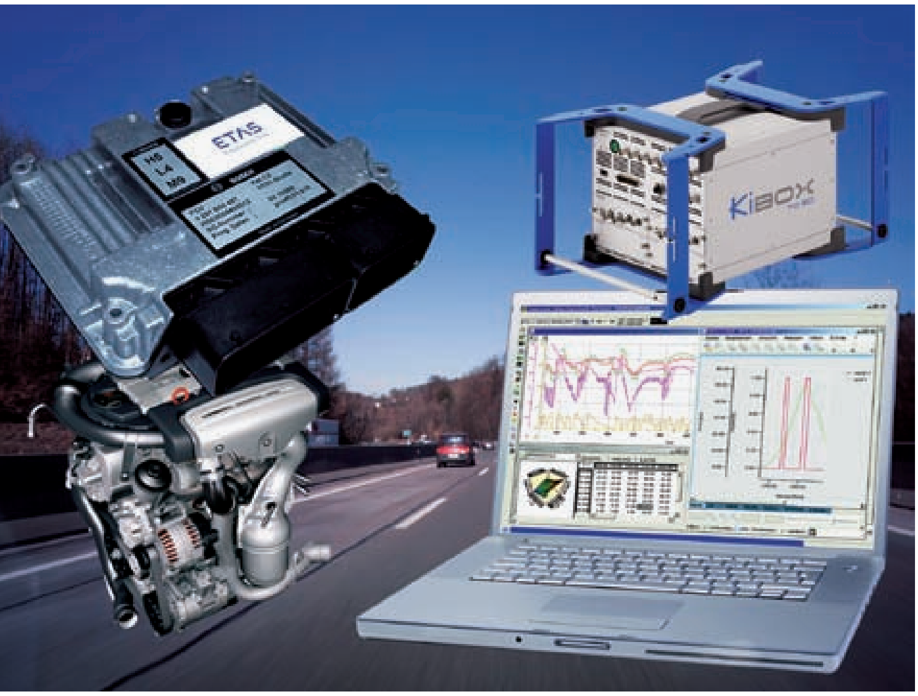
Over the last few years, the standards relating to exhaust emissions and energy efficiency have continually become more stringent. And there is no end to this process in sight. At the same time, the functionality and number of parameters in engine control units have drastically increased. Many of these parameters are directly governed by combustion. Combustion analysis parameters are very important for optimization of engine cold starts and driveability during over-the-road testing. They allow quick identification of the relevant setting parameters in the control unit and help to determine the amount and direction of the necessary adjustments.

During combustion analysis, piezoelectric sensors measure cylinder pressure directly in the combustion chamber under the most extreme operating conditions. If the combustion volume is determined at the same time, the combustion analysis parameters can be calculated. These allow experts to accurately judge the quality of energy conversion. With its „KiBox" Kistler has developed a new data acquisition and processing system specifically designed for in-vehicle cylinder pressure analysis. In addition to an innovative data acquisition concept and simple integration into the „INCA" application system, KiBox features a variety of new characteristics going beyond those of the state-of-the-art. The key combustion analysis parameters can therefore be determined very accurately in real-time under actual operating conditions. Integration into the "INCA" application system ensures that these parameters can be recorded and analyzed synchronously with the actuating data of the ECU. KiBox thus provides a mobile combustion analysis tool that ensures an extremely efficient approach to both: ECU calibration and engine troubleshooting.

Wheel Force Measurement on Test Stands and Over-the-road Testing

The forces and torques acting at the tire contact points must be known to design the components of the entire vehicle related to driving and to optimize driver assistance systems. „RoaDyn" force measuring wheels record these forces and torques with a high level of precision and withstand the harsh operating conditions. They can be used across the full range of vehicles, from racing cars to commercial vehicles. The modularity of the RoaDyn System 2000 allows easy adaptation to suit the particular measurement task. Thanks to its high level of integrability and versatile interfaces, it can be combined with other measuring systems if necessary, for example with measuring instruments which record the vehicle's slip angle, longitudinal and lateral speed and log the vehicle's current position based on GPS.

Universal Signal Conditioning Platform (SCP) and „PiezoSmart" (TEDS) sensor



Over-the-road engine testing and ECU calibration with the "KiBox" system

Quality Assurance Systems Integrated into Production Process

Joining processes – for example the pressing of bearings onto shafts – are very frequently used as permanent connection technique. As non-destructive mechanical testing of press-fits is virtually impossible, quality control integrated into the production process is almost mandatory. The „CoMo Net" and „CoMo View" monitors measure and evaluate the characteristic force-displacement curve for each pressing operation. These control monitors can be connected to the production network via Ethernet. The web technologies used significantly simplify integration into the system. They enable access to the CoMo units at any time from anywhere, for example, to monitor an ongoing process.

Kistler systematically expanded the range of products a few years ago to include electromechanical NC joining modules. The advantages of these compared with hy-

„Products Must Provide Concrete Benefits for the Customers“

In an interview, Rolf Sonderegger, CEO of the Kistler Group, spoke about the further development potential for testing equipment and sensors as well as the contribution of the Kistler Group towards the electrification of the powertrain.

Rolf Sonderegger, CEO of the Kistler Group

Question *In recent years Kistler has grown both internally and externally to become a global company with 1000 employees. What other growth targets have you set?*
Sonderegger *Growth is primarily a consequence of the right strategy; the products in your portfolio must find a market and provide concrete benefits for the customers. Growth per se cannot be the goal. Nevertheless, in order to be a partner to the automotive industry, a company needs to be a certain minimum size so that it can have a global presence and provide its customers with development processes locally. Expressed in figures, we believe that turnover of approximately CHF 500 million is required to attain this size. Over the next few years we expect to achieve our highest growth in Asia and in the USA.*

Question *Simulations are becoming more and more accurate. Soon it will be possible to carry out almost all aspects of engine, chassis and crash development work using virtual methods alone. Will this development make testing sensor technology superfluous?*
Sonderegger *That is a very good question. In theory, it is conceivable that virtual technology could supersede sensor technology. But in reality the opposite is true. Calculations and tests complement one another and are speeding up the development process enormously. Virtual test systems are very cost-effective and indicate a tendency. But in the end, when it comes to validating the virtual values it is always the real test that counts, particularly when one considers that quality and safety requirements are set to grow exponentially.*

Question *Combustion pressure sensor technology is discussed time and again as a method of precision-controlling engines, whether diesel or gasoline. What do you consider to be the technical possibilities from the perspective of the sensor manufacturer?*
Sonderegger *The technology already exists. A combustion pressure sensor which is suitable for series production is a reality, but unfortunately it does not come without a price tag. Combustion pressure monitoring is slowly becoming the standard for large engines. But when it comes to automobiles and commercial vehicles, it has not yet been demonstrated that the benefits outweigh the costs. In close collaboration with a major partner we have developed a product which was almost ready to go into mass production, but there was little interest from the market. If the market changes, we are ready to go.*

Question *What are the challenges in this field?*
Sonderegger *Combustion pressure monitoring is technically feasible and worthwhile, but only at very high volumes. But these volumes are simply not there at the moment. However, as Victor Hugo once said: „Nothing is as powerful as an idea whose time has come“. The combustion chamber pressure sensor's time has not come yet.*

Question *The electrification of the power train and electrical traction are key development trends for automobile manufacturers at the moment. What can Kistler contribute to this?*
Sonderegger *Although electrification is currently the number one mega-trend in drive technology, its economic relevance has been negligible to date. But if you believe the forecasts, the combustion engine – with varying hybridization but still as the primary unit – will always be the main power source. Kistler is focusing primarily on enhancing the internal combustion engine and its integration into hybrid power trains. Since 2006, Kistler has been involved in developing electric motor test stands; this area has seen a fair amount of growth and is also being promoted intensively at our plant in Lorch near Stuttgart. The acquisition of Staiger Mohilo has made Kistler a force to be reckoned with in torque sensor technology. Attractive niches are currently opening up in this area, which we intend to exploit to the full.*

Numerically controlled and force/displacement-monitored joining systems from Kistler

draulic systems are compactness, dynamics, controllability and energy efficiency. In line with market needs, joining modules, servocontrollers, force-displacement monitoring and process control have been further developed to form the flexible and very reliable NC joining system. The cost of integrating all these is reduced thanks to the smaller number of external interfaces.

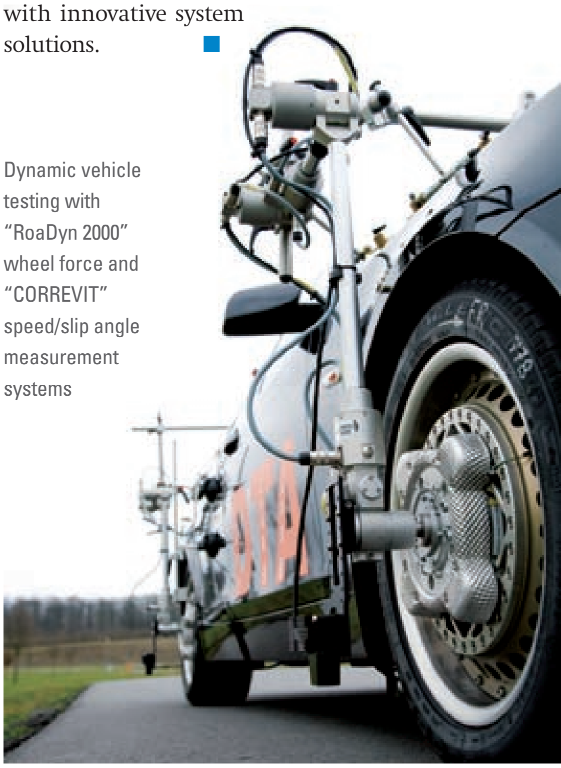
Given the high production volumes, evaluation of the quality of finished plastic parts is very cost-intensive. Since mold cavity pressure is directly correlated to the quality characteristics of the manufactured molded part, the injection molding process can be fully monitored in this way. Sensors reliably measure the filling pressure in each mold. The „CoMo Injection" units capture up to 24 channels simultaneously and evaluate the typical filling pressure curve for each molded part in real time. If the specified tolerances are not met, the machine separates out these parts immediately after the mold is opened. Quality assurance integrated into the process is the only way to guarantee cost-effective zero-defect production. Moreover, by allowing faster process initiation and optimization, for example during a mold change, the system offers additional benefits.

Process and quality information must be available globally at any stage of modern production, since only those who detect defects can eliminate them. The production information system „CoMo MIS" combines the latest web and database technology and features clearly arranged user interfaces. It provides effective information about the current production status of the individual machines and manufacturing sites. It also makes it possible to carry out extensive statistical analyses while documenting the process quality of the parts or batches.

Outlook

In particular, internal combustion engine development demands very high quality results under increasingly extreme operating conditions. In developing piezoelectric sensors and laboratory charge amplifiers we are therefore close to the limits of physics. Alternative technologies are still not sufficiently mature. Further optimization of the individual components in combustion analysis measuring chains scarcely allows any quantum leaps as far as essential measuring data are concerned. However, by focusing even more intensely on the particular task, and taking a more interdisciplinary approach to the mechanical engineering, electrical engineering and computer science aspects, it is possible to open up new opportunities. Just one example is the potential of microelectronics and software for dynamic measurement, which is far from exhausted. Innovation means creating something new by thinking in a different way. Having started to think outside the box quite some time ago, Kistler can be expected to continue to come up with innovative system solutions. ■

„CoMo Injection" systems guarantee zero-defect production and process transparency during injection molding



Dynamic vehicle testing with "RoaDyn 2000" wheel force and "CORREVIT" speed/slip angle measurement systems

Research and Innovation for the Future

The investigation of new piezoelectric crystals, materials, coatings, piezoresistive semiconductor structures and optical measurement principles underpins the sensors of the future at Kistler. The trend is towards enhanced functionality, system capability and miniaturization. The establishment of a global network of technological expertise is proving to be one of the successful formulas in order to meet future system requirements.

Introduction

As a pioneer of applied piezotechnology, Kistler began developing and manufacturing quartz crystal sensors for measuring engine cylinder pressures 50 years ago. A wealth of innovations made possible by a spirit of research, the ability to put ideas into practice and market proximity were to follow. One important prerequisite was Kistler's position as a technological leader, particularly in piezoelectrics. This know-how has been deepened and extended over the decades. The investigation of new piezoelectric crystals, materials, coatings, piezoresistive semiconductor structures and optical measurement principles now forms the basis of the sensors of the future. The impetus generated by ongoing development and greater user expectations demands efficient, cost-effective R&D solutions. Kistler therefore works closely with universities and research institutes to exploit cutting-edge results. This formation of a worldwide network of technical excellence is turning out to be a central factor in the company's success. Some very fruitful examples of this type of research collaboration include the development of „PiezoStar" crystals (and the associated know-how of in-house crystal growing), piezoresistive high-temperature pressure sensors and of an optical probe for detecting light emission in the combustion chamber of combustion engines.

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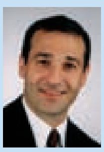

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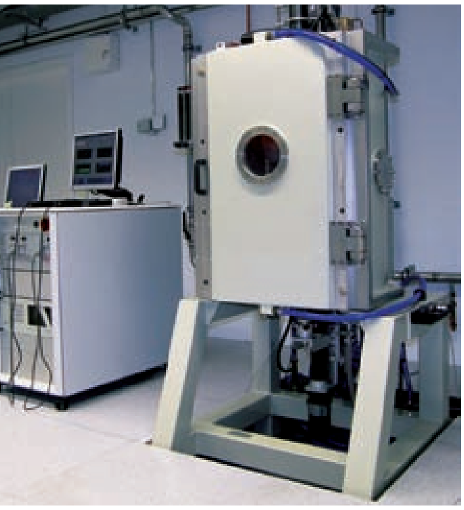
Innovative Crystal Technology

Based on the requirements for combustion chamber pressure sensors for engine combustion analysis, Kistler started an intensive search for new piezoelectric crystals about 20 years ago. The ever-increasing scarcity of space in engines necessitated miniaturized pressure sensors with improved sensitivity and high-temperature characteristics as well. As the potential of quartz was practically exhausted, Kistler focused on investigating new crystals. In collaboration with leading research institutes all over the world, new piezoelectric crystals were grown and characterized. This led to the development of the „PiezoStar" family of crystals with their excellent properties. The decision to transfer the crystal growing know-how to Kistler's own center of technology in Winterthur was in line with the existing corporate strategy.

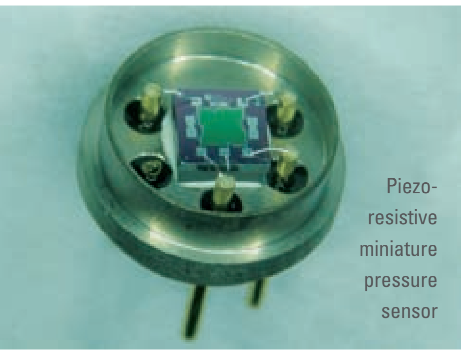
PiezoStar crystals are now used in numerous applications in highly sensitive sensors measuring pressure, force and acceleration in particularly harsh environments, for example in measuring spark plugs with integral miniature pressure sensors. Kistler is also continuing to explore new crystals for the sensors of the future with its research partners. In addition, use of the Czochralski method to grow its own crystals from the melt, is enabling the company to achieve very reliable industrial production within a short period of time.



Kistler's facility for growing „PiezoStar" crystals from the melt

Piezoresistive Pressure Sensors

Kistler was one of the first sensor manufacturers to look into using the piezoresistive effect of silicon for sensors for static measurement. These preliminary studies resulted in the first piezoresistive pressure sensors as long ago as 1973. Kistler mainly specialized in designing silicon sensor chips and devising construction and connection technology for stable pressure sensors. In addition to the standard technology of oil-filled pressure sensors, Kistler is increasingly focusing on high-temperature and high-pressure applications such as injection pressure in internal combustion engines or nozzle pressure in injection molding of plastics. Its research collaborations have therefore developed special high-temperature silicon sensors using silicon on insulator (SOI) technology. These sensors are able to withstand a constant temperature of up to 350 °C and a pressure of 4000 bar. Miniaturized low-pressure sensors, which can cope with particularly harsh ambient conditions, were developed for measuring the intake and exhaust pressure in engines. Achieving the required miniaturization while retaining a high degree of stability in all environments still represents the greatest challenge for piezoresistive technology in current research.



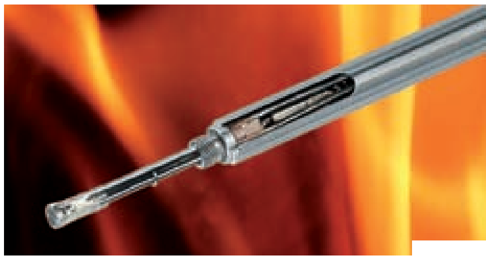
Piezo-resistive miniature pressure sensor

Optical Probe for Measurement of Soot in Combustion Chambers

In addition to further developing existing technologies, Kistler is dedicating resources to new technologies with objectives such as usefully extending the application of piezoelectric measurement technology to internal combustion engines. Pressure is not the only measurand of importance for the development of combustion processes. Other measurands of greater relevance to harmful emissions include the combustion temperature and the soot concentration. Optical systems represent an inexpensive way of recording the total emission of light, from which the combustion temperature and a measure of the soot concentration can be calculated using two-color pyrometry.

The optical measurement system developed by Kistler in cooperation with external partners is sufficiently compact to allow incorporation into pencil-type glow plugs or spark plugs. This technology can therefore be used without the need to modify the enginecylinder head. The system has already been successfully integrated into mass-produced spark plugs as well. This is of particular importance in the case of direct-injection gasoline engines, whose predefined spark plug types and bore locations cannot be changed under any circumstances.

Kistler has particularly focused on the fundamental problem of all optical systems, namely the contamination of their probe, which is coated with soot after a short time when used in diesel engines or direct-injection gasoline engines, making analysis impossible. Many possibilities were explored during the development phase, with thermal self-cleaning of the probe ultimately being favored. The clean burn temperature of at least 560 °C requires that the components of the probe must be extremely resistant to high temperatures.. The temperature-controlled self-cleaning system is now operating reliably, allowing optical analyses to be carried out at diesel engine operating points at which soot is formed, which was previously impossible. The system is ideally suited as a development tool on test stands, allowing conclusions to be drawn about NO_x and soot concentrations in the exhaust. This avoids the need for expensive exhaust systems on engine test stands.



Optical probe for measurement of soot in combustion chambers

One future project is to combine the optical measuring system with the new Kistler „KiBox" combustion analysis system in order to enable determination of the soot formed in each cylinder and cycle, even during driving tests.

In developing an optical measuring system suitable for industry Kistler has set foot in a new technological and application sector. This technology exploiting existing access to the combustion chamber provides valuable information about local events and phenomena during combustion that complements the global information from pressure indication.

Future Prospects

These examples elucidate Kistler's broad technological basis, without which it would not be possible to offer a complete range of sensors for numerous applications. The trends in sensor technology are towards greater functionality, system capability and miniaturization. Collaborations with universities, research institutes and technology companies are therefore becoming an increasingly important means of converting new technologies into new products as quickly as possible. This requires an innovative spirit in close proximity to the market and global competence networking. ■

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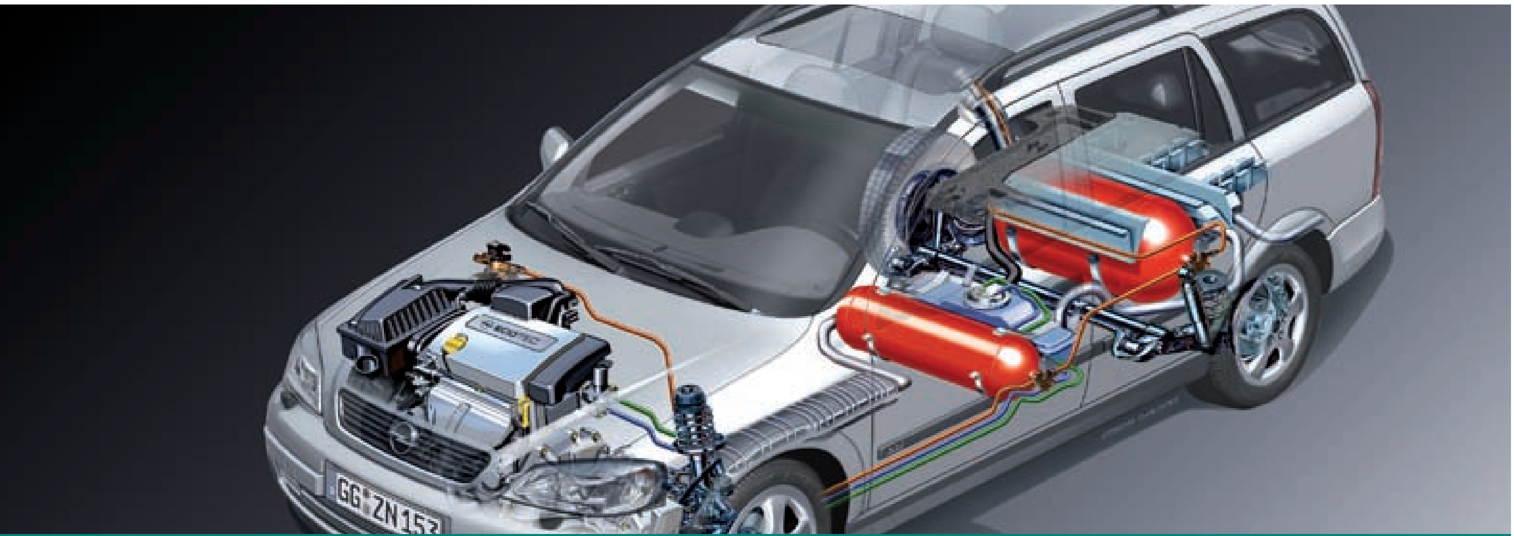

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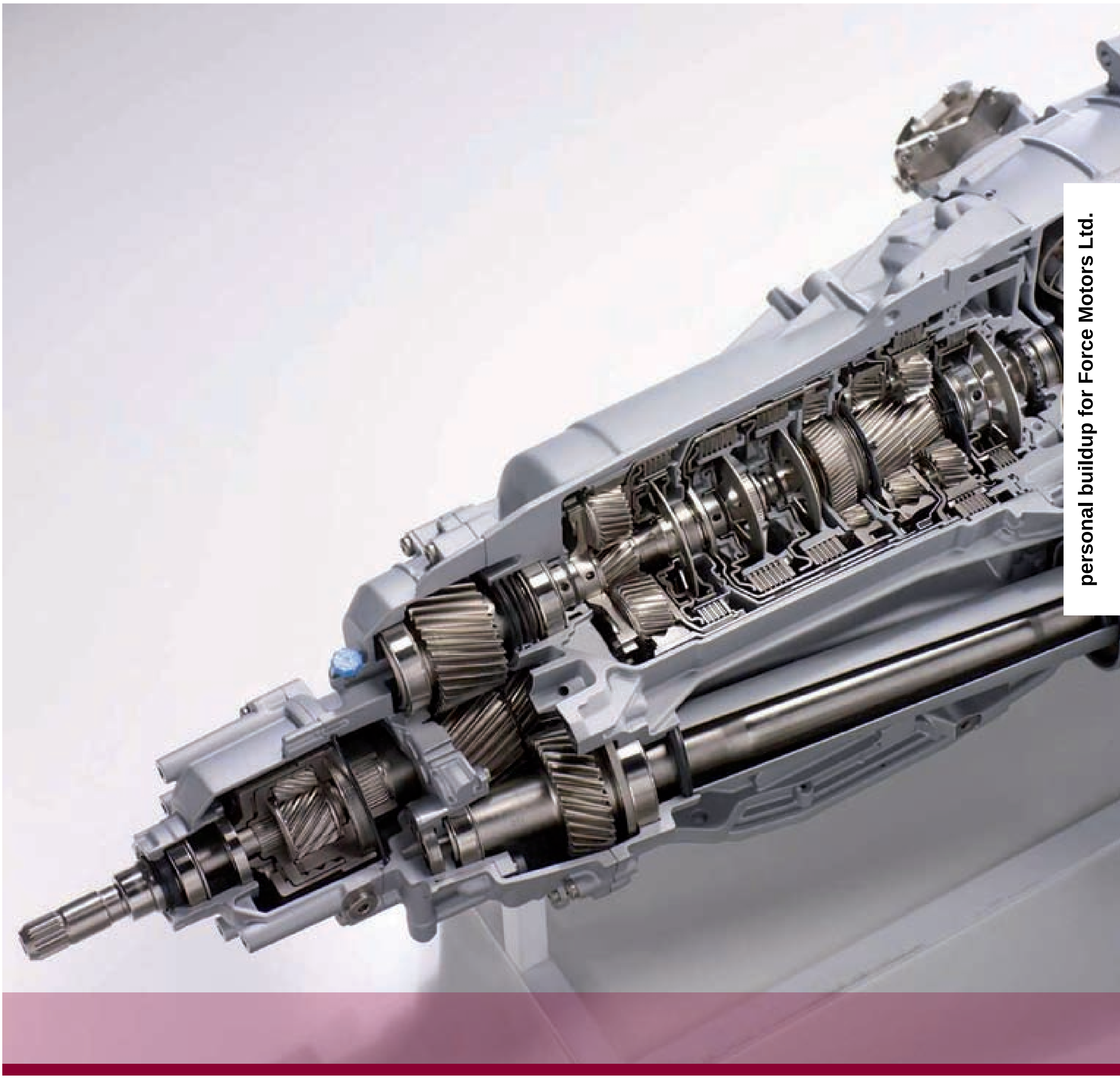
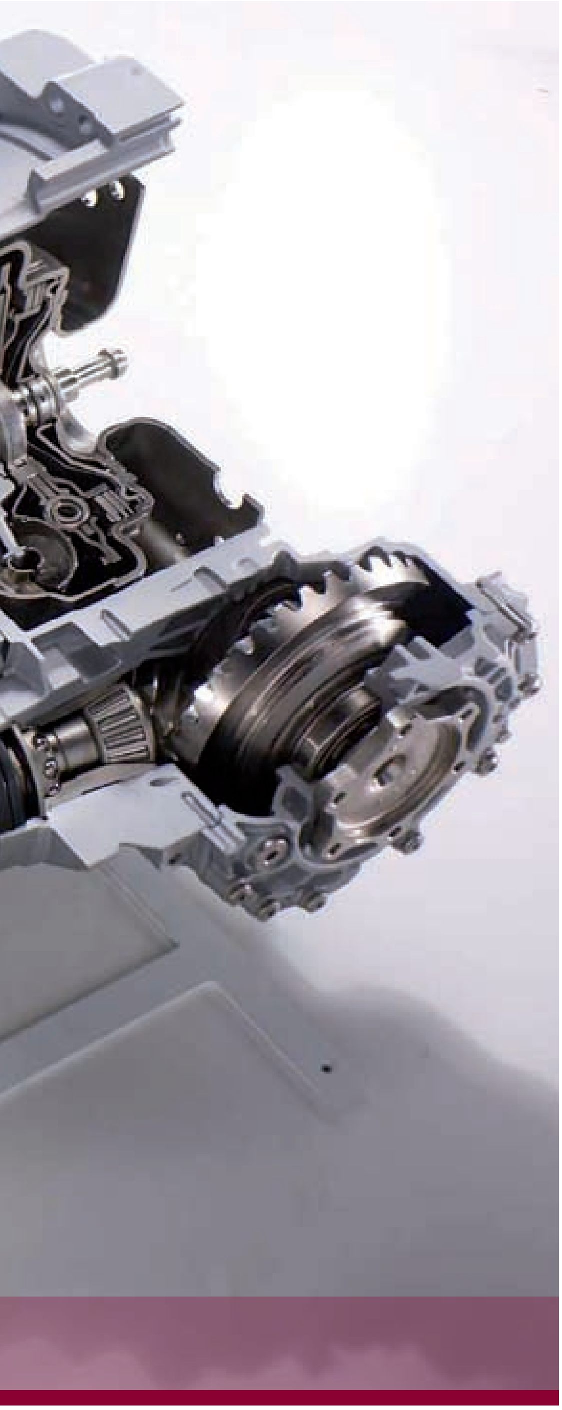


New Bearing Technology Enables Significant CO_2 Savings



In order to improve the mechanical degree of efficiency and to reduce friction losses in the powertrain, the bearing industry has to make its contribution towards sustainability providing innovative bearing solutions. Due to the people's increasing mobility, cars have an increasing effect on the carbon dioxide (CO_2) emission. Therefore the possible saving potential by the use of bearings in respect of power losses in the automotive powertrain is demonstrated by bearing manufacturer SKF.

The Author

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1 Bearings Play a Decisive Role

The automotive industry and its suppliers face a demanding challenge. The increasing energy demand around the world, mostly still covered by fossil fuels, inevitably increases the amount of CO_2 within the atmosphere. In this context the efficiency rate during transformation of energy plays a decisive role. In order to transmit the mechanical power of the combustion engine via clutch, gearbox and axle drives to the wheels, a lot of gear wheels are in mesh. The bearings which support the shafts carrying these gears should run with the lowest friction possible. Therefore the anti-friction bearing plays a central role in the optimisation of a powertrain in terms of power loss, fuel consumption and CO_2 emissions.

Figure 1: CO_2 saving potential in the transmission

In order to approach this topic in a systematic way the following question has to be posed: What are the potential savings attainable from friction optimised bearings compared to any other measures on the vehicle? To be able to answer this question, it is vital to precisely know the loading conditions acting on the vehicle during driving. Depending on the vehicle type, its utilisation profile and the driver's style, the loading situation will vary in a wide range.

Nevertheless the following dynamic resistances will always act:

- rolling resistance between tyres and road
- air drag (dependant mainly on speed)
- climbing resistance
- resistance to car's acceleration.

The amount of all resistances for a particular loading condition multiplied by the vehicle's speed directly equals the demand of engine power required to maintain this driving condition. This mechanical power, generated at the engine's crankshaft, transmitted through the gearbox and the axle drives and finally arriving at the vehicle's wheels can also be expressed as the product of engine torque and engine speed. When knowing the torque level, it is possible to calculate via the gear wheel's geometry the corresponding bearing loads, which are responsible for the bearing's friction torque.

Strictly speaking, it is the ratio of axial and radial load, meaning the number of loaded rolling elements, which are the sources of internal friction losses. Also knowing the bearing's rotational speed, it is easy to calculate the power loss of the bearing.

2 Software VEP Reduces Development Costs

An excellent software tool is required for the precise analysis of the loading conditions on any bearing position and the corresponding impact on bearing friction torque and power loss as a contribution to the CO_2 emissions of a vehicle. Having developed the Vehicle Environment Performance Simulator (VEP) software, SKF possesses a tool which, already at the gearbox design phase, enables the optimisation of the bearing arrangements in terms of friction.

Using VEP, the number of loops during the development process of a new gearbox can be reduced, so that the cost level for prototypes and long term test runs can be minimised.

The optimisation of the internal bearing geometry does not confine itself only to low friction, but considers other important features such as bearing stiffness and bearing service life at the same time. When the bearing losses have been calculated, the software is able to estimate the fuel consumption and the related CO_2 emissions based on the engine map. Since the actual internal bearing geometry (that is the raceway profile) is accurately modelled, it is possible to indicate the effect of even the smallest modifications on the CO_2 balance.

One finding in this context is that the savings potential at the numerous bearing positions along the powertrain is not the same everywhere. Hence it is obvious that for the reduction of CO_2 emissions, it is necessary to determine the loading levels based on a certain load cycle. Afterwards it is possible to identify the bearing position offering the biggest potential saving, **Figure 1**.

Thus the bearing arrangement of the differential of a final drive or of the input shaft of a power take-off unit offers just a moderate saving potential, because of the mainly radial loadings and the rather low rotational speed.

In a manual transmission the savings are considerably dependant on the design of the bearing arrangement. As an exact analysis by VEP shows, the located non-located arrangement (in general deep groove ball bearings with point contact) offers lower savings compared to an arrangement consisting of tapered roller bearings with line contact, which usually runs when axially preloaded.

Comparing the savings potential among the bearing positions in gearboxes and axle drives, one can conclude that the positions with the following loading profile are the most promising:

- bearings mainly axially loaded
- bearings running with quite a high rotational speed (at the same time).

These conditions can be found on the pinion shaft of rear wheel and all-wheel driven vehicles. This is a result of both the axial preload acting on the pinion head and tail bearing and the superimposed axial force generated in the gear mesh, leading to a distinctive load zone in the pinion head bearing. Taking a rear wheel driven middle class car driving at a speed of 130 km/h results for instance in a maximum power loss of 750 W on the pinion head bearing. In total, all four tapered roller bearings of the final drive generate a power loss of up to 1300 W.

Figure 2: SKF ball pinion unit

Figure 3: SKF hybrid pinion unit

3 Energy Efficient Solutions Reduce Vehicles CO_2 Emission

It is evident that with rising specific bearing loading and with increasing speed, the power loss as the sum of rolling and sliding friction and churning losses will grow. Regarding these three different kinds of friction, a ball bearing basically differs from a roller bearing. Indeed in a ball bearing, there is always a point contact between rolling elements and raceways, whereas in a roller bearing there is always a line contact. While in the point contact the sliding friction rapidly increases with growing specific loading, it is more or less negligible for a line contact at moderate loading. Instead, the rolling friction is dominant, which means that the ball bearing gives benefit at low and moderate loading. The roller bearing shows an advantage mainly at high specific load levels. The churning losses, as a consequence of the lubricant displacement inside the bearing, increase with higher speeds and are more pronounced for a roller bearing than for a ball bearing.

Since even nowadays tapered roller bearings are mostly used for the support of shafts along the powertrain, two basic approaches have been applied during the development of the energy efficient bearing portfolio:
- the optimisation of the internal geometry of tapered roller bearings and
- the substitution of tapered roller bearings by angular contact ball bearings.

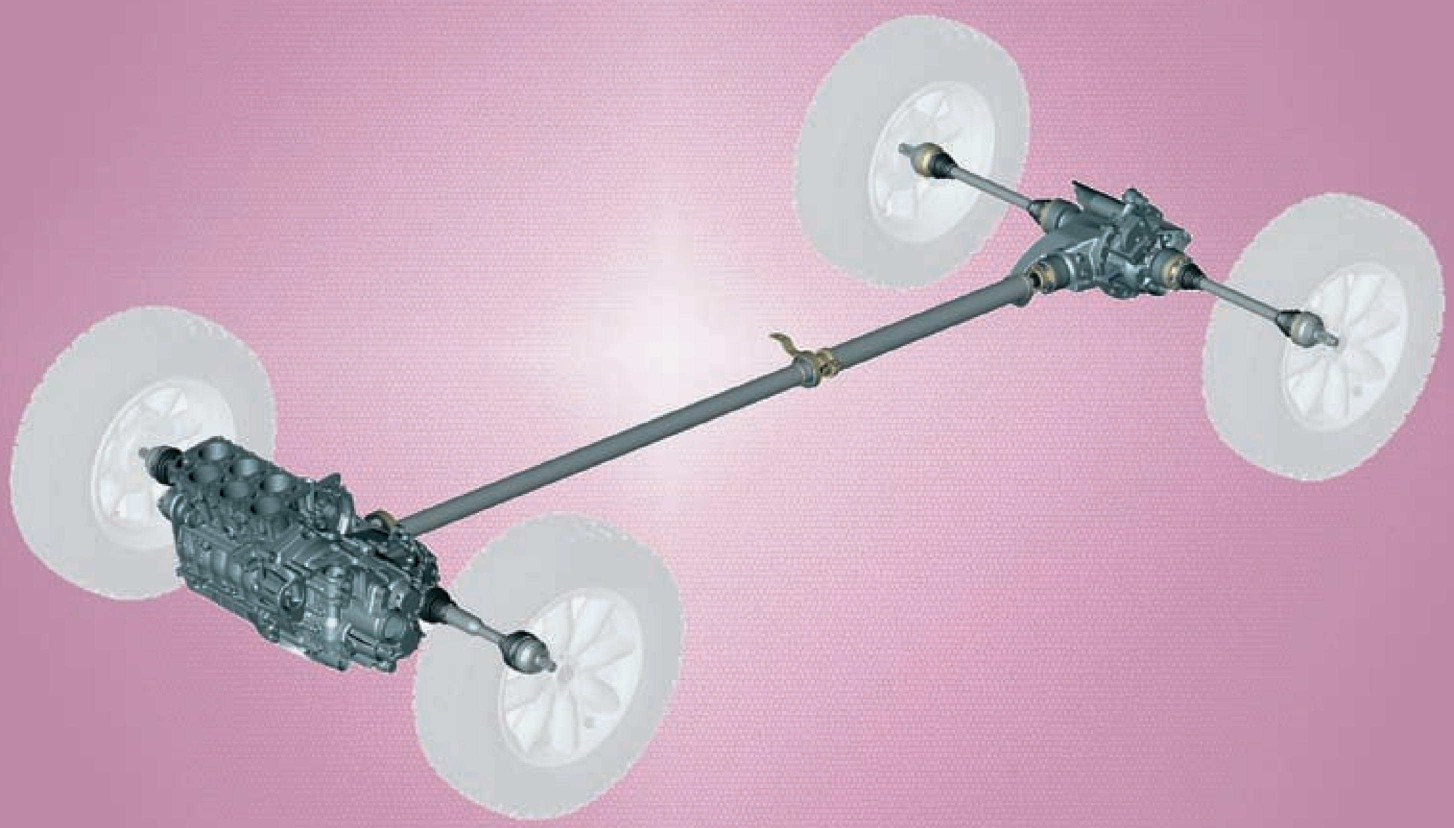
In order to decide which approach is the better one, the application has to be considered as a whole. It is not acceptable to sacrifice important bearing functions like stiffness and service life for the benefit of a minimised power loss.

The SKF energy efficient bearing portfolio therefore covers the following bearing types:
- friction optimised tapered roller bearings with a modified internal geometry
- application oriented driveline angular contact ball bearings
- Ball Pinion Unit, **Figure 2**, a bearing unit based on angular contact ball bearings
- Hybrid Pinion Unit, **Figure 3**, a bearing unit consisting of tapered roller bearing and an angular contact ball bearing.

Because of the gearbox layout, bearing positions in a manual transmission will in the future still need single bearings. Bearing in mind that the service life of the various gearbox bearings should be similar, it is possible to identify and replace bearings which today are still oversized with more energy efficient solutions. This results in an improvement of the gearbox efficiency and finally contributes to a lower CO_2 emission level.

All-wheel driven cars which always need a power take-off unit offer a clear saving potential when the tapered roller bearings on the pinion shaft are replaced by a ball pinion unit or the Hybrid Pinion Unit.

In the case of a rear drive module, the replacement of four traditional tapered roller bearings on the pinion shaft and differential by the Hybrid Pinion Unit on the pinion shaft and by driveline angular contact ball bearings in the differential offers an additional saving of up to 4 g/km CO_2 emissions. ■



Seamless Disconnect System to Minimize AWD Related Losses

Mechanical AWD systems will maintain a significant market share even with the future environmental challenges. Mechanical AWD will still be used in off-road vehicles but also in future hybrid and electric cars. The increasing pressure to reduce fuel consumption and CO_2 emission is now becoming the key driver for the development of new AWD technology. GKN Driveline as a leading driveline component and system supplier is applying its innovative power and long year expertise with AWD systems to develop unique AWD concepts to meet future requirements.

1 Introduction

Even in future people will not give up in their desire for mobility. But environmental and ecological concerns will get more focus. New technology has to address this and has to help to reduce the total energy consumption of future cars to be successful in the market. This applies particular to AWD technology causing an increase in fuel consumption compared to 2WD vehicles due to additional weight and losses of the AWD components. Mechanical AWD systems will maintain a significant market share even with the future environmental challenges. Mechanical AWD will still be used in off-road vehicles but also in future hybrid and electric cars. The trend to smaller and lighter AWD vehicles derived from FWD platforms with transversal engine arrangement does lead to an increasing number of so called "On-Demand" AWD systems on the market. The On-Demand AWD is using a controlled clutch to redirect power from the primary driven front axle to the secondary driven rear axle when demanded for traction or handling. This AWD concept needs two hypoid gears, one in the front (PTU) and a second in the rear (FDU) and is therefore particularly challenging regarding AWD losses. This less efficient hypoid gears have a major impact on the AWD related losses and CO_2 emission of such driveline.

Significant effort has been spent to minimize weight and losses of the AWD components. But maximum impact will only be achieved, if the whole AWD system is optimized in terms of traction (maximum torque), control strategy (duty cycle) and gear ratios, allowing down sizing of all components. The major part of the AWD related losses is caused by the drag and churning losses of the spinning parts. An AWD tuned for traction is transmitting torque only about ten percent of the vehicle life. Therefore it is obvious, that disconnecting the AWD system when not needed will provide a major reduction of AWD related fuel consumption. The challenge of such disconnect AWD is to make dis-connect and re-connect of the system seamless and transparent to the driver and to keep expected AWD performance and driving comfort while achieving maximum fuel saving.

2 AWD Component Optimization

It is known from sources [1, 2] that On-Demand AWD systems are causing additional fuel consumption of 0,7 to 1,2 l/100 km for petrol and 0,4 to 0,7 l/100 km for diesel engines. This fuel penalty is mainly caused by:
- additional weight and inertia of the AWD components
- load related losses (mainly hypoid gears)

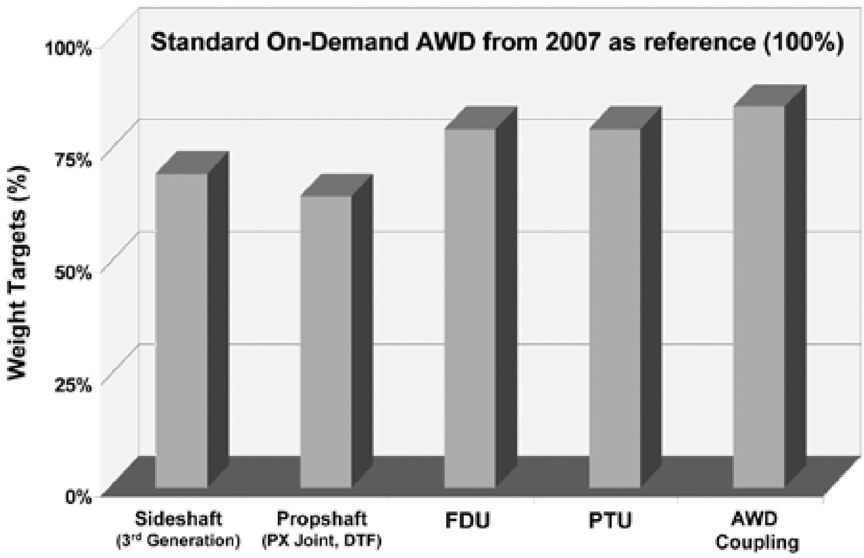


Figure 1: Weight reduction targets for specific AWD components

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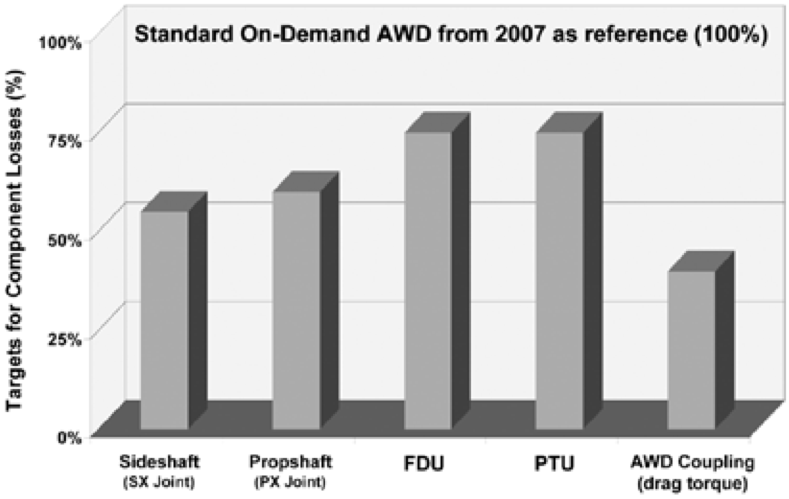

Figure 2: Potential reduction of AWD component related losses

– drag losses (bearings, seals)
– churning losses in the gears.

The detailed analysis of the specific losses identifies following saving potentials:

Calculations based on NEFC (New European Driving Cycle) show that 100 kg additional weight will lead to a fuel penalty of approximately 0,23 l/100 km for petrol and 0,17 l/100 km for diesel engines. Today's average On-Demand AWD systems with a rear axle torque of maximum 2500 Nm have a weight of 80 to 100 kg, which is already pretty good. **Figure 1** gives some weight targets of specific AWD components compared to what is on the market today. It is expected that future On-Demand AWD systems developed for optimized torque and duty requirements will add a total weight of 70 to 80 kg to the vehicle. This would lead to a reduction of the AWD related fuel consumption of approximately 0,05 l/100 km (petrol) or 0,03 l/100 km (diesel) compared to today's system.

The share of drag losses and load related losses on the AWD fuel penalty has been simulated as well based on the specific component efficiency characteristics. The calculation confirms that the drag and churning losses are causing more than 60 %, which is the majority of the losses. This is particular critical in On-Demand AWD systems with a low torque transfer most of the time. Replacing taper roller bearings with low drag angular ball bearings, use of synthetic oil with low basic viscosity and low viscosity/temperature dependency as well as minimizing oil level and optimizing the oil flow in the gears are measures to significantly reduce the churning and drag losses. New joint designs like SX or PX-joints and/or new low friction greases have helped to improve significantly the efficiency of the driveshafts as well. **Figure 2** provides an overview of realised ore intended measures to reduce the losses of typical AWD components. The total of the discussed measures to improve component efficiency will provide an additional fuel saving of about 0,12 l/100 km for petrol and about 0,07 l/100 km for diesel engines.

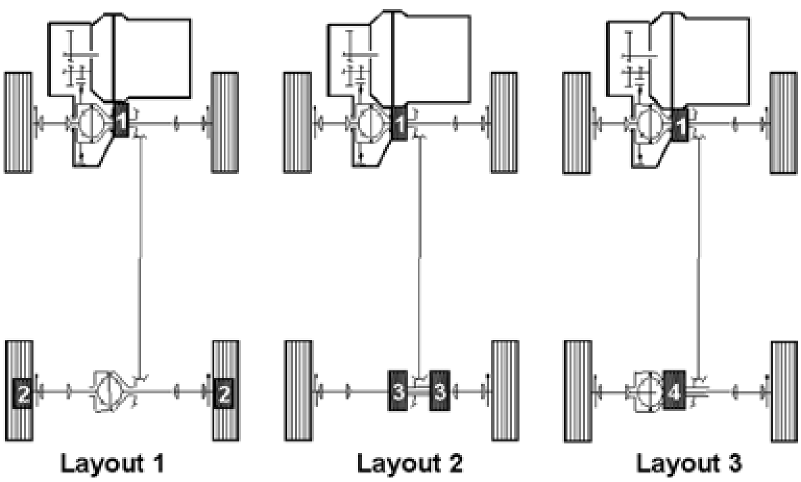

Figure 3: System layouts for AWD disconnect

3 Disconnect AWD

Optimizing all AWD components and the AWD system requirements might provide a total reduction of the AWD fuel penalty of 15 %. This is good but might not be good enough. There are limits to reduce the majority of the losses caused by churning and drag. An AWD tuned for traction is transmitting torque only about ten percent of the vehicle life. So it is obvious, that disconnecting the AWD system when not needed will provide a major reduction of AWD related fuel consumption.

Switchable "Part-time" systems have been used in pickup trucks and SUVs for a long time. They usually come with an T/C disconnect feature allowing the driver to shift from 2WD to 4WD mode. Part-time systems using additional wheel hub, sideshaft or differential disconnect features do avoid spinning the AWD components in 2WD mode to reduce the AWD related fuel consumption. The shift from 2WD to 4WD works only at low or zero speed and requires driver input. This limits the 4WD usage, the performance and the driver comfort of such a system. Transferring part-time technology into an advanced disconnect AWD needs a new set of requirements, clutch and actuator technology and system control. The major challenge developing the new disconnect AWD technology was the integration of appropriate clutch and disconnect systems into PTU and FDU and the development of a suitable control strategy to meet AWD performance as well as NVH, comfort and fuel saving targets.

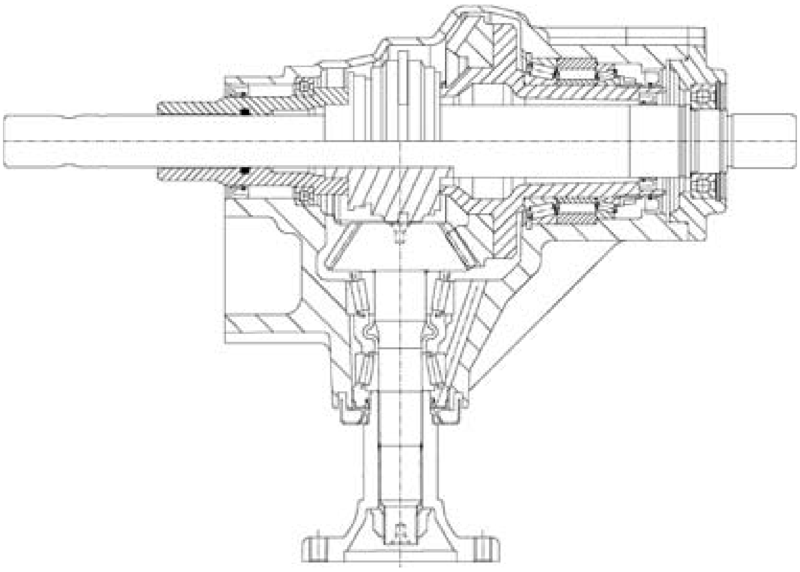

Figure 4: PTU cross section

4 System Layout and Main Components

The number of parts still spinning in disconnect mode have to be minimized to achieve the maximum fuel saving. Hence the AWD driveline has to be disconnected as close as possible to the transmission in front of the PTU hypoid gear and as close as possible to the wheels, downstream to the hypoid gear in the FDU. At the same time drag torque in the disconnect devices should be as low as possible. **Figure 3** shows three potential system layouts for disconnect AWD. All three solutions are comprising a disconnect feature (1) between transmission output and PTU to disconnect in the front. With the wheel hub disconnect (2) even the side shafts are stalling in disconnect mode, which will provide the maximum saving potential. But complexity, tough operation conditions in the wheel hubs and the number of remote actuations are considered as major development challenges and risk. Layout 2 uses a twin clutch arrangement (3) in the rear to control individual rear wheel torque and provide rear axle disconnect. Sideshafts will spin all the time causing little losses, but the two friction clutches with the required actuation will cause high cost and high losses due to clutch drag torque. The third layout uses only one clutch in the rear arranged between ring gear and differential to control torque flow front to rear in AWD mode and decouples the differential from the ring gear in disconnect mode. This layout has been considered as best compromise between complexity and potential fuel saving and has therefore been selected for further development.

4.1 PTU Disconnect

When excessive slip occurs on the front wheels due to lack of traction the AWD has to be re-connected quickly to redirect the driving power to the rear wheels. The best approach in this case would be to put the on-demand clutch in the PTU and use it to accelerate and synchronise the driveline. A simple dog clutch disconnect feature in the rear would than be sufficient enough to re-connect the rear end as soon the driveline is synchronised. The tight packaging around the PTU does in most cases not provide enough space to integrate the bulky on-demand coupling with actuation in the PTU. Consequently the on-demand coupling has to be installed in the FDU and the PTU uses a more compact dog clutch type disconnect combined with a synchronizer. The cross section of a single stage PTU with synchromesh disconnect device is shown in **Figure 4**. A high volume synchromesh ring from a manual transmission adopted to the disconnect requirements has been used to minimize cost and development effort. The disconnect feature should be located in front of the PTU ring gear and ring gear bearings to minimize the losses when disconnected. The arrangement of the bearings on one side of the ring gear allows a compact disconnect design and a cost effective two piece housing. A more conventional bearing arrangement on both sides of the ring gear is possible as well but requires an additional pinion cartridge.

4.2 Rear Axle Disconnect

In most of the On-Demand AWD systems the controlled coupling is located in front of the FDU between propshaft and pinion. For the disconnect AWD this coupling now has been sized for rear axle torque and has been integrated into the FDU between ring gear and differential, **Figure 5**. This makes the FDU very compact and frees up desired space in the propshaft area. In disconnect mode the coupling is released and decouples the ring gear from the differential, allowing the differential and sideshaft to spin with rear wheel speed while the ring gear is stalling. The on-demand coupling is the obvious choice for the FDU disconnect but is not made for the needed ultra low drag torque. In on-demand mode a

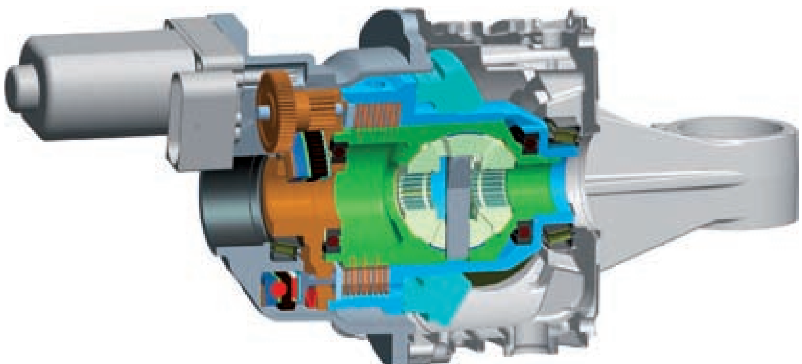

Figure 5: FDU cross section

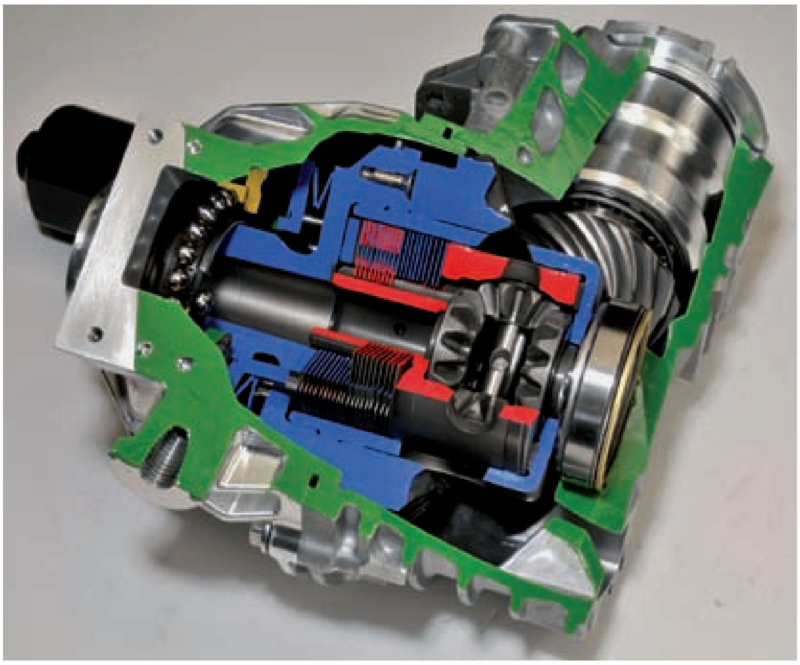

Figure 6: FDU prototype with on-demand & disconnect clutch

high control accuracy and control dynamic as well as good oil flow through the clutch for cooling and lubrication is required. But for the disconnect mode the oil flow has to be small and clutch endplay has to be wide to minimize drag torque and clutch losses. The engineering challenge was to cover both, on-demand and disconnect requirements at the same time. The friction plates have been optimized in terms of oil groove pattern and outer plate design to minimize drag torque. Specific oil channels in combination with the right oil level have been developed to control the oil flow in a way that good cooling and lubrication is guaranteed in control mode (ring gear spinning) and the clutch is almost empty in disconnect mode (ring gear stalling). An ultra low drag torque of around 1 Nm has been achieved in combination with an extremely wide clutch end play. **Figure 6** shows a cutaway model of the FDU hardware tested on the rig and in the vehicle.

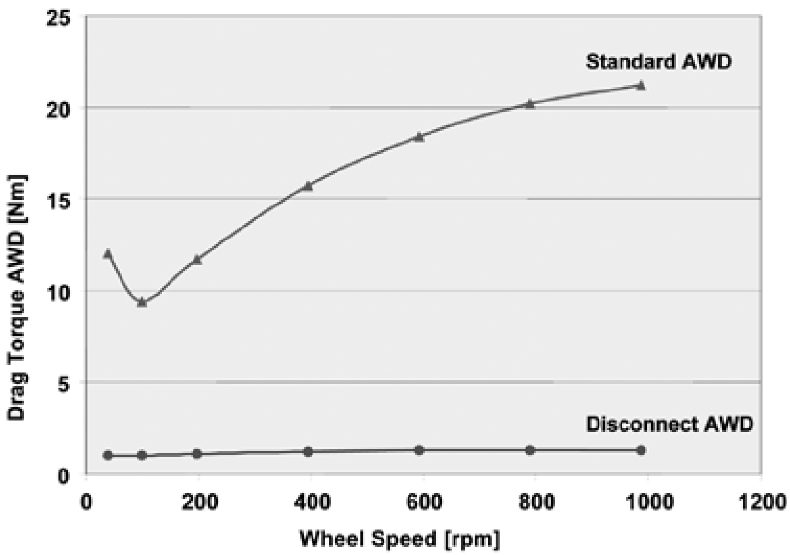

Figure 7: Rig test results of standard and disconnect AWD dag torque

4.3 Actuation

The major challenge for the actuation was to meet the requirements for the on-demand and the disconnect operation at the same time and provide quick and precise transition from one to the other mode. Complexity and costs of two remotely located actuations had to be managed as well as to keep overall system on-cost reasonable. An existing high volume electro-mechanical actuator adapted to the disconnect requirement for connecting speed and actuation stroke has been applied for the PTU disconnect.

For the demanding FDU disconnect an electric-motor driven ball ramp actuator used in controlled limited slip differentials has been applied. The unique patented multi stage ball ramp provides a first ramp section for fast engagement and a second ramp section for precise control. Using a suitable rotation sensor and a highly dynamic e-motor control the actuator meets all requirements for a controlled quick synchronisation and re-connection of the AWD and the precise control of the clutch in on-demand operation.

4.4 System Control

Essential for the customer perception and acceptance of an AWD disconnect system is the smoothness and refinement of the dis-connect and re-connect operation. The re-connect operation has to be optimized regarding NVH, comfort, traction and vehicle dynamic. Fast re-connect response almost like today's on-demand AWD will provide maximum traction and stability but the required extreme acceleration of the driveline inertia will cause totally unacceptable driveline clonk and vehicle reaction. Thoroughly tuning in close link with the car manufacturer is necessary to find an acceptable compromise in terms of seamless and transparent operation and best AWD performance. Pre-emptive control strategies considering weather and surface conditions as well as driver intension and driving situation are essential to have seamless operation and to meet AWD performance and fuel saving targets at the same time.

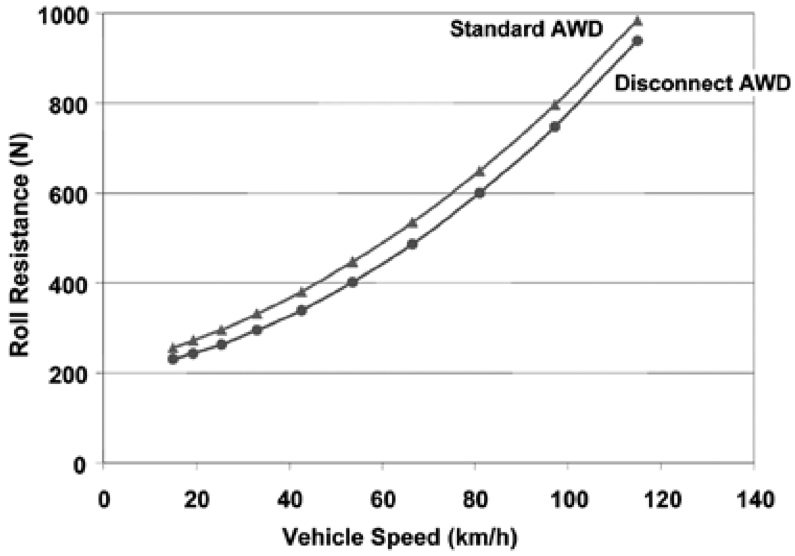

Figure 8: Vehicle test results with standard and disconnect AWD

5 Test Results

5.1 Bench Test

The complete standard and disconnect AWD driveline has been set up on a bench in order to measure driveline drag torque at various speeds and temperatures. The results at 50 °C shown in **Figure 7** demonstrate an impressive effect on the drag torque for the disconnect AWD. The standard AWD shows a pretty high drag torque of 22 Nm leading to 2,3 kW loss at 1000 rpm sideshaft speed. The disconnect AWD has been measured with only 1,6 Nm causing only 170 W losses in the same conditions. Differences are even bigger at lower temperature.

5.2 Vehicle Tests

Vehicle tests have been performed to ultimately prove the AWD disconnect benefits.

The same vehicle equipped with standard and disconnect AWD has been evaluated in coast down tests to define the rolling resistance. The significant reduction of the rolling resistance of the disconnect AWD compared to the standard AWD, **Figure 8**, has confirmed the bench test results. The conducted fuel consumption calculation using the measured rolling resistance and apply a standard driving cycle has shown up to 0,35 l/100 km fuel reduction and roughly 8,2 g/km less CO_2 emission of the disconnect AWD compared to the standard one.

6 Summary

Mechanical AWD systems will maintain a significant market share even with the future environmental challenges. Mechanical AWD will still be used in off-road vehicles but also in future hybrid and electric cars. Fuel consumption and CO_2 emission is now becoming the key driver for the development of new AWD technologies. Optimizing all AWD components and the AWD system requirements might provide a total reduction of the AWD fuel penalty of 15 %. But even for optimized drivelines the majority of the AWD related losses is still caused by the drag and churning losses of the spinning parts, hence disconnecting the AWD system when not needed will provide ultimate fuel savings. Switchable "Part-time" systems have been used in pickup trucks and SUVs for a long time. Transferring "Part time" technology into an advanced disconnect AWD needs a new set of requirements, clutch and actuator technology and system control. The major challenge for the development was the integration of appropriate clutch and disconnect devices into the PTU and FDU and the development of a suitable control strategy to meet AWD performance, NVH, comfort and fuel saving targets. The selected AWD layout with synchromesh disconnect in the PTU and single clutch disconnect in the FDU has shown to be the best compromise between complexity and fuel saving potential. An existing high volume electro-mechanical actuator adapted to the disconnect requirement has been applied for the PTU disconnect. The on-demand coupling integrated into the FDU between ring gear and differential is used as rear axle disconnect and has been optimized for ultra low drag torque and best performance. The electric-motor driven ball ramp actuator known from controlled limited slip differentials has been refined with a multi stage ball ramp and a highly dynamic e-motor control to meet all requirements for on-demand and disconnect operation. The smoothness and refinement of the dis-connect and re-connect operation is essential for customer perception and acceptance of an AWD disconnect. Thoroughly tuning in close link with the car manufacturer is required to find an acceptable compromise in terms of seamless and transparent operation and best AWD performance. The bench test results demonstrate an impressive reduction of the disconnect AWD drag torque and losses by more than 90 % compared to standard AWD. Vehicle coast down tests have been performed. The conducted fuel consumption calculation using the measured rolling resistance and apply a standard driving cycle has shown up to 0,35 l/100 km fuel reduction and roughly 8,2 g/km less CO_2 emission of the disconnect AWD compared to the standard one.

GKN Driveline has been first to develop a disconnect AWD system and has proven feasibility and performance on bench and in vehicle. The selected layout and the applied disconnect, clutch and actuation technology has been optimized regarding packaging, performance and cost and does provide a convincing base for a production system.

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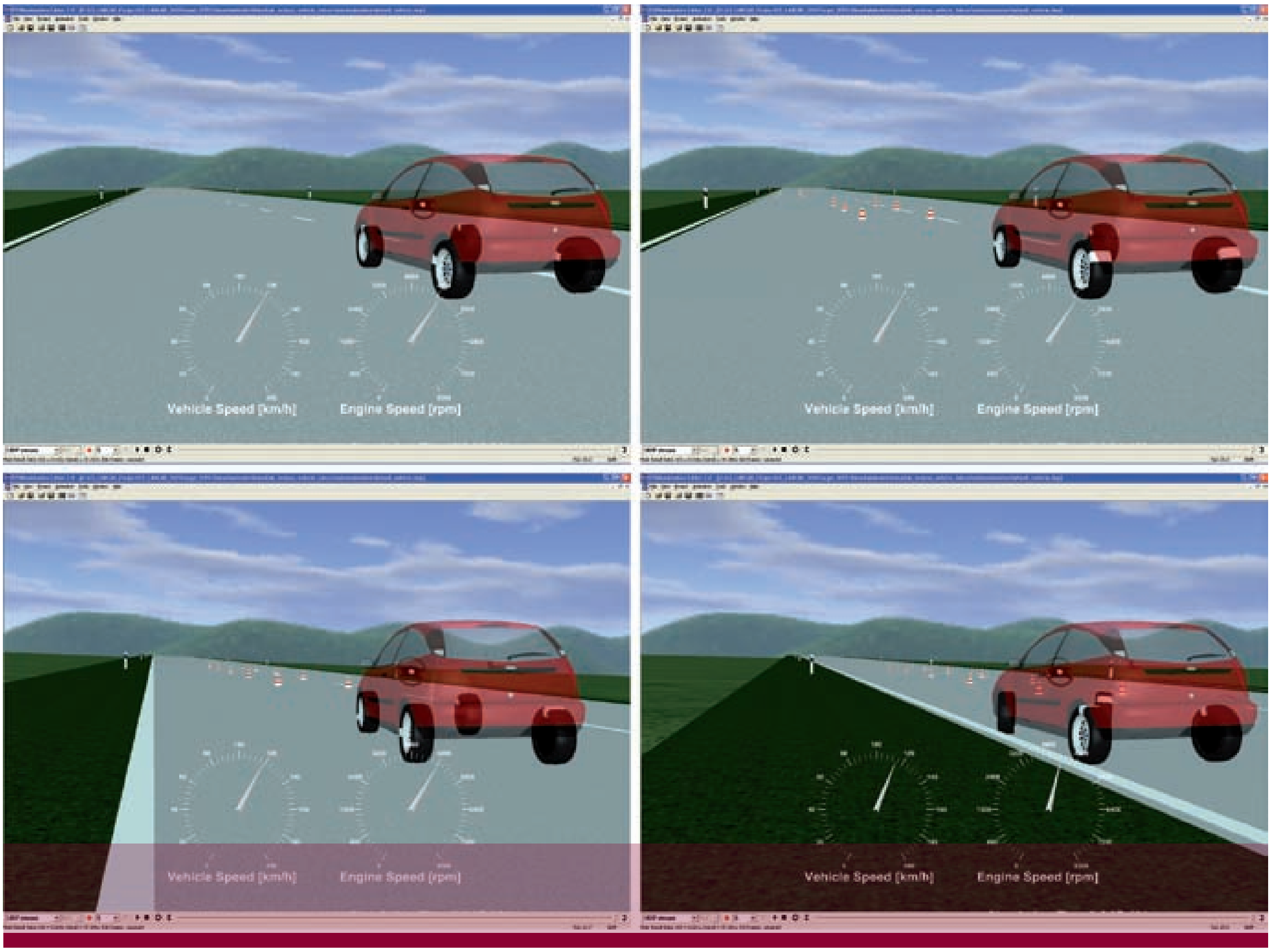

Modular Real-time HiL Testing of Vehicle Dynamics Control Systems

When it comes to testing ECUs for vehicle dynamics systems, Hardware-in-the-Loop (HiL) testing systems make a valuable contribution. All tests can be executed automatically and with real-time reference – with the benefit of accurate reproducibility – in a manner that exposes neither driver nor test vehicle to any hazards whatsoever. The rapid acceleration of system complexity in this area also affects the HiL system. As a result, the conventional approach of visualizing the simulation model and the real-time tests in a single monolithic block is beginning to test its very limits. Novel concepts, such as the separation into modules and plugins discussed below, are realizing decisive benefits not only to driving dynamics systems.

1 Introduction

The testing of ECUs for driving dynamics applications – the so-called chassis systems – involves a large number of test cases that require execution in real-time. These tests are indispensable for the verification of product quality, compliance with statutory regulations, and for addressing product liability issues. HiL testing systems offer a host of options for running every conceivable manner of tests as fully automated routines and with real-time reference. Because critical situations can be rerun any number of times in the virtual environment, substantial benefits are inherent in the reproducibility and automation capability, as well as the resulting safety.

For example, HiL tests simulate – with selectable parameters such as temperature, road surface grip, steering characteristics and tire pressure – the failure of a sensor while negotiating a turn. Because of the substantial test depth they provide, automated tests of vehicle rollovers and pre-crash safety systems also deserve mention in this context.

On the downside, however, the rising complexity of vehicle systems goes hand in hand with increasing demands on the respective HiL system. The persistently growing contingent of relevant environmental conditions, sensors, and test cases calls for a more clearly organized structure of both the simulation model and the HiL system itself. Instances of continual product refinement must lend themselves to cost-effective representation, i. e., enabling the dedicated replacement of individual elements. In all this, the original know-how embodied in both models and test cases must be preserved.

2 CS-Labcar Architecture

One of the essential strong points of the Labcar HiL testing system by Etas is its open and modular architecture. The strict segregation between the domain-specific hardware and the PC-based computing engine facilitates the dedicated replacement and/or addition of individual hardware modules, permitting easy adaptation of the testing system to accommodate both future requirements and functional extensions.

The Labcar core component is the Real-Time PC (RTPC), a high-performance, Linux-based real-time computer. Installing the Labcar-RTPC software turns a standard PC into a high-performance simulation target, which calculates the most complex models concurrently on several processor cores with cycle times – at the time of this writing – of as little as 20 µs. In this way, even highly dynamic physical control processes can be simulated. Communications are handled via the standard PCI, PCIe, or Ethernet interfaces.

An essential factor for the long-term utilization of any HiL system is its openness with respect to the simulation models which, after all, represent a centralized know-how. Labcar is open to integration of numerous models. Besides Matlab/Simulink-based models (for example, Tesis Dynaware), it is also possible to integrate any desired model on C code basis from third-party vendors (for example, Simpack, GT-Power, AMESim, CarSim). Behavior models native to a variety of tools can be directly interconnected.

3 Monolithic versus Modular Structure of Models and Test Cases

In a practical application, the test automation software runs on a separate host PC – and it is therefore not in sync with the simulation model on the real-time computer. As a result, real-time tests frequently require direct insertion in the simulation model. The real-time test case can then be switch-activated during the test and processed in sync with the real-time model. The drawback of this approach is that there is no clear separation between simulation model and test. On systems of higher complexity, this may impose substantial additional burdens on onward development and test variant derivation. The evolved structure is muddled if not complex, compile times are extremely long, and troubleshooting tends to be difficult. A very trying situation occurs when several persons need to work on the model simultaneously (for example, model maintenance or test development). Maintaining the simulation model is further complicated by a large

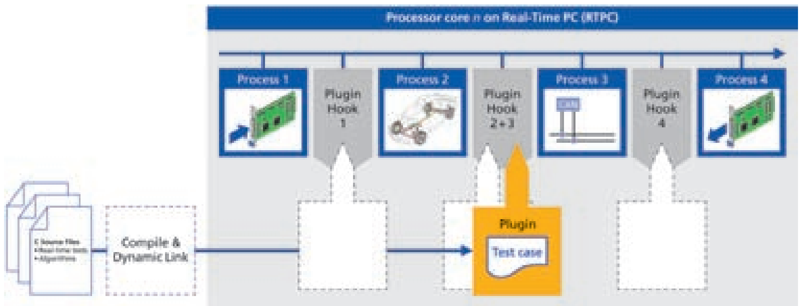

Figure 1: Task chain in a CPU core onboard an RTPC, with possible positions for Plugin Hook placement

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number of model variants that need to be modeled alongside the basic model for the purpose of activating these at runtime. On the whole, all of the above contribute to the generation of gargantuan monolithic simulation models that contain the basic model, its variants, and the real-time tests.

The modular approach offers one solution. In the case of the Labcar HiL system, the simulation code consists of individual modules that can be bundled into a test case and dynamically extended at runtime. The fact that the simulation model's functions and the real-time test can be created and versioned separately is a major advantage. This results in improved manageability and produces a "clean" real-time model, which can be maintained more efficiently and deployed more widely. Thanks to the use of standardized C interfaces, it is also possible to deploy modules created by a variety of tools capable of C code generation (for example, Simulink or Ascet).

There is another benefit that results from the division into modules: On multi-core RTPCs, the individual modules can be concurrently calculated on the separate processor cores, facilitating significant performance boosts. The division into modules also simplifies distributed development and black box testing.

4 Dynamic Real-time Testing with Plugin Hooks

For the RTPC software, Etas has developed a new, real-time capable plugin framework that makes it possible to extend the feature set of the overall simulation at runtime. To this end, the simulation model is equipped with "Plugin Hooks", **Figure 1**. At runtime, these hooks facilitate the insertion and execution of the plugins generated in C code. They therefore run in both synch with the model and within the address range of the simulation code – i.e., access to all variables, parameters, measurement variables, CAN messages, and hardware I/O values, et cetera, is possible.

The individual process steps – the tasks – are daisy-chained, with each task assigned a possible time of condition for task execution. The task sequence is defined in the process chain.

Within the process chain, Plugin Hooks can then be placed at any position and as often as desired in the overall simulation model. The position of the hooks is defined prior to compiling the overall simulation code. Within the context of overall processes, the Plugin Hooks provide an unambiguous specification for the sequence of subsequently inserted plugins.

The RTPC software receives the plugin code and compiles it "just in time" (JIT compilation). The new module is then attached to the respective Plugin Hook in the process chain. The plugin is then executed in the same context as the remainder of the simulation model, until it is again removed.

As the plugin code has full access to the data elements of the remaining simulation modules, it is able to set parameter values, analyze and manipulate measurement values, dispatch CAN messages, and directly access an ECU via XCP, plus perform a host of other functions. This mechanism, for example, can be easily used to exchange CAN communications matrices with the active real-time simulation, or to thoroughly test the variants of a sensor model without having to leave the operating point.

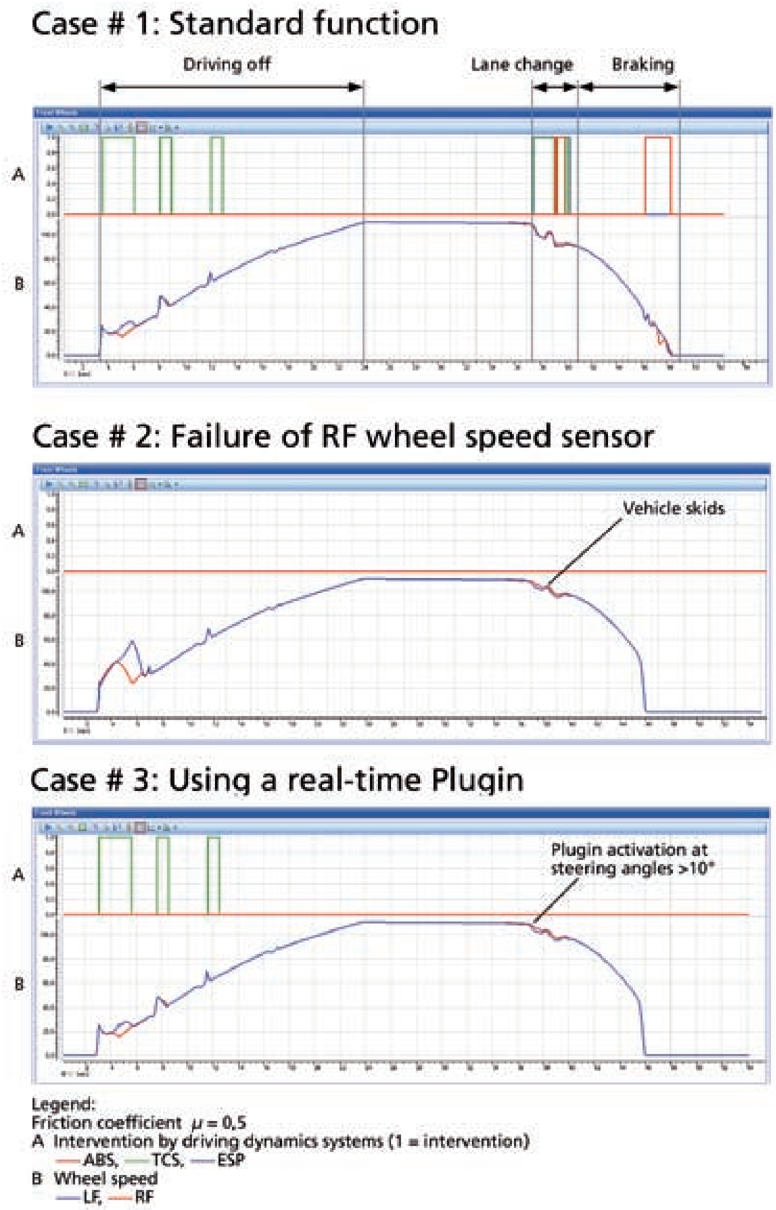

Figure 2: Application example for placement of real-time plugins

Another benefit of this method is the ability to insert or remove the plugins as desired and without the use of an interpreter. In the absence of a plugin, the process chain continues to run without a time delay because the Plugin Hook itself does not require any runtime. It is absolutely possible for plugins to be interdependent.

5 Application Examples for Plugins

Plugins offer various applications, since they can be placed at any position within the process chain. On the one hand, dedicated extensions can be realized very quickly. Aside from the quick and easy means of implementing extensions, the insertion of a given plugin does not necessitate a new compilation of the entire model but only of the modified plugin itself. In addition, Plugins can be versioned together with the software. Some applications are discussed below.

5.1 Influencing Input Signals

If the plugin is placed subsequent to loading the hardware signals and prior to further processing on the part of the simulation model (Figure 1, Plugin Hook 1), it is possible to modify the input signals.

One example of influencing input signals: Repeatedly during road testing, when applying the brakes while on a gravel surface, the ECU detects "Defective brake light" and writes an entry into the fault memory, although an actual brake light failure cannot be verified. Upon closer scrutiny it is found that the brake light switch bounces longer than expected due to the vibrations caused by the road surface. As a remedy, the debounce time in the ESP electronic control unit is extended.

A test on the HiL testing system is designed to verify the function across all variants of the vehicle. This can be accomplished by inserting a plugin. The crucial input variables are the signals obtained from the angular rate sensors and the brake light status. An extended switch bounce is detected when the derivation of the rotational speed exceeds a specific threshold value.

5.2 Dedicated Influence on Simulation

Subsequent to the calculation of a simulation state of the environment model, it is possible to effect dedicated model manipulations or insert complex stimulations (Plugin Hook 2 or 3). At this juncture, it is also possible to simulate several sensor models that are loaded and executed in succession during system runtime, without needing to be considered in the basic model. It is also possible to load an alternative driver model at runtime.

5.3 Bus Manipulations

Residual bus simulations for CAN and Flexray comprise essential elements of HiL operation. At this point, manipulations can be effected, messages falsified or new messages recorded (Plugin Hook 4), before the calculated messages are transmitted to the hardware. For example, in order to simulate the bounce caused by running over a large rock, the signal of the yaw sensor can be manipulated dependent on the distance traveled.

5.4 Signal Manipulation

Before the signals are fed back to the closed-loop simulation by way of the hardware, there is an opportunity for fault simulation. For example, it is possible to simulate intermittent trouble by shorting the signals to ground for very brief periods.

6 Example: Defective Wheel Speed Sensor

In this example, the failure of the front right wheel speed sensor while negotiating a turn shall be assumed. The dynamic response of the running vehicle is depicted in a realistic animation. This is accomplished by integrating CS-Labcar with the "DYNAanimation" animation software by Tesis, and by writing a simple stimulation of the fault in the form of a short piece of C code to serve as a real-time plugin.

It is now possible to simulate a variety of failures on the active Labcar simulation. All of the fault situations are implemented by means of plugins that are simply switch-activated in the running CS-Labcar HiL system. In all cases, the driving sequence remains unchanged, **Figure 2**:

- starting, moving off
- accelerating to 120 km/h
- maintaining speed
- evasive maneuver (double lane change)
- deceleration, braking to standstill.

6.1 Case 1: Standard Function without Plugin

When starting off on a slippery road surface (friction coefficient $\mu = 0{,}5$), the traction control system (TCS) activates. To keep the vehicle in its lane during the evasive maneuver, the Electronic Stability Program (ESP) intervenes. Finally, the brakes are applied until the vehicle comes to a standstill. This calls for assistance by the Antilock Braking System (ABS).

6.2 Case 2: Static Failure of Wheel Speed Sensor

This is a simulation of the front right wheel speed sensor, which may be run as part of standard HiL system operation. It can be seen that the ECUs of the ABS, TCS, and ESP systems no longer intervene. As a consequence, the wheels spin on takeoff, the vehicle breaks out during the evasive maneuver, and the wheels lock up during braking. Since the plugin is positioned independently of the model, it can be easily modified or replaced.

6.3 Case 3: Activation of Sensor Failure at Steering Angles above 10°

The plugin controlling the sensor failure with steering angles greater than 10° is now simply switch-activated. It can be seen that the starting procedure is still correctly supported by the TCS. However, the sensor fails during the evasive maneuver, and the ABS, TCS, and ESP systems are inactive. Here too, operating with plugins provides a high degree of flexibility.

7 Summary and Outlook

The modular structure of model and real-time test paves the way for numerous new options. By introducing a clean segregation between simulation model and real-time tests, this approach greatly facilitates the mastery of very complex systems. The fact that inserting plugins does not necessitate a new compilation of the model will prove to be a true time saver. The modules are also suited to interventions of very high complexity. When combined with the modular architecture of the Labcar hardware, HiL tests can be safely and efficiently configured to suit future applications. These may well extend into areas far beyond the domain of driver assistance systems. ■

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Therefore, since the second quarter of 2008, ATZ and MTZ have the status of refereed publications. The German association "WKM Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik" supports the magazines in the introduction and execution of the peer review process. The WKM has also applied to the German Research Foundation (DFG) for the magazines to be included in the "Impact Factor" (IF) list.

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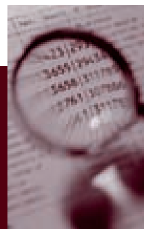

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Obstacle Avoidance for Passenger Cars

Lateral and Longitudinal Feedback Control for Collision Avoidance

Thanks to the increasing application of active and passive safety systems in motor vehicles, the amount of road fatalities has been continuously reduced in recent years. The part of the dissertation that is presented in this article was developed at the Institute of Automatic Control (Prof. Dr.-Ing. Dr. h. c. Rolf Isermann) at Technische Universität Darmstadt with the cooperation project “Proreta – Electronic Driver Assistance System for a Collision Avoiding Vehicle”. This project of TU Darmstadt and Continental followed the goal of developing solutions for collision avoidance in complex critical situations. The dissertation was awarded with the Hermann-Appel-Preis 2008 by IAV.

1 Introduction

The application of safety systems has resulted in a reduction in the number of accidents over recent years [1]. To follow the aim of the eSafety-campaign, which is to reduce the number of road traffic deaths in the European Union by 50% between 2000 and 2010, a further distribution of active safety systems is desired. Project “Proreta – Electronic Driver Assistance System for a Collision Avoiding Vehicle” contributed to the development of driver assistance systems in order to avoid accidents. If the system detects a dangerous situation by means of environmental sensors and the driver does not react adequately, the system will intervene to avoid the collision. An overview on Proreta was presented in ATZ 04/2007 and ATZ 05/2007 [2].

Collisions in road traffic can be avoided by interventions in longitudinal and/or lateral vehicle dynamics [1]. In this project a test vehicle equipped with an electro-hydraulic brake system and an active front steering system was used. Examples of driving situations include rear-end collisions at the end of a traffic jam either caused by an inattentive driver or by line-of-sight obstruction (for example fog, heavy rain) as well as collisions with vehicles that suddenly are cutting into a driver’s lane, **Figure 1**:

- In an unforeseeable situation when the driver’s lane is suddenly blocked, Figure 1a, an accident is avoided with an automatic emergency steering maneuver, if an emergency braking maneuver alone would not be sufficient; for example because of high relative velocity. If the ego-vehicle additionally shall be decelerated a combined emergency steering and braking maneuver would automatically be engaged.
- While the driver is in the process of overtaking a car another vehicle suddenly turns into the ego-vehicle’s lane, Figure 1b. Since further obstacles (for example guardrail, vehicles) yield to constraints regarding the accessible area a steering maneuver is not an alternative to avoid the collision. In this situation an emergency braking maneuver is carried out automatically.

Figure 2 provides an overview of the driver assistance system Proreta. Based on the environmental perception and on the information from the ego-vehicle, predictions for the expected trajectories of the ego-vehicle and the other environmental obstacles are calculated. With these predictions, a decision on the ne-

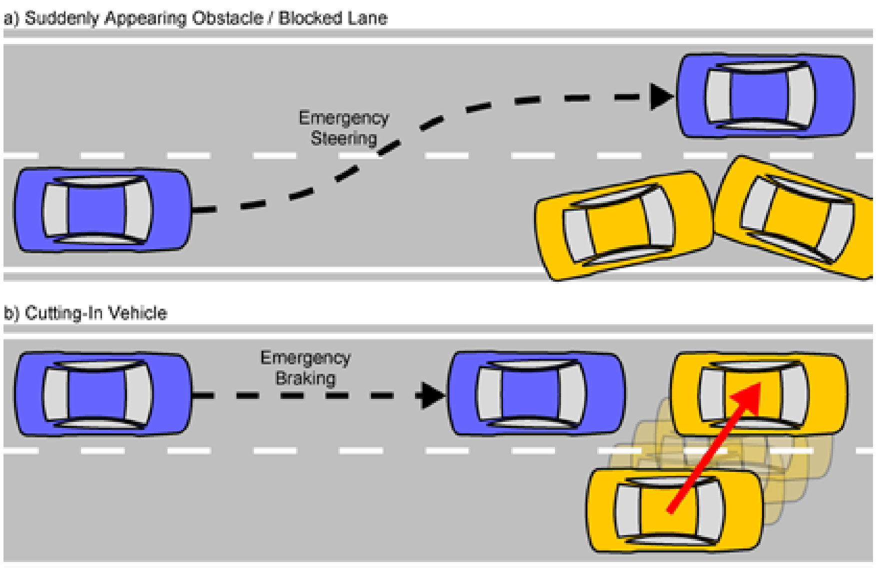

Figure 1: Scenarios “Suddenly appearing obstacle” a) and “Cutting-in vehicle” b) for testing the driver assistance system

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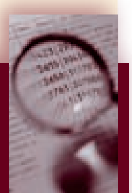

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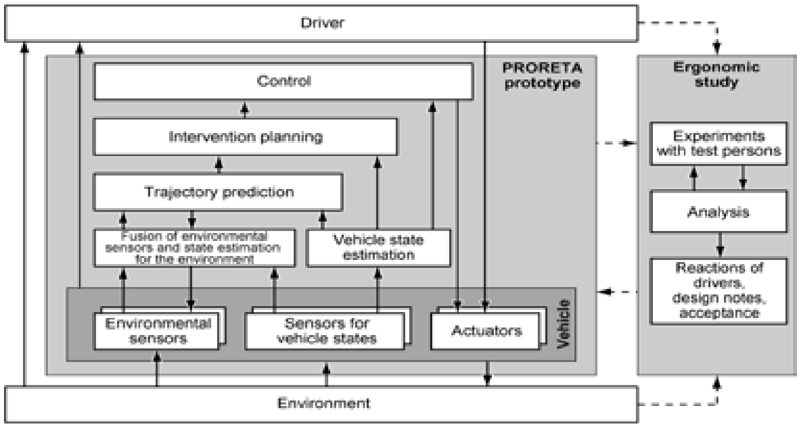

Figure 2: System overview Proreta

cessity of an intervention is made. The planned intervention is then carried out automatically by means of the control algorithms.

The development of the system functions was accompanied by an ergonomic study. The system components can be replaced modularly and therefore can be used for other assistance systems as well. For further information on these components see [1, 3, 4, 5]. Focus of this article is the control algorithms.

Braking and steering actuators have to be driven by feedforward or feedback control algorithms. Due to numerous disturbing influences in cars (variations in vehicle parameters and friction coefficient, influences caused by road and wind) using feedforward control algorithms is not sufficient. Therefore, the application of feedback control becomes mandatory. There, it is necessary to consider the driver as part of the control loop. The driver himself should have the possibility of avoiding an oncoming collision as long as possible. For this reason, interventions must be triggered at the last possible moment, which means at the stability limit of the vehicle's dynamics. The main focus of the presented dissertation was to develop and to test strategies for lateral feedback control of passenger cars at high lateral accelerations as well as to compare the various approaches. These maneuvers can be performed without or with brake intervention in parallel.

In the past, driver assistance systems for collision avoidance mainly focused on interventions in the longitudinal vehicle dynamics [6, 7]. Recently, lateral vehicle control sporadically gained in importance for collision avoidance applications. In [8, 9] the development of a collision avoidance system, which uses, depending on the situation, a brake intervention or a combined brake and steering intervention, is described. Project Proreta has developed a further step towards a collision-avoiding vehicle. By using an active front steering system instead of for example a steering robot a steering system type has been chosen which is already in series production. The driver is still part of the control loop.

2 Vehicle State Estimation

One component of the driver assistance system is responsible for calculating vehicle states that cannot be measured directly. Therefore, signals from other available sensors are used. These vehicle states are necessary for the feedback loop of some control approaches, among other applications. Out of the presented state estimators in this article, only the estimation of the sideslip angle is regarded. For further information see [1].

The first approach for sideslip angle determination has been published in a similar form [10, 11] and is based on a nonlinear observer. In project Proreta, brake and drive torques were available and therefore could be incorporated directly.

The second approach is based on an Extended Kalman-Filter. Three variants have been developed. The variant with adaptation of the lateral tire force coefficients k_α by means of a recursive least squares (RLS) algorithm showed the best results. **Figure 3** illustrates the structure. The vertical tire forces as well as the brake and drive torques are calculated using the sensors of vehicle stability control, brake system, and active front steering. Based on this, the longitudinal tire forces are determined. With the elements of the state vector x (longitudinal velocity v_X, lateral velocity v_Y and yaw rate $\dot{\Psi}$ of the vehicle) the lateral tire force coefficients $\hat{k}_\alpha$ are adapted and then used for estimating the vehicle state vector x in the Extended Kalman-filter. The meaning of the symbols is presented in the **Table**.

Figure 4 illustrates results of a test drive with sinusoidal steering angle input and of a double lane change maneuver (lateral accelerations up to $8\ m/s^2$). In comparison to the nonlinear observer the Kalman-filter based sideslip angle estimator achieved better results, which also has been confirmed by means of a quadratic quality criterion. The second used quality criterion was based on the

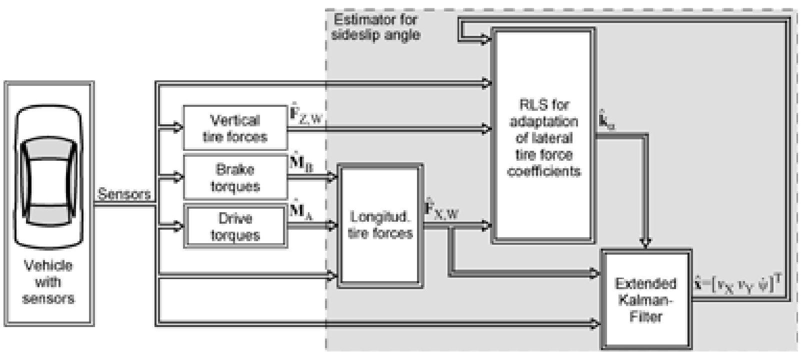

Figure 3: Structure of the Kalman-filter based sideslip angle estimator

Table: Explanation of the symbols

Meaning	Symbol	Unit
Lateral acceleration	a_Y	m/s²
Brake force	F_B	N
Longitudinal tire force	$F_{X,W}$	N
Vertical tire force	$F_{Z,W}$	N
Acceleration of gravity	g	m/s²
Lateral tire force coefficient	k_α	N/rad
Vehicle mass	m	kg
Drive torque	M_A	Nm
Brake torque	M_B	Nm
Brake pressure	p_B	Pa
Desired position (earth-fixed)	w_{X_E}, w_{Y_E}	m
Longitudinal velocity	v_X	m/s
Lateral velocity	v_Y	m/s
State vector	$\boldsymbol{x}$	–
Position (earth-fixed)	x_E, y_E	m
Sideslip angle	β	rad
Steer angle	δ	rad
Friction coefficient	μ	–
Yaw angle	Ψ	rad

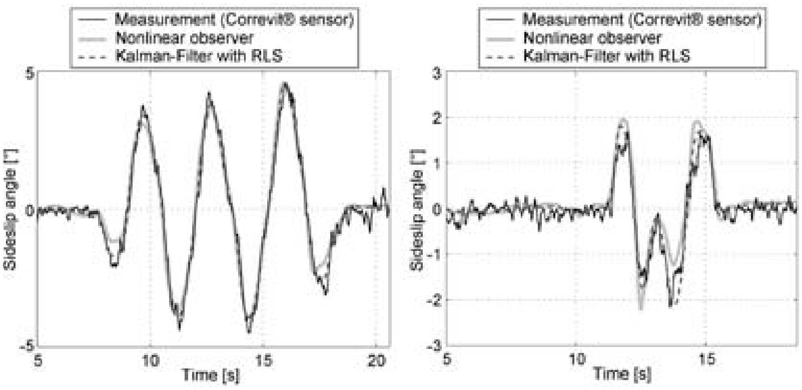

Figure 4: Estimated and measured sideslip angle for a sinusoidal steering input (left) and for a double lane change maneuver (right)

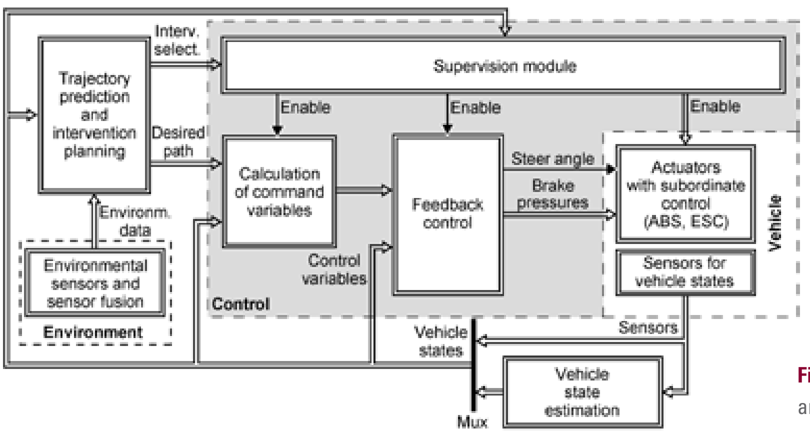

Figure 5: System components for the task of combined lateral and longitudinal vehicle path following control

absolute value of the difference between measured and estimated sideslip angle and showed adequate results.

3 Path Following Control

A motor vehicle is a coupled, nonlinear system [12]. For this reason longitudinal, lateral and vertical dynamics can't be reckoned separately. While lateral vehicle control stand-alone still can be handled quite well, the combined lateral and longitudinal vehicle control is more complicated.

The main task of path following control is to guide a vehicle on a desired path. Mostly an earth-fixed coordinate system is used. Usually no time information is given; the velocity can be chosen independently. The geometric deviation between desired and driven path should be minimal over the whole evasion maneuver. The sigmoid function (form of a lying "S") has been introduced as an easily applicable mathematical function for the representation of evasive trajectories [4].

In project Proreta, the interface between intervention planning, based on environment and vehicle data, and control module has been generally defined. This geometric path description utilizes also other path description variants; such as, connected clothoid parts. Out of these path points, the necessary command variables (for example, curvature κ) are calculated individually for each control approach. A specific prediction time is also taken into account. The control algorithm hands over the desired brake pressures and the steering angle request to the actuators, **Figure 5**. A supervision module evaluates the activation flags of the intervention planning module and activates the components of the control module.

Out of the examined respectively developed lateral feedback control approaches, without brake intervention, five are presented in [1]; out of the approaches with brake intervention, there are two. To apply the control algorithms

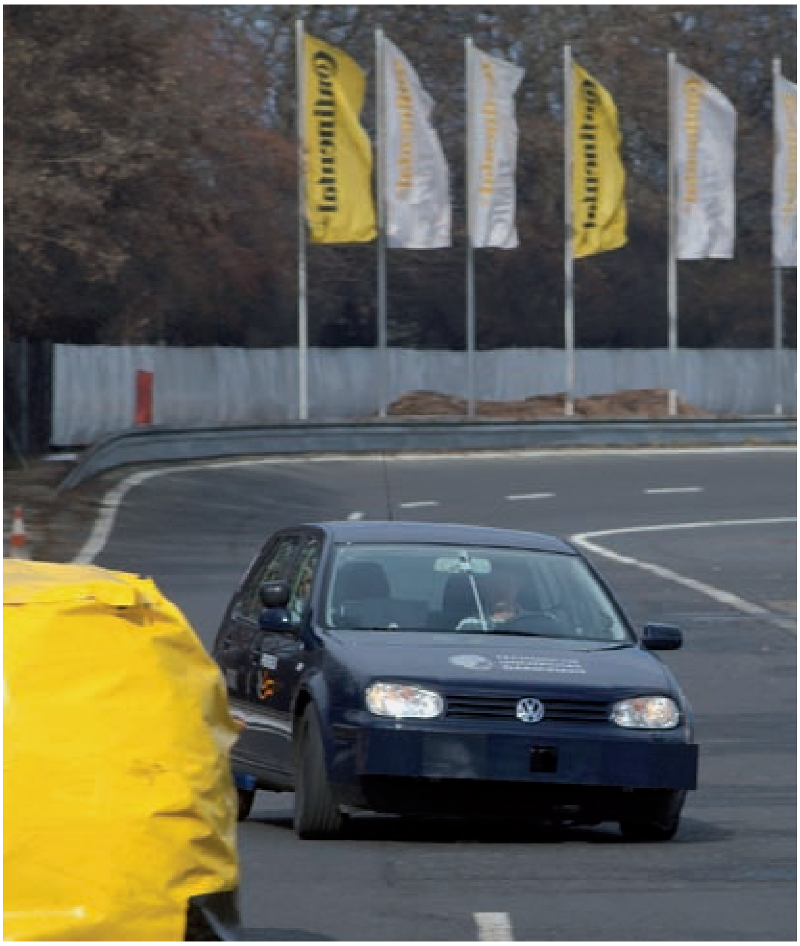

Figure 6: Test vehicle and crash safe obstacle while performing an emergency steering maneuver

vehicle data like position, velocity or sideslip angle are needed. These variables could not be measured directly in the test vehicle and thus had to be estimated as already shown for the sideslip angle. For development of the mentioned control approaches, a complex two-track simulation model based on [13] and test drives have been used. **Figure 6** exemplarily shows the verification scenario “emergency steering in front of a standing obstacle”. For comparison of different control approaches, an evaluation scheme on the basis of qualitative and quantitative criteria has been used. Simulation results, as well as test drive results, have been taken into account. By means of simulation of the intervention maneuvers, the performance of each control algorithm could have been compared under identical conditions. Among others, the qualitative criteria contained the maximum path deviation; as well as, a quality criterion based on path deviation, steering effort, roll angle, and roll angle derivation.

3.1 Lateral Feedback Control without Brake Intervention

The feedback control approaches for lateral vehicle guidance cover a significant spectrum of the existing feedback control methods; linear and nonlinear approaches; as well as, single-variable and multivariable systems have been taken into account. The first approach, a linear feedback control with feedforward, showed promising results. This control approach uses multiple speed dependent local linear controllers. Its huge advantage is a transparent structure and the possibility to easily adjust the parameters.

The second feedback control approach has been developed according to the design principle Internal Model Control. This approach uses the vehicle’s course angle as control variable. Because of its good quality of control, this approach also showed good results in the vehicle position. Anyway, adding a cascaded feedback loop should make it possible to react better to disturbances in the vehicle position. The third feedback control is based on a formerly published approach [14], which had to be modified. Design principle for this control is the Nonlinear Decoupling and Control theory. This approach demonstrated robust behavior and the desired and actual position correlated well. Due to the needed feedback loops (among others, the sideslip angle) and to the nonlinear theory the implementation and the parameterization are more complicated than for the first two control approaches.

Feedback control number four uses the theory of Nonlinear Asymptotic Output Tracking, which is another nonlinear state space control. Results and implementation effort are comparable to the previously mentioned approach. The fifth approach uses the kinematical vehicle model. For this model flat outputs can be defined, so that a flatness-based feedback control can be designed. In order to get a velocity independent control, a time-distance-transformation was performed. This control approach was already published for the application of a parking assistance system [15]. Even though the kinematical vehicle model is used, a high quality of control has been achieved. Comparing the different feedback control approaches led to the result that each approach is usable for the task of lateral vehicle path following control at high lateral accelerations without brake interventions.

3.2 Lateral Feedback Control with Brake Intervention

For combined lateral and longitudinal vehicle guidance two approaches are presented. The first approach treats lateral and longitudinal dynamics as being decoupled, **Figure 7**. For lateral control the already presented speed-dependent local linear feedback control with feedforward is used [2]. Based on desired position w_{x_E}, w_{Y_E} and desired curvature κ a steering angle is calculated which consists of a feedforward component δ_{FF} and of a feedback

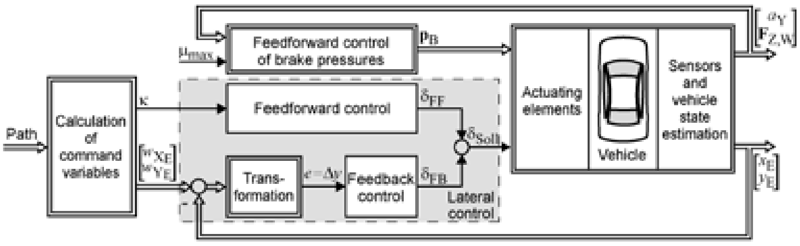

Figure 7: Structure of the combined lateral and longitudinal path following control consisting of local-linear lateral feedback with feedforward combined with brake control

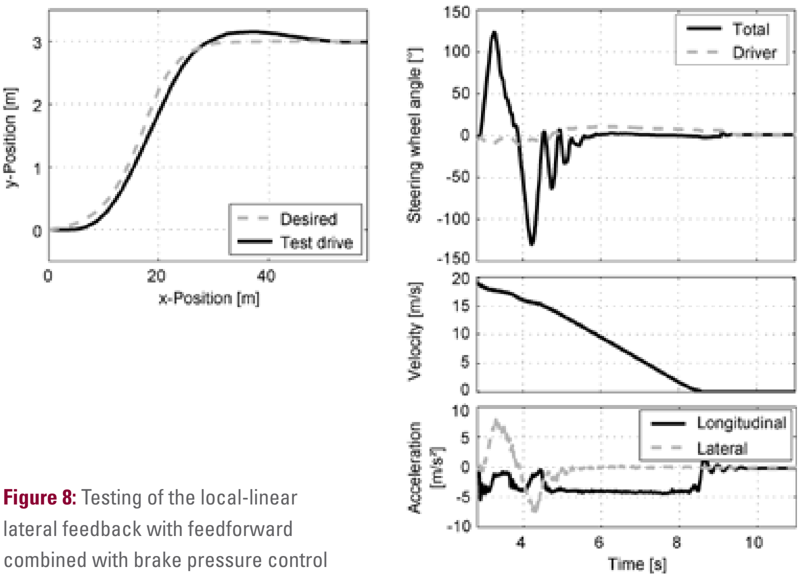

Figure 8: Testing of the local-linear lateral feedback with feedforward combined with brake pressure control

component δ_{FB}. In parallel the resulting maximum braking potential $F_{B,max} = m \cdot \sqrt{(\mu_{max} \cdot g)^2 - a_Y^2}$ for the overall vehicle is calculated using the maximum friction μ_{max} and the actual lateral acceleration a_Y. The resulting longitudinal force is distributed to the four wheels according to the vertical tire forces and afterwards is converted to wheel individual brake pressures. This approach leads to a control module that easily can be implemented and parameterized. The results are good, even though the path deviation is bigger than in comparison to a pure lateral control approach.

Figure 8 illustrates results of a combined steering and braking maneuver with an evasion width of 3 m. The desired position and the actual position correspond well, apart from a slight deviation during the dynamical part of the path following. At the transition between lane change and straight run, a slight overshoot occurred. The vehicle reliably came to a standstill because of the brake intervention. Compared with maneuvers without brake intervention, the absolute value of the steering angle sum is higher (130°). This also corresponds to theoretical analysis [1]. The lateral acceleration reaches up to 8 m/s². It can be concluded that combined lateral and longitudinal maneuvers are limited by the available friction potential of the tires as well as by the maximum possible steering velocity of the active front steering actuator.

The second approach is a nonlinear multivariable feedback control, which is based on the Nonlinear Decoupling and Control principle. In the literature, a similar approach already existed [16, 17] which only took into account longitudinal wheel forces at the rear axle; therefore, this approach had to be modified. The complexity of this approach is much higher than the complexity of the mentioned lateral feedback control with brake pressure control in parallel. Due to the Nonlinear Decoupling and Control principle, couplings and nonlinearities of the system can be balanced. This leads to a system with linear behavior; the dynamics can be chosen by setting the poles. **Figure 9** shows the structure. The command variables (desired position w_{X_E}, w_{Y_E} with derivatives) are calculated depending on the current lateral acceleration and on the maximum available friction potential. The state vector consists of sideslip angle β, yaw angle Ψ and derivative, velocity v, sum of longitudinal tire forces $F_{X,W}$ and vehicle position x_E, y_E. The achieved results reached similar quality as the results with the first mentioned approach, but implementation and parameterization cause higher efforts.

Figure 10 illustrated test drive results for an evasive width of 3 m. Desired position and actual position agree rather well apart from the slight deviation in the dynamical part. Concerning a potential overshoot, no conclusions can be made; because of the brake intervention the vehicle came to a standstill at the end of the lane change. The needed steering angle reached more than 200° and therefore was significantly higher than for respective maneuvers without brake

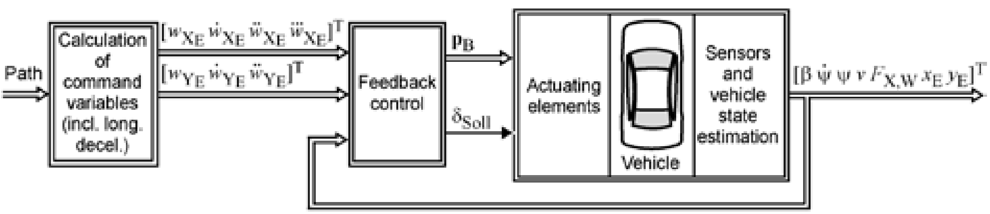

Figure 9: Structure of the nonlinear multivariable feedback control

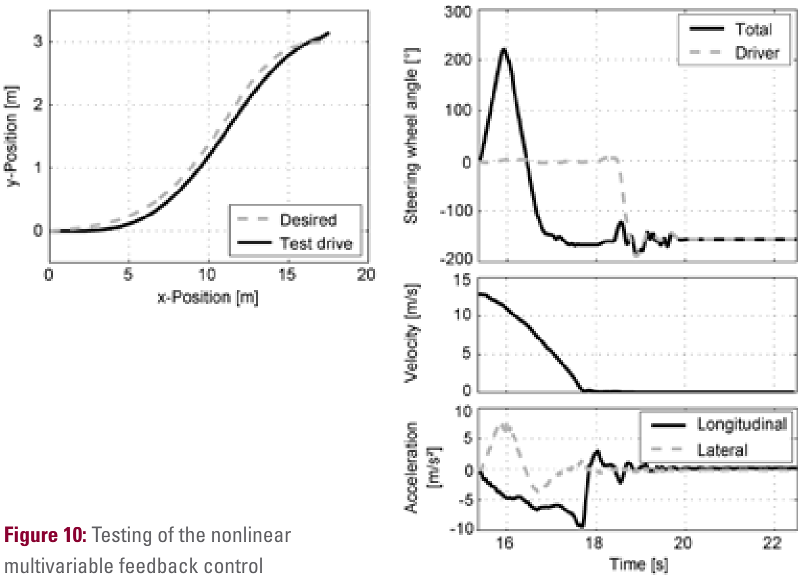

Figure 10: Testing of the nonlinear multivariable feedback control

intervention. Lateral acceleration was about 7 m/s. As expected the longitudinal acceleration rose to its maximum at standstill; in parallel the lateral acceleration fell.

4 Conclusions

The major part of driver assistance systems for collision avoidance so far only performed interventions in the longitudinal vehicle dynamics. With project Proreta, also interventions in lateral vehicle dynamics for collision avoidance have been examined. The project for electronic driver assistance for a collision-avoiding vehicle was carried out at TU Darmstadt in close cooperation with Continental and financed by Continental. The focus of the presented dissertation, created at the Institute of Automatic Control, was the development of control algorithms for lateral vehicle guidance. The control algorithms were designed so that emergency steering maneuvers can be performed in the last possible moment at high lateral accelerations.

The combined lateral and longitudinal vehicle guidance was discussed as well. The evasive trajectory can be transmitted using an interface which is independent from the mathematical path description function. Thus, different functions can be used. Using the Active Front Steering system, an already existing series production steering system has been chosen; the driver is part of the control loop. Vehicle states that could not be measured directly have been estimated using the signals of other sensors.

It has been illustrated that all control approaches as well as the overall driver assistance system have been integrated in a real vehicle. The driver assistance system was able to prevent collisions by automatic interventions if the driver did not react himself. The respective maneuvers have been presented also providing the possibility to non-project-related persons that they could drive the Proreta prototype. The system performed reliably.

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