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10 October 2011 | Volume 113

METHODS of Testing Camera-based Lighting Assistance Systems

VIRTUAL Torque Sensors for Electromechanical Steering Systems

ANALYSIS of Lateral and Longitudinal Distributing Drive Train Systems

/// INTERVIEW

Andre Seeck
BASt

PROGRESS IN VEHICLE SAFETY

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COVER STORY

PROGRESS IN VEHICLE SAFETY

4, 10, 14 I Electric vehicles must have the same high level of safety as cars with conventional drive trains. Against this background, BMW has analysed all the risks involved in the life cycle of an electric car on the basis of the ISO 26262 safety standard. In order to meet the requirements of the new US regulation on crash testing, FMVSS 226, in the case of a vehicle rollover, Bertrandt has developed a new test bench for side airbags.

COVER FIGURE © Daimler **FIGURE ABOVE** © Audi

VISION ZERO

Dear Reader,

Safety is a very wide-ranging subject. Many people think of it in terms of safe driving and ESC, which involves optimising the frictional forces between the tyres and the road. However, safety also includes the ongoing development of side airbags, an area where Bertrandt is currently designing new test benches, see page 14. Developers of electric cars are investigating methods for charging batteries safely from the mains, as described by BMW from page 4 onwards. Protecting vehicles against theft or break-ins is often also categorised as safety, but strictly speaking this comes under the heading of security. In all these areas, it is essential to be familiar with and follow the requirements of legislation and test procedures, which differ slightly from country to country and take the form of regulations such as NCAP tests and Federal Motor Vehicle Safety Standards (FMVSS).

Why should a crash test to evaluate pedestrian protection be different in China and in Sweden? Why does a pedestrian dummy in Germany have a different design from one in the USA? Accident injuries are just as painful for Chinese cyclists as for Australian passengers. It is clear that we have an increasingly urgent need for standardisation in this area. This is the only way that we can achieve the objectives of the EU "Vision Zero" initiative, which aims to reduce road accident death numbers in the EU by half by 2020. Is the figure of zero a Utopian vision? Even in Germany, which is one of the leading countries with regard to road safety, the number of deaths on the roads increased to 1809 in the first half of 2011, following four years of gradual falls.

In addition, accident figures all over the world vary considerably and are still too high in many countries. For example, in Bulgaria there are 120 road deaths per million inhabitants, whereas in Sweden the figure is only one third of that (43 persons). This makes it all the more gratifying that China and Germany are taking the first steps towards working together to analyse road accidents. The German Federal Highway Research Institute (BASt) has been cooperating with the Chinese research centre Catarc since July 2011 to investigate accidents in five Chinese cities using the German model.

As Professor Andre Seeck, president of Euro NCAP and head of the vehicle technology division at BASt, explains in an interview that starts on page 10, China will bring in passive safety measures much more quickly than we have done in the West and will reach our level by 2012. We can only hope that standardised tests will soon be introduced, so that we do not lose sight of the zero vision.

Best regards,

Michael Reichenbach

DIPL.-ING. MICHAEL REICHENBACH,
Vice Editor-in-Chief
Wiesbaden, 9 September 2011

SAFETY OF ELECTRIC VEHICLES DURING THEIR LIFE CYCLE

Electric vehicles are usually developed for the global market so that worldwide legislation provides a basic profile of requirement for safety. Besides, consumer protection organizations, like NCAP, now provide in many large markets specifications as well. When it comes to electric vehicles, a few unique characteristics have to be noted – an article by BMW.

AUTHOR

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ELECTRICAL DRIVES

In the context of its Efficient Dynamics Strategy, BMW had already commenced the electrification of the drive chain in series projects over 10 years ago. The corresponding vehicles, start-stop automatic, since 2006 ("Micro Hybrid") and BMW active hybrid 7 ("Mild Hybrid") also indicate the development trend towards a greater role for electrification, as illustrated by the BMW active hybrid X6 ("Full Hybrid"), MINI E and BMW active E, ❶, which as purely electrical vehicles have no internal combustion engine and do not carry fuel.

From a safety aspect it is here that special attention has to be paid to the subject of charging from the electrical grid network, since the dangers that are associated with the grid network also affect the car and vice versa. The future will tell us, which of these manifestations or their mixed formats (e.g. Plug-In hybrid as a mixed format with a greater proportion of electrical drive mode and charging options or electric battery vehicles with range extender, i.e. a small internal combustion engine for recharging the batteries en-route) will dominate.

SAFETY STANDARDS

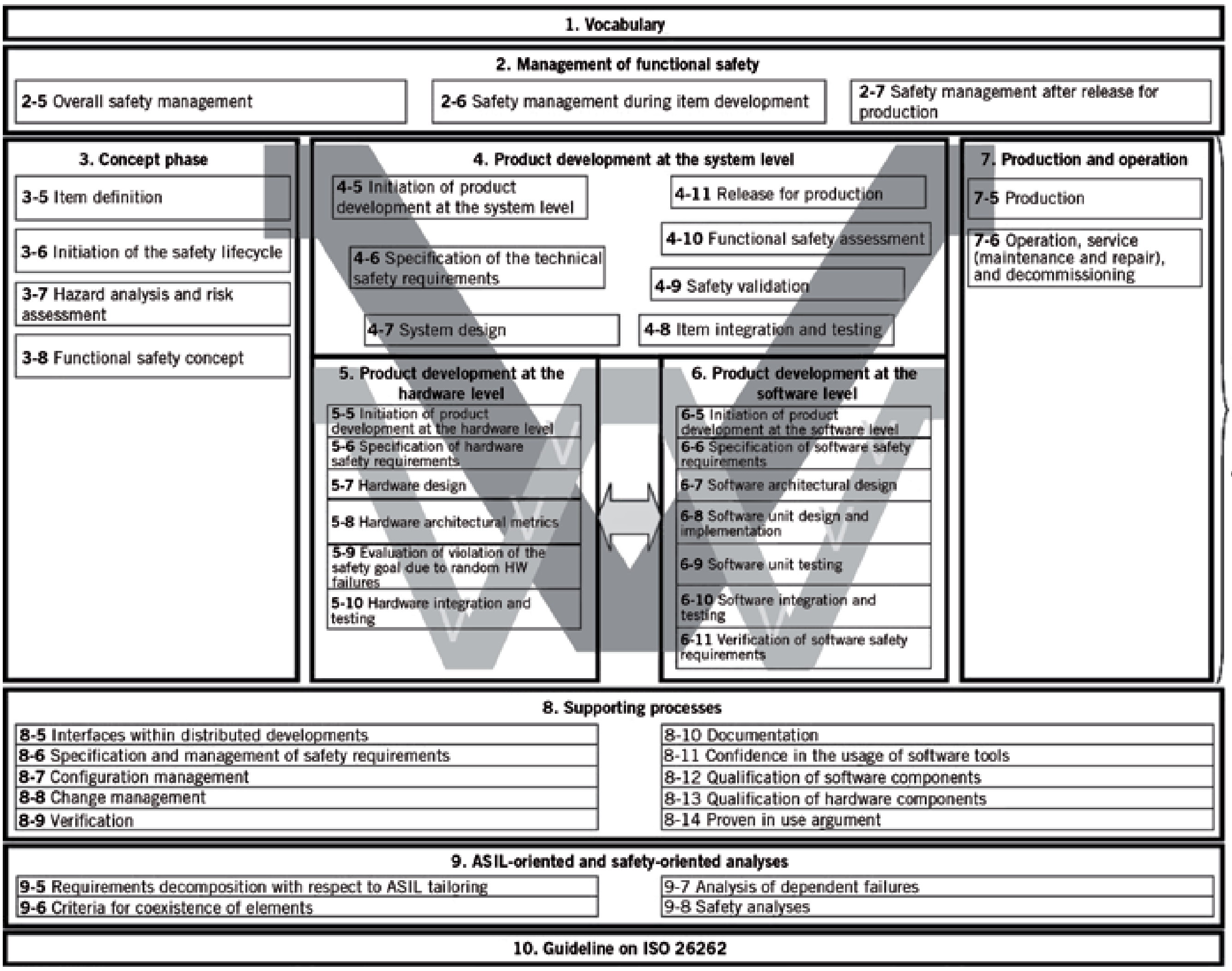
First of all, the safety standards that apply to electrical vehicles are the same as those for conventionally driven vehicles: As a rule, all major manufacturers are developing these vehicles for the worldwide market, so that the worldwide regulations effectively provide a basic requirement profile. Moreover the consumer protection organisations (NCAP = New Car Assessment Programme) meanwhile also prescribe requirement profiles in many of the large markets, for example Crash test load cases.

In addition, these requirements are supplemented by knowledge gained from accident research, in order that actual accident experience can be taken into account in the design of the vehicles.

Then, of course, there are the current and upcoming standards and regulations relating to hybrid vehicle operating safety that have to be satisfied.

The question of the safety of electronic systems in vehicles has already been posed for the German automobile industry with the introduction of the electronic accelerator pedal and the air-

❶ BMW active E and its components



❷ Structure of ISO 26262, aligned with the V model

bag in the 1980's. The safety philosophy that has arisen from this remains valid today, almost unchanged and demands no more nor less than a very rigourous development process, in which the very detailed requirements are derived from analyses and the solutions are theoretically and practically verified with reference to their fulfilment of the requirements.

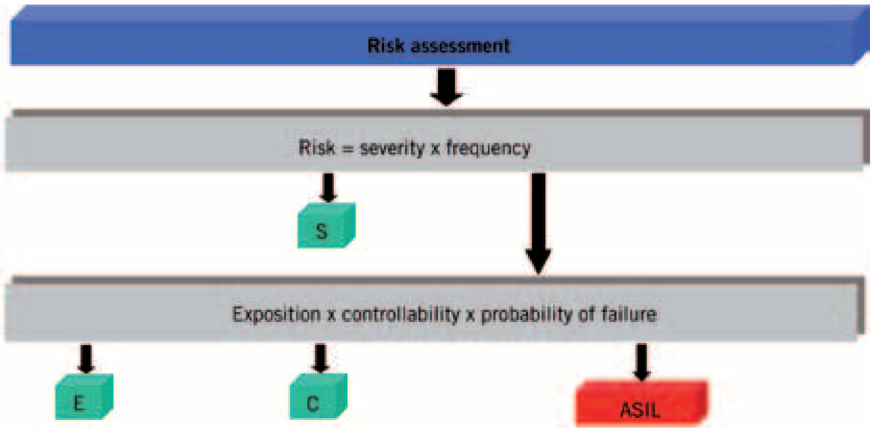
This is also the philosophy underlying the Electronic Safety Standard IEC 61508, which was published in the 1990's. On its basis analogous derivatives have arisen for rail technology, medical technology, etc., and in the case of the motor industry the document concerned is ISO 26262. Germany was and is the main driver of the standard, represented in the very forefront by the overall international project leader of the work on the standard (convenor) in the person of Christoph Jung, of Jung Consulting and Hans-Leo Ross, of Continental, who leads the German mirror committee of the DIN in cooperation with the VDA: Working group 16 of the automobile technology standards committee. Currently the standard is in the process of publication; the final draft of which has been available since 2009, ❷.

RISK ASSESSMENT FROM THE STANDPOINT OF POTENTIALLY ENDANGERED PERSONS

The most important step in the safety-aligned development of E/E systems is the hazard and risk analysis, which contains the following steps, undertaken by a team of experts under the leadership of the responsible safety authority:

: Critical malfunctions are identified on the basis of the present technical concept of a system and its interfaces in the vehicle overall (ideally with the aid of a system FMEA).
: The relevant operating situations are identified for these malfunctions from a situation tree and evaluated in terms of the frequency and duration of their occurrence (in cases of doubt with the aid of field data from customer business in the most important markets). The persons at risk are identified by this means and their period of exposure to risk and frequency of risk is assessed independently of the vehicle from the standpoint of the respective individual - Exposure "E".

- The controllability of the malfunction by the driver or other participants in the respective situation is evaluated, supported in cases of doubt by separate expert opinion, simulations and/or test studies) – Controllability "C".
- The severity of damage for the case, in which the fault is not controlled, is derived from investigations involving accident research – Severity "S".
- These three factors are then used to derive the necessary level of safety measures using a methodologically closed procedure – Automotive Safety Integrity Level „ASIL", ❸.



❸ Derivation of the ASIL (Automotive Safety Integrity Level)

SAFETY TARGETS

The following essential safety targets have been identified by BMW in respect of electrical mobility, as described above:

- Erroneous positive maximum torque (unintended acceleration): The acceleration capability of conventional internal combustion engines is not exceeded by electric motors, since on the corresponding top models the drive power is in any case already at the limits of the traction. Thus, as a rule the level of the safety targets and measures relating to internal combustion engines can be transferred to electric motors and accordingly this is not discussed here in greater depth.
- Erroneous negative maximum increase in torque (unintended deceleration/recuperation): Depending on the performance class and drive concept, Hybrid vehicles and BEV's have to satisfy high safety targets since, depending on the concept, the braking effect can lead to the jamming of a drive axle, in particular on roads with a low coefficient of friction (wet, snow, ice). This behaviour of the ride dynamics of the vehicle can be traced to measures relating to chassis control/braking systems and is not dealt with here in greater detail.
- Electric shock and vehicle fires: These safety targets are presented in more detail and with greater differentiation in the following with respect to the vehicle life cycle, together with their consequences.

DEVELOPMENT

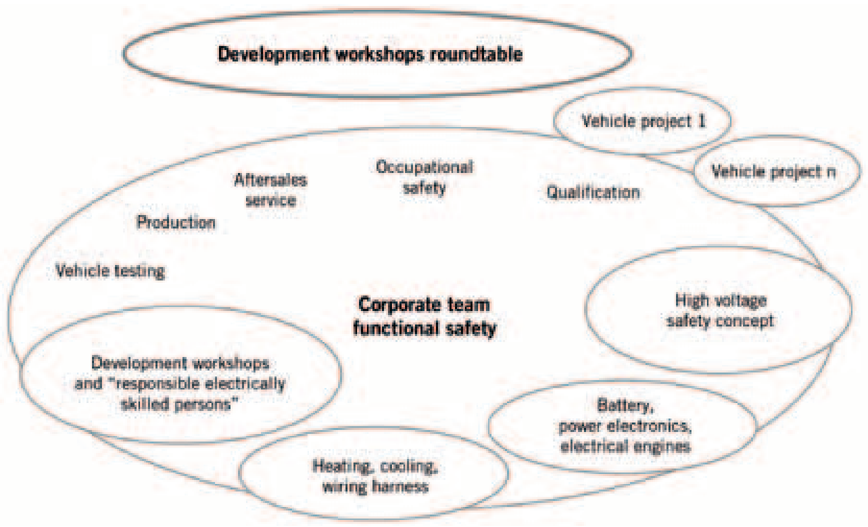
Electrical contact and fire protection are assessed over the entire development process by an interdisciplinary team from safety at work, training ("electrical specialists"), on-board power network specialists, specialist development areas, vehicle projects, testing centres and workshop operators, under the guidance of safety experts, ❹. In this way a level of safety is defined for the trials operation as derived from the series vehicle task, which depending on the development status of the vehicle, more or less defines additional measures in the vehicle and user restrictions.

PRODUCTION

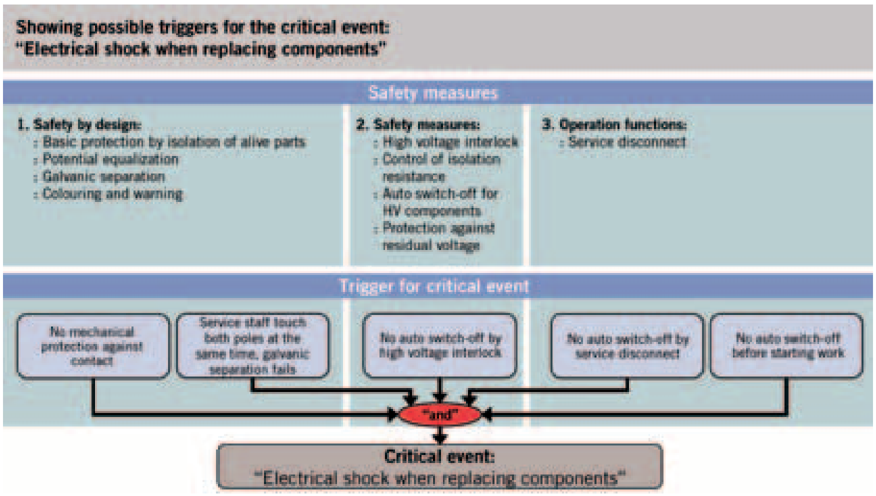
BMW has framed the vehicle concept in such a way, that in the production sequence there is no difference to conventional vehicles with regard to safety at work, however the post-treatment in the works involving special work on the vehicle onboard electrical system and the high voltage components by electrical specialists is intensified, in line with the aftersales concepts for the workshops (see below).

DRIVING OPERATION

As might be expected, normal driving operation is completely non-critical with regard to the danger of electrical contact, since fundamentally no components of the high voltage system are accessible from within the vehicle. This state of affairs is also already regulated by statutory requirements. Here the chemical and



❹ Structure of the BMW internal safety circuit alternative drives



❺ Basic structure of the fault tree for workshop safety

FORESEEABLE MISUSE ASSESSED BY EXPERT TEAM
Road side assistance, 24 V jumpstart, wrong external charging/starting
Exchange 12 V battery, fuses, lamps
Exchange/filling washing water, coolant, oil, brake fluid
Dismantle covers
Lifting car at wrong position (by manual lifter, auto lifter, fork lift, crane)
High pressure engine bay washing
Pouring water (2-l bottle bursts)
Damage by additional fittings (drilling into wires, loudspeakers, …)
Pushing, pulling, tieing at HV components
Damage HV system (e.G. curb driving, bump)
Marden bites into HV wires
Damage HV components by knocking ice off the car

❻ Example list of the themes relating to predictable misuse

thermal safety of the battery is the challenge, since understandably the cells do not lend themselves conveniently to the requirements of the automobile.layout. To this end test methods are currently being developed in order to be able to substantiate the safety of the cells at the start of series production of the respective vehicle.

CHARGING

Unfortunately standardisation of the charging procedure has not so far made much progress internationally, so that many charging technologies and connector concepts are having to be developed in parallel. Collaboration with the infrastructure to achieve a balanced level of safety requires the coordination of the risk assessments between vehicle and infrastructure.

TIME SPENT IN THE WORKSHOP

The internal requirement has also been defined on the basis of operating economics, such that the vehicle is quasi "intrinsically safe", i.e. in the event of defects the replacement of HV components can be carried out by an "electrical layman" with merely basic HV training. All the measures to be implemented for this are entered in a fault tree and detailed down to the component level. Given the failure rate of the individual components it is now possible to calculate the overall probability of the occurrence of the dangerous event, ❺. This information then facilitates the demonstration in discussions with other manufacturers, professional associations and the German vehicle industry and trade, that the vehicles achieve a safety level, which permits the exchange of components by electrical laymen.

FORESEEABLE MISUSE

The themes, ❻, which are able to represent a particular risk with reference to the high voltage system, have been respectively devised and evaluated in detail by a team of experts in risk analysis and risk assessment; these are detailed in FMEA´s and are safely implemented by geometric, functional and system side measures.

It applies to most themes, that because of the intrinsically safe conception of the vehicles for workshops, no additional measures are necessary.

ACCIDENT AVOIDANCE

Due to the clearly lower noise emissions in the electrical drive mode will be countered by BMW in future vehicles though the provision of an additional source of noise, which will make pedestrians aware of the approaching vehicle as they are of conventional vehicles. This will lead to scientifically derived psychoacoustic requirements on the basis of accident research data and a group of such requirements will be defined, which are best suited to regulate the start up, identification, localisation, speed and driving dynamics of electric vehicles.

ACCIDENT

The following functional measures for protection from electrical contact and fire are implemented in the electric vehicles in order to also provide "intrinsic safety" for the crash case:
: crash switch-off via the airbag control unit with direct cable connection to activate the battery contactor
: active short-circuit of the electric motor in order to prevent possible recovery of the supply
: active discharge of the capacitors in the HV consumer items, in order to dissipate the residual energy as quickly as possible from the system.

RESCUE AND RECOVERY

The aim is that rescue/recovery resources will be able to react quickly without specific training/equipment. The measures are two-fold: On the one hand the HV components, chiefly the HV accumulator as the sole energy source, which cannot be discharged, are to be arranged in the vehicle in such a w ay, that in the context of the envisaged accident scenario no electrical contact or fire risk can arise. Secondly, the HV on board network is designed for switch-off and discharge in all the envisaged types of accident (see "Accident").

DISPOSAL

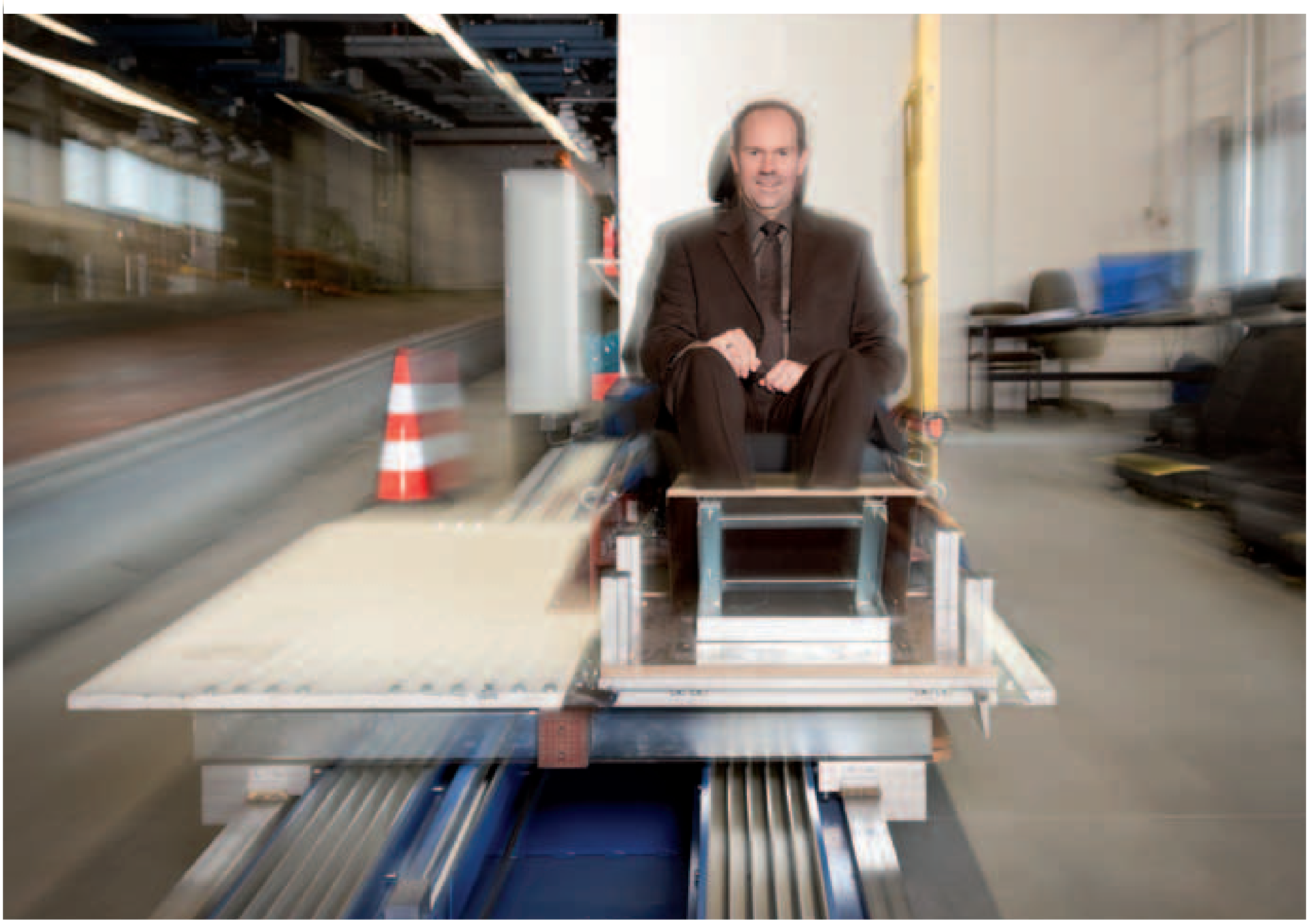
The decommissioning and dismantling of the vehicles can, as a rule, profit directly from the concept of intrinsic safety in the workshop case – special measures are not necessary here, so long as "only" components are dismantled.

SUMMARY

With the introduction on the market of the first vehicle in the World with Lithium-Ion-Traction batteries (Mercedes S-Class and BMW 7-Series) the market for electric vehicle drives began to gain enormous impetus.

At the same time the draft of ISO 26262 was published as a basic standard for the functional safety of motor vehicles.

With this twin introduction, for BMW it was a logical step to evaluate all risks associated with electric drives, irrespective of the technology from which they have arisen and in accordance with the methods of this standard, so that a completely uniform and well-balanced level of safety can be achieved over the complete life cycle. Oriented on the basic vehicle safety standard ISO 26262 safety targets relating to mechanical, electrical, thermal and chemical risks are derived, whose fulfilment can be targeted through a precisely balanced construction involving electronic and non-electronic measures. To this end ISO26262 provides the framework for a unified mastery of the risks, which can arise for the most diverse groups of persons during the life cycle of vehicles with an electric drive chain.



"WE HAVE TO DEMONSTRATE THE BENEFIT OF ASSISTANCE SYSTEMS"

It is still early days for the automotive industry as regards test processes for active and integrated safety systems. Professor Andre Seeck from the BASt sees this as an historic opportunity. Because at a sufficiently early stage there is scope for working on internationally harmonised standards. ATZ spoke with the Head of Vehicle Technology of the Bundesanstalt für Straßenwesen (Federal Highway Research Institute) about new test procedures for innovative driver assistance systems and new techniques for assessing their usefulness.

Andre Seeck (47) studied mechanical engineering at the Technical University of Braunschweig, specialising in vehicle technology. He has worked at the Federal Highway Research Institute (BASt) since 1993. He began in the "Passive vehicle safety, biomechanics" unit, where he managed the research projects paving the way for European motor vehicle safety regulations. In 2001, Seeck took over as head of the newly established "Vehicle safety assessment, driver assistance systems" unit. Since 2008 he has led the vehicle technology department. The accident researcher also represents the Federal Ministry for Transport, Building and Urban Development on the Board of Directors of the European New Car Assessment Programme (Euro NCAP). In 2010 he was elected president and chairman of the Euro NCAP.

ATZ _ The proliferation of international safety standards for assessing passive safety systems is unstoppable. Is it still now possible to prevent similar mistakes from being made in the testing of active and integrated safety systems?

SEECK _ Yes. When it comes to existing test procedure standards for passive safety systems, we have more or less missed the standardisation boat. Although there are exceptions. In terms of the Euro NCAP side impact protection test, the European crash test dummy is being replaced by the internationally standardised WorldSID. Admittedly, that will not be achieved, as planned until just recently, by 2014 but it will be by 2015 at the latest. When it comes to testing active and integrated safety systems, car manufacturers, accident researchers and consumer protection people have the historic opportunity of nipping proliferation in the bud, for example for test procedures for assistance functions for pre-emptive pedestrian protection. Researchers are doing important preparatory work in this area because downstream harmonisation, at a political level, is possible only with great difficulty.

What specifically can be standardised?

For example the test involving a pedestrian dummy and the accident scenarios for pre-emptive pedestrian protection. To date, researchers in the USA and Germany have been applying two different test methods. Either the dummy is swung out of the way at the last second prior to impact That is the approach that we here at the Federal Highway Research Institute favour. Or else the dummy is extremely light and soft, which avoids damaging the vehicle and its sensors upon impact. Neither method is wrong. I think that we will soon agree a common approach the Americans.

It doesn't always make sense to agree international standards because there are regional differences.

Correct. Many accident scenarios occur very frequently in one country – for example fatalities caused by the vehicle rolling over, in the USA. And in other countries

"We are becoming increasingly involved in China."

this sort of accident is of lesser importance. This does not appear to be so much the case with pre-emptive pedestrian protection. This is borne out by initial studies that we have conducted jointly with the North Americans.

China is the most important market nowadays. Who is taking the lead from whom when it comes to accident prevention?

China will take the necessary steps faster than we did. But the Asians are also following in our footsteps. In terms of passive safety system testing, we anticipate that the country will have reached the level of Europe and USA by 2012. The BASt is in close touch with the national Catarc, the organisation responsible for NCAP in China. Within the framework of a corporation contract on joint accident research – we are supporting a research project on the German model in initially five, subsequently eight, Chinese cities.

And how are regional differences taken into account here? Just for one, I'm thinking of the numerous cyclists.

Certainly a country such as China still needs to gain experience and discover which accident focus points the experts are deriving from it. In this respect we will continue to develop our research collaboration with China as to the methodological approach.

Will protection for cyclists be a special topic?

The issue is protecting unprotected road users, whether pedestrians or cyclists. Ultimately, the question is where do I absorb the kinetic energy in a collision? Passively between the cranial roof and engine block in the form of a deformation path in the vicinity of the bonnet and in the case of cyclists, possibly with airbags at windscreen level. Or else the energy is converted, so to speak, in the brake disc, thereby reducing the collision speed. Or else I avoid an accident altogether by intelligently warning the driver.

Isn't the potential of passive safety systems already exhausted? With the really major progress towards zero traffic deaths to be found in active systems?

That's what many people think. Incorrectly. Euro NCAP is currently considering a package of measures: In 2015 we are introducing new crash test dummies and a second variant of the frontal crash test. Adaptive restraint systems – not just on the rear seat – receive insufficient attention. Here alone there is considerable potential for improvement. But what is also clear is that integrated safety is a large field in which numerous and fundamental developments are in hand. We have to organise ourselves in a concerted manner. To this end, we need an assessment methodology that we are jointly in the process of developing within an alliance between the automotive industry, the insurance industry and Dekra. The challenge is to be

Andre Seeck in discussion with ATZ editor Markus Schöttle

The BASt is developing research vehicles to observe the driver and his behaviour

able to quantify the added value and benefits of assistance systems. What for example is the benefit of reducing the impact speed from 40 to 32 km/h using active systems compared with reducing the HIC value from 1300 to 700 using passive protection measures. These factors need to be incorporated in a rating scheme, which we at Euro NCAP can subsequently use to award bonus points.

You have been working for years on analysing accident data using Gidas, German In-Depth Accident. Do you also use Gidas to assess assistance systems?
We have been using Gidas for accident research for more than 30 years. Admittedly, in the past the methodology was predominantly focused on passive safety. We are collaborating with vehicle manufacturers on new methods. Assistance systems and how they operate will be linked in the expanded Gidas database. In this way, we are supplementing surveys providing us with information about the accident occurrence phase. Gidas is used to reconstruct each accident event up to four seconds before a crash.

What actually happens?
For example, a sensor and its usefulness are assessed by, in the truest sense of the word, running its specification such as aperture angle, calculation algorithms, speed and range through Gidas. Our aim is to calculate how many accidents might have been avoided or else their gravity reduced if one or the other driver assistance system, in this case a sensor with other parameters or alternatives, had been on board. Based on the assessment, the car manufacturers can then see whether it is worth installing another sensor and another system. This then subsequently allows the driver assistance system parameters to be selectively designed to make them more effective.

What results have you already achieved?
We can discern a clear trend towards assistance systems for pedestrian protection or rather for avoiding accidents involving unprotected road users.

Your conclusions are based on the what if principle. But the number of accidents that have actually already been avoided as result of assistance systems remains a mystery?
We are in the process of getting to the bottom of this mystery as well. This is precisely where accident research kicks in. Initially we can make a simple and arithmetic approximation, as has already been done in the case of ESP. To demonstrate the benefit of ESP, accident researchers have established the difference in the number of vehicle accidents with and without the stability programme. In future we will be able to do this more accurately: Using another new method we are concentrating – in parallel with Gidas – on accident occurrence situations affecting the driver. The English name we have given the method is Naturalistic Driving Study, which we are developing in conjunction with the Automotive Technology Research Association FAT. What interests us is what exactly happens in the four or even ten seconds before the accident? Our accident researchers will analyse driving processes. How did the driver behave? In what direction did he look? Why possibly did the driver not react? These are questions that we want to answer using test subjects in research vehicles.

How does the method work?
We are still in a pilot phase in which production vehicles are equipped, among other things, with cameras observing the surrounding area and the driver. As a result of our collaboration with the automotive industry, we have access to the CAN bus, which already provides a large amount of sensor data almost free of charge. This also allows us to record numerous near misses, so-called incidences, giving us a broader database. This generates vast quantities of data that have to be filtered sensibly and according to specific criteria: This is where data from the infrastructure, vehicle and driver come together.

So, does Joe Public drive expensive research vehicles?
Yes. They are supposed to be normal vehicles in which the necessary sensors and recording technology have been installed almost unnoticeably. To keep the cost and effort to a reasonable level, we are investigating which sensors and cameras are required and how we can reduce and sensibly evaluate the flood of data.

What driver assistance system would you like to see in future?
The junction/intersection assistant, which can help to avoid numerous accidents. But currently that is not yet technically feasible.

Professor Seeck, thank you for the interesting discussion.

INTERVIEW: Markus Schöttle
PHOTOS: Alexandra Lechner

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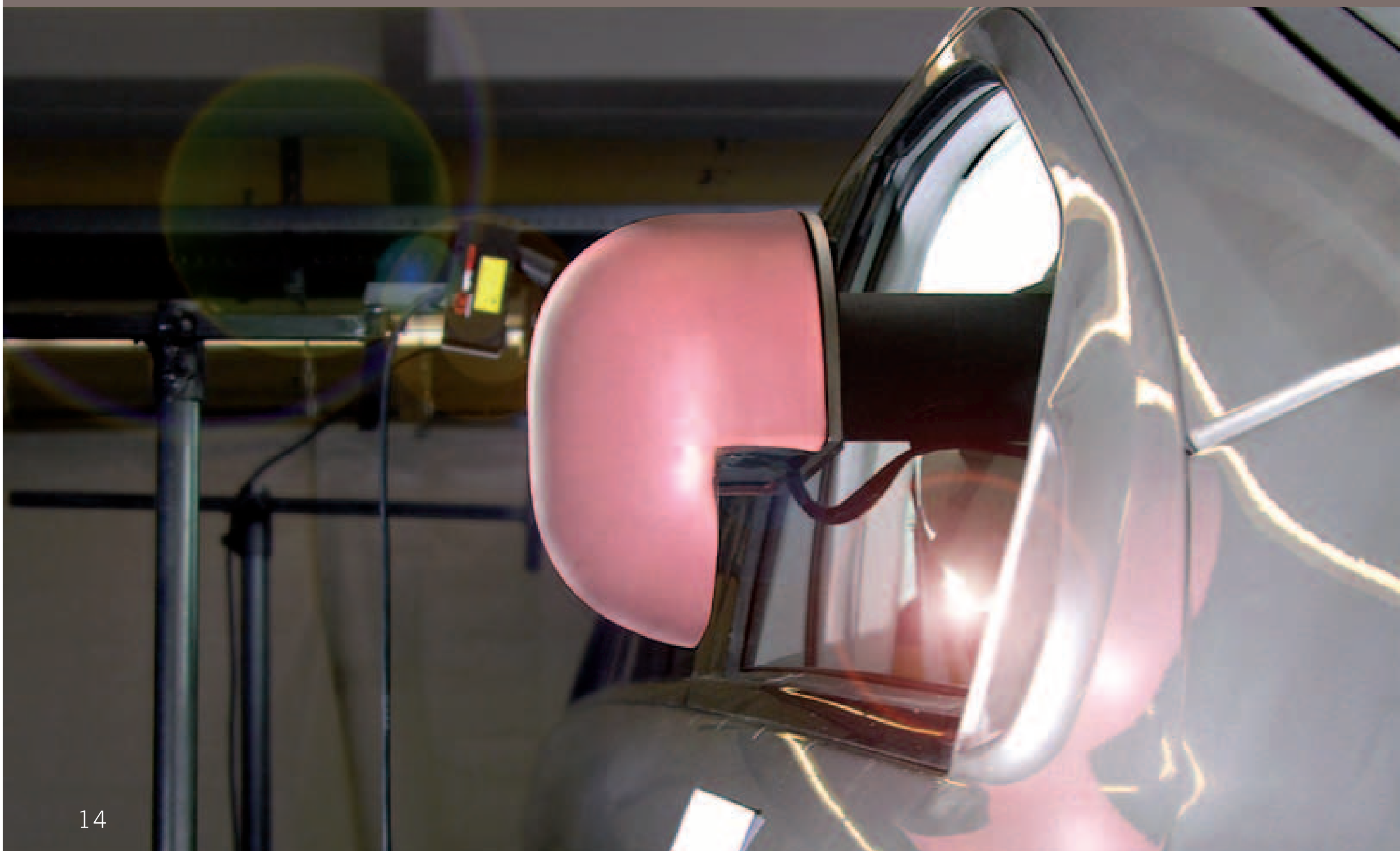
NEW ROLES FOR SIDE AIRBAGS

At the beginning of 2011, a new US Federal Motor Vehicle Safety Standard (FMVSS) was published, covering vehicles launched and sold on the US market. The new standard focuses on protecting occupants in the event of the vehicle rolling over, in order to prevent them from being ejected from the passenger compartment through lateral window openings. Bertrandt in Munich has started using one of the first test rigs that allow vehicles to be tested in accordance with the latest regulations.



AUTHOR

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NEW STANDARD FOR THE US MARKET

Car companies intending to sell their products on the US market find themselves confronted with a wide variety of standards. There are currently more than 60 FMVSS standards, one of which is 226, introduced in January 2011. In early 2011, the new standard was adopted as a final rule in the field of passive vehicle safety. The standard will gradually be introduced between 2013 and 2017. By that time, all new vehicles available on the US market must meet the requirements of FMVSS 226 in full. The FMVSS standards currently do not apply to vehicles registered in Europe.

Until 2011, restricting the ejection of the vehicle occupants through the side windows in rollover crashes did not form part of US legislation. Testing in this area mainly took the form of rollover tests using complete vehicle bodies which were thrown off catapult ramps and embankments. In addition, partial vehicle bodies were tested in rollover simulators. These tests provided basic information about the behaviour of vehicle occupants in an accident, but they were extremely costly. As a result of the influence of a large number of external variables, it was not possible to ensure that the tests were comparable, because it was difficult to make the entire test set-up reproducible.

ADDITIONAL PROTECTIVE FUNCTION

These tests were carried out in accordance with the road traffic regulations which apply in the USA, where seat belts are mandatory everywhere except the state of New Hampshire. However, under the provisions of the legislation, vehicle occupants who are not belted in must also be protected by airbag systems or other restraint mechanisms. The consequence of this is that all the tests must be based on the behaviour of an occupant who is not restrained by a seat belt. There is no requirement of this kind in Europe. However, for manufacturers who intend to sell their vehicles in the USA, the requirement forms an important basis for future sales success.

Existing vehicle safety systems, such as curtain airbags, were developed with the aim of reducing or preventing injuries to occupants in the event of an impact with part of the vehicle interior. This is clear from the design of the airbags currently used in production models. Because they must comply with the requirements of FMVSS 214 in the case of a side impact, the airbags are designed to provide additional cushioning in critical areas such as the A, B or C pillars. With the introduction of FMVSS 226, these airbags now have an additional job, which means that the relevant test has to be developed further, ❶.

Side windows made from safety glass provide further protection for the vehicle occupants, because they absorb additional energy during the impact and help to prevent the occupants from being ejected. The majority of production models are currently fitted with single-pane safety glass as standard. However, single-pane safety glass has no influence on the vehicle's ability to restrain the occupants, as it is assumed that the side windows will be completely smashed right at the start of the crash.

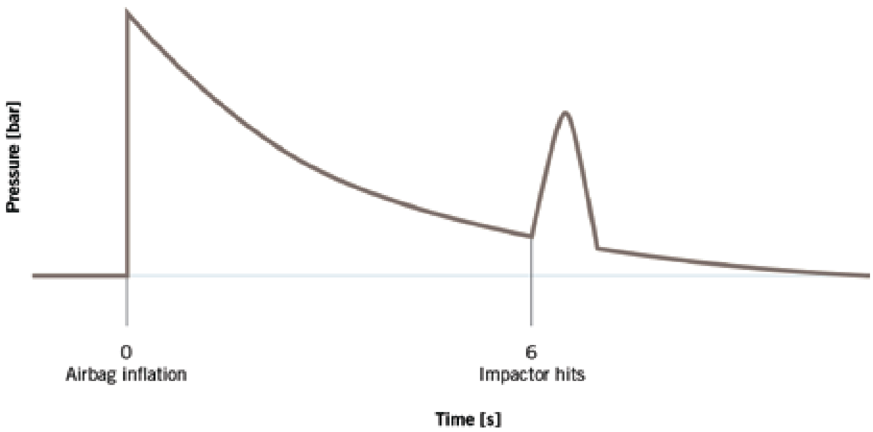
FMVSS 226 INTRODUCES STRICTER LIMITS

FMVSS 226 sets an excursion limit beyond which vehicle occupants must not be ejected from the vehicle in the case of a rollover accident. The requirements drawn up by the NHTSA are based on the one hand on accident statistics from the USA and on the other on preliminary tests with complete and partial vehicle bodies. The statistics show that accidents in which vehicles roll over represent around 35 % of all fatal crashes. These figures also include cases where occupants are partially and completely ejected from the vehicle.

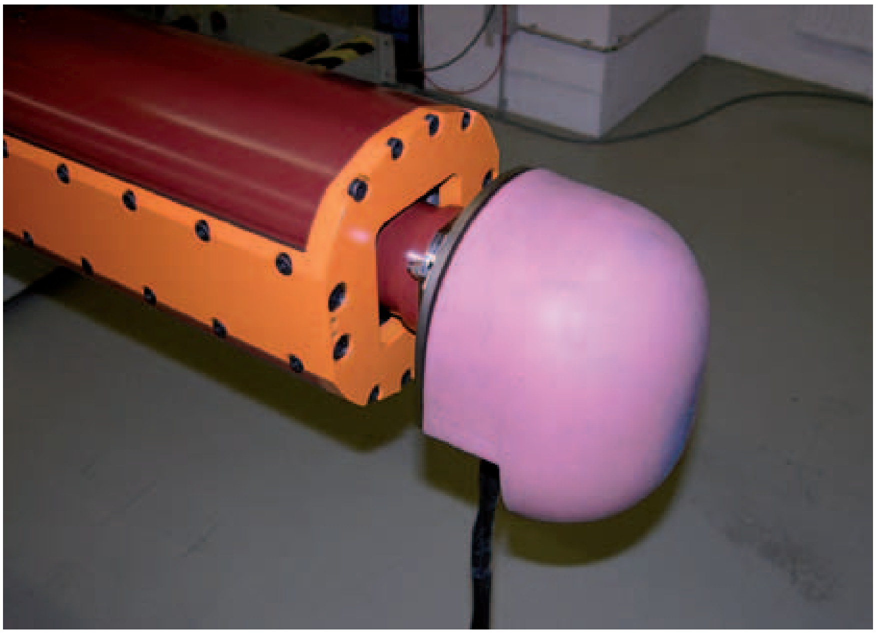
Particular attention was paid to sports utility vehicles (SUVs), which, because of their design, their high centre of gravity and their increasing popularity, present the greatest risk in rollover crashes. However, the required ejection mitigation performance applies to all categories of vehicle up to a gross vehicle weight of 4.536 t.

NEW TEST DUMMY

The results of a number of different comparisons and tests showed that the curtain or window airbags developed to provide protection in the event of a side impact offered the greatest potential for restraining the vehicle occupants, in combination with side windows made from laminated safety glass. In order to test the effective-



❶ Pressure changes in a curtain airbag during the course of the test



❷ An ejection mitigation impactor on a linear impactor unit

ness of these systems and different combinations of them, the NHTSA developed the test procedure which uses a stationary vehicle and a guided moving dummy. A special form of dummy has been developed that consists only of the most critical parts of the occupant's body in relation to this type of crash. It is a hybrid form made up of the side of the head and the shoulder, ❷. These critical areas were identified during the course of the preliminary tests referred to above.

In order to keep the cost and time needed for the test to a minimum, the NHTSA decided on a static procedure. The vehicle being tested is positioned on a special test bench. The complete vehicle is tested in its production form or as close to it as possible. The requirement to test the complete vehicle presents one of the major challenges for the design of the test system. The test unit must be designed in such a way that it can be put in position through the side windows of the vehicle.

TEST RIG SPECIFICATIONS

The test set-up consists of two fundamental areas. On the one hand, there is the test rig side, which includes all the fixed elements of the test environment and is the same for every vehicle. On the other hand, there is the vehicle side, which is made up of all the aspects that are specific to the vehicle in question. The test bench consists of a basic set-up with an acceleration unit that can move a guided impactor sled and the dummy headform attached to it in a linear motion longitudinally at speeds up to 25 km/h, ❸.

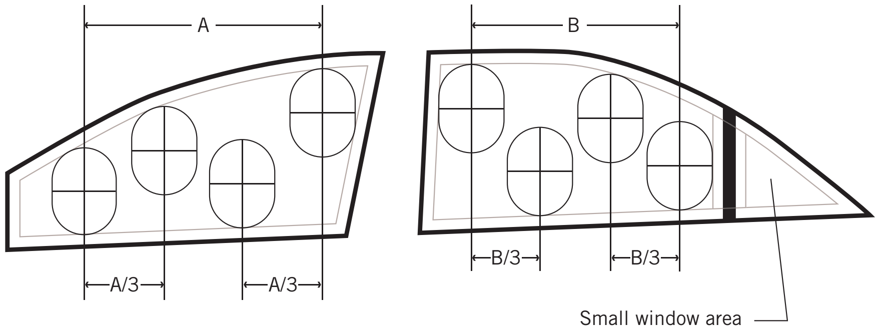
In contrast to the "free motion headform" used for FMVSS 201, the dummy or so-called featureless headform does not have a realistic face. It consists of the side of the head and the shoulder, which are the most critical parts of the body in the case of a side impact and rollover crash in the window area. It is not a realistic representation of a body part, but a hybrid form. This often leads to misunderstandings because the impactor has the appearance of a human head.

Apart from the headform, no specifications are given for the design of the linear impactor. However, it has to meet a series of static and dynamic requirements. For example, the weight of the impactor sled and the dummy (the moving part of the unit) is restricted to 18 ± 0.05 kg, in order to guarantee the correct energy input at the specified testing speeds.

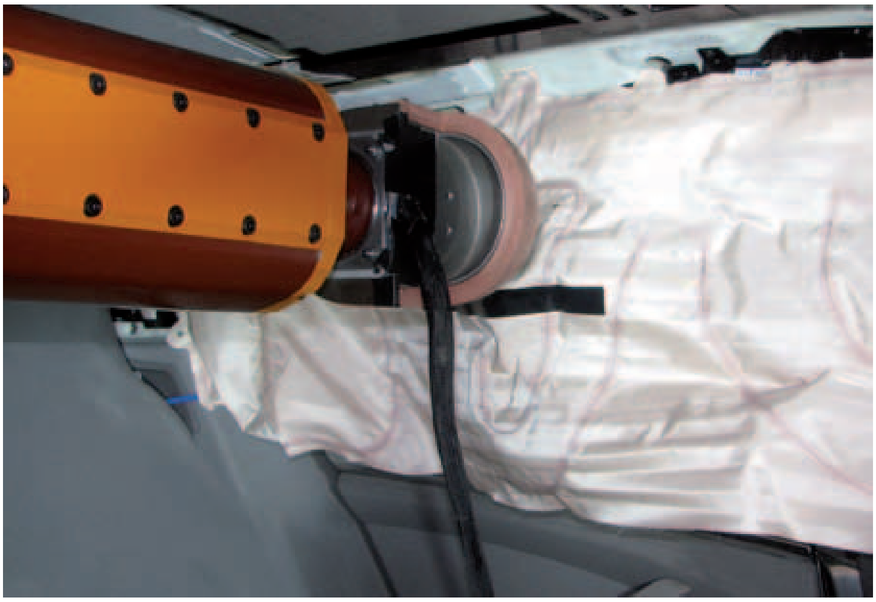
PREPARING THE VEHICLE

The specifications covering the vehicle that is being tested state that the doors on the side of the vehicle opposite the test side can be removed. If necessary, the tailgate can be opened or removed, which can be helpful for the positioning of high-speed camera systems. The doors on the test side must be closed, but must not be locked. The windscreen and the rear window must be fitted for reasons of stiffness.

❸ Test area for FMVSS 226 testing at Bertrandt in Munich



❹ Identifying the target locations in the side windows



❺ Positioning the linear impactor unit in the vehicle

In order to ensure easy access and assembly, components in the interior of the vehicle can be removed, provided that this does not influence the test results. For example, the trim on the A, B and C pillars and the doors must remain in place in case the airbag is supported in these areas or the airbag inflation process could be affected. If the test is carried out with safety glass installed, all the necessary additional components, such as window channel strips and seals, must be correctly fitted to ensure that the windows are properly positioned and behave as normal.

TEST PROCESS

In addition to the specifications relating to the test environment, there are extensive instructions concerning the implementation of the test. These instructions are included in the text of the standard and described in detail in the accompanying test procedure TP-226, ❹.

The instructions cover the positions to be tested, the preparation of the vehicle, the test configurations and the process of documenting and evaluating them, ❺.

The positions to be tested are identified using a specific diagram with a maximum of four target locations for each side window.

By additionally tilting the impactor, a larger test area can be covered. Experience shows that the most critical target locations are those furthest forward in the vehicle. In this area it is particularly difficult to provide adequate airbag coverage. The test is carried out on each of the target locations at impact speeds of 16 km/h and 20 km/h, which correspond to the changing speeds during the course of the vehicle rollover.

As a result, the first contact involves higher levels of energy. By the time of the second impact, the energy has reduced to a certain extent. The intervals between the time at which the restraint system is triggered, the first contact and the second contact are fixed, in order to reproduce the events of the crash accurately.

Although the test procedure is highly detailed, there are unresolved issues in some areas. For example, there is no comprehensive explanation of how fixed side windows should be handled. They meet the requirements of the standard without the need for airbags (for instance using plastic panes), but there is no definition of what counts as a fixed window (quarterlight, sliding window).

Despite only making use of the test procedure for a short time, Bertrandt is a strong partner in running the test and in designing and developing safety concepts, based on the information and experience it gained in advance. In order to make the standard more tangible, Bertrandt is holding a practical workshop in Munich in collaboration with carhs Training GmbH, which will introduce participants from the automotive industry to the new subject and enable them to experience it at first hand.

TASK

Driver assistance systems aim to provide optimum support to the driver in coping with the driving situation while helping to enhance road safety. Intelligent headlamps are not merely limited to cornering light or adapting the beam pattern to different road classes but also use additional driving-environment sensors to further optimise roadway illumination.

In most cases, these systems are camera-based and detect and classify infrastructure and other road users ahead of the vehicle. Using controllable light sources, optical systems and intelligent algorithms, the light distribution is dynamically adapted to traffic conditions. Hence, the adaptive distribution of light provided by lighting assistance systems aims to optimise roadway illumination for the driver and traffic environment, ❶.

TEST SCENARIOS

Given the complexity of traffic situations together with the rather limited reproducibility of traffic scenarios on public roads and test grounds, the demands placed on testing lighting assistance systems prompted IAV to design and construct a high-tech indoor vehicle-lighting test facility. The large and self-supporting building has created a platform on which the Light and Vision, Driver Assistance and Driving Environment Sensor Systems departments can work closely together in close proximity whenever necessary.

This synergy effect provides the capability of evaluating lighting and system performance in all of its relevant aspects. All facets of lighting are evaluated under constant and reproducible boundary and general conditions. The exceptional size of the vehicle-lighting test building makes it possible to verify and validate innovative and classic automotive lighting devices and the lighting functions directly associated with them both qualitatively and quantitatively. This reference environment is used for producing light conditions of complete darkness with a very low level of residual light below the detection limit $< 0{,}001$ cd/m^2 of the test equipment. Adjustable in a defined way, a large-scale and evenly distributed daylight facility can create twilight conditions from 0 to 5000 lx. In designing the building, importance was also attached to ensuring that the daylight facility can reproduce different light scenarios (e.g. shadows cast by building walls).

A special feature is the moving sun-angle simulation facility that is capable of producing a light intensity of up to 50,000 lx. The special floor covering and the mobile black-out system can be used for reproducibly tailoring the environment

NEW METHODS OF TESTING CAMERA-BASED LIGHTING ASSISTANCE SYSTEMS

Modern and innovative lighting and lighting assistance systems provide an automatic and dynamic distribution of light to suit the prevailing traffic situation. A new indoor vehicle-lighting test facility at IAV in Berlin enables qualitative and quantitative studies to be carried out on such systems.

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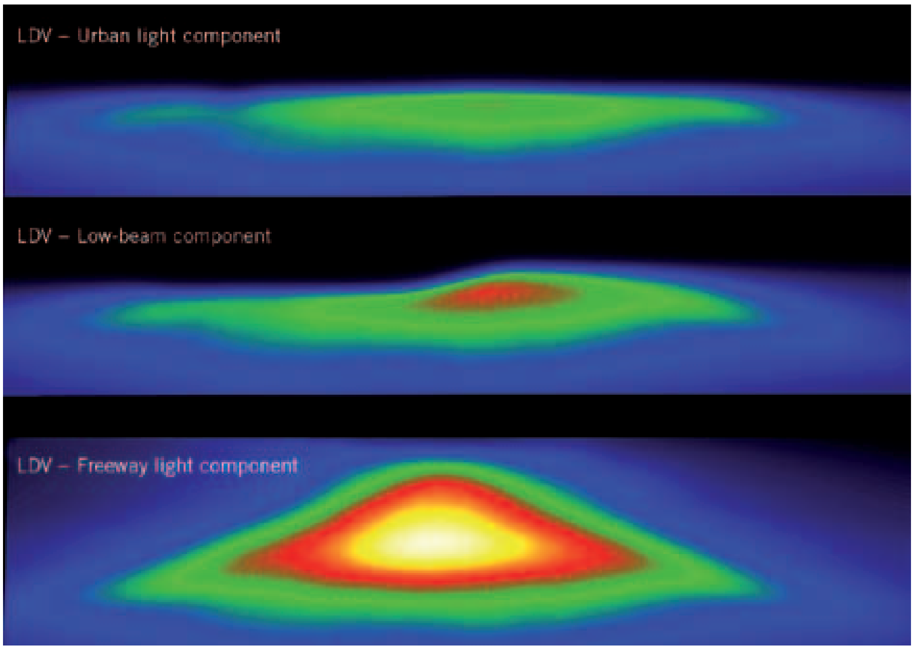
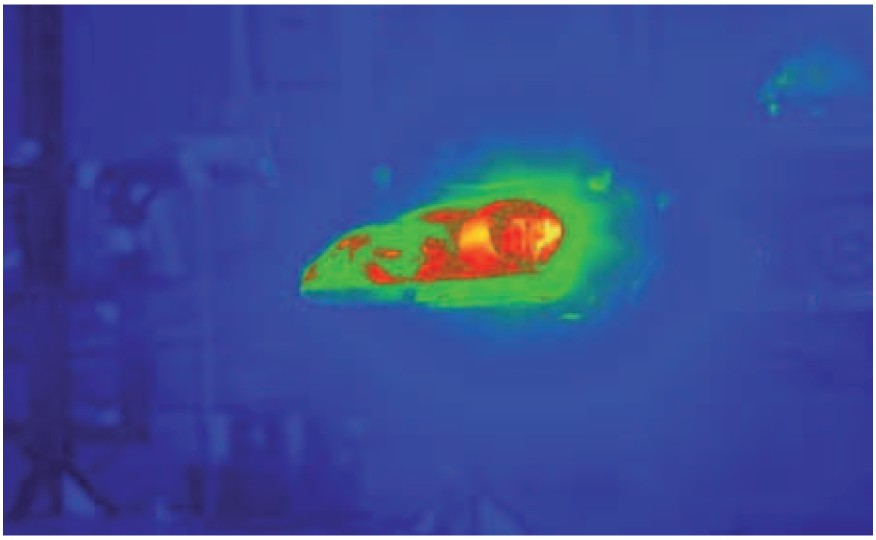


❶ Dynamic luminance distribution patterns (LDV)

❷ Glare from oncoming traffic



❸ Headlamp glare luminance

to the requirements of a particular test. This flexibility makes the vehicle-lighting test facility ideal for testing at any level – from a bare component to an entire lighting assistance system. Due to the size of the building, other road users (target-object vehicles) can also be positioned in the surroundings of the vehicle under test. In terms of package and position, for example, this also provides the option of realistically integrating typical light sources from other road users into the testing process on a reproducible and interactive basis.

The increasing capabilities and complexity of lighting make it necessary to record both the static and dynamic aspects of light distribution. Measurement and evaluation concentrate on parameters relevant to homologation, such as contrast, glare, homogeneity, sharpness, colour, stray light and overall appearance. To do this, IAV uses a measuring station that comprises a spatial-resolution luminance camera in conjunction with the indoor lighting test facility. Obtained statically, the measurement readings can then be superimposed with the dynamic behaviour of lighting assistance systems and consequently serve as input variables relevant to evaluating lighting assistant functions in the overall system ❷ and ❸.

HIGH BEAM CONTROL

For high beam control, the systems currently on the market can be divided into three development levels. Typical high-beam assistants switch the high beam on and off automatically. The headlight-levelling lighting assistance function shifts the horizontal light/dark cut-off line and adapts it to the traffic situation. The currently most complex lighting assistant functions can shift both the horizontal as well as the vertical light/dark cut-off line. This makes it possible to shade or darken only specific segments of the high beam. Systems of this type are referred to as glare-free high beam.

These systems have the aim of selectively masking out other road users while driving with headlamps switched to high beam, leaving the remaining traffic environment fully illuminated. In addition to improving driver comfort, road safety is improved on two counts as well. To begin with, roadway illumination, and thus the visible area in front of the vehicle, is further improved over low beam, high-beam assistants or headlight levelling, and can help the driver to identify potential hazard situations sooner. It also prevents other road users from being exposed to glare as a result of the driver not switching from static high beam to low beam quickly enough or failing to switch to low beam at all, ❹.

Intelligent lighting systems, such as glare-free high beam, are dependent on the performance of the driving-environment sensor system (typically a camera) and the performance of light distribution radiated from the vehicle itself. Objective and, above all, comparable measurement readings are hard to obtain from dynamic lighting assistance functions, as ambient conditions constantly change and testing conditions on the actual road can only be reproduced to a limited extent or at high cost and effort.

Here are a number of relevant ambient conditions by way of illustration:

- environmental effects (snowfall, rain, fog, position of the sun, time of year)
- traffic (type, number, position, dynamics of other road users)
- infrastructure (road type and condition, delineators, road signs)
- illumination (direction, luminous power and shading of natural and artificial light sources)
- the vehicle's own driving dynamics (speed, yaw velocity, pitch and roll).

The diversity of the influencing factors shown here by way of example means that extensive, time-consuming and thus cost-intensive statistics as well as subjective assessments are providing the basis for evaluating overall system performance. The validity of statistical data is determined directly by the volume of information fed into the statistics, i.e. the mileage that can be evaluated.

In addition to it not being possible to reuse much of the statistical data in the event of changes to the system, the availability of the overall system, which in most cases is not given until late on in the development process, also has an effect on calibration testing and validation. This is because key components of lighting assistance systems, such as the front glazing and headlamps, are significant design elements of the vehicle and can only be used under real-life road conditions at a late stage.

According to IAV's estimation, the testing approach based solely on statistics and subjective assessment comes with particular weaknesses with regard to:

- duration between system availability and system evaluation
- reducing testing work through delta tests
- reliability of system evaluation
- comparability of system evaluation
- generation of quantitative data with regard to response time, reliability and robustness.

SOLUTION

IAV is addressing this challenge by constructing the indoor vehicle-lighting and lighting assistance test facility, which provides a concept for resolving the problems given.

The overall vehicle system or individual components can be positioned at any defined point inside the building. The required ambient conditions, such as a specific ambient luminance, are selected to provide the necessary testing environment. Using a measuring cart, real-life light sources (such as halogen, xenon or LED headlamps, halogen or LED tail lamps, bicycle headlamps) can be moved around all three axes and in relation to each other.

This measuring cart is moved from set positions in defined directions in front of the vehicle under test. This provides the capability of simulating various driving scenarios involving different travelling speeds and cornering radii. In the measurement scenario under study, the system is stimulated by "oncoming traffic". This scenario can be simulated from the combination of two different movement cycles. On the one hand, the light sources are moved towards the vehicle, with the distance between both light sources being increased on the other, thus reflecting the situation encountered on the road in the real world. The driving scenarios required can be reproduced and repeated as often as necessary.

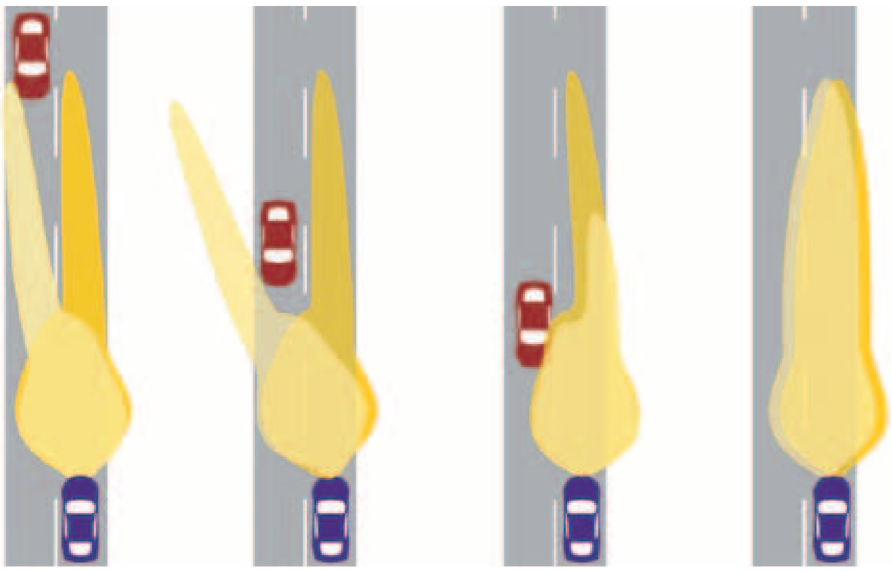
The following measurement readings can be accurately determined and evaluated:

- headlamp swivelling angle and swivelling speed
- repetition accuracy and adjustment precision
- horizontal and vertical distances of headlamp light/dark cut-off lines from the target object
- verification of computed system tolerances from individual tolerances
- validation of the camera coordinate system.

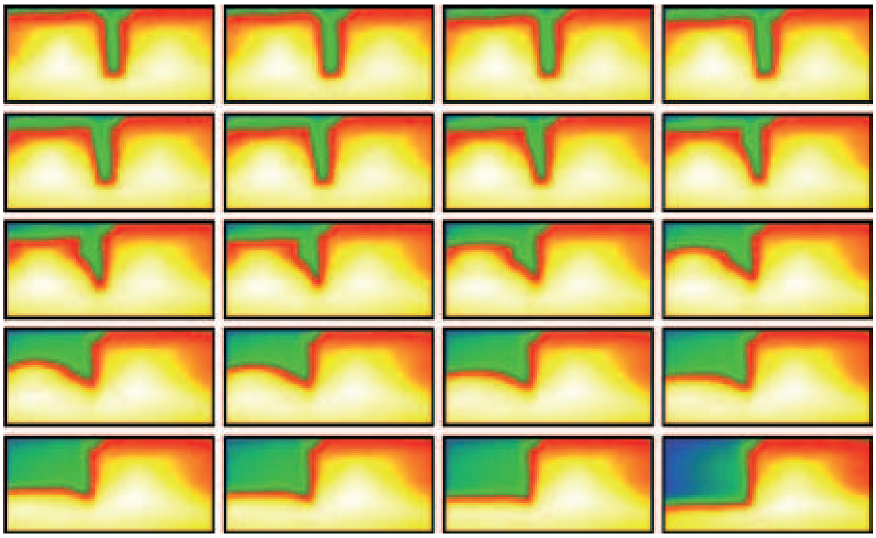
Being able to compare different systems or sub-systems means that the various lighting systems and relevant components must be referenced under constant conditions. The complexity of dynamic light distribution makes it necessary to measure the headlamp component and its light-distribution pattern before starting to test the system.

In order to permit evaluation of light distribution, IAV focuses on the direct emission of light and its luminance distribution. For this measurement scenario, bulb shields are positioned in the beam path in such a way that only allows the headlamp's direct rays to meet the measurement wall. Components such as forward reflection are absorbed by the black-out system, the special measurement floor and the bulb shields. The overall measurement set-up permits manual selection of previously defined parameter sets, such as travelling speed, vehicle inclination, object size and position. Once the headlamp has adapted its light distribution to the control signals, the particular light distribution pattern is measured for the parameter set concerned. Among other aspects, measurement and evaluation cover contrast ratio, glare, luminance or illuminance distribution.

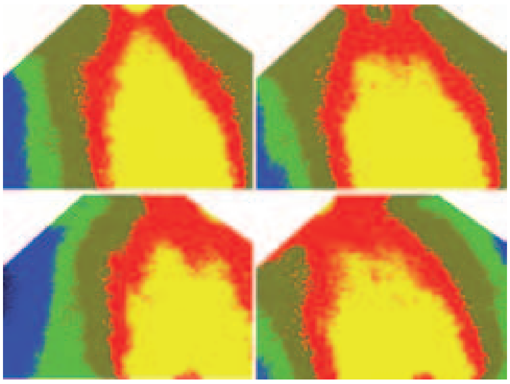
Depending on the requirement, it is also possible to determine the sharpness and course of the light/dark cut-off line.



❹ Schematic diagram of glare-free high beam functionality with IAV SceneSuite



❺ Luminance distribution patterns for a glare-free high beam (25 m measuring screen)



❻ Luminance distribution patterns from defined viewing angle

Obtained in this way, the results can then be superimposed with the results of the dynamic tests on the overall system, including stimulated traffic environments, to provide the basis for evaluating the overall system, ❺ and ❻.

Comparing the specified values with the measurement readings provides verification that the swivelling angles and adjustment speeds are met. The key added value is produced after taking the luminance images into account. This combination makes it possible to demonstrate whether and how intensely oncoming traffic is exposed to glare and for how long.

Different software versions and hardware releases can also be compared with each other in reproducible tests at an early stage of the development process. This can be taken as a basis for deciding whether it is worthwhile testing specific hardware and software in the real-life environment and in which scenarios problems can be expected.

It is also possible to calibrate the overall system, including prototypes, at a basic level. This significantly reduces the need for road tests and the costs they incur.

In the future, it is planned to extend the test concept in such a way that permits re-use of at least part of the statistical and subjective evaluations gathered in road tests. To this end, the feature vectors and the test results from the indoor testing facility (interlinked by mapping the test vectors) are to be correlated with statistical and subjective evaluations in the appropriate manner.

THANKS

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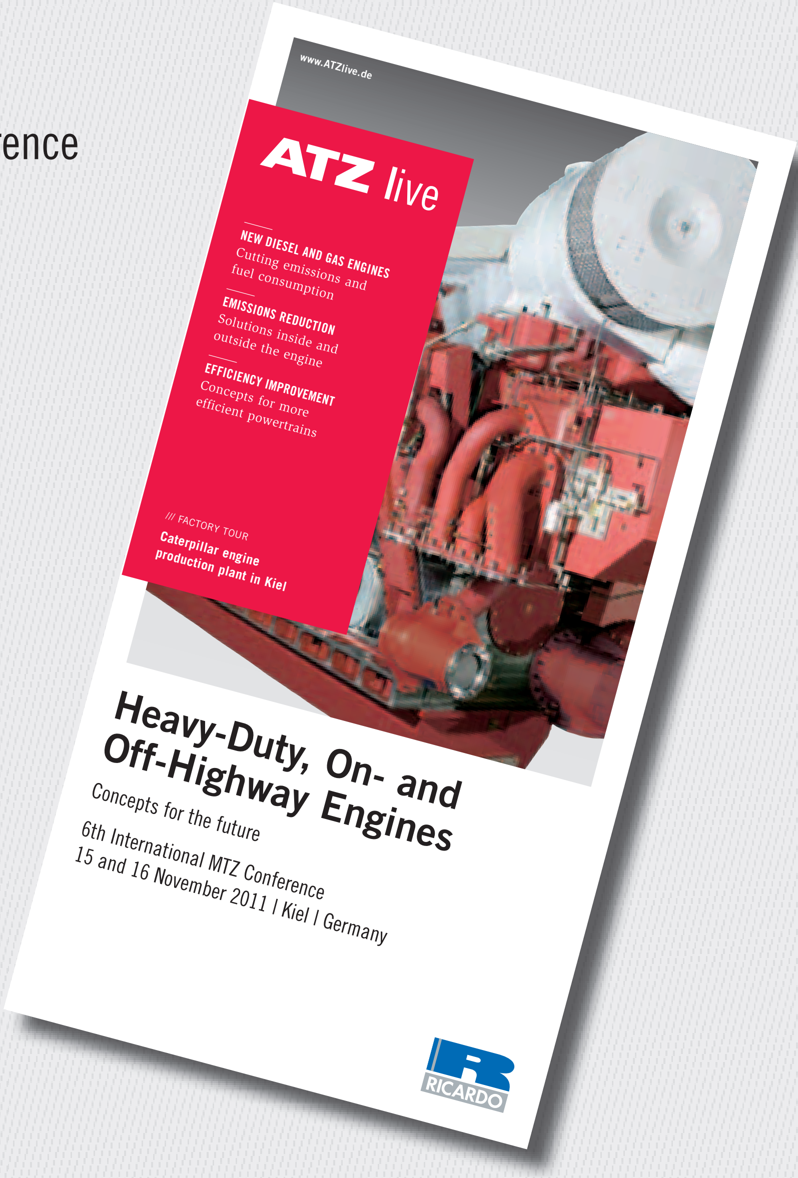

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PROBLEM DESCRIPTION

A principle problem is encountered in the case of single-track motor vehicles, as they are driven around curves due to the inclination of the motorcycle. As a rule, the headlamp is rigidly connected to the motorcycle. The inclination angle of the illumination device is practically the same as of the motorcycle itself. Therefore, in curves and at corners the headlamp no longer illuminates the roadway in front of the motorcycle in an optimum fashion. A straightforward way to remedy this problem is to embed the entire illumination system into a gimbal-mounted assembly which correctsfor all movements of the motorcycle.

Such a mounting is expensive and awkward, since the entire headlight must be swung when driving around a curve. One must move a relatively large mass, the movement becomes slow, and furthermore, much structural space is required. Another solution uses a rotating optical fibre image converter [1]. This approach is very complex and corrects only the angular position of the light beam pattern in the horizontal plane.

At Zizala Lichtsysteme, an illumination device for single-track motor vehicles was invented by means of which one can compensate the angle of roll depending on the direction of the turn and the curve rating. Inherent to the system this steerable beam pattern functions as “curved light”. The cut-off of the lower-beam headlamp stays level [2]. Additionally this new system corrects movements of the motorcycle in the vertical plane which is parallel with the course. Therefore pitching movements due to change of velocity (slowdowns & speedups) and different loading conditions do not influence the quality of the light distribution.

The dipped beam stays high enough for good vision without dazzling oncoming drivers. This first ever adaptive Xenon Headlight is implemented in the new BMW K1600 GT/GTL motorcycle which is available on the market since the spring of 2011.

SYSTEM DESCRIPTION

The adaptive headlight is based on a Xenon projector system using a Philips D1S HID-lamp. The rolled position is

ADAPTIVE XENON HEADLAMP FOR MOTORCYCLES

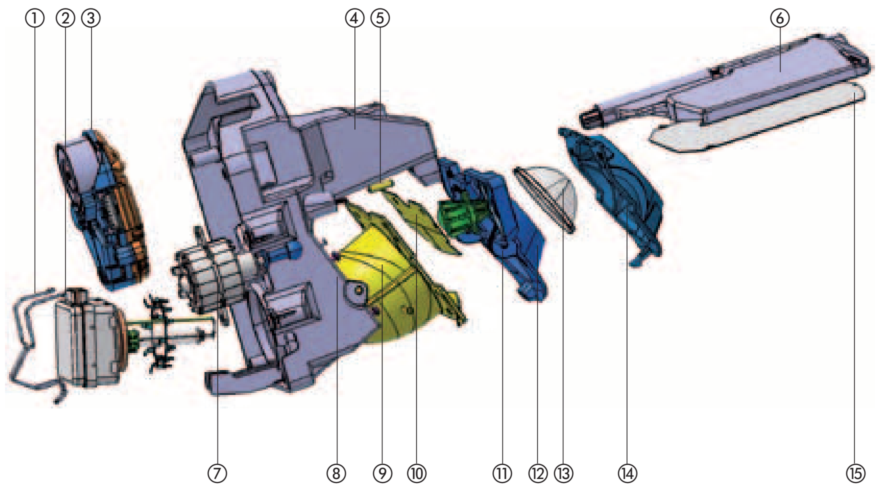
Zizale developed a new adaptive headlight for BMW Motorrad which is based on a Xenon projector system with a moveable lens for correcting the pitch. The inclined position will be compensated by a movable mirror which aims the plane of the dipped beam in all situations. This system is the first system of its kind in volume production. The adaptive lightsystem creates visibility and safety.

compensated by a movable mirror. A thin mirror plate is mounted in a holder. This mirror is pivot-mounted in the base body of the module. A stepper motor is the second bearing point and rotates the mirror in either direction. Therefore bank angle corrections of approximately 25° are possible. The pitch angle is compensated by a movable lens. The glass lens tilts about an axis which lies in focal point plane. A linear actuator dislocates the lens holder in such a way that the translational displacement tilts the lens up or down. The adaptive headlight is based on a Xenon projector system consisting of the parts shown in ❶.

❷ shows the technical data of the adaptive cornering light for motorbikes.

OPTICAL PATH

This special illumination device consists of a centrally positioned HID projection module with a movable mirror. The conventional projection headlight system comprises a light source (for example HID), the main reflector, a tiltable lens and a bezel for the purpose of forming a dipped-beam light distribution. The HID module directs light upwards at an angle of approximately 45°. A mirror diverts the light distribution straight forward at the legal required lowering of 1 % (0.57°), ❸.



① Lamp holder
② Xenon D1S
③ Steppermotor 1
④ Modul base
⑤ Bolt
⑥ Adapter mirror
⑦ Steppermotor 2
⑧ Adapter motor
⑨ Reflector
⑩ Beam diaphragm
⑪ Bold
⑫ Adapter lens
⑬ Lens
⑭ Cover
⑮ Mirror

❶ Exploded view of the headlight

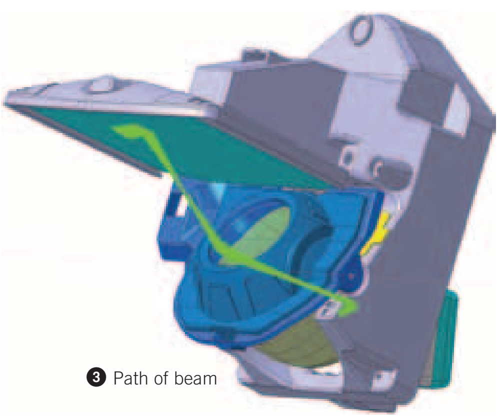
As the vehicle moves in a straight line, the propagation direction of the light distribution, the optical axis of the light module and the swing axis of the mirror

❷ Technical data

THE NEW ADAPTIVE CORNERING LIGHT FOR MOTORBIKES FROM ZKW – FACTS & FIGURES	
Presentation	17 September 2010
Time under development	Four years
Automotive partner	BMW
First used	October 2010
First used in	BMW K1600
Innovation	The world's first adaptive cornering lights for motorbikes with roll and tilt angle compensation
Improvements to safety provided by	: Compensating for the dipping and raising of the headlamp when braking and accelerating : Compensating for the tilt of the headlamp when cornering
Result	The light-dark line on the carriageway always stays straight for a decisive improvement in driving safety.
Light source	Xenon projection module
Luminosity	3200 lm
Drive and control technology in the headlamp module	: Two electric motors for headlamp range adjustment and roll angle drive : Two control units + sensors (for tile recognition, installed in the vehicle) for the pivoting and Xenon module
Lamps in the headlamp module	: Xenon bulb for the roll/tilt angle : Two halogen lamps for the high beam : Two LEDs with heat sinks for the position light
Design	: Polycarbonate cover with two decorative lines : Two design elements, printed onto the mirror mount by means of gravure printing : Additional trim, painted : The typical BMW light rings with LED power supply are used for the position light
Power supply	12 V standard via the on-board electronics

will lie in a vertical plane. As a rule, this vertical plane is identical with the longitudinal mid-plane of the motorcycle. The rotation axis of the lens is perpendicular to this longitudinal mid-plane.

Illumination is particularly good when the angle of the mirror swing axis corresponds roughly to half the angle that is formed by the optical axis of the light module with the longitudinal axis of the vehicle. A typical value for the angle between the optical axis of the light module and the longitudinal vehicle axis is 45°. This is the best choice for this angle, as it requires little structural space in order to achieve an optimum light distribution. The HID lamp is fitted in the reflector in a mounting position of 10° up. This position was chosen to save space and to have a better way to point the light onto the mirror above it.



❸ Path of beam

To be able to use a mirror with small dimensions, it is advantageous when the swing axis extends close to the reflection surface. The distance between the lens and the mirror should be as short as possible to reduce the image size of the bezel on the reflection surface. The projection system must be compact, so that a lens with short focal length can be used.

The light module comprises two optical elements which invert the image. The light module bezel must be mounted upside down. Therefore the Xenon HID-lamp is also mounted in such a way, that the ceramic tube of the lead wire lies above the arc. This special installation position of the HID lamp (Philips D1S) has little impact on luminous flux (approximately 100 lm decrease).

FUNCTIONAL LAYOUT OF THE ADAPTIVE XENON HEADLIGHT

Level sensors at the front and rear suspension provide data for permanent headlight levelling. A stepper motor tilts the lens and corrects the angle of pitch. Due to the pitch compensation, the headlight sheds light in the optimum pre-set area when the motorcycle is travelling straight ahead, regardless of load condition and riding state caused by speed changes.

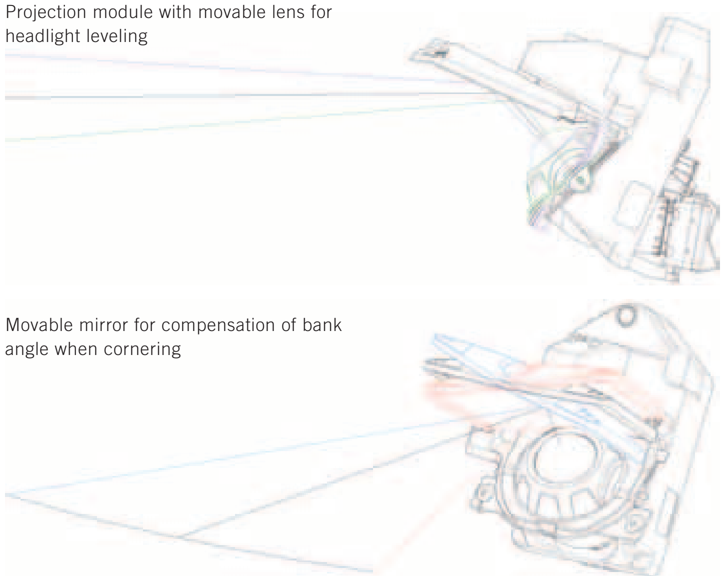
On-board solid state gyros measure the linear acceleration factors and the angular speeds of rotation in respect to natural axis. The electronic control unit determines the ongoing banking angle of the motorcycle. A stepper motor turns the movable mirror around the swing axis and compensates the roll angle. In addition to pitch compensation, the light of the dipped-beam is also balanced in relation to the banking angle. This results in significantly improved illumination of the road when cornering and therefore an enormous increase in active riding safety. At right-hand turns the glare impact on oncoming traffic is eliminated.A special setting of the swing angle of the mirror provides a tourist solution, ❹.

LIGHT BEAM CORRECTION DURING TURNING

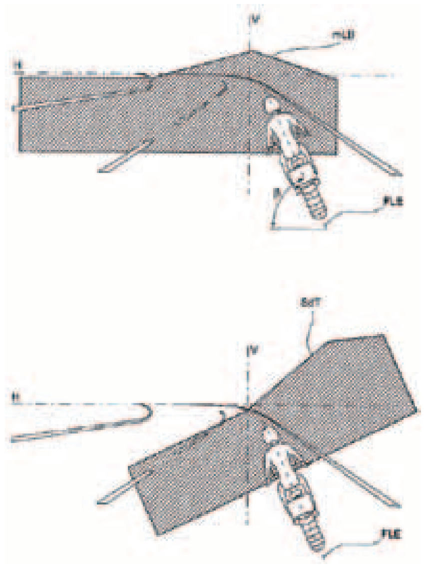
Corresponding to the inclination angle of the motorcycle, the mirror is swung in the direction opposite to the bank of the motorcycle. The rotation angle of the mirror amounts to approximately 55 % of the inclinations angle. Therefore this new adaptive headlight system keeps the cut-off in the correct horizontal position parallel to the road, independent of the driving condition of the motorcycle.

Through the combined movements of the lens and mirror, changes occur in the imaging behavior of the beam aperture. In dependence of bank and pitch angle, different areas of the mirror are illuminated. One should consider that the corrections of all of the movements are neither independent nor linear functions.

The inclined position of the motorcycle induces a "natural" bending light, because



❹ Adaptive headlight function



❺ Movement of the light distribution for a left-hand turn

the emission center moves to left or right. The center of the light distribution moves in left-hand turns towards the left curbside and vice versa, ❺. The maximum lateral movement is 9° at a bank angle of 25°.

Additionally, change of velocity (acceleration and braking) causes additive pitching movements of the motorcycle. Different loading conditions are also considered. The lens tilts accordingly, so that the cut-off is lifted to the correct horizontal position.

The adaptive Xenon headlight system actively equalizes all these movements and functions as an automatic headlamp leveling device. Therefore the active and passive safety of motorcyclists is enhanced. The light beam correction in summary:

: bank angle correction in curves: the moveable mirror rotates the cut-off as a function of the bank angle of the motorcycle
: pitch angle correction because of speed change: the moveable lens corrects these pitch actions
: the legal requirement for xenon headlight modules of range adjustment is also achieved by means of the movable lens.

ILLUMINATION ENGINEERING DETAILS

The light module is a classical projector type system with two half-shell reflectors. The lower part produces a broad light distribution. The upper part concentrates light into the center. The system uses a lens with short back focal length and small lens-diameter in order to retain a great numerical aperture. A particular challenge was to reduce shadowing effects of the glass plunger and the ceramic isolation tube of the HID lamp. The mirror is made of thin sheet metal Alanoid to minimize the mass which must rotate.

ELECTRONIC SYSTEM

The horizontal inclination adjustment system uses several electronic devices:

: a sensor cluster
: two level sensors
: a motorcycle ECU
: a headlamp ECU and two stepper motors.

The output of the sensor cluster, consisting of three angle rate sensors and two acceleration sensors, is used by the motorcycle ECU for the computation of the inclination angle of the motorcycle. Two level sensors, one on the front wheel and one on the rear wheel, are used to measure the average amount of suspension. These two values are used to determine the current pitch angle.

The signals of the level sensors, the computed inclination angle and some other signals, such as the motorcycle's speed, are fed into the headlamp electronic control unit to calculate the target position of the headlamps actuators. Therefore an algorithm electronically rebuilds the mechanical dependence of the motorcycle roll and pitch angles and computes the necessary angles for the lens and mirror to keep the cut-off horizontal and the range of illumination constant. This algorithm calculates not only the position but also the optimal speed of the stepper motors to reach the target position in an appropriate time. The difficulty here is to find parameters for the algorithm, which allows the system to move the stepper motors very fast to the target position without jerking light/dark boundary of the low-beam light distribution.

The HID ballast and the electric power supply of the other lamps are standard components as used in car applications. The LED module for position lamps consists of a heat sink and a driver unit including a chip LED as light-source. The driver unit is a simple step-up-converter with protective elements to avoid damage due to reverse current or over voltage. The stepper motors are commercially available motors for leveling and AHL in automotive applications.

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VIRTUAL TORQUE SENSORS FOR ELECTROMECHANICAL STEERING SYSTEMS

Until now, the steering system had to be deactivated in the event of a severe torque sensor fault. A new virtual torque sensor now makes it possible to continue using the steering system and still rely on electrical support. The Braunschweig plant of Volkswagen AG develops steering systems as complete components in line with IEC 61508 using a process environment landscape according to Automotive Spice in accordance with ISO/IEC 15504.

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TASK

In order to meet customers' current and future safety and availability requirements, all safety concepts for automotive components need to be continuously refined and improved. A high level of availability can be structurally achieved using redundant hardware. However, this usually has negative effects on the installation space required and involves higher costs. The challenge is therefore to ensure maximum safety and availability for the driver using the existing series-production steering system structure and series-production sensors. This goal can be achieved by an intelligent approach using software algorithms that use the sensors already installed in the vehicle to generate software functions that increase safety and availability.

This article deals with the generation of a virtual torque signal in electromechanical steering systems. Both the concept and implementation using software are shown. Furthermore, the concept of emergency operation and the resulting increase in the availability of electromechanical steering systems is described.

HISTORY OF ELECTROMECHANICAL STEERING SYSTEMS

At the latest since the introduction of the Audi A7, electromechanical steering systems have become a component of cars in almost all vehicle classes. In the year 2000, only the Lupo 3L model was equipped with an electromechanical steering system. In 2010, already more than the half of all vehicles throughout the VW Group featured this steering system type.

The challenge in terms of steering systems is no longer primarily the basic system functionality and coordination of the steering behaviour, which is equivalent to the steering feeling of hydraulic steering systems [1], but an increase in the availability of electromechanical steering systems. When taking into account electronic components with the highest failure probability, a state-of-the-art steering system is of a single-channel design. For economic reasons, the central components, the CPU (Central Processor Unit), GDU (Gate Drive Unit) and PCM (Power Chip Module), cannot yet be provided with redundancy to increase availability. All basic safety objectives are fulfilled even without this redundancy, but result in an avoidable shutdown of the system in the case of a fault.

With this single-channel design, calculated system availability cannot be structurally below a theoretical threshold. However, there is always the possibility to individually assess peripheral components regarding their contribution to a sudden shutdown and to develop an emergency operation strategy for each fault mode, replacing sudden system shutdown by a system reaction that can be better controlled by the driver. In this way, the structurally imposed limit of a single-channel system can be reached.

The virtual torque sensor is part of this emergency operation strategy for improving availability. Through clever usage and the combination of further vehicle-internal sensors of other systems via a software algorithm, it is possible to replace the steering-internal torque sensors in particular without having to provide redundant hardware components.

OVERVIEW OF THE VIRTUAL TORQUE SENSOR

The concept being pursued is based on the generation of a third torque sensor channel as an input variable for the closed loop of the support force generation facility. In the case of supporting steering systems, the driver's intent is identified by a torque sensor. In general, this sensor consists of a torsion bar and a unit that converts torsion into an electrical signal. If this sensor, which is generally of a dual-channel design, fails, this is synonymous with failure of the entire steering system, as a single sensor without redundant plausibilisation cannot provide the required diagnostics, or at least can do so only to a limited extent.

In the following section, the virtual torque sensor is described with special reference to the components, sensors and implementation. The essential parts are allocated to the function and, finally, the relevant software algorithm is described.

Normally, the driver selects a steering angle via the steering wheel and thus applies a torque to the system via the torque sensor described above. This is

❶ Overview of the components for virtual torque generation

evaluated by the electronic system and a supporting force according to the driver's intent is provided at the rack. In normal operation, the ESP steering angle sensor is only used for purposes of plausibilisation and is not involved in the generation of the support force.

SERIES-PRODUCTION SENSORS AS INVOLVED COMPONENTS

As can be seen in ❶, there are two angle sensors that can be used to generate the virtual torque signal independent of the torque sensor. In normal operation, the torque sensor passes on the torque to the electronic system via two channels. If one torque sensor channel fails, steering is still possible via one channel using the emergency operation concept. In this case, the driver's intent is confirmed by the virtual torque sensor. For the torque sensor that now operates on a single-channel basis, limited diagnostics is thus ensured. To enhance system controllability, this operation is maintained for a maximum of three seconds, while the support force is constantly being ramped down. Subsequently, the following state – failure of both channels – is assumed.

If both torque channels fail, the steering angle sensor identifies the driver's intent via the changing steering angle. Here, the torsion bar of the steering system acts like a spring, which introduces mechanical inertia into the system. In normal operation, the motor position sensor outputs a highly accurate steering angle, which is internally used by the steering system. In the case of a fault, both the motor position sensor and the steering angle sensor generate the virtual torque.

VIRTUAL SIGNAL GENERATION CONCEPT

In normal operation, the redundant sensor channels mutually back up each other. There is always the possibility to create a further branch by providing additional redundancy. However, this approach inevitably incurs additional costs for the overall system without offering real added value that has a functional effect.

In order to replace the signals of the torque sensor in the case of a fault without having to deploy further hardware components, a third independent torque signal needs to be used for comparison purposes. In this case, the virtual torque signal is calculated by a software function in which the virtual torque signal is generated from the difference between the calculated internal and external steering angle signals.

FUNCTIONAL IMPLEMENTATION AND SOFTWARE ALGORITHM

As described above, reliable information about the driver's steering intent is unknown to the steering system if one or both torque sensor channels fail. The behaviour of the steering system in the case of a sensor channel failure is controlled by another software function. Depending on the plausibility of the sensor channel signals and the validity of the calculated virtual torque signal, the support for the steering system is either ramped down or abruptly reduced, or the steering system is shut down completely. The support force during emergency operation can be adapted to the vehicle's requirements within a certain rane. A manual torque signal for further processing by other steering functions and a status signal for evaluating further software components are output. Emergency operation is indicated to the driver both visually and acoustically.

During emergency operation, only the pure rack force is applied. Other comfort functions such as the automatic reset function are specifically switched off. Here, the objective is to provide the driver with comfortable steering with supporting force even if all important sensors fail. The main focus in the development was not the control loop itself but the signal conditioning before any signal can be used in the control loop. The sample frequency, lag times and jitter from the different, non-coherent sources required intense algorithmic work until the acoustic and haptic behaviour was satisfactory for the driver. ❷ shows a small section of a driving slalom in normal mode and in virtual torque sensor mode. In both cases, the car was controllable without problems and quite comfortable to steer in emergency mode.

MONITORING THE SOFTWARE REDUNDANCY FUNCTION

The safety concept of the steering system requires an independent path to check the output of the main function. The output is constantly compared to a redundant calculation carried out in the monitoring path. The steering will only switch off if there are significant differences in both values. Additionally, this redundant plausibility check has to be carried out without having an independent measurement channel.

❸ shows the system reaction if the values from the two redundant calculations differ for more than a value that is considered plausible. This ensures a maximum of availability of the steering system without getting anywhere near any safety critical behaviour.

SUMMARY AND OUTLOOK

Even if the torque sensor fails, emergency operation still provides supporting torque from the motor to the driver. It can be assumed that, within the scope of a higher integration or a reduction in component costs, even the central components can be provided redundantly. In a dual-channel system (1oo2), this design provides for an enhanced emergency operation strategy and a significant increase in availability.

In a further step, consistent ongoing development will realise a three-channel steering system (2oo3) that is fully functional even if one of the three complete motor controls fails. Evidence then has to be provided whether, in this case, the mechanical fall-back level – the steering column – can be dropped. When this evidence is provided, this is the step towards a steer-by-wire system in which the steering wheel can be used in complete isolation from the supporting force generation unit (motor and rack).

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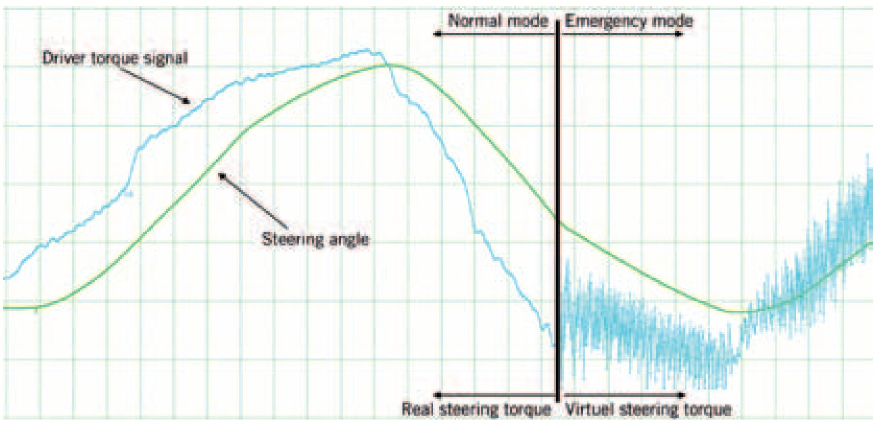
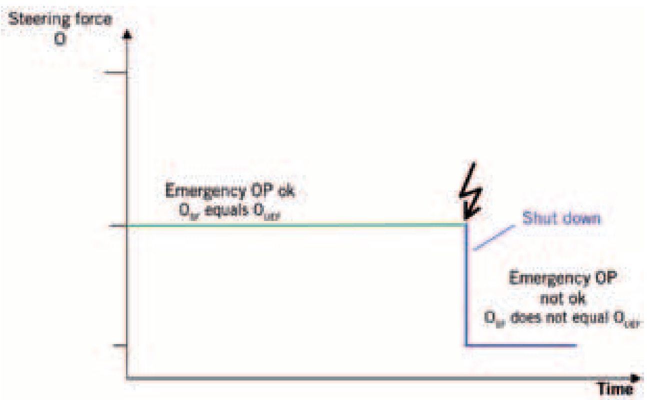
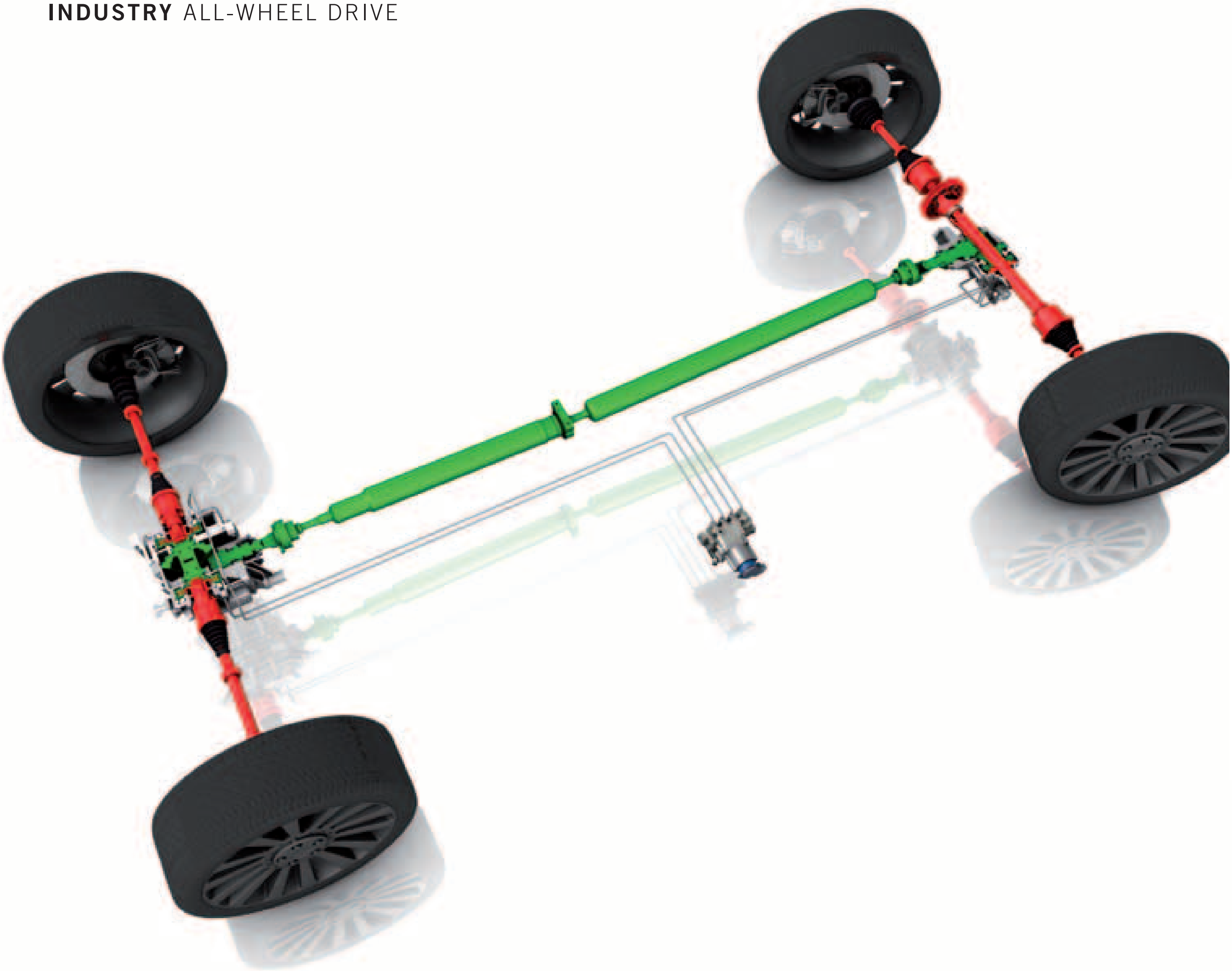


❷ Comparative driving slalom in normal and emergency mode



❸ Emergency operation and system shutdown



INCREASED EFFICIENCY AND VEHICLE DYNAMICS WITH AN ADAPTIVE ALL-WHEEL DRIVE

In the all-wheel drive sector one has to face up to the challenge of reducing fuel consumption in all-wheel drive vehicles very early on. In addition, vehicle dynamics have to be increased. Getrag All Wheel Drive (Getrag AWD) designed an adaptive four-wheel drive system on the basis of Twinster couplings where the increased consumption is reduced by 80 % in real driving cycle. Also the final customer's appreciation of four-wheel drive performance can be increased.

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STATE OF THE ART

A global annual volume of 1.6 million axles and power-take-offs (PTUs) makes Getrag the world's biggest independent supplier in the all-wheel drive (AWD) sector (Getrag announced the selling of its daughter Getrag All Wheel Drive to GKN). This also means that one is dealing with the challenges of decreasing a four-wheel drive vehicles' fuel consumption at a very early stage [1].

Efficiency optimisation measures such as the reductions in weight, bearing and sealing frictions [2, 3] as well as splashing losses have already found applications in today's four-wheel drive systems and can therefore be considered to be state-of-the-art technology. This article illuminates the possible saving potentials that can be introduced by eliminating the load-independent losses that are imposed by four-wheel drive gearing.

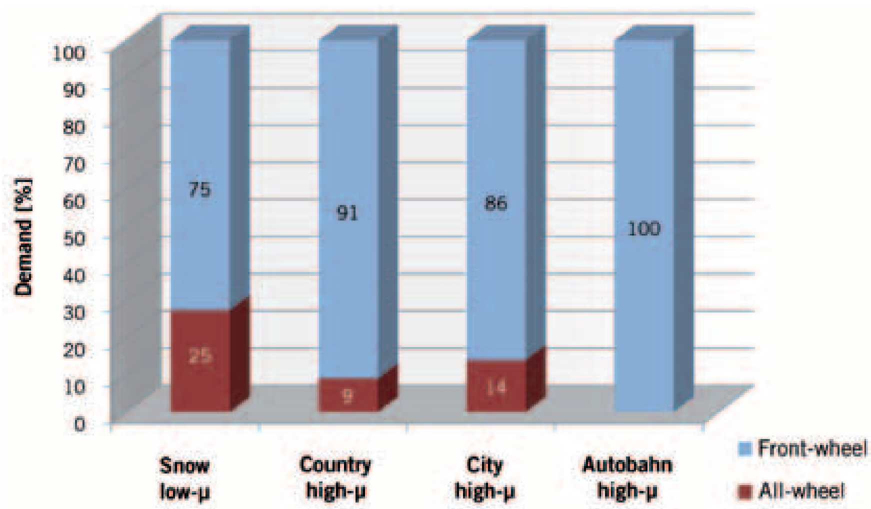
BACKGROUND TO SOLVING THE PROBLEM

❶ shows the frequency distribution of the active utilisation of a "hang-on" four-wheel drive system. The assessment shows that on streets with low friction values µ (like snow) for the usage of the all-wheel drive system is 25 %, and on streets with high friction values it is only 1 % active with regard to the propulsion, for example when driving on a autobahn. The intension of Getrag, which is also based on these facts, was to develop an adaptive four-wheel drive system, which immobilises the hang on drive line whenever it is not needed.

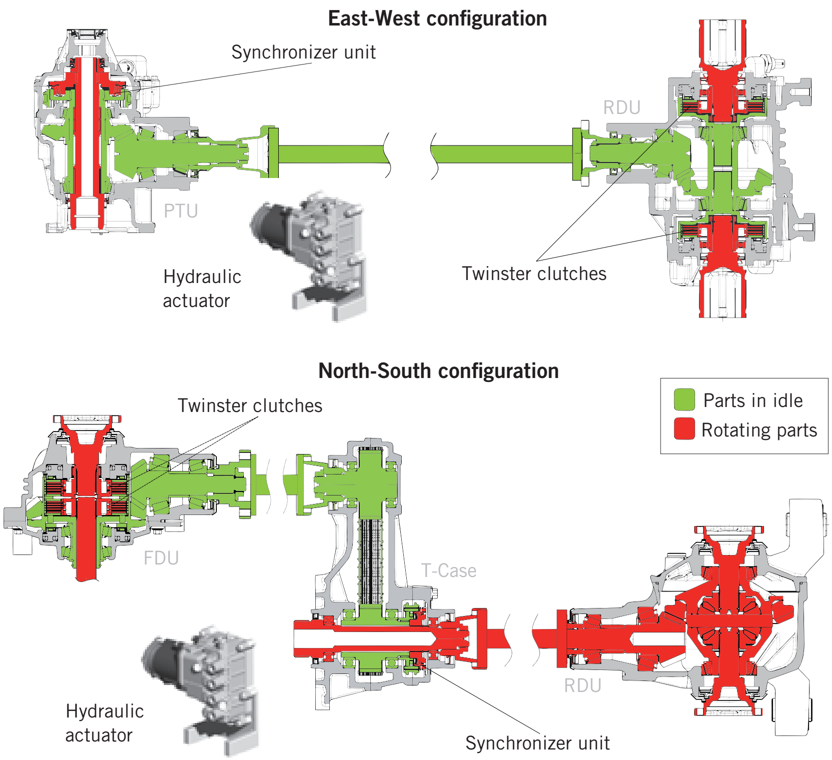
This solution to the problem is comparable to courtyard lighting. You can use energy-saving lamps to reduce the electricity consumption, which will also produce a simultaneous efficiency optimisation or use a motion detector, which will switch the lights on (hang-on) when they are needed and off (hang-off) when they are no longer needed.

SOLVING THE PROBLEM

Losses that are introduced solely by the rotation of the drive components had to be eliminated in order to improve the consumption benefit of an inactive AWD system. This means that the four-wheel drive train has to be immobilised as close as possible to the transmission output, and to the wheels. This will ensure that power losses are only generated by just a few components as a result of no-load rotating. Systems fitted with wheel hub gears (seasonal AWD disconnect systems) are already being mass-produced. However, their disadvantage is that these seasonal disconnect systems have to be activated by the driver. And the dog clutch cannot ensure a dynamic driveline connect and disconnect functionality.



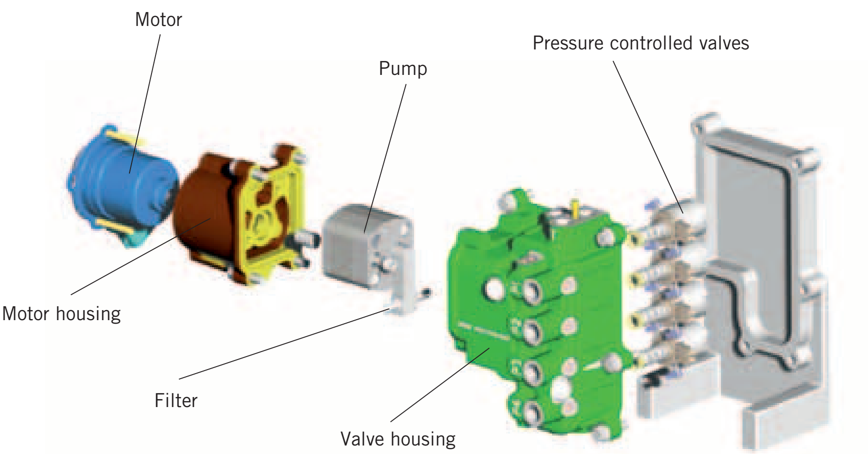
❶ Acquisition frequency of the AWD demand for a mid-size passenger car on different friction values µ



❷ Modular system architecture of the disconnect system for transversal (top) and inline driveline (bottom) between power transfer unit (PTU), front drive unit (FDU) and rear drive unit (RDU)

The consumption benefits that can be realised are only depending on the driver and they do not meet the required CO_2 classification stipulated by the legislative authorities for obtaining tax relief. This is why adaptive connecting and disconnecting has been stipulated as the main requirement in the specifications. Here once again is a summary of the system requirements:

: adaptive connecting and disconnecting of the four-wheel drive system
: suitability for front-transverse as well as inline mounting vehicles (modular design)
: consumption benefit bigger than 0.2 l per 100 km
: presence of four-wheel drive availability when needed and no loss of dynamic driving performance
: application of the same parts as those used in the Getrag transmission kit.



❸ Layout of the hydraulic actuator system

MODULAR SYSTEM DESIGN

When choosing the system you must always ensure that the disconnecting system uses the same components for front-transverse as well as inline mounting, so that an economy-of-scale system can be realised with low cost. ❷ shows the principle design of the disconnect system between front drive unit (FDU) and rear drive unit (RDU), which uses a greater number of same components, such as a Twinster coupling as well as synchronisation and hydraulic actuators for both drive train configurations.

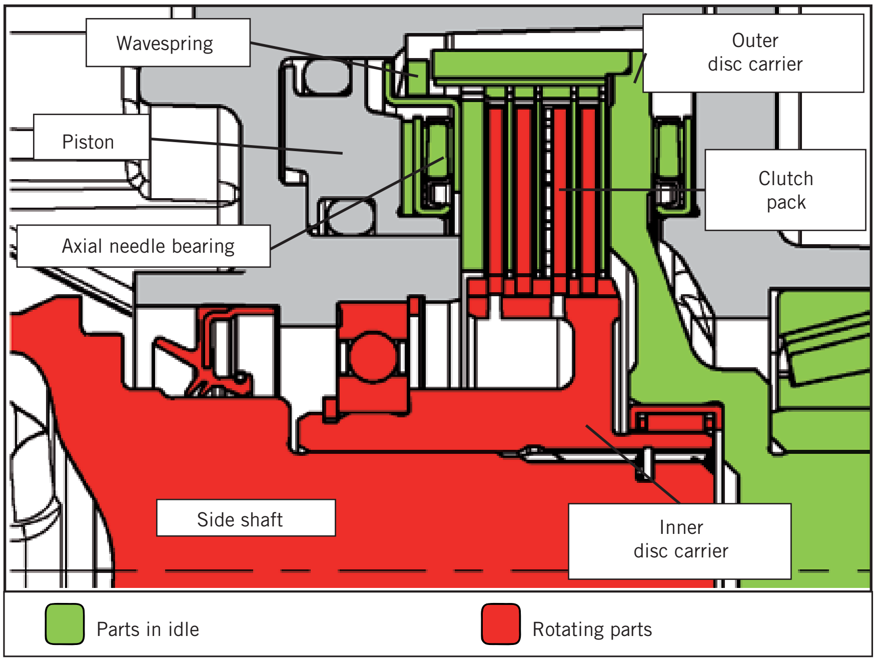
TRANSMISSION AND WHEEL DECOUPLING

The decision was to use a synchronisation for the transmission-side decoupling, so that the rotating weights are accelerated away from the engine and independently from the wheels during decoupling. This prevents for critical driving conditions, for example a loss of the wheel on low-µ roads, through wheel brake slip produced by a wheel-side driveline connect.

The Twinster couplings, which were developed by Getrag, transfer the drive torque to the wheels without any differential. The independent coupling controller ensures that the torque is fed separately to the drive wheels. The focus [4] has been permanently on the driving dynamics since the start of the Twinster development and this has resulted in both couplings being positioned close to the wheels so that they can be used for disconnecting the four-wheel drive system. No additional separating components – such as dog clutches [5] – are needed and the dual functions of the hang-on coupling and the decoupling of the drive train can provide an economical solution.

ACTUATION

A four-wheel disconnect system that uses several actuators presents a new requirement with regard to actuator technology as compared to a hang-on four-wheel drive system, in which only one coupling is controlled. ❸ shows the layout of the actuator system. A brush-less electric (BLDC) motor is used to drive the hydraulic pump, and the pressure control valves control the coupling and the synchronisa-



❹ Coupling design; the drag torque can be optimised efficiently by the constructive layout

tion. The advantage of using this type of hydraulic power pack is that it makes spatial allocation inside the vehicle variable. The system can be mounted directly on the axle or the T-case. It can be also mounted as a so-called remote fitting if the vehicle's environment makes this necessary, for example due to space or temperature conditions (exhaust system). Switching times of 350 ms have been realised by the hydraulic actuation.

The electronics control unit (ECU) has been especially developed as a self-contained control unit for use in a four-wheel drive disconnect system. The ECU has the capability to be able to cover the AWD system disconnect functions, the driving dynamics and the functional safety (ASIL), which are needed in a twin coupling system.

SYSTEM OPTIMISATION FOR INCREASED POTENTIAL SAVINGS

In order to be able to realise the savings potential stipulated in the specifications, the requirement to trim the friction torque to the disconnecting components, that means the synchronisation and the Twinster coupling, and keep it at the lowest possible level became apparent during the development of the four-wheel drive disconnecting system. Reduction of the drag torque on the coupling presented a new challenge, as opposed to synchronisation, which has already been optimised in the direction of reduced drag torque by the use of transmissions [6]. It was assessed as being unrealisable.

❹ shows the layout of a coupling module, in which the drag torque can be optimised by the design layout. The wheel that has to be decoupled is linked to the coupling's inner plate carrier by the side shaft. Only the rotating inner plates, the two pilot bearings and the radial shaft seal at the axle output generate drag loss when the four-wheel drive system is disconnected. The outer plate carrier with the two thrust bearings, which exhibit relatively high drag torque due to the design, are linked to the axle and remain still.

It is shown here that the oil in the shear gap takes the majority of the drag when the coupling drag torque is optimised. An active oiling system had to be developed to reduce this effect. The crown wheel in a four-wheel drive system takes the lubricant from the oil sump and hurls it into a cascade, from where it is fed through ducts to the coupling's inner plate carrier. If the four-wheel drive system is disconnected then the crown wheel is stopped and this interrupts the flow of oil going to the coupling. This development of a simple oiling principle enables a customised concept to be used for this function.

Active coupling oiling is realised when four-wheel mode is active and a very low drag torque of < 0.5 Nm is generated in disconnected mode as a result of the oil flow being interrupted.

SAVINGS POTENTIAL THROUGH AWD DISCONNECTING

In order to be able to evaluate the consumption benefits of the all-wheel drive disconnect system not only as a simulation but in real life as well, a demonstration vehicle based on a Land Rover Freelander was rebuilt in 2009. It was subject to the following test programme which was run on a four-roller dynamometer:

: hang-on four-wheel drive operation compared to hang-on disconnecting operation
: NEDC "hot" and "cold" tests
: constant speeds at 50, 100 and 150 km/h.

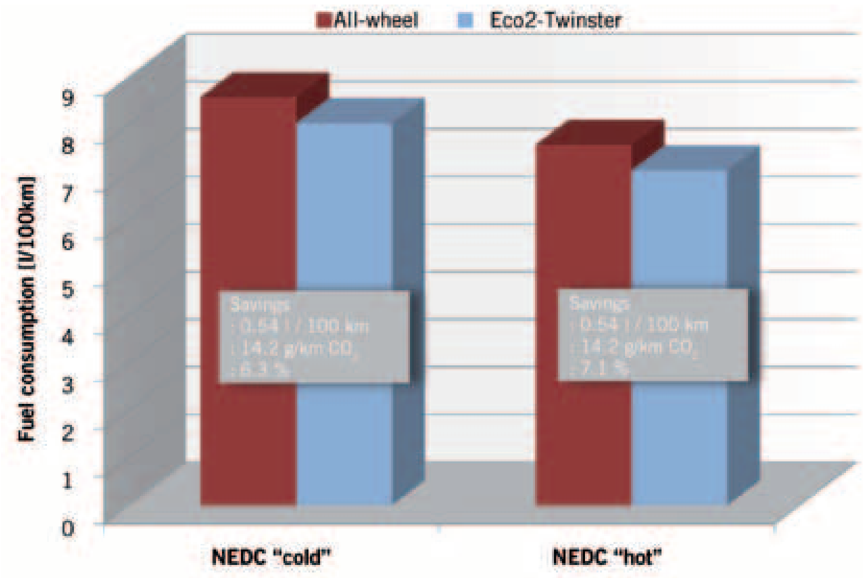
As shown in ❺, a consumption benefit of 0.54 l per 100 km and a saving of 14.2 g CO_2 per km was determined using the Eco2-Twinster AWD disconnect system.

The customers accept increased consumption caused by the four-wheel drive system when driving under winter road conditions, as this is compensated for by beneficial increased mobility. However, this increase in consumption is hard to justify in a summer drive, for example from Hamburg to Munich. Therefore, the results from the constant driving measurements have been used in another evaluation in order to show how the consumption benefit of the AWD disconnect system relates to and is affected by different friction coefficient road profiles, ❻, and less surprising is that the best savings potential of 0.6 l/100 km is shown for town traffic. The slightly lower potential of 0.37 to 0.48 l/100 km recorded for highways and motorways can be explained by the use of the Getrag series PTU and RDU with regard to their optimisation of the splashing losses at faster speeds.

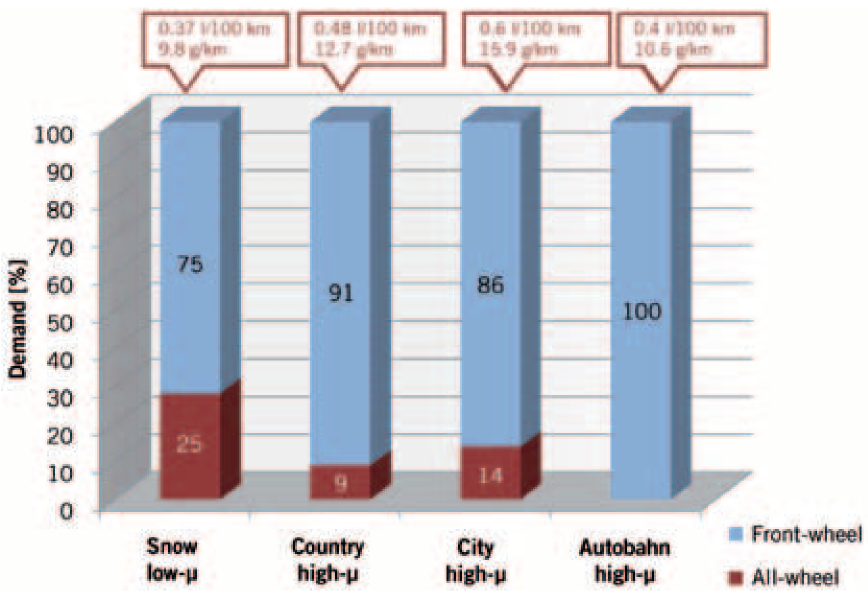
DYNAMIC DRIVING BENEFITS OF THE TWINSTER SYSTEM

The two couplings used in the AWD disconnect system have multiple functions. Both, they are being used as the disconnecting component at the axle output and in connect mode they can also be used to positively influence the dynamic driving characteristics. The system enables a variable torque distribution to be realised between the front and rear axles as well as between the drive wheels on the hang-on axle. The centre differential lock and the axle differential lock functions are realised in relation to the traction potential of a four-wheel drive vehicle. The best possible mobility can be determined for tyre traction capacity differences that are caused by friction coefficient or wheel load changes in the longitudinal or transverse directions, that means µ split and µ transition.

The selective wheel torque control option is also used here in order to improve the vehicle's yaw characteristics. Secondly, more torque is placed on the outer wheel in the curve when cornering under load and this means that the system provides active yaw support, that means the typical four-wheel drive under-steering has to be fought and the maximum transverse acceleration has to be increased. The system can be used with great effect to damp the vehicle's yaw reaction during severe yawing, that means by over-steering.



❺ Fuel consumption of the Eco2-Twinster AWD disconnect system in comparison to a conventional all-wheel drive in NEDC "cold" und "hot"



❻ Possible savings of the AWD disconnect system; effected by the advantages (of fuel consumption in l / 100 km and CO_2 emission in g/km) at different road-profile friction coefficients µ

SUMMARY

The all-wheel drive disconnect system from Getrag gives the users an excellent, overall solution that is suitable for everyday use. The increased consumption introduced by four-wheel drive systems can be reduced by up to 80 % with the Eco2-Twinster, in real driving cycles without having to compromise on the availability – short switching times of 350 ms. In addition to this the two Twinster couplings produce a clear increase in the mobility and the dynamic traverse driving characteristics, which is a welcome gain as compared to conventional "hang-on" four-wheel drive systems and this gain is not only for drivers with sporting ambitions.

The disconnecting concept, which has been developed by Getrag, enables both vehicles with front-traverse mountings of the combustion engine as well as inline mountings to use the same modules. The overlapping platform utilisation provides an interesting overall concept for OEMs, which, by using the scaling effect, can be marketed for use by customers. The reduction in consumption contributes to environmental protection as shown by the use of future-orientated technology.

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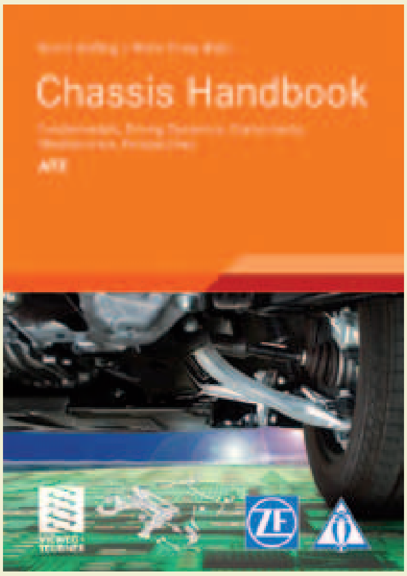
Tyres, wheels, suspension – how comfortable are our cars?



Bernd Heißing | Metin Ersoy (Hrsg.)

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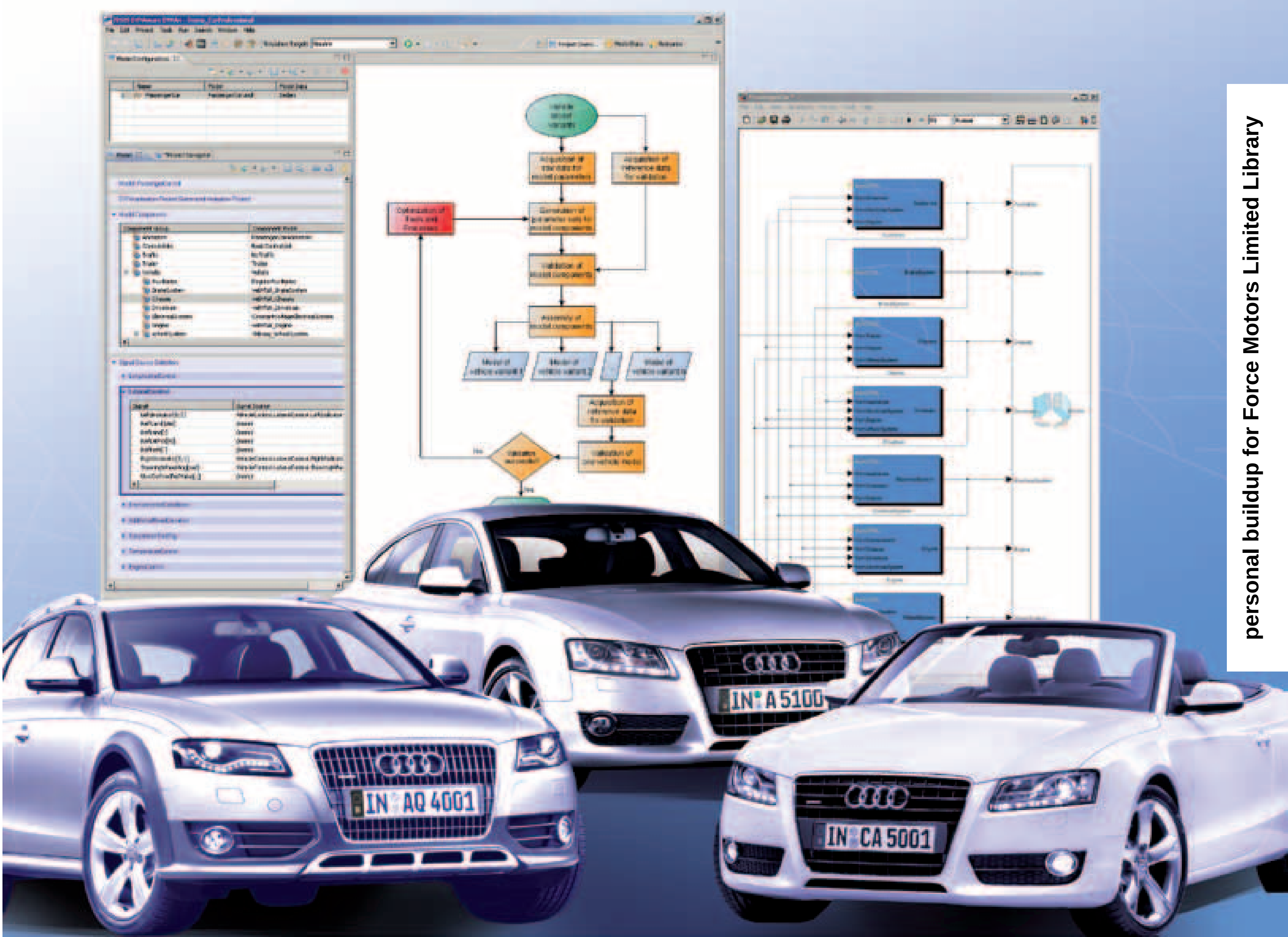

MANAGING VARIANT DIVERSITY WITH PROCESS RELIABLE SIMULATION

Due to the great diversity of variants and complex ECU functions, extensive virtual testing of functions and properties is required in addition to real-life test drives in order to guarantee product quality, safety and reliability. Tesis Dynaware and Audi have developed a process for this purpose that makes complete vehicle models available on the basis of validated components. These reliable variant models enable Audi to meet the challenges of virtual large-scale validation.

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CHALLENGES: DIVERSITY AND COMPLEXITY

The continuously growing diversity of automobile variants for new vehicle series combined with the increasing number and networking of ECU functions means that vehicle development is faced with constantly new challenges. For the wide range of variants that are offered to the customer, control systems that have an influence on vehicle dynamics must be guaranteed to function as intended in all customer-relevant situations. This applies in particular to safety-critical systems such as the vehicle dynamics control ESC.

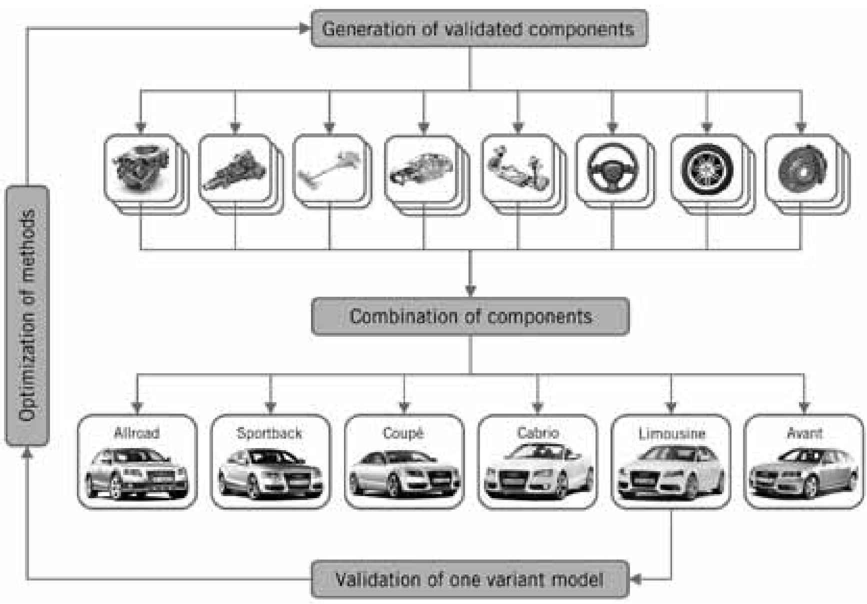
Maximum product quality, safety and reliability in the controlled complete vehicle are guaranteed by extensive test scenarios for the ECU functions. The time and costs required for such large-scale validation are tremendous.

The simulation has been an established partner of vehicle testing for several years in order to cope with the high testing requirements. Hardware-in-the-Loop (HiL) simulation in particular offers various methods for intensively testing control units and their software. The software of the vehicles can be tested without actually building real vehicles. However, in order to test and evaluate vehicle handling characteristics with the aid of simulation, the simulation models must represent realistic vehicle dynamics with a sufficient degree of accuracy.

One possible and also commonly used method of harmonising simulation and reality is the validation of a vehicle model in which both a real vehicle and the corresponding simulation model are subjected to certain scenarios. In this process, the differences between measured data and simulated quantities must be within tolerable limits. The process of complete vehicle validation does, however, conceal the problem that a corresponding real vehicle must also be available for every vehicle version modelled. In the meantime, however, variant diversity is so extensive that validation of all variants is no longer possible.

VARIANT MODEL GENERATION: COMBINATION OF INDIVIDUAL COMPONENTS

In order to meet the requirements for simulation models for numerous vehicle variants while at the same time maintaining high model quality, Audi and Tesis Dynaware have developed a process that makes complete vehicle models available on the basis of validated individual components, ❶. The precondition for this process is the sub-division of a vehicle model into components that are oriented towards real assemblies of a vehicle. The process can go into any



❶ Process for creating complete vehicle models for variants of a vehicle series depth as required. It makes sense to select the sub-division of the assemblies in such a way that all relevant vehicle variants can be represented by exchanging individual components. Which variant differences are classified as relevant will depend mainly on how the models are to be used. For example, for the validation of the dynamics of an ESC-controlled vehicle, it is important to distinguish between different brake system configurations or engines.

A further perspective in the sub-division of a vehicle model is the determination of the data for the parameterisation of the model components. The parameterisation of the model for a certain assembly comes from the data from the department in which the corresponding assembly is developed. Coordinated data supply agreements between the departments ensure the flow of data and and their quality.

As mentioned before, the process of producing complete vehicle models is based on a combination of validated individual components. Therefore, a key aspect is the harmonisation of component models with corresponding reference data. The condition of the reference data is thus also an important criterion for a sensible sub-division of model components. As a reference for component validation, test stand measurements on real assemblies are the preferred solution.

Often, it is possible to make use of measured data obtained during the development of the assembly independent of their subsequent use for model validation. After consultation with the test stand operators, further test sequences are usually also possible in order to enable the model characteristics to be evaluated in more detail. In each case, it is important to validate the component model using reference data from a single source in order to guarantee the consistency of the reference data and therefore the quality of the model. A component sub-division that Audi has found to be suitable for the large-scale validation of vehicle dynamics control systems is shown in ❷. Here, the complete vehicle is classified in the components suspension, steering, wheels, body, brakes, engine, transmission and powertrain.

PROCESS SUPPORT: GUIDELINES FOR MODEL DEVELOPMENT

In addition to the pure sub-division of the model into components, it is important that these are independent of each other with regard to both modelling and parameterisation. The modelling guidelines developed for the process include, for example, the determination of the interfaces between the components and the requirement that parameters of a component model may only be used within the allocated component. This ensures that individual assembly models can actually be exchanged and can be combined almost entirely without restrictions. Furthermore, this also supports the smooth exchange of component models between different simulation departments, thus ensuring that the expert knowledge of other departments on individual assemblies is made available more efficiently.

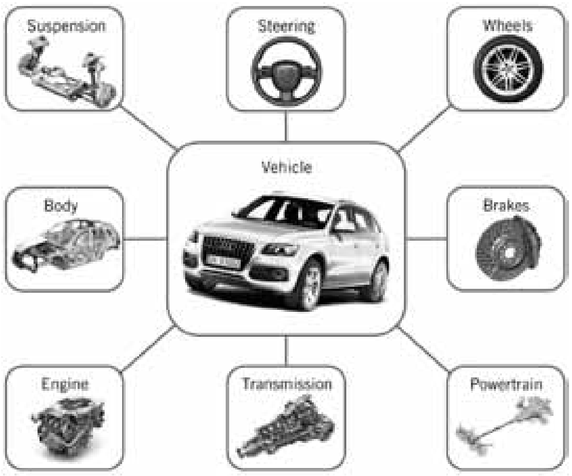
The modelling experts for the respective assembly are provided with a general process framework as a guideline for the model component to be produced. This stipulates that the parameterisation of the model components from raw data takes place largely automatically. The process also requires that the validation of the model components on the basis of the reference data be automated. The reasons for these requirements are the following three items:

: at first, a constant model quality
: the reproducibility of all process steps
: less time expenditure.

The most important requirement of the process framework, however, is that the validation of the model component must be traceable, that means, it must be completely documented. The source of the parameter raw data and the validation reference is just as important as the representation of the model behaviour with regard to the reference. The modelling experts are largely free to choose how the process for the respective component is implemented. The expertise of Tesis Dynaware and the dialogue with the specialist departments at Audi who are responsible for the development have been applied to create a wide range of virtual assembly test stands that enable parameterisation, validation and documentation of the component models to be carried out in a continuously automated process.

EXAMPLES: AXLES AND TYRES

Two examples, the simulation of axles and tyres, shall illustrate the procedural method. The development of axle kinematics uses Adams multibody simulation models [1] that are currently not suitable for the virtual testing of functions and properties on HiL simulators due to their complexity and high computing requirements, but they can nevertheless be used as a source for the parameters of real-time-capable models. The parameterisation of the Adams models is automatically transferred into parameter sets for MBS axle models of Tesis Dynaware (TD), which were optimised for operation in real-time applications, for example by reducing the possible degrees of freedom. Subsequently, both the Adams model and the TD model are exposed to



❷ Sub-division of the complete vehicle model into individual components various steady-state and dynamic load cases on a virtual axle test stand. During these tests, the parameters of the TD model are optimised in order to compensate for the effects of model simplifications. After completion of the parameter optimisation, a comparison of the behaviour of the Adams model and the TD model is automatically represented in a document. As an option, the measured data from a real axle test stand can additionally be used as comparative values. Overall, this ensures that kinematics development and the virtual testing of functions and properties work with comparable models and therefore generate consistent results.

By contrast, the parameterisation and validation of the tyre models are based exclusively on real measured data. These are generated on a tyre test stand, where the real tyres are subjected to various longitudinal and lateral dynamic tests and combined load cases. These measured data are subsequently also used as raw data for parameters and as reference data for a validation comparison. After initial preparation of the measured data, the parameters of the tyre model used are automatically determined in an optimisation process, with the result that the virtual tyre has a behaviour that is comparable with the test stand measurements. At the end of the process, a detailed document is produced that compares the real and virtual tyre and also contains evaluations of measured data, parameter fitting and general tyre properties.

PLAYING IT SAFE: CHECKING THE BASIC VARIANT

To confirm the applicability of the process, a representative basic variant in every automobile model series is used as a real test vehicle for the model validation of the complete vehicle. According to the process, this occurs three times in every model series. The first comparison is performed with a test vehicle in the early series development phase to ensure that the test drives and the virtual tests work with comparable test vehicles. The second comparison is performed with a close-to-production prototype directly before the virtual validation of the functions and properties and the subsequent software freeze.

In the third phase, the complete model validation is performed with a series-production vehicle after start of production (SOP) in order to guarantee the availability of the model at the start of the project for the new model series. The aim of these important components of the model generation process is to ensure quality assurance during the entire series development. If there are non-tolerable deviations between the real test vehicle and the complete vehicle model, the process permits exclusively methodological adaptations of individual component test stands, but does not allow changes to the complete vehicle model itself. Previous experience has shown that this procedure is very effective and reliable in the generation of variant models.

THE KEYS TO SUCCESS: QUALITY, DOCUMENTATION AND AVAILABILITY

A process is generally successful only if the result is accepted by potential users. In this case, three factors make a decisive contribution to this:

1. constantly high or increasing quality of the models due to a) the applied expertise in the fields of modelling and process support, b) the automated tool chain, c) the consistent further development of the implementations
2. user-friendliness due to detailed and comprehensible documentation
3. a high level of availability of complete vehicle models.

With the described procedure, all variants of the different vehicle series are available as models, ensuring maximum confidence in the model quality and therefore in the test results. These advantages can be used by all departments who develop and test ECU functions. As a result, Audi has laid the foundations for high-quality results from virtual testing.

REFERENCE

[1] Adams. Software für die Simulation der Mehrkörperdynamik. Website, 22 July 2011: http://www.mscsoftware.com/germany/Products/CAE-Tools/Adams.aspx

SIMULATION OF LOCAL MATERIAL CHARACTERISTICS AT FAURECIA

The models used by crash simulations do not normally take into account the local differences in geometry and material characteristics resulting from the various manufacturing processes. These traditional models are idealised, and therefore only provide an inexact reflection of reality. In an effort to obtain an accurate picture of reality, Faurecia became the first company to use a new software application from the Fraunhofer Institute SCAI in St. Augustin, Germany. The SCAIMapper application makes it possible to integrate the results of production simulations into the crash model. This improves the information value of the crash simulations and so assists in the development and manufacture of components.

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MOTIVATION

To meet the increasing requirements for vehicle safety and weight and to combine these conflicting properties, innovative techniques and procedures are needed. Faurecia recognised this early on and has consistently put innovation into practice in its Automotive Seating, Emissions Control Technologies, Interior Systems and Automotive Exteriors divisions, ❶.

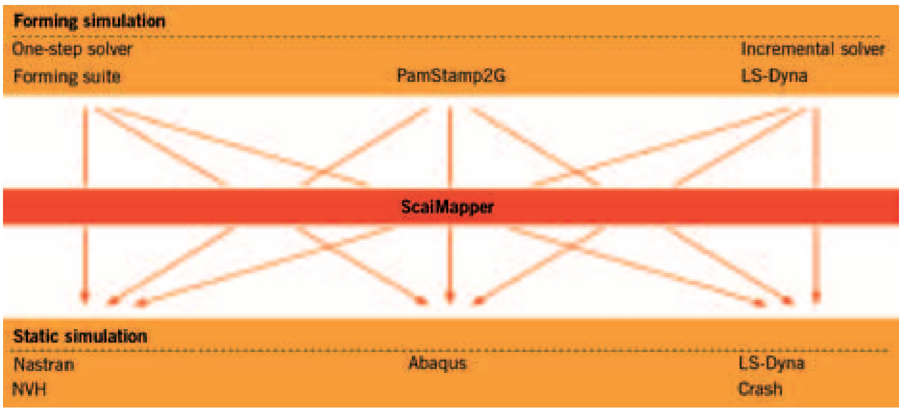
The components used by today's automotive industry are made of uniform material. This requires some compromise between rigidity and energy absorption capability, even though it would make sense for some components to have a higher rigidity in certain areas and higher energy absorption in others. Dual phase (DP) and TRIP steels, for example, can easily be produced with different characteristics by choosing different austenitisation or cooling conditions.

DP and TRIP steels are used because of their easy formability. However, their material properties are altered during the shaping process: the material becomes stiffer with lower residual strain, which means that the forming process must be taken into consideration. Otherwise the behaviour of the component in the crash simulation would not correspond to its real-life behaviour.

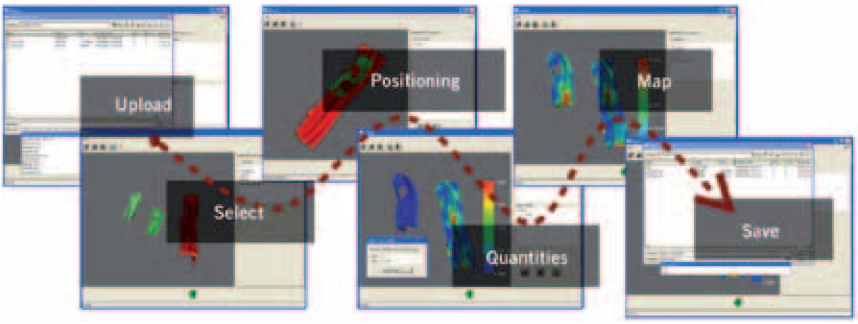
Explicit design software helps to optimise components and manufacturing processes, especially with regard to vehicle safety and weight reduction. No vehicle is developed in today's automotive industry without using these programmes.

There are a number of tools available that can help with the design of the manufacturing process. Most of the critical body parts for the crash test are manufactured using the deep draw process. This process starts off with a flat sheet of metal. Some components undergo further heat treatment in order to improve their material properties. Certain characteristics, such as rigidity, for example, or the thickness of the sheet metal, change during the deep draw process. These variables have an affect on the crash behaviour and therefore have to be included in the crash simulation. Because of the different methods of computing sheet metal forming and crash simulations, different quantisations are normally used, and this means a relatively fine mesh.

Especially in the early development phase, there is a good deal of scope for using new materials and manufacturing processes, ❷. This scope will be exploited if new materials and



❶ ScaiMapper – a standard tool within the design workflow manufacturing processes offer significant advantages over traditional materials and processes. In order to leverage this potential and obtain as realistic a model as possible, the production related, local geometry information and material parameters of the forming simulation and other processing simulations must be included in the crash simulation model.



❷ With the tool one takes full advantage of the greater design opportunities and avoids over-engineering

DEVELOPMENT AND OPERATION OF THE SCAIMAPPER

The Fraunhofer Institute SCAI, in partnership with the VDA-FAT Working Group "27 AG", developed crash simulations of these types of body panels manufactured using a deep draw process and subsequently heat treated if necessary. The development was supported by a research project carried out by AiF Projekt GmbH, a company funded by the German Federal Ministry of Economics and Technology. The project looked into the use of heat treatment methods designed to influence the crash behaviour of high-tensile body components.

The ScaiMapper software was a spin off from the results of this research. It enables the user to transfer the metal forming simulation results into subsequent crash safety simulations and to perform load analysis and noise-vibration-harshness (NVH) analysis, ❸. The data transfer is essentially carried out in three steps. First, the forming geometry and results, along with the target geometry for the indicators of crash, structure and NVH, are read. The source and target areas in both geometries are then assigned. Finally, mapping is carried out and the data exported to the target file. Here, the software supports the file formats of many of the codes used in forming and crash simulation. It is compatible with a variety of different solvers. For example, data from solver A can be transferred to any solver B, something that is not a given in the world of simulation.

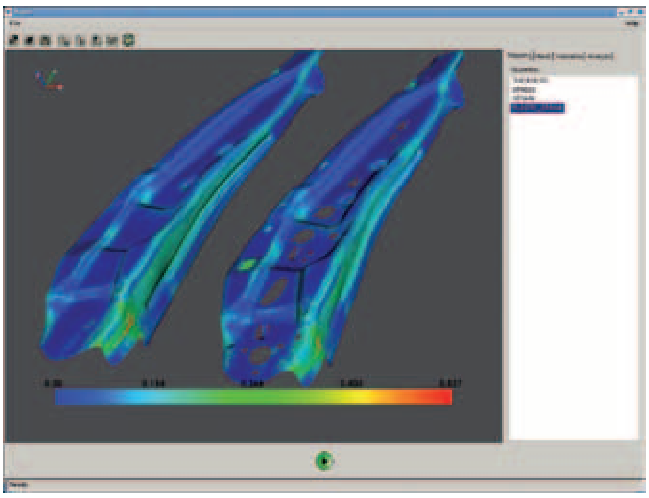
In short, the ScaiMapper offers a very robust process for transferring node, element and shell-based variables, ❹. Transfer between different types of computer models is also possible. The software can also calculate local distances between two mesh models, which the user can use to precisely check the compliance of his stamping and crash simulation models.

All functions can be controlled via the ScaiMapper's graphical user interface. The user selects the components in the source and target mesh that he wishes to include in the data transfer. If different coordinate systems have been employed in both models, the components can be rotated and mirrored. Automatic alignment achieves an optimum superposition of the meshes.

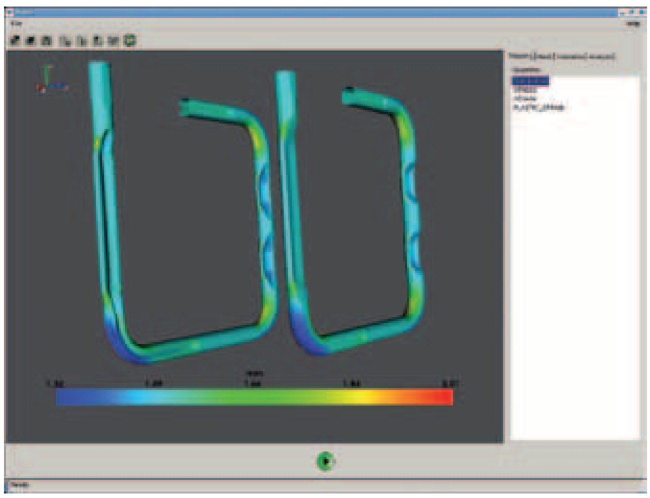
After specifying the components and their positions, the quantities, or the physical variables to be transferred, may be selected. Mapping is then carried out and the transferred data appears in the graphics window on the target mesh. This allows the quality of the data transferred to be checked once again.

THE SCAIMAPPER AT FAURECIA

The previous crash models at Faurecia, both for components and complete vehicles, were idealised. Although the models took the design of a component into account during a crash, the component's manufacturing history had to be included if you wanted an accurate analysis. This is because the production process can cause



❸ Mapping of the plastic strain of a back spar designed by Faurecia



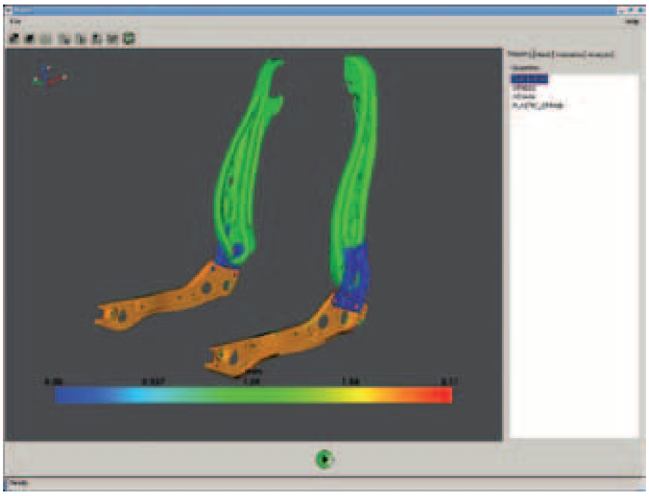
❹ Mapping of the material thickness of a pipe designed by Faurecia changes in the component's structure, for example, or in its residual stress. These changes were very important for Faurecia because they reveal design alternatives for lightweight construction and vehicle security.

The company therefore became the first licensee of ScaiMapper and implemented the software tool in its automotive seating division. In Faurecia's largest division in terms of sales in 21 countries complete seats, frames, adjustment mechanisms, cushions, seat covers and headrests, armrests and pneumatic comfort systems are produced and every day 100.000 seats assembled.

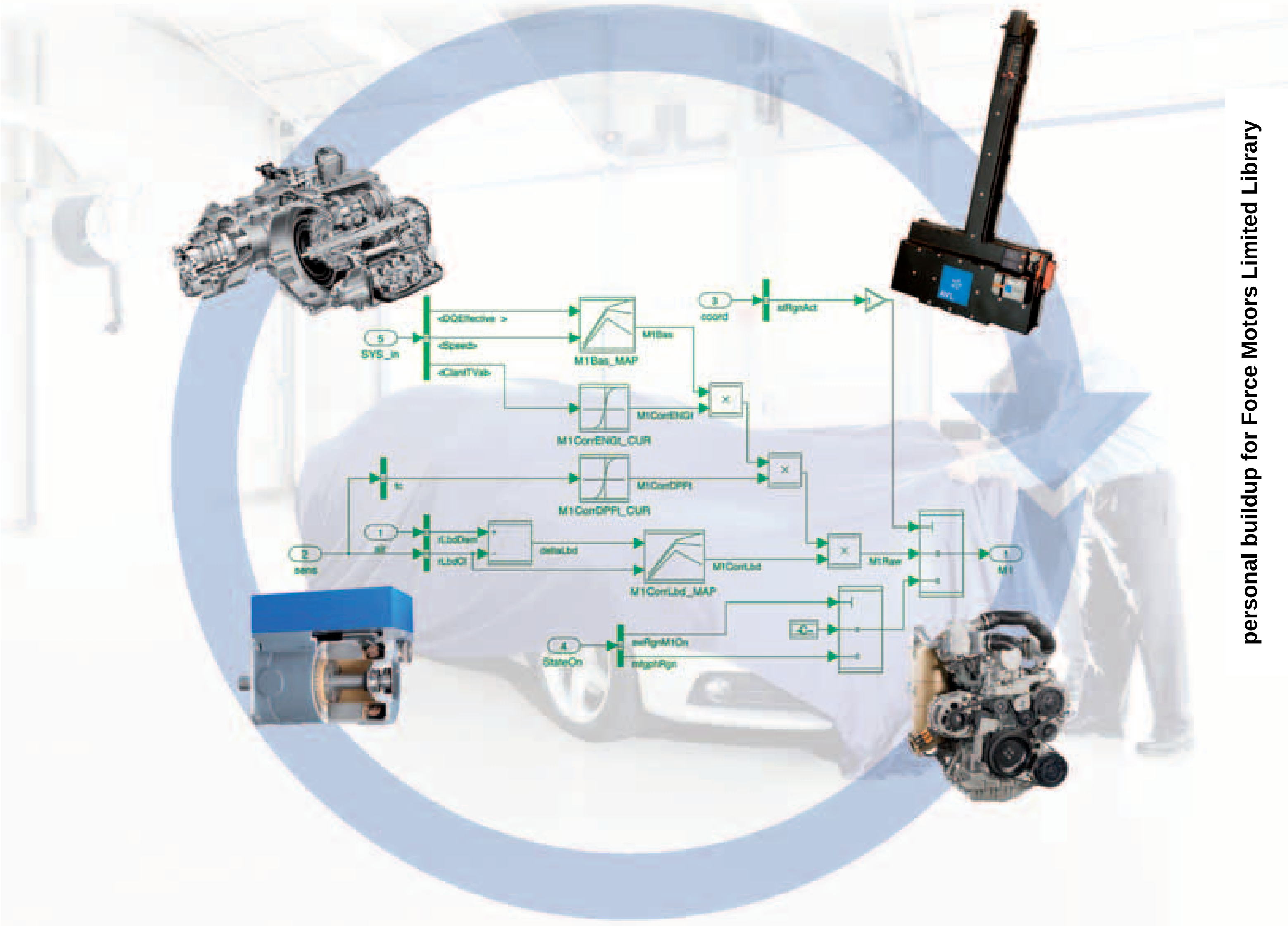
Faurecia first deployed the ScaiMapper successfully in April 2006 during a project at the company's German headquarters in Stadthagen. The project was for the Alpha Beta front seat for its customer Volkswagen. In 2007, the company integrated the software throughout the group as a transfer tool in all stages of its seating design process.

Today the software is used for crash simulations when physical forming variables such as plastic strains or material thicknesses exceed or fall short of certain critical thresholds. In order to fix these thresholds, Faurecia carried out a number of studies into the buckling behaviour of the relevant seat components. The company specified particular criteria, and by comparing this with the real values, was able to determine whether it is possible to influence a component and what results this influence has.

The basic workflow at Faurecia takes the following format: The automotive supplier produces a preliminary design for the seat. This design is checked for feasibility in the forming simulation process. A one-step analysis is carried out. When the component is considered manufacturable, its data are mapped in terms of the crash model. The final stage involves integrating the data. The benefits of ScaiMapper, and consequently of extensive simulation, are that it enables the company to take full advantage of the greater design opportunities offered by new materials and manufacturing processes while avoiding over-engineering and the high cost that this can incur. ScaiMapper contributed to the development and market launch of Faurecia's new generation of seat mechanisms, ❺. These incorporate metal structures, rails and height adjustment systems whose weight Faurecia was able to reduce by over 30 %. The new mechanisms are part of Faurecia's current range of automotive seating solutions and are included in all new seat frame projects.



❺ Mapping process of a Faurecia seat



FROM VEHICLE REQUIREMENTS TO MODULAR HYBRID SOFTWARE

The increasing complexity of modern hybrid powertrains requires the use of systematic development methods. In order to derive a modular software architecture from the vehicle requirements, AVL focuses on the requirements engineering and a clear structure of the resulting software.

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BACKGROUND

Hybrid electric powertrains in all variations are well established on the market and contribute significantly to the reduction of CO_2 emissions. The electrification of the conventional powertrain not only increases the system complexity, but also gives special importance to the control software in order to achieve the vehicle targets.

The full potential of a specific powertrain configuration can only be taken advantage of if the interaction between the internal combustion engine and the electric motor is optimised from a system point of view. This requires the software to fulfil a wide range of requirements. However, beyond optimising the software to a specific system, reusability and modularity are becoming increasingly important for manufacturers. Various components and even different configurations need to be covered by one single hybrid software architecture to ensure time- and cost-efficient usability over different variants and carlines.

VEHICLE REQUIREMENTS

The definition of targets for a mechatronic system is based on system requirements that are derived from use cases. The use cases define the entire usage space for the system.

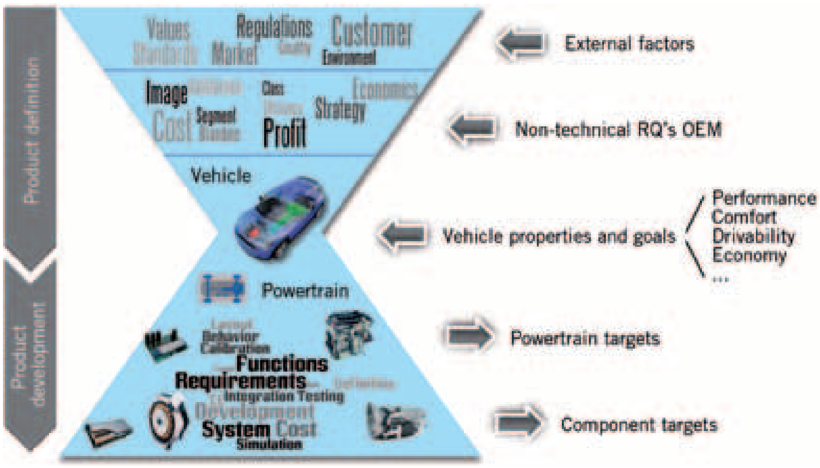
A passenger car must usually fulfil a wide range of use cases that consequently lead to complex requirements on the vehicle level. Based on a multitude of external factors and internal requirements at the OEM, a target list for the vehicle is defined, which forms the starting point for the product development of the powertrain and its components, ❶.

The target list is based on use cases linked directly to the end customer usage (for example, fuel efficiency or vehicle performance) and use cases without end customer reference (for example, the OEM's platform strategy or diagnosis systems for service).

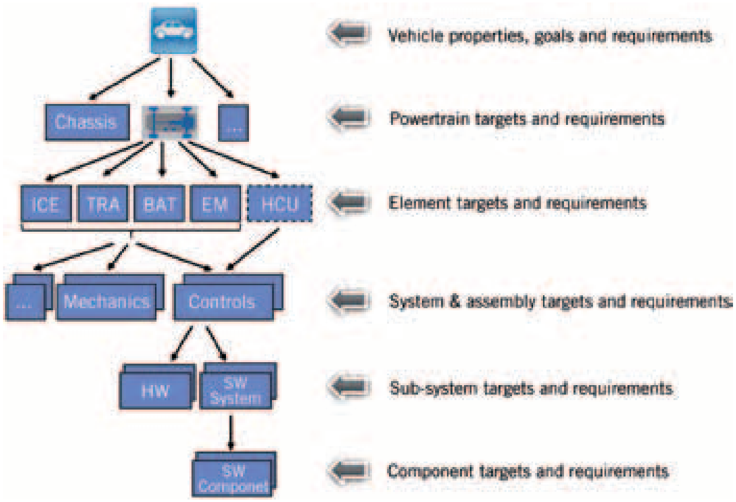
However, the features of the powertrain are defined based on the target list and the corresponding use cases. The features of a mechatronic system are defined by the system components, the interfaces and a corresponding control system. Hence, requirements on the system level, which in this case is the vehicle powertrain, have to be leveraged down to the powertrain components and the corresponding control systems.

VEHICLE REQUIREMENTS DEFINE COMPONENT REQUIREMENTS

The specifications of the powertrain components and the corresponding control systems must be derived based on the defined targets and use cases at the vehicle level during the system development. This process, referred to as requirements engineering, cascades from the vehicle level via the powertrain down to the powertrain components and the control system on powertrain level, and further down to the main domains of electrics, mechanics and the corresponding control systems, ❷. Each control system is based on hardware components (sensors, actors



❶ Target list of the vehicle



❷ Cascade of requirements

and the control unit) and software, which includes the control algorithms.

Finally, each and every component feature and control function can be correlated individually to a specific target and use case at the vehicle level. Each use case defines a corresponding test case on the component and system level.

For hybrid systems, especially full hybrid powertrains, the correlation between component features and control functions and the use case at the vehicle level is relatively complex. Hence, requirements engineering must be supported by appropriate tools for requirements management. Within defined engineering processes, such tools support the networking of vehicle targets, use cases, component features and test cases throughout the entire development, from concept to start of production.

There is an obvious structure for the component requirements based on automotive use cases. These are initially classified according to driving and non-driving functions. This is followed by a sub-classification of the dynamics, according to

- highly dynamic (0 to 2 s; vehicle dynamics)
- short-term (0 to 20 s; individual driving sequence)
- intermediate (0 to 2 min; individual driving manoeuvre)
- mid-term (0 to 1 days; max. 1000 km)
- long-term (approx.1 year or 20,000 km)
- lifetime (approx.10 years or 200,000 km).

A typical example is the requirements for the electric motor performance: starting the internal combustion engine requires 180 Nm of electric motor torque (highly dynamic), while the vehicle power (boost support) leads to a requirement of 100 Nm for short-term accelerations. Long-term and lifetime requirements are based on a set of typical reference cycles which refer to the real life usage profiles. These reference cycles are integrated into the overall validation program.

The features of the main powertrain components and the corresponding network (system architecture) define the entire usage space of the hybrid vehicle. The powertrain control system defines the powertrain configuration in each operation mode (for example, pure electric or combined mode), the required torque and the transition phases between different modes. Consequently, the control system has a dominant influence on the system behaviour.

Although the control system on the powertrain level is at a similar level with the components from a hierarchical perspective, it nevertheless has a special role. The final system behaviour is significantly influenced by the control functions that coordinate the co-operation of the different powertrain components.

MODULAR, UNIVERSAL SOFTWARE STRUCTURE

This method of developing requirements is the key to the development of a universal hybrid software structure. An architecture that can be applied in a broad range of use cases must cover requirements from an equally broad range of hybrid topologies. This requires the top level requirements to be systematically broken down to the software system and the software components.

AVL has used this approach to develop a universal architecture, which could then be optimised with regard to scalability, reusability and configurability even before implementation.

The basic layout of this software architecture is shown in, ❸. Characteristic of the developed structure is the partitioning of the functionality into layers with clearly defined interfaces.

The purpose of the first layer, "interfaces and observers", is to provide the necessary information from the vehicle and its components. This "abstraction layer" generates signals independent of the hybrid topology and the components used.

The next layer, "parallel mode calculation", determines the quasi stationary requirements to the powertrain components for all modes, as well as the so-called rating. A quasi static phase of the hybrid powertrain during a dynamic drive cycle is referred to as a mode of operation. It is defined by the torque distribution between the electric motor and the internal combustion engine, the energy flow between energy storage systems and energy consumers and the state of the powertrain (for example, the internal combustion engine engaged, selected gear, etc.). Examples of operation modes are recuperation, boost, electric driving, vehicle standstill with internal combustion engine off, etc.

Three designated software components are available for each mode. The component "energy management" defines the available amount of energy and the charging capacity. "Requirements" calculate the corresponding requirements to the relevant components of the powertrain. Finally, the component "ratings" calculates a rating that assesses the "suitability" of each mode in the current driving situation. These calculations are made independently of the vehicle targets and the control strategy implemented. They take into account the previous, current and future driving situation, the driver demand and the current state of the components. The implemented algorithms can range from simple feed forward based estimations from maps to complex optimisation methods.

The selection of the most suitable mode is handled in the layer "Mode Selection" by switching through the one mode that has the highest rating of all. This approach contributes significantly to the universal applicability of the control software. The principle as well as the algorithm for the selection of individual modes is independent of the number and the properties of modes. This makes the structure usable for a wide range of hybrid powertrain variants.

Dynamic drive states and transitions between individual modes are covered in the layer "Dynamic Drive Train", which consists of four software components. The components "Dynamic Coordinator" coordinates the correct chain of events during transitions and triggers the activation of the other three components, which serve as complex drivers. "Dynamic Configuration" executes the transition between powertrain states (for example, it actuates the separation clutch). "Dynamic Power Distribution" commands the dynamic requests for torque and speeds, and "ICE Stop-Start" controls the start and stop procedures of the internal combustion engine.

EXAMPLE AND ADVANTAGES OF THE SELECTED CONCEPT

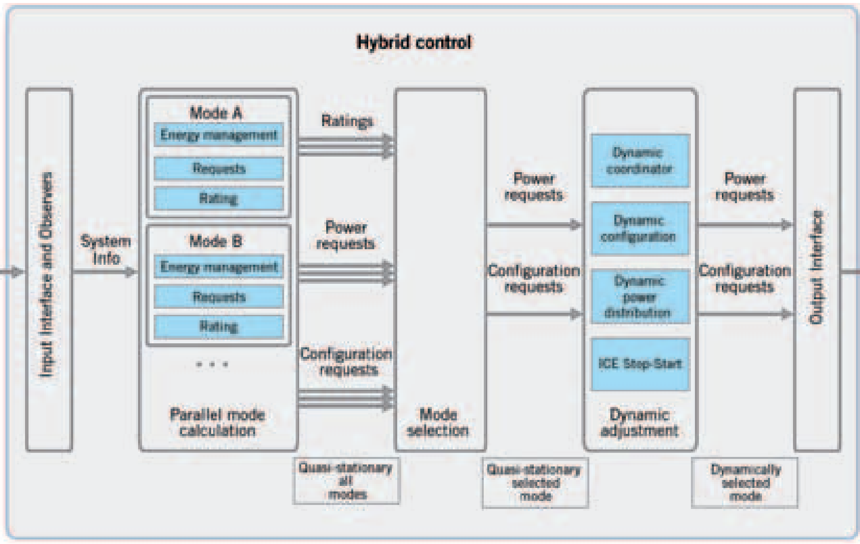
The vehicle measurement of a parallel hybrid in a well known start-stop situation as shown in ❹ illustrates how the described controls concept works:

In the beginning of phase 2, the rating of the mode "Idle charging" exceeds the rating of the previously active "ICE deactivated" due to a change in conditions, for example the state of charge of the battery is low. Subsequently, the mode "Idle Charging" is selected in the layer "Mode Selection". The related quasi stationary requests are further processed in the component "Dynamic Coordinator".

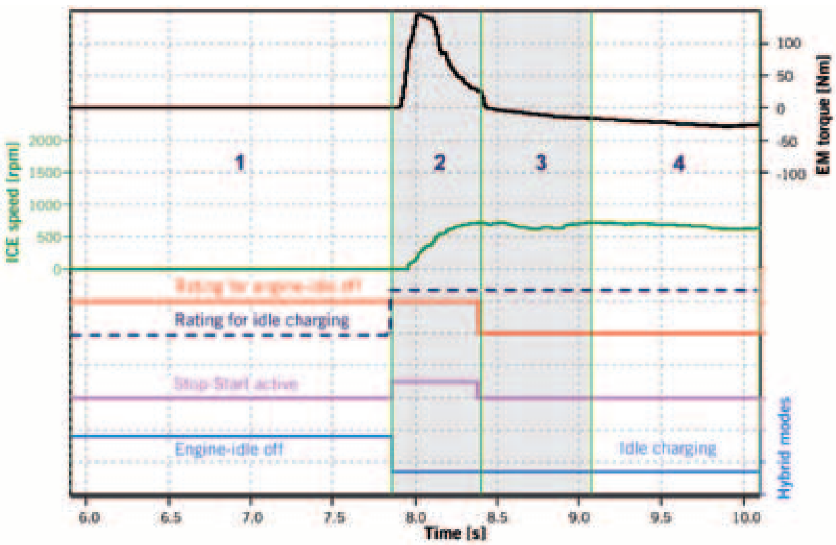
According to the sequence defined in this layer, firstly the component "ICE Start-Stop" is activated, which commands the necessary electric motor engine speed. As soon as the combustion engine is ignited and idle speed is reached (end of phase 2), the component "Dynamic Power Distribution" requests a blending of the electric machine torque and the internal combustion engine torque in order to achieve a smooth transition to the mode "Idle Charging" (phase 3).

The architecture can be tested and calibrated in a modular manner and is also scalable and extendable in scope. Various control strategies for a broad range of use cases can be implemented with low adaptation effort. The effort for calibration decreases accordingly as changes in individual functions can be performed largely decoupled from other functions.

The algorithms for the mode selection and the sequence of dynamic transitions can be developed, tested and calibrated equally independently of the number and the properties of modes. This concept allows modes of operation to be exchanged or additional modes to be added at a later point in time. The developed architecture therefore not only satisfies currently known requirements, but is also ready for potential future functional extensions.



❸ Universal software architecture of the AVL hybrid control



❹ Signal flow of a vehicle with parallel hybrid topology in start/stop operation

SUMMARY

The increasing complexity of modern hybrid powertrains requires the use of systematic development methods. The key issue is to consistently break down and link the requirements from the vehicle level down to the subsystems and components. This is the only way to make sure that subsystems and components act together properly as a complete system, satisfying all customer requirements.

This collaboration is orchestrated by the hybrid control with the selection and controlling of all operation modes. The hybrid control contributes substantially to satisfying virtually all requirements and use cases.

In this article, a modular control architecture based on the broken-down requirements was presented. This architecture is decisive for achieving efficient testability, simple calibration, easy maintenance and effective reuse.

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SYSTEMATIC ANALYSIS OF LATERAL AND LONGITUDINAL DISTRIBUTING DRIVE TRAIN SYSTEMS

Mechatronic systems are increasingly used for active torque distribution between the axles and the wheels. They are predominantly based on adjustable multi-disc clutches, which are subject to kinematic restraints. They in turn affect the drive train layout. The interaction between kinematics, different layouts and the ability to generate agility improving drive torque differences will be discussed in this article by the Technische Universität Braunschweig.

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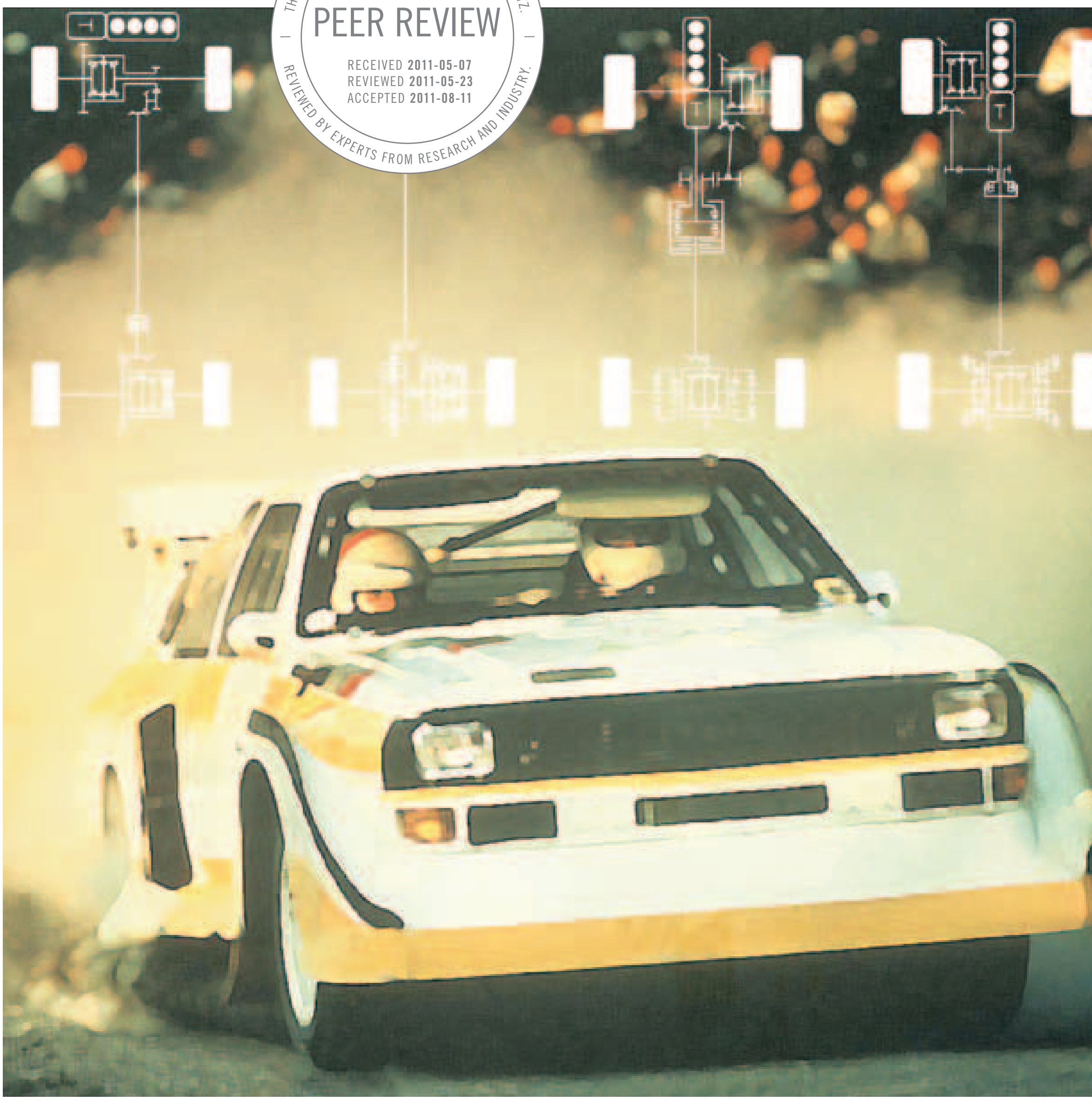
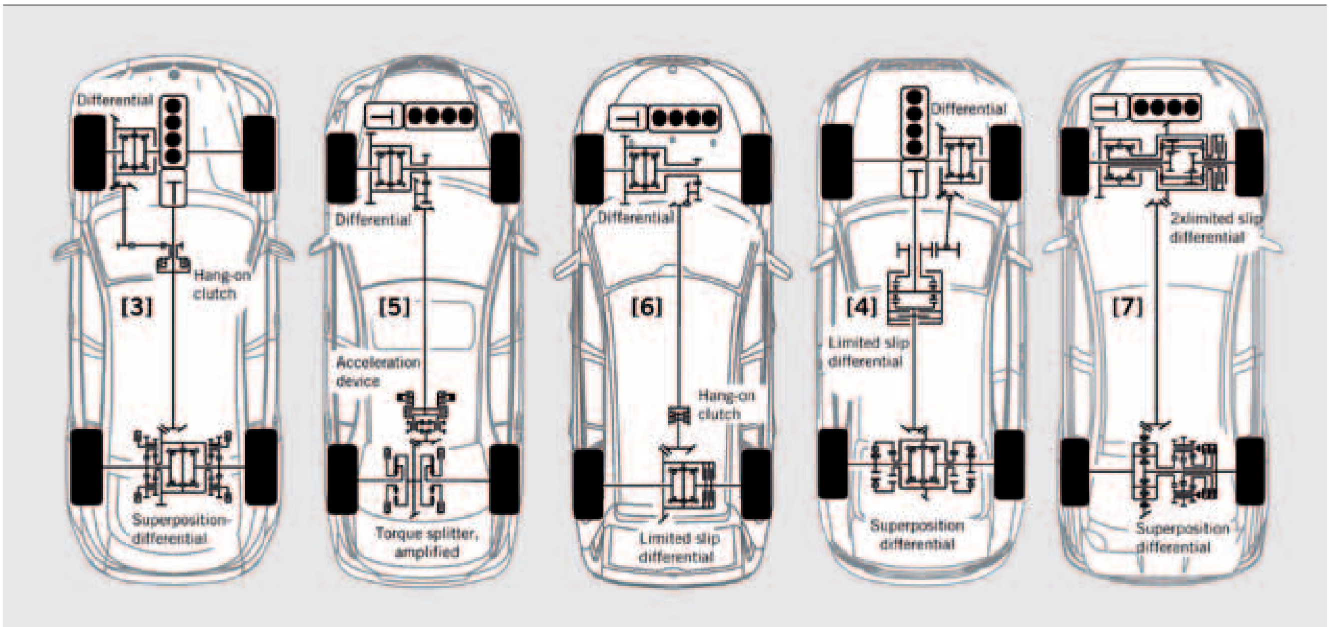




❶ Modern drive train systems with longitudinal and lateral distributing components

1 INTRODUCTION

The drive train technology has been characterized by continuous innovations since the 1990s. It started with superposition differentials in front and all-wheel drive mass production vehicles by Japanese car makers, followed by the use of identical technologies in cars from German producers [1 to 4]. The increase of the lateral dynamic performance potential has become more and more important, so these systems are not only used for SUVs, but also for saloon cars with a sporty character [3 to 7], ❶.

At the Institute of Automotive Engineering, comprehensive studies were conducted to analyse longitudinal and lateral distributing drive train systems used for different drive train concepts.

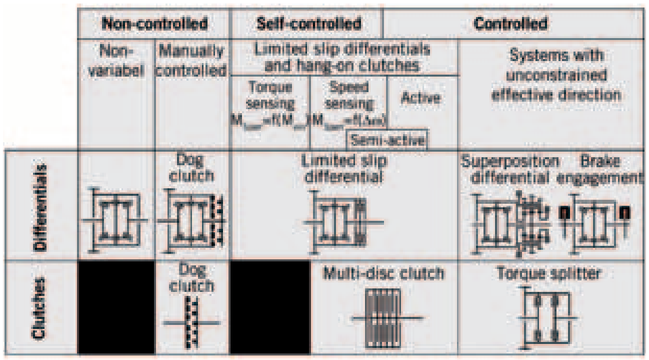
The considered systems have one thing in common: the use of mechanical friction clutches for drive torque transfer, resulting in characteristic system properties and problems with different designs. This article focuses on the description of these characteristics and their relation to the dynamic behaviour.

2 MULTI-DISC CLUTCH BASED DRIVE SYSTEMS

Torque distributing systems can be divided into differential and clutch systems [9]. ❷ shows the schematic classification. In differential systems, a fixed torque bias ratio is used to drive both output shafts, which can be varied by limited slip differentials, superposition differentials and brake intervention. Alternative systems which generate asymmetric torque distributions directly by use of an electric motor [8] are not considered here. The systems can be used for longitudinal and lateral distribution, while clutch systems with just one clutch can only be used for longitudinal distribution. Such all-wheel drive systems are also called hang-on systems. Systems including two clutches and without a basic torque distribution by a differential are called torque splitters and can also be used for longitudinal and lateral distribution.

3 KINEMATIC SYSTEM BEHAVIOUR

The direction and the amount of torque transfer for a friction clutch are determined by the effective speed differential. In general, torque transfer is only possible from the fast rotating part of the clutch to the slow rotating one. The speed differential for the clutch mainly depends on the wheel speed and the speed ratio determined through the drive train layout. The ratio configuration is therefore of crucial importance for drive torque transfer in longitudinal and lateral distribution components. The resulting system



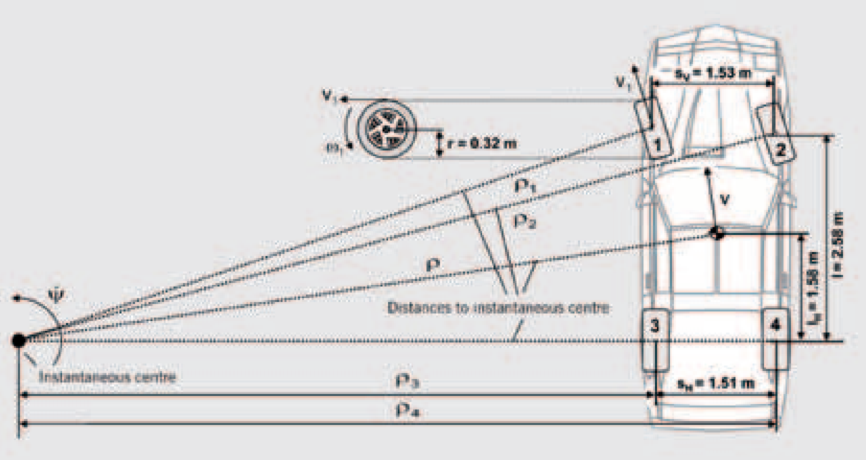
❷ Classification of torque distributing systems based on multi-disc clutches characteristics are to be considered here, based on the kinematic model represented in ❸ and the given wheel speed ratios (Eq. 1 to 6). This approach is valid, if lateral and longitudinal wheel slips are small. A limited slip differential and a superposition differential will be analysed first (❹, rear-axle application assumed for reasons of simplicity).

To correct understeering and increase agility, drive torque needs to be transferred to the outside wheel. To achieve this with a limited slip differential, the speed differential for the multi-disc clutch in a left-hand bend has to be bigger than zero, Eq. 9. This is identical to the requirement that, in accordance with Eq. 10, the instantaneous centre ratio is bigger than one. This is not possible. Under normal road conditions, the required speed differential can only be achieved through the increased traction slip at the inside wheel resulting from accelerating when cornering. Since traction slip is always connected to a respective engine load, the limited slip differential is called a load-dependent system. The inward yaw moment cannot be maintained in case of load changes, which might result in unwanted understeering, especially when used in combination with front wheel-drive [10]. The drive concept is not relevant for the kinematic behaviour of the limited slip differential, but it has to be taken into account that significant traction slip in all-wheel drive systems is generated much later than in single-axle drive systems.

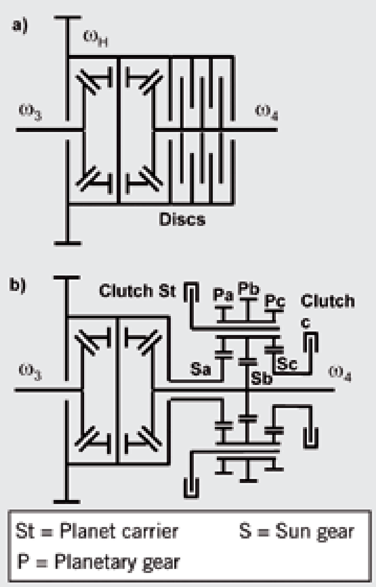
What is achieved is a torque difference independent of the vehicle state. Lateral distributing superposition differentials are used for this purpose.

The behaviour of the superposition differential, ④, is specified by the stationary gear ratio z (Eq. 11 to 13). According to Eq. 14, the

EQ. 1	$\rho_1 = \sqrt{(\sqrt{\rho_2 - l_H^2} - s_v/2)^2 + l^2}$
EQ. 2	$\rho_2 = \sqrt{(\sqrt{\rho_2 - l_H^2} - s_v/2)^2 + l^2}$
EQ. 3	$\rho_3 = \sqrt{\rho_2 - l_H^2} - s_v/2$
EQ. 4	$\rho_4 = \sqrt{\rho_2 - l_H^2} - s_v/2$
EQ. 5	$v = \dot{\psi} \cdot \rho$
EQ. 6	$v_i = \dot{\psi} \cdot \rho_i = \omega_i \cdot r \quad (i=1\text{–}4)$



❸ Kinematic approach: determination of wheel speeds



EQ. 7	$\omega_H = \omega_{Sa} = 0{,}5 \cdot (\omega_3 + \omega_4)$
EQ. 8	$\omega_{Sb} = \omega_4$
EQ. 9	$\Delta\omega_{discs} = \omega_3 - \omega_4$
EQ. 10	Instantaneous centre ratio: $\lambda_\rho = \frac{\rho_3}{\rho_4} = \frac{\sqrt{\rho^2 - l_H^2} - s_H/2}{\sqrt{\rho^2 - l_H^2} + s_H/2}$
EQ. 11	$z_{ab} = \frac{z_{Pa} \cdot z_{Sb}}{z_{Sa} \cdot z_{Pb}} = \frac{\omega_{Sa} - \omega_{St}}{\omega_{Sb} - \omega_{St}}$
EQ. 12	$z_{bc} = \frac{z_{Pa} \cdot z_{Sc}}{z_{Sb} \cdot z_{Pc}} = \frac{\omega_{Sb} - \omega_{St}}{\omega_{Sc} - \omega_{St}}$
EQ. 13	$z_{ac} = z_{ab} \cdot z_{bc}$
EQ. 14	$M_{Sb} = M_{St} \cdot \frac{1}{1/z_{ab} - 1} + M_{Sc} \cdot \frac{1 - 1/(z_{ab} \cdot z_{bc})}{1/z_{ab} - 1} = M_4 - M_3$
EQ. 15	$\Delta\omega_{ClutchSt} = \omega_{St} = \frac{v}{\rho \cdot r} \cdot \frac{\sqrt{\rho^2 - l_H^2} - z_{ab} \cdot (\sqrt{\rho^2 - l_H^2} + s_H/2)}{1 - z_{ab}}$

❹ Kinematic behaviour of a limited slip differential (a) and a superposition differential (b) torque transferred through the sun gear b complies with the torque differential between both wheels. The respective stationary gear ratios also connect the sun gear torque to the clutch torques of the planet carrier and the sun gear c. The torques of the sun gear c and/or planet carrier complies with the actuator torques.

Torque transfer is only possible if the differential speeds of the clutches are bigger than zero. Since the differential housings support the clutches, the differential speed of the clutch corresponds to the absolute speeds of planet carrier and sun gear.

The main equation for the speeds of planetary gears and the wheel speed ratios can be used to determine a relation between curvature radius and gear ratios. The most important issue is to ensure torque transfer for all curvature radii that are relevant in terms of driving dynamics. This complies with the requirement that the speed differential of the clutch must not equal zero until a certain curvature radius limit ρ_{gr} is reached. Applying this to the speed ratios of the planet carrier (Eq. 15) results into the following conditional equation for the gear ratio zab if the wheel speeds are taken into account:

EQ. 16

$$z_{ab} = \frac{\sqrt{\rho_{gr}^2 - I_H^2}}{\sqrt{\rho_{gr}^2 - I_H^2} + 0,5 \cdot s_H}$$

In compliance with Eq. 11 and Eq. 12, the gear ratios z_{bc} and z_{ac} can also be determined now.

If the gear ratios are known, the basic behaviour of the superposition differential can be characterised.

Further issues include the minimum effect on the overall efficiency achieved through avoiding meshing and slipping, a compact as possible actuator design and low friction losses in case of actuation. Four objective parameters, listed in ❺, can be used to assess if the requirements are met.

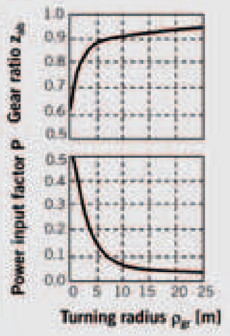
The procedure of determining the resulting objective parameters can be used for any type of superposition differentials.

❻ shows exemplary results for four primary types of superposition differentials (see also [11]). They can be divided into non-amplified and amplified systems. Non-amplified means that there is at least one half of the clutch linked directly to the drive shaft. In amplified systems, on the other hand, a planetary stage is used to transmit the clutch torque. For the example in ③, this results in an amplification of 7 for the selected radius limit. Amplified systems use electromechanical or electromagnetic control, non-amplified systems usually require electrohydraulic control (for example [12 to 14]). Another advantage of this design is that there are no meshing gears when driving straight ahead. On the other hand, the speed differential of the clutch complies with the wheel speed. In a shaft-to-cage system, the generated actuator torque is supported by the differential carrier, while it is supported by the second half shaft in shaft-to-shaft systems. In non-amplified systems, the differential torque can therefore be doubled. The advantages of non-amplified systems include easy controllability as well as avoidance of losses caused by low slipping speeds when driving straight ahead. On the other hand, meshing always occurs with straight-ahead driving.

The loss factor P indicates that power loss of the clutch is the product of actuator torque and clutch speed and it is identical for all designs. This applies for any superposition differential.

The most important issue results from the performance ratio P depending on the curvature radius limit, which is also represented in ⑤. The narrower this radius, the higher are the friction losses in the clutch package. This in turn affects the dimensions of the discs and the cooling concept. The loss factor P increases progressively especially in the range of the turning circle, which requires a compromise between friction losses and availability.

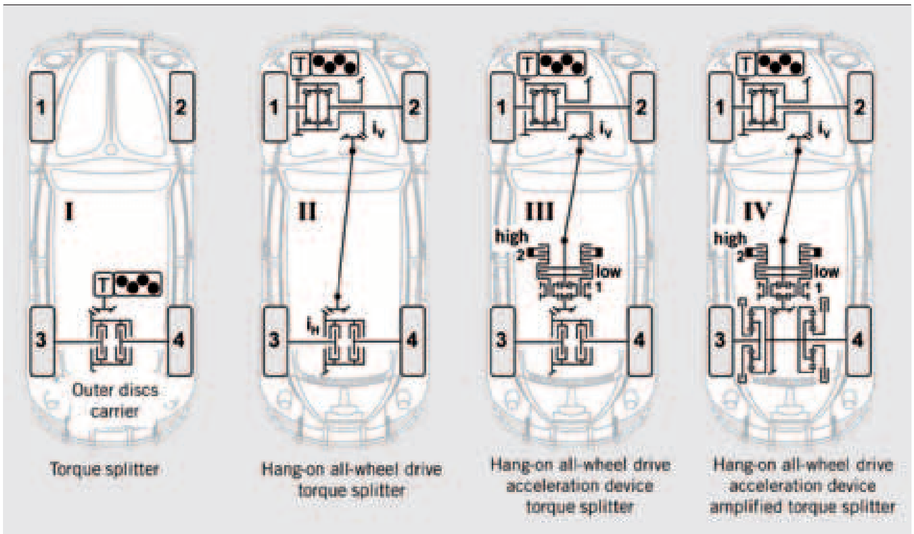
Amplification = ratio of wheel torque difference to actuator torque	$G = \frac{M_a - M_b}{M_{bc}, M_b}$
Slipping ratio = normalized slipping speed at straight-line driving	$D = \frac{\omega_{gr} \cdot \omega_b}{\omega_a}$ $(\rho \to \infty)$
Meshing ratio = normalized meshing speed at straight-line driving	$W = \frac{\omega_{b,a,c} - \omega_b}{\omega_a}$ $(\rho \to \infty)$
Power input factor = normalized power input during actuation	$P = \frac{D}{G}$



❺ Objective parameters for the characterisation of superposition differentials

Non-amplified				Amplified			
Cage-to-shaft		Shaft-to-shaft		Cage-to-shaft		Shaft-to-shaft	
Sun gear a to b, clutch B	$z_{ab}(\rho_{gr} = 5.5 m) = 0.88$ $G_{bB} = 1$ $D_B = 0.14$ $W_b = 1.14$ $P_B = 0.14$	Sun gear a to b, clutch B	$z_{ab}(\rho_{gr} = 5.5 m) = 1.33$ $G_{bB} = 1.75$ $D_B = 0.24$ $W_b = 0.75$ $P_B = 0.14$	Sun gear a to b, clutch A	$z_{ab}(\rho_{gr} = 5.5 m) = 0.88$ $G_{Ab} = 7.00$ $D_A = 1$ $W_b = 0$ $P_A = 0.14$	Sun gear a to b, clutch A	$z_{ab}(\rho_{gr} = 5.5 m) = 0.75$ $G_{Ab} = 7.00$ $D_A = 1$ $W_b = 0$ $P_A = 0.14$
Sun gear a to c, clutch A	$z_{ac}(\rho_{gr} = 5.5 m) = 1.17$ $G_{bA} = 1$ $D_A = 0.14$ $W_c = 0.86$ $P_A = 0.14$	Sun gear a to c, clutch A	$z_{ac}(\rho_{gr} = 5.5 m) = 0.75$ $G_{bA} = 2.33$ $D_A = 0.33$ $W_c = 1.33$ $P_A = 0.14$	Sun gear a to c, clutch B	$z_{ac}(\rho_{gr} = 5.5 m) = 0.57$ $G_{Bb} = 7.00$ $D_B = 1$ $W_c = 0$ $P_B = 0.14$	Sun gear a to c, clutch B	$z_{ac}(\rho_{gr} = 5.5 m) = 0.57$ $G_{Bb} = 7.00$ $D_B = 1$ $W_c = 0$ $P_B = 0.14$

❻ Objective parameters of different superposition differentials



❼ Versions of torque splitters

The amplification for a downsizing of the actuators is also limited by availability.

The basic characteristics of a lateral distributing superposition differential do not depend on whether they are used in a single-axle or all-wheel-drive vehicle since the yaw moment generation is independent of the vehicle state. The efficiency, however, can be increased to the maximum by utilizing the interactions resulting from rear axle use. This will be discussed in the following section.

The kinematic behaviour of torque splitters mainly depends on the selected drive concept. This will be explained for the versions represented in ❼.

The first version is a rear-axle drive. The external disc carrier has to spin faster than the outside rear wheel to achieve torque transfer that increases the agility. In this case, the outer disc carrier is only connected to the manual transmission and the engine. The speed increase required for the external disc carrier can therefore only be achieved if the engine load is increased. In traction mode, there are no kinematic limits, but the maximum torque transfer complies with the final drive input moment. The inward yaw moment cannot be maintained without engine load.

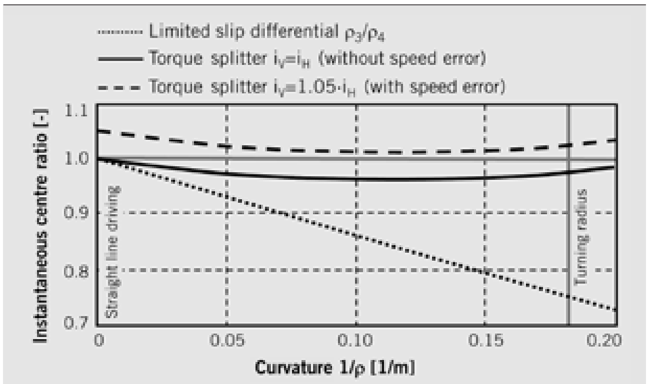
The second version is a hang-on all-wheel drive. Both clutches of the torque splitter are used for longitudinal as well as lateral distribution. The outer disc carrier is connected to the front axle; the following instantaneous centre ratio results for torque transfer to the outside rear wheel:

EQ. 17
$$\lambda_P = \frac{\rho_1 + \rho_2}{2 \cdot \rho_4} \cdot \frac{i_V}{i_H}$$

❽ represents the instantaneous centre ratio for identical and different final drive ratios i_V and i_H. An error in the final drive ratio results in a speed error, which allows the generation of inward yaw moments that are independent of traction slip on the front axle, resulting in a instantaneous centre ratio bigger than 1. It is a disadvantage that this results in a speed difference for the clutch when driving straight ahead and therefore the losses caused by clutch slipping increase.

In the third version, the speed error can be switched on or off to increase the drive train efficiency is. A planetary stage is used for this purpose. The system provides two modes, the low range and the high range mode. In the low range mode, the planet carrier and a sun gear are locked by clutch 1. The system rotates as a block and only the bevel gear ratio is effective. In the high range mode, clutch 1 is open and the planet carrier is fixed to the housing through clutch 2. A double spur gear stage is connected ahead of the bevel gear pair and generates the speed error. The spur gear stage is called acceleration device.

In the fourth version, the tor que splitter is used as anamplified system; its effect has already been discussed in relation to the superposition differentials. It has to be taken into account that the amplification has to increase the required final drive speed error, which in turn has to comply with the radius limit. This system also corresponds to the system described in [5]. Finally, versions 3 and 4 do not differ in terms of the vehicle dynamic function.



❽ Instantaneous centre ratios of different all-wheel drive systems

4 INTERACTIONS WITH VEHICLE DYNAMICS

The kinematic behaviour determines the basic ability of transferring drive torque to the outside wheels. However, the actual wheel speeds only result from the consideration of the traction slip. In connection with the dynamic wheel loads, interactions between longitudinal and lateral distribution systems occur, which have been analysed with a non-linear dual track simulation model [15]. ❾ shows the curve of the steering wheel angle in relation to lateral acceleration as well as the percentage of the drive torque at the rear axle for different final drives to illustrate this. A centre locked all-wheel drive with different rear axle gears is considered for this purpose. The centre locking can be achieved through a torque-sensing or controlled differential lock and a hang-on all-wheel drive clutch. The all-wheel drive with conventional rear axle differential is characterized by understeering.

The variant with the superposition differential illustrates the basic effect of lateral drive torque distribution.

Torque transfer to the outside wheels has two major effects: on the one hand, the asymmetric driving force generates a yaw moment, which supports a yaw reaction and reduces the steering wheel angle requirements. On the other hand, the driving force distribution is adjusted to the dynamic wheel loads, so the maximum lateral distribution is increased significantly. Comparing the drive torques of the rear axle is also interesting. With an open rear axle differential, a maximum of 50 % of the overall torque is transferred at the rear axle; with a superposition differential it amounts to 75 %. This is due to the fact that slip at the inside rear wheel is significantly reduced through the asymmetric driving force, so the rear wheel speed in comparison to the front wheel speed is reduced. More drive torque is transferred to the rear axle due to the centre locking, which indirectly further reduces understeering.

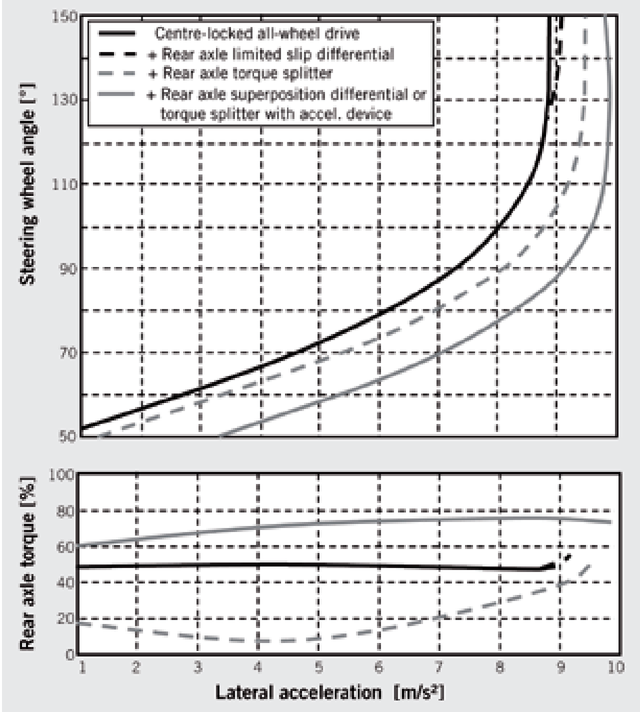
The maximum effect of a lateral distributing drive train system is therefore achieved with rear axle installation and in combination with in an inter axle locking all-wheel drive system. Furthermore, the rear axle application has advantages in terms of package and avoids interactions with the steering system.

With the rear axle limited slip differential, the desired effect is only achieved at the adhesion limit, when the inside wheel passes the outside wheel due to the relief and the instantaneous centre ratio is exceeded. In terms of an increase in agility, it has only limited effect, because under normal road conditions this requires a sporty driving style.

The torque splitter without speed error achieves the maximum yaw moment when the drive torque is only applied at the outside wheel. To exceed the instantaneous centre ratio traction slip on the front axle is needed. This occurs with increasing lateral accelerations. In comparison to a limited slip differential the instantaneous centre ratio is closer to one, so that small inward yaw torque can already be generated at the beginning of the manoeuvre. But only with high lateral accelerations they achieve a significant effect. The maximum yaw moment depends on the engine load, so the lateral distribution level of superposition differentials is not reached. It has to be taken into account for simple torque splitters and differential locks that the inward yaw moments cannot be maintained in case of load changes. This is only possible with superposition differentials and torque splitters combined with an acceleration device.

5 SUMMARY

This article summarises essential design objectives for lateral distributing drive train systems. For the generation of torque differentials independent of the vehicle state, speed errors have to be generated, which in turn has negative effects on the drive train efficiency. Lateral distribution is most effective when used with a rear axle gear of an all-wheel-drive vehicle since all primary and secondary effects are amplifying each other here and since interactions with the steering system occurring at the front axle as well as package problems can be avoided. An inter-axle locking device is required to achieve maximum benefit from these effects.



❾ Interaction of longitudinal and lateral distribution on circular track during acceleration (2m/s²)

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