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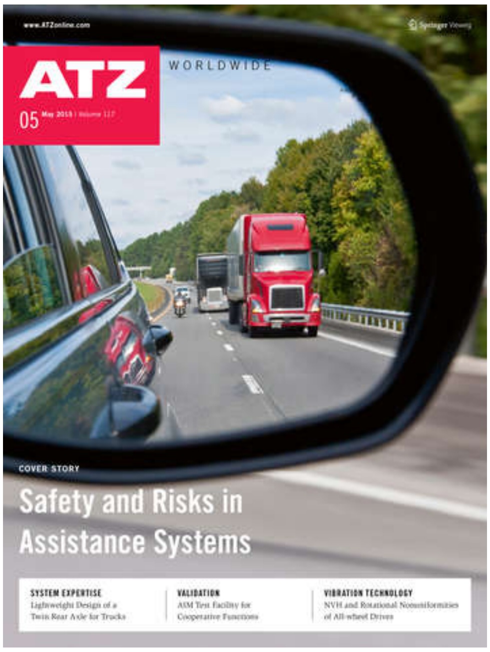

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COVER STORY

Safety and Risks in Assistance Systems

SYSTEM EXPERTISE
Lightweight Design of a Twin Rear Axle for Trucks

VALIDATION
AIM Test Facility for Cooperative Functions

VIBRATION TECHNOLOGY
NVH and Rotational Nonuniformities of All-wheel Drives

CONTENTS

COVER STORY

Safety and Risks in Assistance Systems

On the one hand, driver assistance systems create added value, for example by supporting motor cyclists during braking and accelerating. Or when a camera-monitor system replaces the six rear-view mirrors on a truck, making life easier – and safer – for the truck driver. On the other hand, these electronic systems may also create certain risks, and these need to be addressed both technically, with regard to functional safety, and legally by the Vienna Convention if autonomous driving is to become a reality one day.

COVER FIGURE © Carolyn Franks | fotolia
FIGURE ABOVE © Continental

Braking Point

Dear Reader,

By the year 2020, autonomous cars will be a common sight on our roads, with their drivers free to relax and read a newspaper or send a few emails – at least that is the brave new world envisioned by various car makers and suppliers. We have every right to doubt this optimism, as decades of research are still required before humans can be replaced behind the wheel.

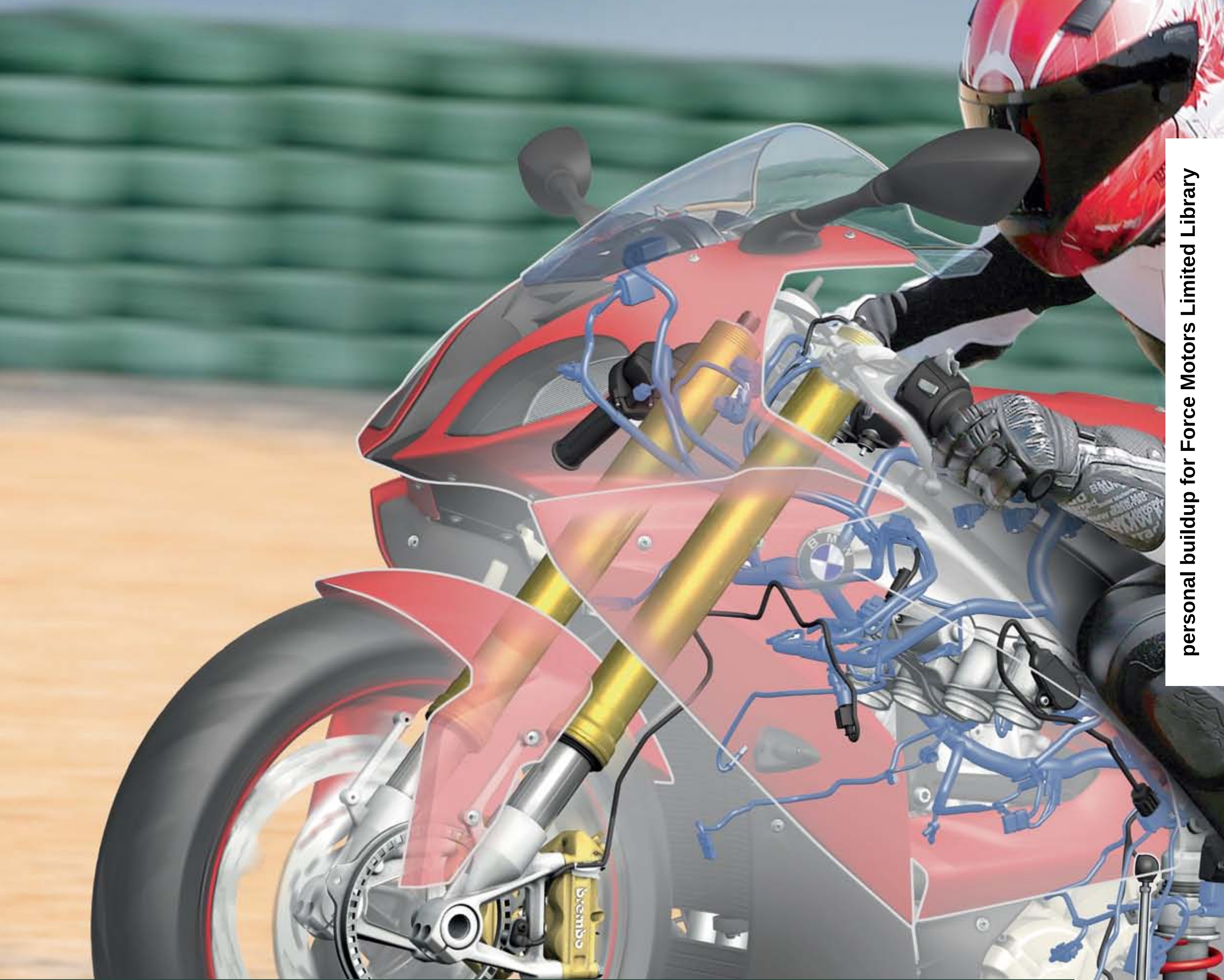
What are putting the brakes on the introduction of automated driving are not so much the underlying technology, the costs and the infrastructure. Questions of customer acceptance as well as the legal and political framework have not been finally decided, but at least they are on the agenda. Far more serious are the technical obstacles in detail, which necessarily lead to a more conservative assessment of the roadmap towards autonomous driving. More than ever before, the focus is on the functional safety of some of the systems involved.

In concrete terms, it is the semiconductor chips that are currently causing the greatest headaches for car manufacturers. At the moment, OEMs have to rely on products from consumer electronics, which are not necessarily suitable for tough continuous operation in vehicles. This also applies in particular to the safety-relevant functions in the cameras used for driver assistance systems, and quality managers in the automotive industry are already sounding the alarm. ATZ and its sister magazine ATZelektronik have looked at this subject in detail. The cover story of this issue of ATZ provides an interesting overview of the topic. Throughout the year, ATZelektronik will often examine the problem of the functional safety of consumer electronics in vehicles.

One thing is certain: the integration of consumer electronics into cars will require the automotive industry to refocus on quality standards. Interestingly, it is the semiconductor manufacturers above all who are warning of the risks. They have formed a ZVEI working group aimed at defining the categories relevant to development and production in a dialogue with OEMs in order to identify potential risks as early as possible and in a targeted manner. Initially, this process will not speed up the introduction of automated driving but will slow it down. But it is nevertheless an important one, as otherwise it will be the customers themselves who will refuse to accept autonomous vehicles.

Best regards,

Dr. Alexander Heintzel
Editor in Chief
Wiesbaden, 20 March 2015



Functional Safety for E/E Systems in Motorcycles

ISO 26262 rule provides the guiding principle behind the safety-based development of electrical and electronic systems. Originally developed for the passenger car sector, this standard is currently being adapted for motorcycles. BMW Motorrad explains the specific requirements for two-wheel vehicles and, working from this, determines requirements for the revision of ISO 26262 for motorcycles. As an example an E-throttle system serves for safe development.

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WHAT REQUIRES ISO 26262 AND WHERE IS IT TO BE APPLIED?

Safety-related vehicle functions for electrical and electronic systems (E/E systems) are becoming increasingly common in motorcycles. They contribute on the one hand to vehicle safety and make it possible to adapt the vehicle's characteristics (dynamic mode, rain mode, etc.). On the other hand, however, these systems can pose a risk of malfunction. Development in accordance with state-of-the-art safety is necessary to control these risks, **FIGURE 1** shows a selection of safety-related E/E systems for the example BMW R 1200 GS [1].

At BMW Motorrad, the "area of application" of functional safety is described by means of extended model of the traction circle, **FIGURE 2**. The vertical vector (green) is the longitudinal force (proportionate to the acceleration) of the vehicle. The horizontal vector (green) describes the lateral forces. The vehicle system is stable as long as the product of adding the two vectors (green, dotted) together is inside the green circle (point ① in **FIGURE 2**).

If, for example, undemanded acceleration of the vehicle occurs due to a malfunction of the electronic throttle (E-throttle) system, this acceleration is added to the normal function as an additional vector (red). This causes the vehicle system to cross the limit into the yellow, uncontrolled area of the vehicle. This is referred to as a safety-critical malfunction (point ② in **FIGURE 2**).

The question of whether the vehicle remains controllable in the event of a malfunction depends on how quickly the system detects this safety-critical malfunction and returns it to a safe state by technical means (for example safety mechanisms) (point ③ in **FIGURE 2**). This is expressed by the yellow vector.

This relationship offers a clear description of the work area of functional safety. Motion-based functions such as E-throttle systems are monitored by safety functions in the hardware (HW) and software (SW). These ensure that malfunctions are detected and that the vehicle is returned to a controllable, safe state in the event of a fault, **FIGURE 2**.

The development of these safety functions is described by ISO 26262 according to state of the art. This requires the cases of faults to be analysed for safety-related E/E functions and safety goal to be defined to enable these risks to be avoided.

Based on the E-throttle example, the fault in the acceleration function must be considered in the context of safety-related development, **FIGURE 3**. If this causes a malfunction, then the safety goal is violated. The thresholds for violations of the safety goals and the associated fault reaction time for a return to a safe state must be defined on a vehicle-specific basis.

These safety goals are to be proven at a technical level with safety functions. The safety goal achievement must be confirmed according to the standard through validation and verification tests as part of development.

The task of functional safety is the detection and control of malfunctions in

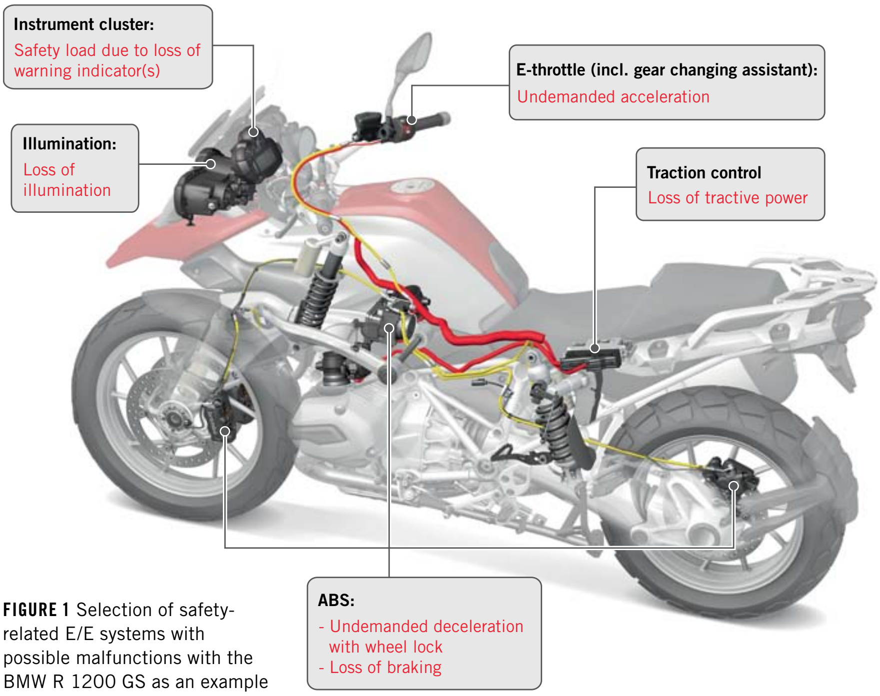


FIGURE 1 Selection of safety-related E/E systems with possible malfunctions with the BMW R 1200 GS as an example

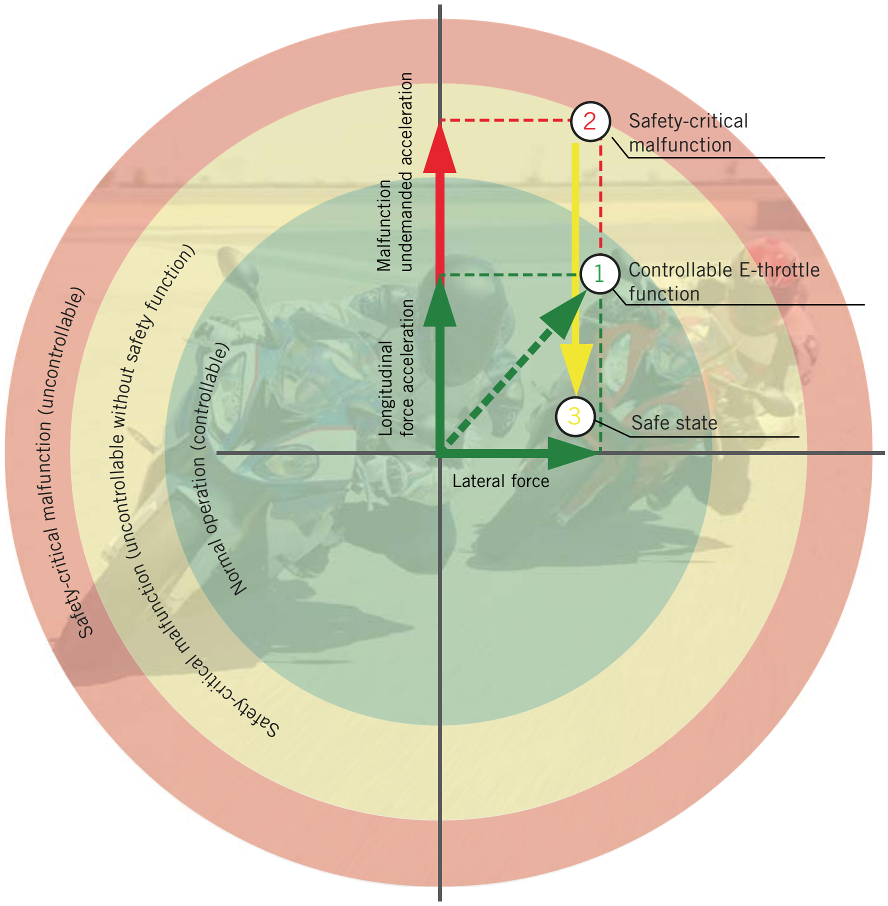


FIGURE 2 Riding situation “acceleration when banking”: circular model analogue to traction circle for functional safety at BMW Motorrad, developed from the traction circle diagram; this describes the relationship between the E-throttle function ①, the occurring malfunction ②, and the safe status ③ [2]

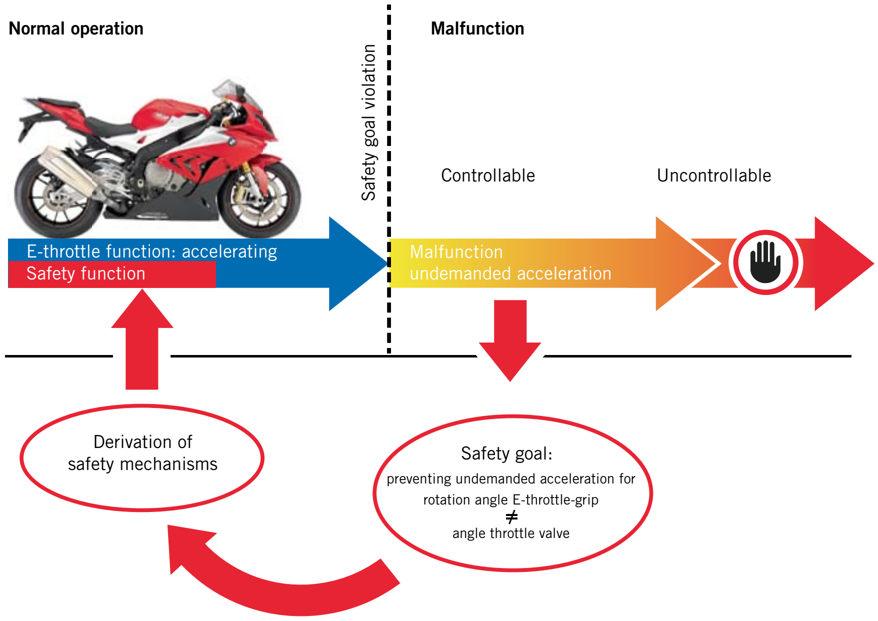


FIGURE 3 Implementation cycle of a safety-oriented E-throttle development: working range of the normal function with safety-related monitoring function for the "undemanded acceleration" fault; threshold for violations of the safety goal; formulation of the safety goal for this malfunction, derivation of a safety mechanism and technical implementation as part of the E-throttle function [2]

E/E systems. ISO 26262 placed demands on the safety-oriented development process and the technical layout of the E/E systems.

CURRENT REQUIREMENTS AND SPECIFIC ADJUSTMENTS FOR MOTORCYCLES

ISO 26262 has been the valid standard for cars since 2011. It has established itself as the basis for safety-oriented development in the automobile sector of the BMW Group. This is why BMW Motorrad is also developing technically comparable systems based on this standard. It was possible to gather experience based on applicability in the motorcycle industry. It became clearly apparent that the existing ISO 26262 standard provided a good basis for safety-oriented development, but that the specific requirements of motorcycles needed to be taken more into account. For this reason an ISO working group was established for motorcycles (ISO/TC22/SC38/WG3) in the industry which revised the standard for motorcycle development in line with the internationally established state of the art.

The most important point in the revision was the hazard analysis and risk assessment in part 3 of the standard. In future the risk classes of a safety-related E/E system for motorcycles will be expressed by the Motorcycle Safety Integrity Level (MSIL). This classifying makes it possible to quantify the specific risks to motorcycles from malfunctions and to determine the appropriate requirements for the design of safety-related systems from this.

Based on hazard analysis and risk assessment as specified in ISO 26262, a motorcycle-specific evaluation basis was drawn up for the three evaluation parameters severity (S), exposure (E) and controllability (C).

Thus, a worldwide accepted standard for protective clothing for riders was agreed as the first step in finding a basis for evaluating severity. In the second step, all the accident data available from the OEM was analysed and used to produce uniform evaluation specifications.

An evaluation of the probability of the motorcycle-specific road situations, such as banking, was carried out by analysing the usage profiles provided by manufacturers worldwide. In comparison with cars, particular attention was paid to the differentiated usage patterns of motorcycles, for example in relation to night time use, restricted use due to weather conditions or usage specific to particular motorcycle types (for example enduro rides).

The controllability of a two-wheeled vehicle which is by its nature physically unstable, is much more dependent on the rider than that of a car. This was taken into consideration in a classification table covering controllability. This was supplemented with examples and specifications for evaluation methods and techniques for determining controllability classes. In addition, the qualification of the assessors (expert riders) was formulated in a separate section.

Based on this evaluation specification for the S, E and C parameters, the current revision level of the standard, part 3 arrives at a risk classification according to MSIL in four risk classes (A to D; D is the highest risk classification). Depending on the classes, this gives rise to requirements in relation to the development process, layout and associated validation and verification tests of the safety-related E/E systems. These are described in part 4.

Part 5 and 6 of the standard describe the requirements for the development of hardware and software, **FIGURE 4**. These parts of ISO 26262 have been revised by the working group over the last three years. The aim was to anchor the internationally established state of the art in relation to development processes and technical solutions of motorcycle industry.

These amendments should be available in the form of a Publicly Available Specification (PAS) by 2015 and will be incorporated in the revision of ISO 26262 (Revision 2). This process will be supervised on the German side by a VDA working group.

DERIVING SAFETY GOALS FOR MOTORCYCLES

Safety-oriented development based on the described hazard analysis and risk assessment is determined through the safety classification (MSIL) for a system. Safety goals for the system are derived from this. Depending on this classification, the standard makes demands that can be divided into three blocks for simplicity:

1. The documentation requirements of ISO 26262 include the definition of safety responsibility and planning of safety activities in the project as a description of the functional and technical safety concept with the associ-

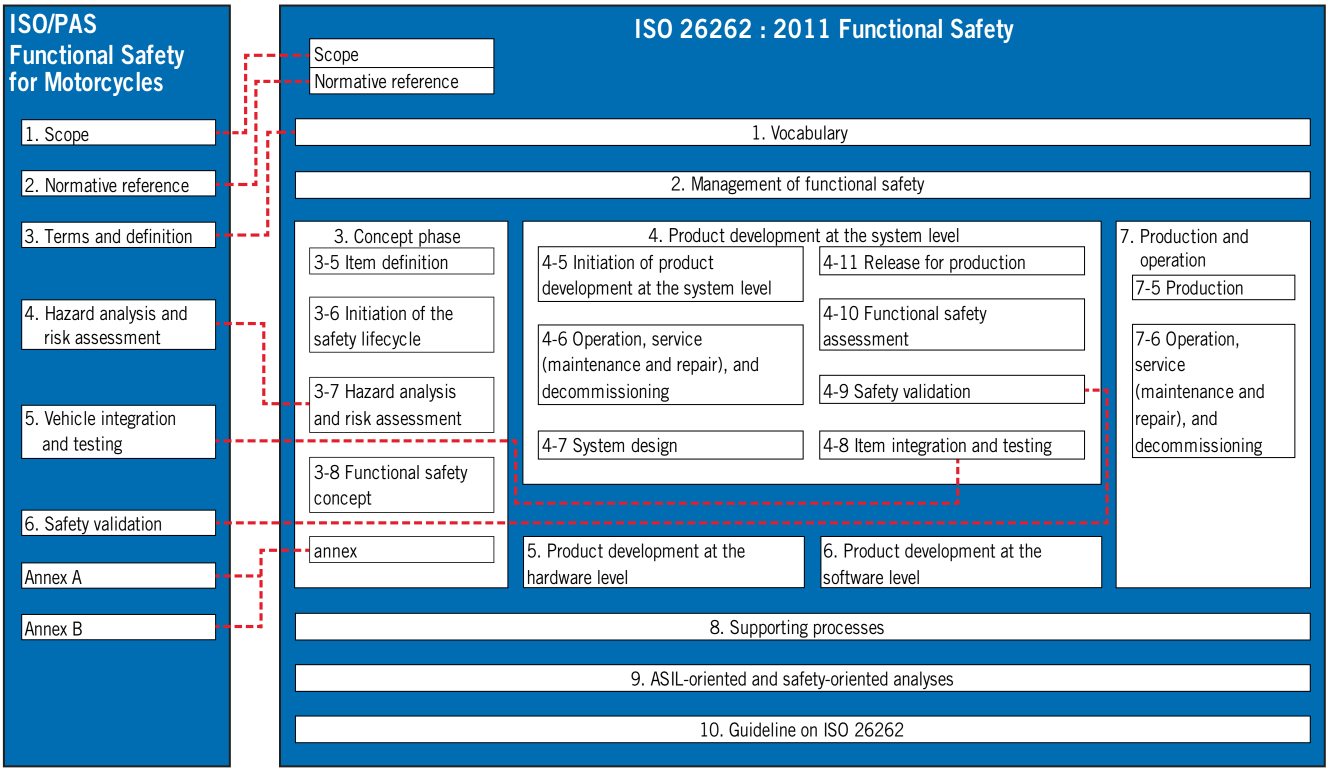


FIGURE 4 Summary of ISO 26262 and the amendments drawn up for motorcycles aspects with assignment to the existing ten parts of the standard [3]

ated interfaces (HW/SW interface). In addition, it is necessary to plan and document tests for safety activities and the attainment of their goals. Transparent documentation management for all process products provides the basis for comprehensive verification of all safety activities in line with the standard.

2. The standard requires analyses in order to verify the technical safety concepts. These depend on the MSIL. In detail these are FMEA (for fault analysis), methods such as FMEDA (for determining the probability-based metrics for random hardware faults) and FTA (for determining failure rates and establishing the degree of control of simple faults).
3. The basis for standards requirements is the risk-dependent layout of the HW and SW. Here the standard requires for technical configurations, such as component and signal path redundancies or independence of hardware components or software monitoring solutions. It is necessary to prove the effectiveness of all measures by means of tests on component, system and vehicle level.

Requirements in relation to permissible residual failure rates exist for the HW configurations. In addition, the detection and control of single-point faults, multiple-point faults and latent faults are required. Part of this standard involves monitoring this safety-oriented development process by means of reviews and assessments according to the dual control principle and confirming the attainment of the goals in a safety case summary.

The common theme in all of the required activities is end-to-end traceability of safety requirements, beginning with the safety goal and continuing until the confirmation of the implemented safety function in the vehicle. The development process and the associated safety-oriented development can be clearly shown as a V development model, **FIGURE 5**.

APPLICATION OF ADAPTED ISO 26262 IN PRACTICE

An E-throttle system will be described as an example of safety-related development for motorcycles. The basic data is provided by the hazard analysis and risk assessment for the system using the engine-specific assessment requirements.

One of the safety-related system malfunctions is "undemanded acceleration". The following situation is evaluated as part of hazard analysis and risk assessment: secondary road, medium speed of 50 to 100 km/h. In order to assess the damage, the risk must be evaluated according to the standard from the following parameters: severity, exposure and controllability. The MSIL is calculated from this.

Accident statistics provide the basis for the severity (S-table in **FIGURE 6**) of the malfunction. A fall in the situation mentioned before is often associated with life-threatening to fatal injuries. In addition, when travelling on secondary roads there is also a risk of collision, for example with barriers or oncoming vehicles.

The exposure (E-table in **FIGURE 6**) involved in travelling on a secondary road is evaluated with the help of the usage profile. The basis for this is provided by the analysis data from the vehicle analysis and the usage profiles of the vehicle classes determined worldwide among all OEMs. Accordingly, the figure for a super sports motorcycle based on the operating period in the time range can be set at > 10 % according to the standard.

If the E-throttle fails in this situation, it is necessary to analyse the extent to which the rider can take action to avoid danger. This evaluation is in accordance with the controllability parameter (C-table in **FIGURE 6**). In order to prevent "undemanded acceleration", it is possible to declutch or to interrupt ignition by pressing the emergency stop button. The question of whether the response time will suffice is model-specific and depends on the road conditions. Factors such as engine output, the layout of the drivetrain and the level of experience of the rider are to be taken into account. The standard requires test rides and expert assessments. In practice, the evaluation is performed by expert riders.

The addition of evaluation parameters S3, E4 and C2 produces classification MSIL C (reference: ISO 26262/PAS 19695. ver 6.3.1, table 6). The safety goal for the system is formulated as follows: "The E-throttle system must detect that the motion impulse on the throttle grip and the throttle actuator setting do not match and return the system to a safe state with a fault reaction time to be defined". This safety goal is to be developed according to MSIL C requirements.

A functional safety concept will be drawn up according to these requirements. This is a documented concept design for how the safety goal can be achieved at functional level.

For the E-throttle system, **FIGURE 7**, this can mean, for example, that the sensors for the motion impulse and the throttle actuator position need two signal channels. The signal channels are read into the engine controller and are subjected to a plausibility check. In order to ensure integrity, a multi-layered software concept has developed in the drive area [4].

The technical safety concept developed in the next step describes the structure and architecture of the safety system in detail, right down to the safety obligations for the individual components. The standardising requirements of safety-related systems are to be implemented here (HW redundancies, independences from HW modules, SW monitoring functions, etc.).

The interfaces for the systems are also to be described (hardware/software interface) and appropriate tests for the safety function are to be defined. The analysis methods demanded by the standard (for example FMEA, FTA, FMEDA) form an important element in the development of the safety concept.

The functional and technical safety concepts developed in the concept phase are tested at component, system and vehicle level in the confirmation phase and validated with the safety goals and verified. This generally occurs on system and component level on test benches or by means of functional simulations. The confirmation of the fault reaction times for controlling the "undemanded acceleration" system fault by means of injecting a fault during a road test makes it possible to prove the attainment of the safety goal at overall vehicle level. The full implementation of the requirements of the standards even in relation to documentation, review and assessment checks will be definitively described in the safety case summary.

FUTURE CHALLENGES

The number of safety-related E/E systems in motorcycles will grow further in the coming years, **FIGURE 8**. They are an important element in vehicle safety and product differentiation, as well as an innovation feature for all motorcycle manufacturers. What began a number of years ago with the development of the E-throttle, traction control and ABS is set to continue in a range of other E/E systems.

Thus, on the one hand, system improvements such as ABS or light for motorcycle-specific applications (banking) as well as additional functions and

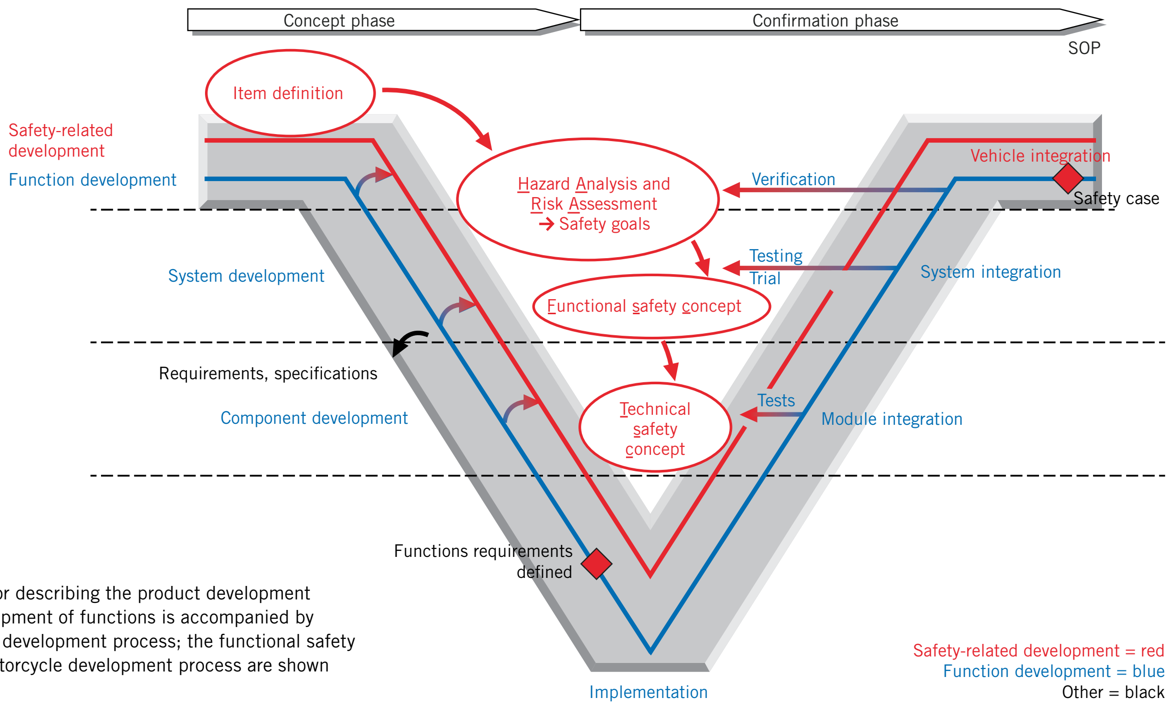


FIGURE 5 V model for describing the product development process: the development of functions is accompanied by the safety-oriented development process; the functional safety activities in the motorcycle development process are shown in extract form

Severity	S0	S1	S2	S3
Injuries	None	Light and moderate	Severe and life-threatening (survival probable)	Life-threatening (survival uncertain), fatal

S: S3 ➔ Life-threatening or fatal injuries ... crash barriers, oncoming traffic

Exposure	E1	E1	E3	E4
Probability of exposure regarding duration in operational situations	Incredible	<1 % of average operation time	1-10 % of average operation time	>10 % of average operation time

E: E4 ➔ High probability

Controllability	C0	C1	C2	C3
Ability of people at risk to avoid harm	Controllable in general	Simply controllable	Normally controllable	Difficult to control or uncontrollable

C: C2 ➔ Normally controllable ... brake, declutch, emergency stop

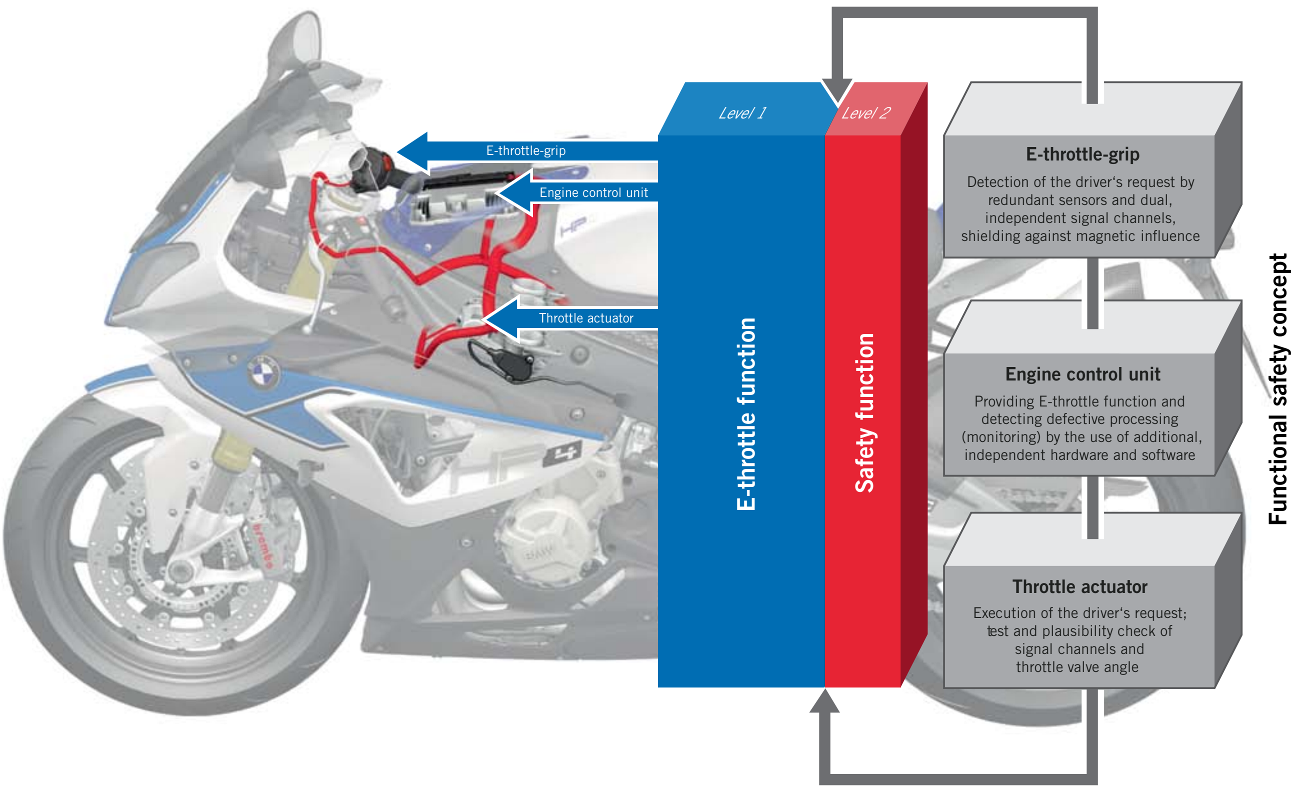
FIGURE 6 Demonstration of severity (S-table), exposure (E-table) and controllability (C-table) for the "undemanded acceleration" system malfunction

comfort features (gear changing assistant, active suspension functions, etc.) that have to be developed according to the requirements of functional safety.

At the same time, the motorcycle industry is starting to get involved in electric mobility on the other hand. Functional safety in relation to the development of electric drives, recuperation and energy storage plays a key role in safe products.

If a forecast for the future is derived from safety-related passenger car systems, then all possible kinds of driver assistance systems, connectivity topics and airbag systems would be theoretically conceivable for use in motorcycles. In future, many of these systems will need to exchange data with databases or systems outside of the vehicle. The dissemination of this "motorcycle to environment" message via vehicle interfaces is an additional challenge for the development of future safety-related systems.

The revision of ISO 26262 for motorcycles established the basis for a meaningful and forward-looking standard. The



Result:
Rotation angle E-throttle-grip = angle throttle valve ➔ OK
or
Rotation angle E-throttle-grip ≠ angle throttle valve ➔ not OK

FIGURE 7 E-throttle system of BMW S1000 RR: the E-throttle function is monitored by the safety function which is implemented according to the functional safety concept described

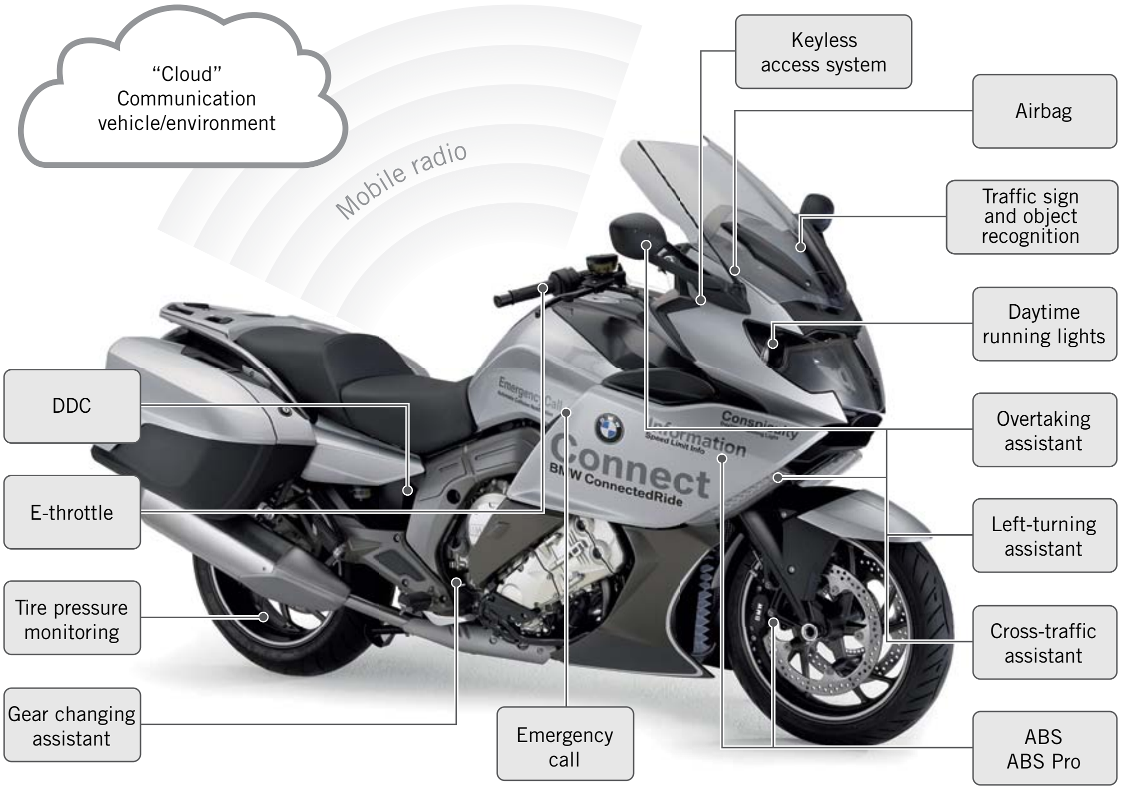


FIGURE 8 Examples of potential safety-related innovation topics for driver assistance systems

determination of motorcycle manufacturers not to permit unacceptable risks for the rider or the environment through safety-related E/E systems means that these systems will quickly become a key element in the product development process.

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Camera-Monitor System as Mirror Replacement in Commercial Vehicles

The goal of the new camera-monitor system (CMS) developed by MAN Truck & Bus is to ensure that the driver has an overview of the entire vehicle and its surroundings at all times. The system replaces all exterior mirrors by monitors which increases driving safety as the driver can see what is happening around him more quickly and more accurately. At the same time, omitting the exterior mirrors improves the drag coefficient, thereby saving fuel and protecting the environment. Thus, the three core topics in truck construction, namely safety, efficiency, and environmental protection, are all enhanced in an innovative way.

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NEW CONCEPT

The R&D Department at MAN developed this new concept for mirror replacement systems in close cooperation with the Institute of Ergonomics at the Technische Universität München, presenting it for the first time at the IAA Commercial Vehicles trade fair in 2014. The CMS combines the exterior mirrors on the driver's and passenger's sides into two monitor images, thereby focusing the driver's attention, as he no longer has to constantly switch between several mirrors on each side. Professional drivers are currently testing the system on public roads in the German state of Bavaria. Initial results are very positive.

TRUCK MIRRORS AND FUTURE MIRROR REPLACEMENT SYSTEMS

Six mirrors are currently required for commercial vehicles in the European Union. These comprise the two main side view mirrors (class II), the two wide-angle side view mirrors (class IV), as well as a close-proximity exterior mirror on the passenger's side (class V), and a front view mirror (class VI), **FIGURE 1** [1].

Currently, only class V and VI mirrors may be replaced by camera-monitor systems, whereby class V mirrors must be displayed permanently, while the front area (class VI) only needs to be displayed when driving straight on at a speed of up to 10 km/h (6 mph). Discussions are currently being held at the European level about approving mirror replacement sys-

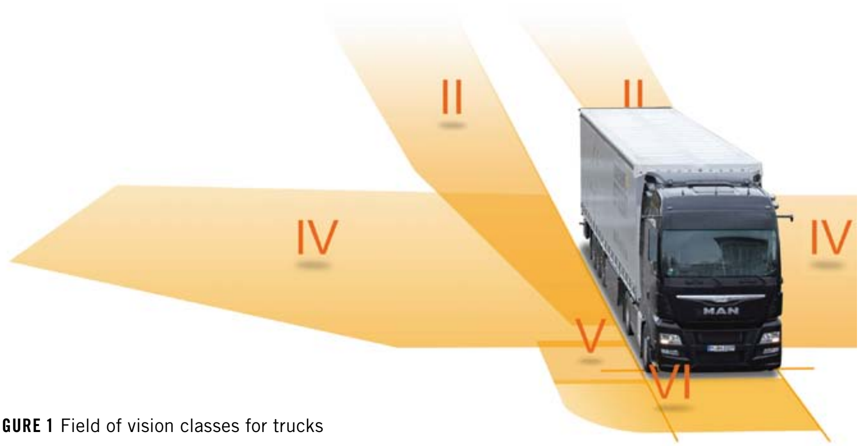

FIGURE 1 Field of vision classes for trucks

tems, based on the new draft of the standard ISO FDIS 16505 [2]. A modified UN-regulation No. 46 on indirect visibility is expected by 2016.

EYE AND COGNITION

In technical terms, the human eye as a sensory organ is a dual system comprising a high-resolution narrow-angle camera and a wide-angle camera with poor image quality [3]: the former is responsible for foveal (central) vision in a range of approximately 2°, allowing sharp perception of objects. Information in this range is perceived and processed consciously by the brain. The latter – also known as peripheral vision – allows extremely efficient perception of contrasts and movements, and is very sensitive to light. A widespread change in contrast (optical flow) perceived throughout the entire retina is interpreted as movement. This harmonious image flow does not trigger a saccade, a fast movement of the eye. However, if an object is moving relative to the main optical flow direction, a saccade toward that object is subconsciously triggered. Then, as soon as the eyes are focused on the object, it now lies in the foveal field of vision and can be consciously perceived and processed [3, 4, 5].

The peripheral detection of objects in the exterior mirrors is greatly impaired by the demands of the continuous optical flow. Therefore, the driver is responsible for looking at the mirrors regularly in order to discover environmental stimuli in time which would otherwise escape his peripheral vision.

The capabilities of foveal and peripheral vision are already being tested as part of the process of acquiring a truck driver's license [6]. This is because looking in the mirror provides the truck driver with relevant information on his own vehicle's position in relation to the other road users and allows him to assess pending movement sequences.

DRIVER SURVEYS AND TEST STUDIES

To provide the driver with an optimum display of the objects in his indirect field of vision, it is first necessary to analyse how he interacts with his current mirror system. Therefore, various studies were conducted with professional truck drivers under real traffic conditions. Here, both the directions of view as well as the upper body and head movements of the drivers were recorded, **FIGURE 2** [7, 8]. The results provide detailed information about mirror use in everyday and during specific driving situations. Main parameters included, for example, the duration of glances into the individual mirrors, glance duration away from the main viewing direction (eyes on the road), glance sequence, and the frequency of glance changes. Alongside these objective parameters, the drivers were also asked how often they used the mirrors. Together, subjective and objective data allow for an optimum design of new CMS.

First off, studies performed with conventional mirrors show that the acceptance of current mirror systems among drivers is very high. This is mainly due to their familiarity of use.

However, results also indicate that monitoring of all mirrors leads to long eyes-off-the-road times, shown both in preliminary studies with the digital human model RAMSIS and the driving studies described above, **FIGURE 2**. Reasons include the time that is required per fixation to recognise objects in a mirror, and also the time to perform the head and eye movements necessary to change from one fixation point in a mirror to

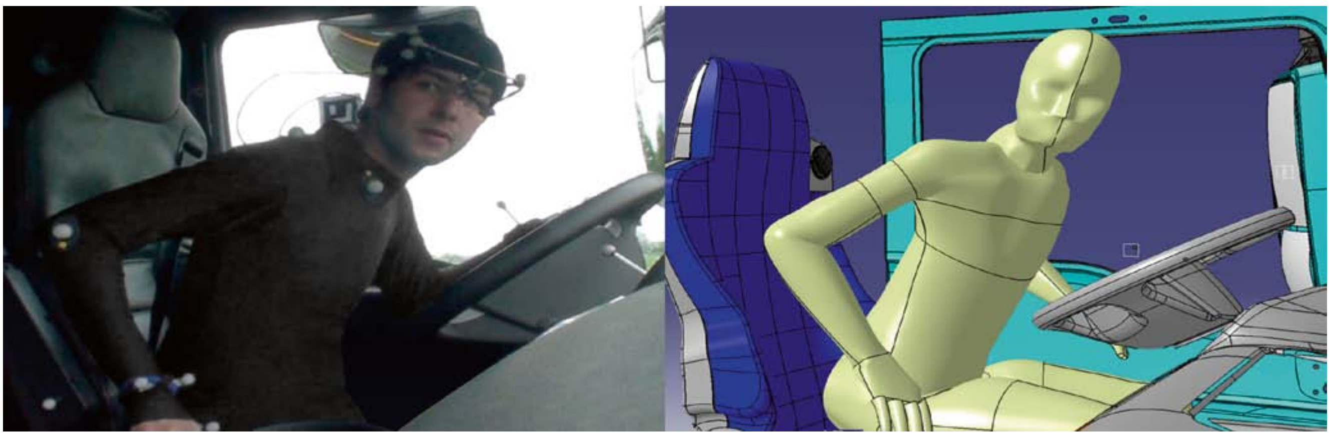

FIGURE 2 Analysis of upper body and head movement

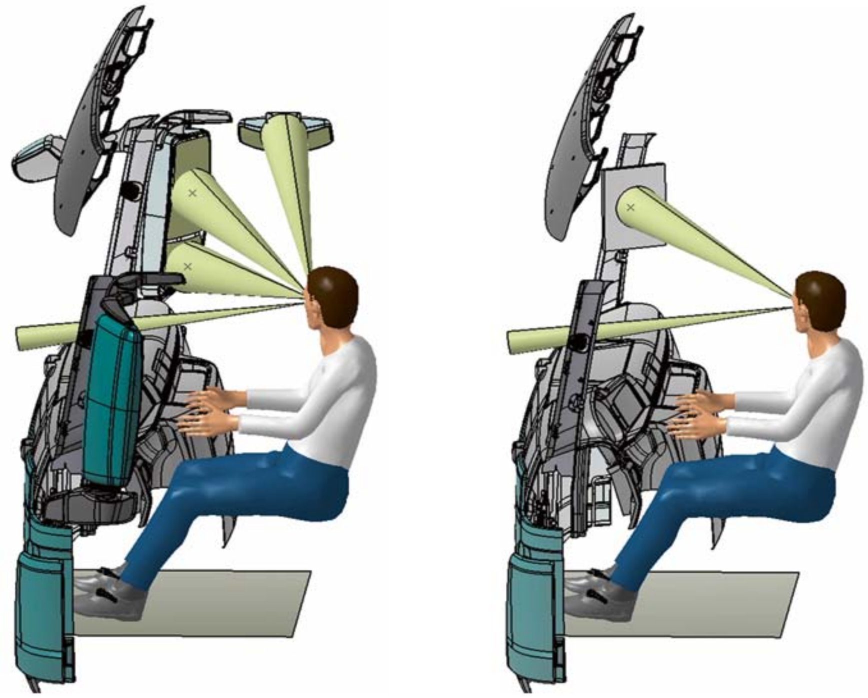

FIGURE 3 Eye tracking analysis: three glances into the mirrors (conventional system, left), one glance into the monitor (KMS, right)

another. If, for example, the driver checks all three mirrors on the passenger's side in succession, he must look away from the road for at least two seconds [9]. As a result, experienced drivers have developed strategies that allow them to monitor traffic conditions as effectively as possible under these difficult conditions. The strategies are specific to both drivers and situations, and are usually self-taught. However, even with these strategies in place it is often impossible for the driver to be aware of all that is happening around the vehicle in complex driving situations.

Thus, displaying only one intuitively understandable image per vehicle side can reduce the strain on the driver and significantly lessen the eyes-off-the-road times, **FIGURE 3**.

DISPLAY CONCEPT

In conventional CMS solutions, each mirror for side area monitoring of the vehicle is shown on a separate display. MAN, however, is investigating an innovative display concept. In this concept, the viewing areas of the main side view mirror, the wide-angle side view mirror and the close-proximity exterior mirror are combined into a single continuous display, **FIGURE 4**. Now the driver has to check only two monitors instead of five mirrors. The operating principle can best be explained using the example of an aspherical mirror of the type frequently used on automobiles: the image of the main mirror field is displayed without distortion on the monitor. On the outside of this undistorted area, there is a compressed area which represents the wide-angle area. The close-proximity exterior mirror area is displayed below these two areas. Thus, all requirements of the ISO FDIS 16505 standard with respect to magnification factors are met.

In addition to the described standard view presented to the driver in most driving situations, a manoeuvring view is also implemented in the MAN CMS, which is freely selectable by the driver when driving at low speed. In this view, the viewing area for one side is displayed on the monitor without distortions. The manoeuvring view can be of great assistance to the driver, for instance, in situations where the semitrailer or trailer is at a tight angle when manoeuvring, thereby masking the main viewing area, **FIGURE 5**. The manoeuvring view also provides the driver with a fast and undistorted view of what is taking place at the side of the vehicle.

In addition, when driving, an automatic switch-over function from standard to manoeuvring view was implemented for a defined articulation angle between the truck and semitrailer. If the driver manoeuvres through a tight bend or turns at a tight angle, the inner bend side is shown in the manoeuvring view as soon as the semitrailer masks the complete area of the class II mirror. Using this automatic switch-over function, the driver is guaranteed to be shown the optimal field of vision at all times.

INTEGRATION IN THE VEHICLE

Since the side of the truck and the visible area behind it leading up to the horizon must be captured and clearly presented to the driver, the cameras should be positioned as far at the front and as high as possible, taking into account aerodynamic criteria. This applies for both the driver's and passenger's sides [10].

Monitor positioning is considered separately for the driver's and passenger's sides: On the passenger's side, the monitor can be installed directly on the A-pillar. This way, visibility is not impaired by the system, but even greatly improved in comparison with conventional mirrors. In addition, the position also approximately corresponds to the usual

FIGURE 4 Integrating three side mirrors in one monitor

mirror position, making it unnecessary to change the direction of view when looking at the monitor compared with the mirrors, **FIGURE 6**.

However, due to age-related accommodation difficulties (presbyopia), positioning a monitor on the A-pillar on the driver's side can be unfavourable. Here, the eyes would be too close to the display, which might cause blurry vision particularly in older drivers [11]. Hence, the MAN CMS is positioned directly on the windshield, thereby realising the maximum monitor distance possible from the driver. The vertical position of the monitor is defined so that its bottom edge is slightly above the horizon from the driver's perspective and therefore does not impair direct visibility.

FIGURE 5 Manoeuvring view

SYSTEM BENEFITS

The intuitive layout of the image in the CMS enables the driver to easily assess objects in relation to his vehicle and to follow these objects beyond the boundaries set forth by the respective fields of vision of each individual mirror. Information is presented to the driver in a single continuous image that he otherwise would have had to assemble from three individual mirrors. This makes it easier for the driver to perceive what is going on at the sides and the rear of the vehicle, as less effort is needed for perceiving, processing, and integrating relevant information.

As another benefit, the driver no longer has to decide in advance which of the mirrors' fields of vision he wishes to check or in what order. He is provided with a simultaneous and compact overview of all fields of vision on both sides, thus significantly increasing his chances of peripherally perceiving objects compared with the conventional approach.

OUTLOOK

The MAN CMS prototype is currently being tested in driving trials of about 45 min lengths. Like in preliminary studies, both the eye movements and head movements of the truck driver are being recorded while driving on a defined route including freeway, highway, and urban sections. Initial evaluations show that test drivers quickly get used to the new system. This familiarisation phase is measured by so-called blind glances towards the no longer present left mirror. These are still registered frequently at the beginning of the test drives, but drop to zero after a short while. The eyes-off-the-road times and head movements are also reduced compared with the conventional mirror system. Evaluation of the subjective data underlines the acceptance of the camera-monitor system by the professional drivers: All test drivers stated in the survey that they could imagine using the system on a daily basis.

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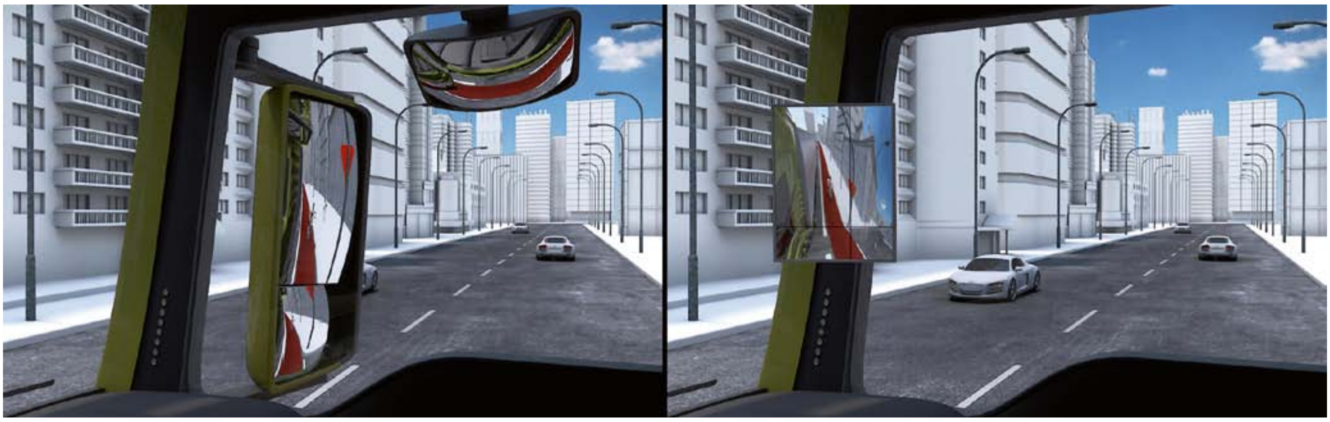
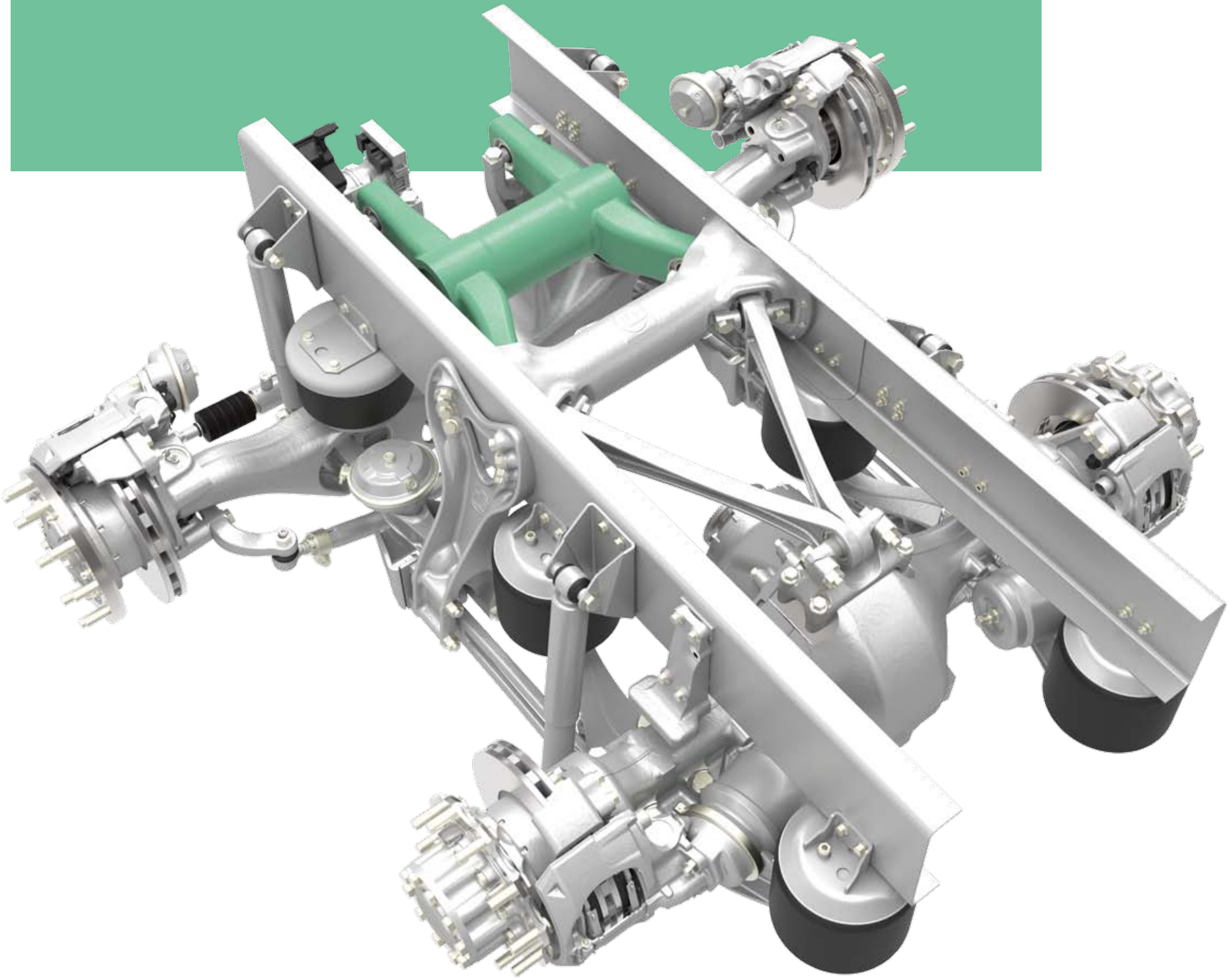


FIGURE 6 Improved direct visibility through a reduction in hidden areas

System Expertise and Lightweight Design – Concept for a Twin Axle for Trucks



Using the example of a twin rear axle for heavy trucks, ZF demonstrated the potential in commercial vehicle chassis for novel approaches in lightweight design. The advanced engineering project combines overall system optimisation with detailed mass-reduction approaches for the chassis system to achieve significant impact to vehicle performance. Some of the researched solutions – such as a further mass-optimised four-point link – are also transferable to other truck and passenger car applications.

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INCREASING EFFICIENCY

In recent years, lightweight design for truck applications has become increasingly important. Although lightweight design for increase of efficiency is already well-established for passenger car applications, these considerations are just starting to develop in the commercial vehicle sector. In this process, goals and statutory provisions regarding the reduction of carbon dioxide emissions have proven to be drivers as significant as economic considerations. With a view to the limitation of total vehicle mass, a reduced system mass would allow additional vehicle payload, which, in turn, will significantly increase cost-effectiveness via primary and secondary effects (for example fewer transports), in particular for mass transportation rather than volume transportation. In such a way, the fuel consumption per ton of transported cargo will be reduced.

Current approaches for lightweight design comprise all functional areas of trucks, from the engine to the driveline and the body. Recent efforts have shown that even the truck chassis accommodates a huge potential for mass saving efforts. In this context it is vital that an integrated system approach is adopted which is based on a holistic lightweight concept. Those methodologies only guarantee that the highest impact is achieved to the system in terms of mass, functionality, and cost.

In an effort to demonstrate the potential of a consistent and holistic lightweight design strategy in truck chassis, ZF has developed an innovative twin axle unit for heavy trucks as part of an advanced engineering project. The implementation and combination of all single measures results in a mass reduction by up to 950 lbs (430 kg) in comparison to a traditional reference vehicle. As an example of an integrated lightweight design concept, a cast axle body, an GFRP four-point link as well as an optimised bolt connection will be presented in more detail below.

LIGHTWEIGHT DESIGN AND SYSTEM APPROACH

The different lightweight design approaches are tightly interwoven. However, in public perception material lightweight design is frequently recognised as key approach in lightweighting. The focus of this approach is the substitution of conventional materials (in particular steel) with alternative materials having high specific properties (lightweight materials). As increasingly acknowledged, the substitution of materials must be supplemented and supported by other lightweight approaches, in particular conceptual lightweight design (as integration of additional functions) as well as geometric lightweight design (as topology optimisation).

With a view to this insight, ZF pursues a holistic lightweight approach with systematic consideration of all different lightweight design strategies. In comprehensive potential analyses, new concepts and methods for construction of commercial vehicles and their components are assessed, researched and explored in detail, **FIGURE 1**.

LIGHTWEIGHT DESIGN AXLE CONCEPT

The ZF lightweight design concept for trucks is based on a twin axle unit. On the example of the two axles the applied approaches for functional integration (conceptual lightweight design) will be illustrated.

For the leading axle, the stabilisation for the upper link level is implemented by a lightweight four-point link. For the driven rear axle, this integration occurs within the lower link level by an optimised stabiliser link. Consequently, this concept results in a significant mass reduction, as the number of parts and connection points are decreased. A fundamental decision of engineering design is introduced by rotating the leading axle by 180° in the axle arrangement. As a result, one of

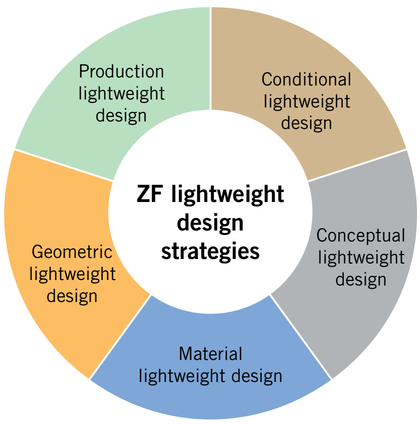

FIGURE 1 Holistic lightweight design approach with a focus to material, concept, geometry, requirements and manufacturing strategies (according to [1]) which are often closely interrelated in practice

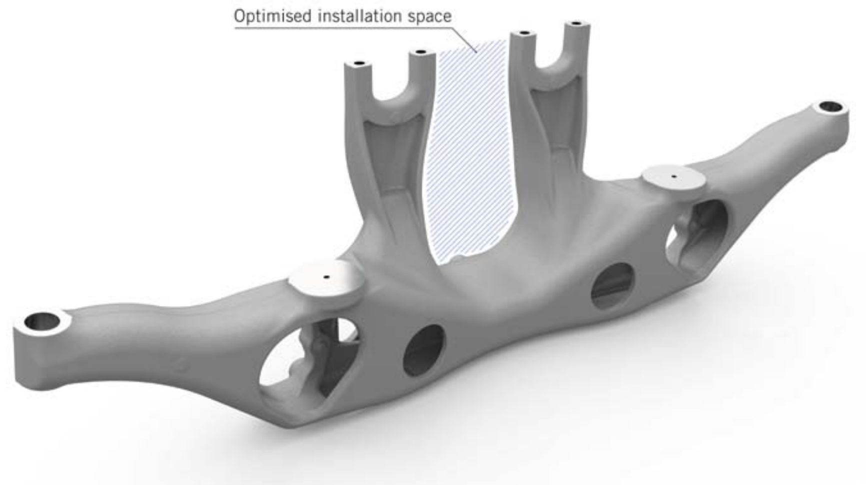

FIGURE 2 Body of the leading axle made from high-strength hollow cast with integrated connection points for the upper and lower link level as well as for the air spring module and steering actuator

FIGURE 3 Lightweight design in every detail was even implemented successfully for the joints, here for a support bracket on the chassis frame with a reduced number of required joining elements (blue concept)

the two conventional support beams becomes expendable and the two are connected to one central beam. However, to ensure an ideal kinematic design, a manufacturing process with high geometric flexibility must be selected for the body of the leading axle. Subjected to this limitation, a concept based on a hollow cast structure is chosen which also optimises stress distribution at maximum stiffness. In the section of the axle junction, a structure is developed by this hollow cast concept that provides very high torsional strength in the brake load event while the installation space and material use is reduced at same time. The application of this concept requires a high-strength casting material with improved mechanical properties, which also delivers the required flexibility for the geometric design of the part. The main hole-like openings in the lower link level act as a feedthrough for the tension respectively pressure links. In such a way, the optimal kinematic length of these components is achieved. By means of component integration, the axle features multiple connection points for the upper and lower link level as well as for the air spring module and steering actuator.

A U-shaped recess clearance gains additional installation space, which – in combination with the four-point link – creates the vertical clearance for the drive shaft, **FIGURE 2**. For this purpose, vertical stiffening ribs are added and the axle body is shifted towards the front as these actions will noticeably increase the available vertical installation space. Despite the minimal use of the vertical installation space, the required stiffness and strength of the axle body can be obtained. As a result, the proposed concept for the body of the leading axle shows a significant advantage: a single-piece drive shaft is facilitated between the transmission and the driven axle. With a view to the commonly applied multi-piece drive shafts, an appropriate single-piece component offers remarkable mass potential in a range up to 90 lbs (mid-double-digit kilogram range). Apparently, this may lead to significant cost savings. In such a way, an integrated lightweight design approach will not only result in a mass reduction of the system, but may additionally contribute to cost efficiency.

Another detail of the lightweight design concept – lightweight support brackets – is illustrated by **FIGURE 3**. As a geometric lightweight approach, a load-conforming positioning of the brackets is performed in a way that a minimal number of joining elements (for example bolts or rivets) is required.

LIGHTWEIGHT DESIGN FOUR-POINT LINKS

ZF's four-point link combines three fundamental tasks for the truck chassis in one single component: not only the longitudinal and transverse axle guidance, but also roll stabilisation. In addition, the installation of the four-point link increases vehicle ground clearance. This is possible because of its special geometry and elasto-kinematics with specifically defined torsional stiffness. It provides high lateral stiffness for axle guidance, as well as specific longitudinal compliance for better comfort behaviour. This integration of functions within the four-point link allows omitting the three-point link, the stabiliser, and other chassis connection components. As a result, a significant mass advantage is achieved in the 100 lbs range (mid-double-digit kilogram range) for the overall axle.

The current series version of the four-point link, which is based on a heat-treated, ductile, and high-strength ADI (austempered ductile iron) cast, is further developed for the presented lightweight design axle concept. For this purpose, the cast material is replaced by glass-fibre reinforced plastics (GFRP). In such a way, material substitution is combined with conceptual lightweight design in terms of functional integration. The impact of this novel concept results in a mass reduction from about 100 lbs (46 kg) for the ADI version to less than 70 lbs (32 kg) for the GFRP version, **FIGURE 4**.

In this context, ZF was able to compensate for a design-related disadvantage of the metal version of the four-point links: the drawback originates from the fact that the deformation capacity needed for the kinematic and elasto-kinematic properties is induced to a large extent within the connection of the control arms via large-volume rubber bearing components with different radial stiffnesses. The lower material stiffness of the GFRP compared to ADI cast may lead to lower requirements for the deformation properties of the bearings, which, in turn, may enhance the fatigue life for these parts. For example, a targeted selection of fibre angles in the FRP composite component enables transferring a significant part of the deformation capacity to the body of the four-point link itself while allowing a simpler and cheaper design when constructing the rubber bearing components. Furthermore, the kinematic properties of the body can be adjusted within a wide range and, thus, can be specially customised to the requirements from certain vehicle manufacturers and to special vehicles.

The design of the fundamental concept for the GFRP version of the four-point link implements a differential construction concept which is based on simple fundamental elements. In this so-called H-design two beams are connected by a tubular torsion body. The utilisation of a closed torsion beam guarantees the compensation of the reduced material stiffness of the FRP component in comparison to the ADI cast version having an open torsional box. In such away, ZF succeeds not only in utilising a lightweight material with high specific properties, but also in designing a four-point link with a new, advantageous structural concept that enables both an efficient and clear load transfer with reduction of multi-axiality (fibre-conforming design). The selected concept also demonstrates significant advantages for the manufacturing process for volume production due to the differential construction method.

The single components can be fabricated by use of appropriately modified standard processes on an industrial scale with a clear focus on cost efficiency. Furthermore, specialised fibre-conforming joining processes based on winding methods were developed which do not require the utilisation of any metallic inserts. However, these processes ensure a load-safe assembly and can be implemented within a framework of highly-automated production.

The currents design predominantly employs glass fibres and a thermoset matrix. Obviously, the distinct laminate thickness appears to be a particular challenge in this respect. Accordingly, customised production environments including resin chemistry and processing parameters (for example process times) are required in order to control exothermic reactions. Moreover, construction and design of components are also affected by this limitation.

The promising concept design of the GFRP four-point link developed for the lightweight rear axle may also be transferred to other applications – not necessarily limited to the field of commercial vehicles. The metallic four-point links, which are currently in series production, may be replaced on a medium-term view by the new design, in order to take advantage of the mass reduction and the variable stiffness adjustment for the vehicle manufacturers.

The mass of the lightweight four-point link – and therefore the savings potential by the lightweight design approach – initially appears relatively insignificant compared to the total mass of a heavy truck. However, the result has to be considered within the context of the extensive mileage performance of current long-distance commercial vehicles. With a total mileage of more than 550,000 miles (900,000 km), even a limited mass reduction will gain additional payload and fuel savings which quickly pile up to significant additional revenue for the fleet owner – in particular for those trucks operating in the bulk material and liquids transport sector.

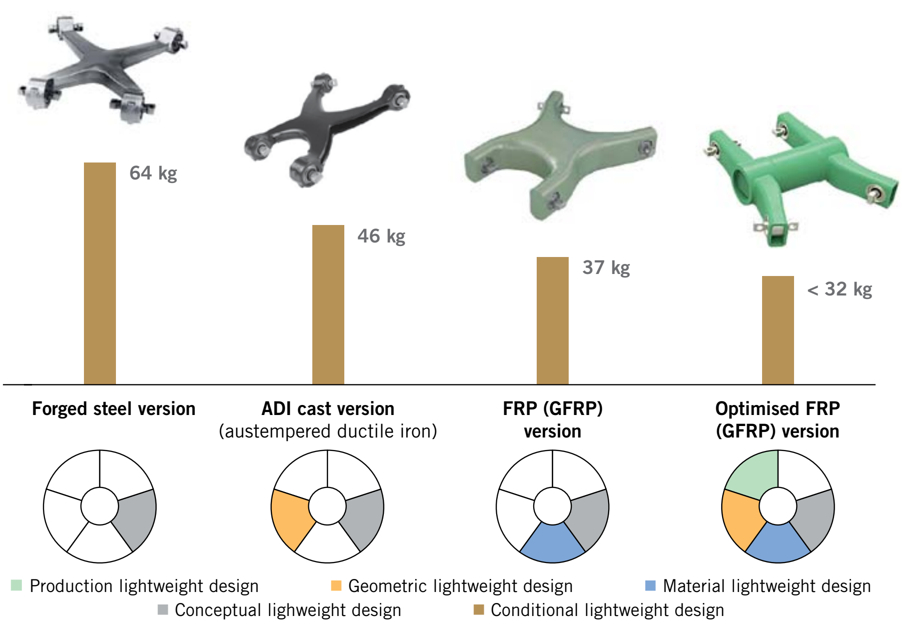

FIGURE 4 Applied ZF lightweight design strategies (according to **FIGURE 1**) exemplified by the four-point link generations for truck rear axles

FOCUS ON CONDITIONAL LIGHTWEIGHT DESIGN

One future topic for lightweight design efforts at ZF Friedrichshafen AG will have a particular focus to lightweight approaches with a view to conditions and requirements. In addition to extensively assessing current requirements and specifications, existing load spectra will be refined while keeping the same level of reliability and safety for the specific component. Improvements in simulation and validation methodology may widely unveil additional lightweight design potential that is currently still buried in the "reserves" of the customer-specific load profiles and safety factors. In particular, the huge uncertainties of the fatigue load characteristic for components made of fibre-reinforced plastics (FRP) carry major potential as excessive safety factors may be significantly reduced for future designs. Due to the anisotropy of these materials, the property profile relies not only on the load cycle, but is also strongly dependent on the load direction, the type of loading, as well as interaction during the load history. Furthermore, component requirements may be further differentiated into performance classes to reduce over-design for a number of applications. Current results suggest that the conditional lightweight design will lead to optimised and customised components conforming to requirements and loads, which, if applied intelligently, could release significant potential in terms of mass and cost efficiency.

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Adaptive Calibration on the Commercial Vehicle Test Bed

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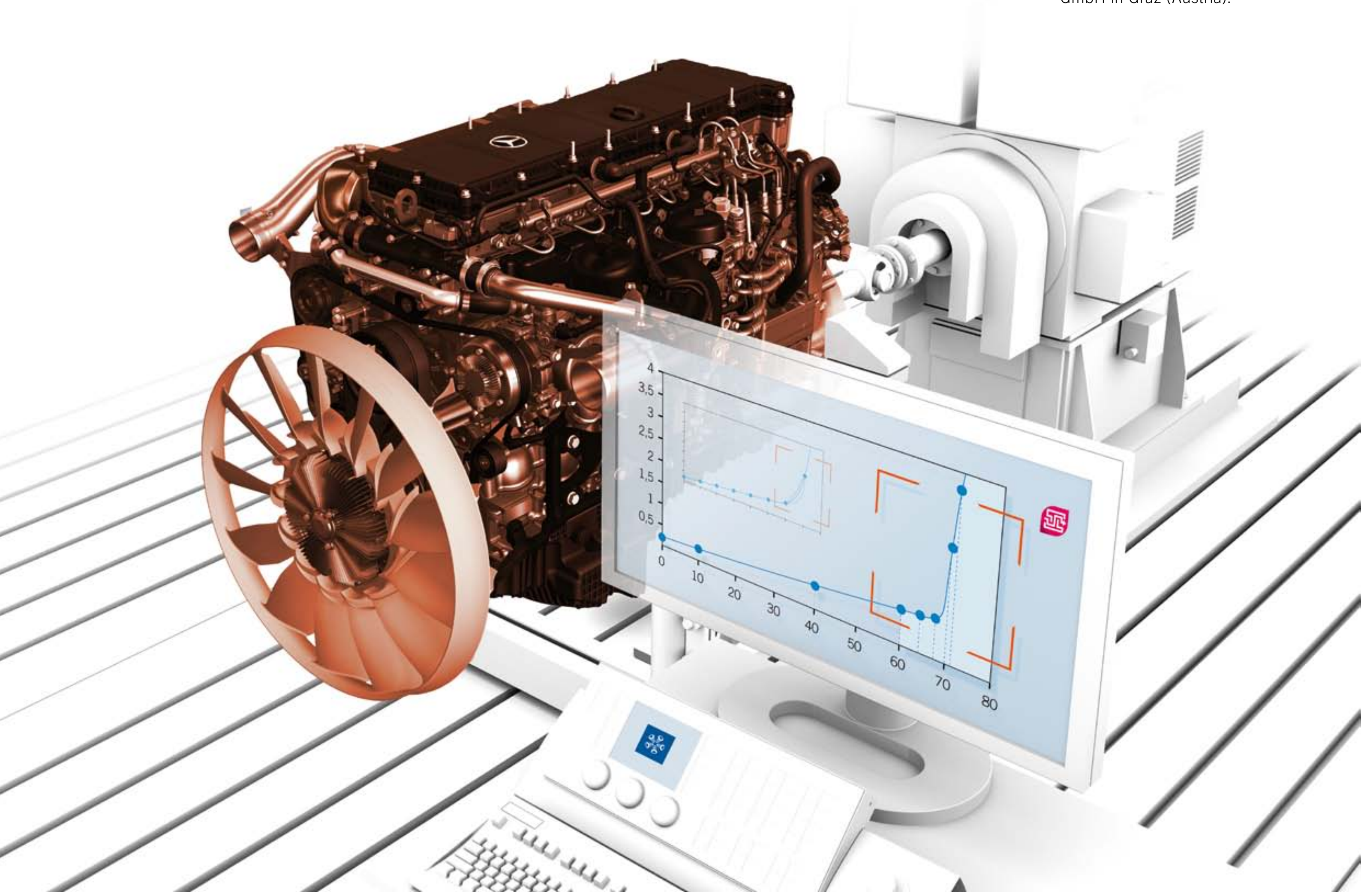
The requirements for calibrating modern commercial vehicle engines are becoming more and more demanding. AVL and Daimler did find a possibility to combine DoE experience with automated modelling. The new process allows to design DoE much more robust and more efficiently, particularly in the case of nonlinear response values.



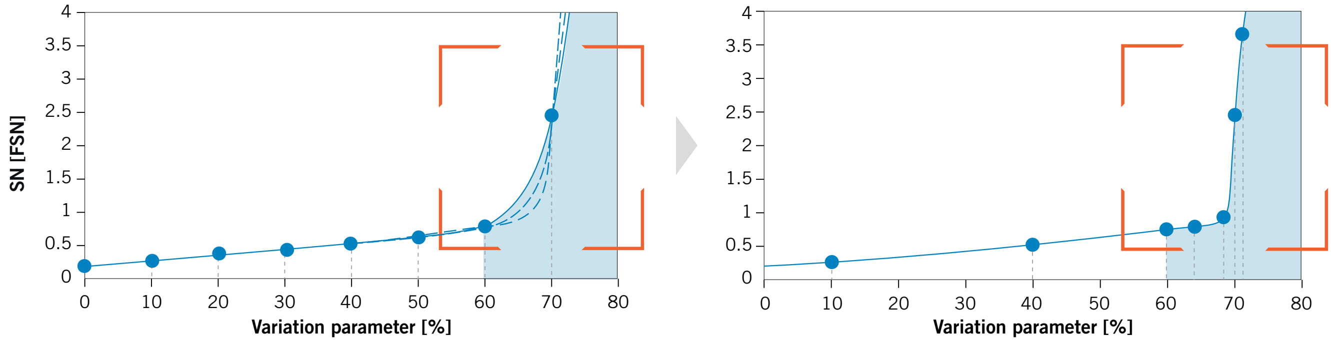


FIGURE 1 Nonlinearity can be described more accurately by adding specific measurement points using the COR design

CHANGING TEST AUTOMATION

The calibration of modern commercial vehicle combustion engines places high demands on the test bed environment, the measurement devices used and above all the methods implemented. In recent years, DoE (Design of Experiment) has proven to be a successful process for handling the perpetually growing number of variation parameters on the one hand and for reducing the required measurement times on the other. Moreover, using test automation makes it possible to take advantage of off-peak hours such as operation at night and on weekends [1]. COR DoE (Custom Output Range DoE) described as follows provides an effective extension to the familiar concept and also takes into account the target values when selecting the combination of parameters to measure.

CHALLENGES

To utilise the full potential of engines, the quality of the model is extremely important. The quality determines the predictive accuracy of the true engine behaviour and thus the applicability of the optimisation results. Some response values often present difficulties in this case: As is known from combustion simulations, particle emissions as well as combustion stability or misfire rates (in spark-ignition engines) are very hard to predict. This is because of the extremely nonlinear behaviour, which is affected by a wide variety of forces at work in the combustion chamber. The true engine behaviour can only be determined by engine measurements. But this would significantly increase the number of required test points [2].

DoE designs are limited traditionally to observing the range of variation, that is on the calibration parameters [3]. The actual development objectives, such as emission behaviour, fuel consumption, etc., are not yet taken into consideration at this point. Familiarity with the unit under test and/or the task in place during DoE planning offers tremendous potential [4].

The challenge is in planning a DoE experiment in such a way that the generated models are sufficiently accurate within the range of the optimum target to be found. To do this, the range of variation selected must be sufficient so that the optimum target, which is often at the engine's operability limits, is actually covered and can be identified. On the other hand, the distribution of test points must also be sufficiently compact. This is essential for good modelling, particularly in the case of the mentioned extremely nonlinear response values like the Smoke Number (SN) shown in **FIGURE 1**. SN is often measured as a Filter Smoke Number (FSN).

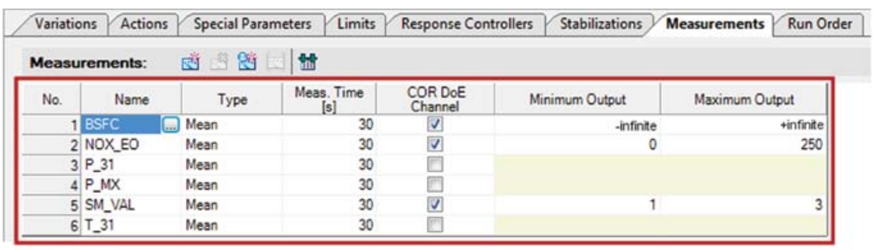
Through efficient test automation, it is possible to analyse test data during the test run and to adapt the test plans online at the test bed accordingly [5]. The AVL Cameo software routines have been used to meet these challenges. This approach reduces the measurement times while at the same time improving the quality of modelling as well as subsequent optimisation considerably.

ITERATIVE TEST PROCEDURES

Iterative test procedures have been in use in engine development for some time now. However, previously a certain amount of experience and familiarity was required on the part of the user to set the parameters for these types of test runs, and the quality of the results strongly depended on this experience.

COR DoE is a method that aids the application users in their work through the use of models. This intelligent, adaptive test run procedure makes it possible to specify the required targets for the task using a clear parameter configuration interface. For each of the engine's operating points, it is possible to provide all measured quantities that are relevant for subsequent modelling in the measurement list and to define the required target, **FIGURE 2**.

Models are developed through automation from the DoE initial design measurement results for all required measuring channels. New measurement candidates are then selected within the required and modeled measuring range.



No.	Name	Type	Meas. Time [s]	COR DoE Channel	Minimum Output	Maximum Output
1	BSFC	Mean	30	✓	-infinite	+infinite
2	NOX_EO	Mean	30	✓	0	250
3	P_31	Mean	30			
4	P_MX	Mean	30			
5	SM_VAL	Mean	30	✓	1	3
6	T_31	Mean	30			

FIGURE 2 Setting the parameters from the target of the application task

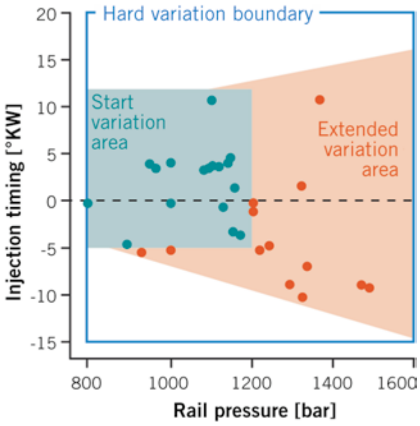


FIGURE 3 Example of extending the range of variation using COR DoE

An improvement by COR DoE is the flexible handling of the range of variation. The algorithm automatically finds and adapts the optimum range of variation by increasing each individual variation parameter incrementally as necessary, as long as it appears useful for the particular task. At the same time, unfavourable areas are hidden and ignored going forward, and the area of interest becomes the focus, **FIGURE 3**. Each individual limit violation, such as exceeding the maximum permissible values for the peak cylinder pressure, exhaust gas temperature, etc., is also taken into account at the same time during further calculation of the candidates [6].

EXAMPLE OF USE

The DoE method has been established and used on a regular basis in Daimler's truck engine development [7]. Usually the so-called AdaptiveOnlineDoE Cameo iProcedure is used on the engine test bed, which offers effective methods for online limit monitoring and limit handling. This enables safe and fully automated measurement even in critical operating ranges up to the operability range limits. Alternatively, a two-stage process developed by Daimler for measuring limits and for the DoE test is available. During the first stage, the process determines the entire mobile operating range so that during the second stage it can measure a DoE test planned within the determined range [8]. In contrast, COR DoE has the advantage of being able to account for the target in addition to the limits of the modeled quantities through automation.

So far, Daimler Trucks has dealt with the challenge of correctly defining the range of variation with D-optimal third order designs and online monitoring of limits for the exhaust gas lambda and NO_x emissions during screening. For quantities available online, it is possible to ensure that the test is restricted to the relevant measurement range. In the case of particle emissions there is no reliable, online test signal proportional to the SN, and therefore individual test runs need to be repeated or supplemented iteratively.

The effectiveness of the COR DoE has been comparatively tested in a project. For the comparison, a current heavy duty engine was used, which features a boost-pressure regulated air path, cooled high-pressure exhaust gas recirculation and a highly flexible common rail injection system with pressure booster. Four variation quantities were studied at different stationary points: beginning of main injection (BOI), rail pressure (PRAIL), rail pressure amplification parameters (NOP) and position of EGR valve (S6EE). Response values: fuel consumption (BEFF), NO_x emissions (MNOXP) and particle emissions or smoke number (SN), taking into account various engine limit values.

A series of experiments according to the traditional DoE methodology was measured as the basis. In this case, the AdaptiveOnlineDoE strategy with ramp adjustment and a D-optimal initial design with 39 measuring points was used. During the screening, the NO_x emissions were restricted to an area width of 7 g/kWh. For the series of comparative tests using COR DoE, a central composite design (face-centred CCD) was used as the initial design and extended by 15 COR points. Even this series of experiments was carried out with ramp adjustment, and screening was limited to the same NO_x range. As the target Custom Output Region (COR), a NO_x area width of 5 g/kWh as well as an upper limit for the SN was specified.

FIGURE 4 shows the initial design (blue circles) resulting from the screening process, which was supplemented by the COR settings (green squares) obtained from online modelling. At the start of the COR phase in this example, the NO_x and SN models were insufficient for the target, resulting in misses (green triangles) – outside the NO_x and SN limits,

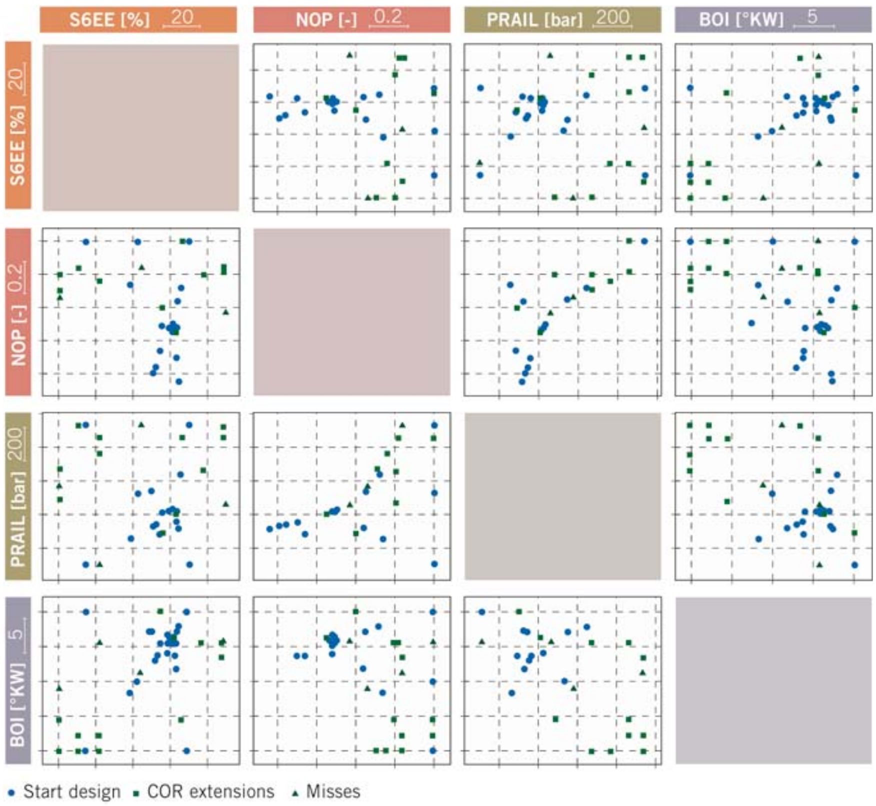


FIGURE 4 Supplementation of the initial design using COR DoE in the variation region

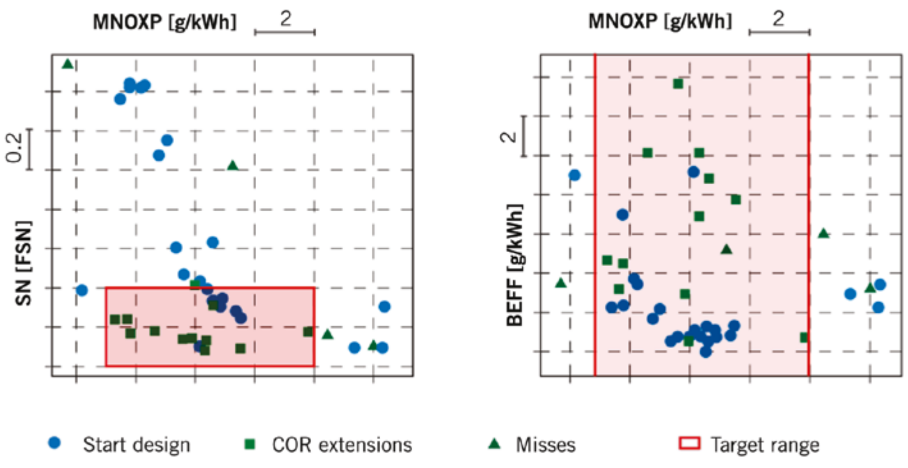


FIGURE 5 Distribution of measured values in the desired target

Measurements	RMSE reduction
BEFF [g/kWh]	15 %
MNOXP [g/kWh]	45 %
SN [-]	7 %

TABLE 1 Reduction of the RMSE mean prediction error for relevant measurements

FIGURE 5. With the continuation of the experiment and iterative, automatic improvement of the models, the target is then hit correctly.

Models were developed from the measured data of both series of experiments, and then from the models of the traditional DoE design experiment a NO_x/SN trade-off was calculated, taking into account the engine limits within the range of the optimum target. These settings were measured as verification points and used to analyse both models. The Root Mean Squared Error (RMSE) of the verification points not used for modelling served as the criterion of quality. In the mean across all the operating points, the models from COR DoE show a reduced RMSE compared to the traditional DoE, **TABLE 1**.

The comparison shows that, with the same experimental work using COR DoE, the model quality target is improved. The method described integrates seamlessly into existing tools and processes at Daimler Trucks and is therefore useful without extra effort.

CONCLUSION

The trend is that the requirements for calibrating modern commercial vehicle engines are becoming more demanding. This example demonstrates that it is possible to combine DoE experience with automated modelling. The process automatically selects additional variation points with which a configurable target region is fully covered. High model quality is ensured while the experiment is underway, particularly within the range of the optimum target to be found. Using the same number of test points, the model quality is significantly improved compared to the conventional process. Alternatively, without changing the model quality, the effort required for measuring can be reduced. With the process presented here, applying DoE can be much more robust and more efficiently designed, particularly in the case of nonlinear response values.

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Compliance of an ACC System to StVO German Traffic Regulation

Assistance systems like Adaptive Cruise Control (ACC) help the driver during his task keeping the distance. In this connection, the driver is even supported by technology if he adjusts gap-in-time values that do not respect the conventional thought of safety distance according to German StVO traffic regulation. Based on examinations at TU Braunschweig, adjustments of gap-in-time values of three ACC systems are scrutinised in consideration of StVO compliance and ISO 26262 controllability.

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RIGHT FULFILMENT OF THE DRIVING TASK

When talking about the compliance of assistance systems according to the German traffic regulations (StVO), the question arise if there is a need to fulfil these requirements. Anyway, these systems assist the driver during the fulfilment of his driving task, which he might handle relating to the rules of conduct of this regulation. Thus, the first task of an assistance should be to thereby support the driver.

According to the requirements of the StVO regulation it can be assumed that the traffic will go on without accidents and the driver can control every traffic situation. This assumption is based on the fact that the StVO describes a redundant and divers traffic system. Uncontrollable states can arise when the driver does not respect these requirements and when the assistance does not help him to come back into a compliant system state.

Here, the emergency braking assistant should be mentioned as an example. This work will deal with the ACC in detail. Three ACC systems 1, 2 and 3 from different OEMs were investigated.

EXAMINATION OF DISTANCE PARAMETERS OF ACC SYSTEMS

Before the examination of the system parameters can be started for an ACC system, several relevant requirements contained in the StVO are described, which are conjoint to the distance parameters of the ACC system. Literature [6] describes a gap in time with the value of 1.8 s, which can be mentioned as controllable, if the driver's response time does not expand one second.

In addition, if the driver uses smaller gaps in time, he is forced by StVO regulation to compensate his behaviour with more attention [6]. Under these conditions smaller gaps in time are possible. Also it is mentioned that the gap in time will never be lower than 0.8 s, because this value identifies a hazard state with the possibility to an accident [6].

With this information it is assumed that the examined ACC systems will not carry out a gap in time, which is lower than 0.8 s, but it is possible that they carry out gaps in time, which are less than 1.8 s. According to [4, 7] the required situation awareness is not provided by the driver. With this knowledge all gaps in time below 1.8 s are rated as not compliant to the StVO.

IDENTIFICATION OF GAPS IN TIME

For the identification of relevant gaps in time, different original manuals from three car manufacturers are investigated. The results are shown in **TABLE 1**. The two manuals to ACC 1 and ACC 2 provide data of gaps in time with more or less detailed information about the concrete values. If we look at ACC 1 there is only a single gap in time value (1.8, represented in bold type in **TABLE 1**) as well as data to speed and related distance (ACC 2). As ACC 1 had only one value, the other values had to be calculated/approximated. The other values are approximated with a polynomial function. ACC 3 gives no information in the manual about the exact gap in time values but makes mention of five qualitative gaps in time.

The published gaps in time contain values lower than 1.8 s. For this reason the ACC 1 and ACC 2 must be rated as not compliant to the StVO. Based on this fact it is important to evaluate their controllability. Therefore the gaps-in-time values of ACC 1 are used, because there are more values available. Its results can later be transferred to the other systems.

CONTROLLABILITY EVALUATION

For the controllability evaluation it is assumed that an expanded response time [4] in fact of adaptation will not be taken into account. Furthermore it is assumed that a driver would response in a non-expanded way, when he is not assisted. Under this assumption the evaluation takes place under best-case conditions.

If a critical traffic situation arises, it is assumed that the only action, which can be performed by the driver is an emergency brake. This assumption can be related to his driver education. To get an idea, which braking values shall be used for the controllability evaluation, braking values are collected at the begin (Ref_01) and at the end (Ref_02) of several driver safety trainings, **FIGURE 1**. For the collection of the data a driving school vehicle is used. The collected data are based on 225 participants. The gender balance was 40 % female and 60 % male. The median of the age was 19 years.

The measured braking values at the beginning of the training (Ref_01), **FIGURE 2**, reflect a naive driver and how he reacts in the best-case of braking (protected and almost real testing area). All trails are performed at a speed of 40 km/h and on a specific place at the training area, **FIGURE 1**. The results of the

	ACC 1 (polynomially approximated)	ACC 2 (calculated)	ACC 3 (from the manual)
Gaps in time [s]	0.80	–	Very small (n/a)
	1.10	Small, approx. 30 m at 80 km/h (makes 1.35)	Small (n/a)
	1.30	–	–
	1.80	Middle, approx. 40 m at 80 km/h (makes 1.8)	Middle (n/a)
	2.20	Long, approx. 50 m at 80 km/h (makes 2.25)	Long (n/a)
	–	–	Very long (n/a)

TABLE 1 Extracted gaps in time out of manufacturers manuals

braking values in the driver safety training are shown in **FIGURE 2**. Also the training effect is recognisable: At the end of the training 50 % of all participants can brake as well as test driver [1]. As a naive driver is normally a not so well educated driver, it should be paid attention to the training aspect during selection of test persons to perform a controllability evaluation.

After the braking values are all entered, the controllability test should be performed with the ACC 1 system in a follow up traffic situation like this: The vehicle in front gets the braking performance 8.4 m/s² and the vehicle in the back 6.7 m/s². The ACC 1 system will support the following driver with a minimum response time of 500 ms [5] and with a braking capability of 3.5 m/s². The response time of the driver in the assisted vehicle can assumed with 1 s for an unexpected braking of the vehicle in front [6]. Due to the distance behaviour mentioned in [3], the assumption of an 1-s gap in time is permissible.

Thus, a gap in time of 1.1 s can be found. As the gaps in time are distributed not linear it is assumed that the driver selects the gap in time in the average so that he follows the vehicle in front with a distance of 1.3 s, which corresponds roughly to his usual distance behaviour [3].

Based on the fact that the driver in front brakes with the assumed deceleration and the following vehicle reacts as assumed, **FIGURE 3** shows that the controllability of this ACC 1 system exists only for the longest gap in time. Even at 1.8 s a minimal collision cannot be suspended. If this procedure is evaluated like ISO 26262 the controllability classification value must be set to C = 3 for all gaps in time besides the longest, because this is controllable. This classification results from the choice of the deceleration ability as a median.

50 % of the participants in this scenario would cause an accident with the vehicle in front. But this scenario would be controllable if the braking values at the end of the driver safety training (Ref_02) were hypothesised. Indeed, this does not justice to the naive driver and shows that the input of a professional test driver had led to a false positive result in this scenario.

FIGURE 1 Braking area at the driver safety training

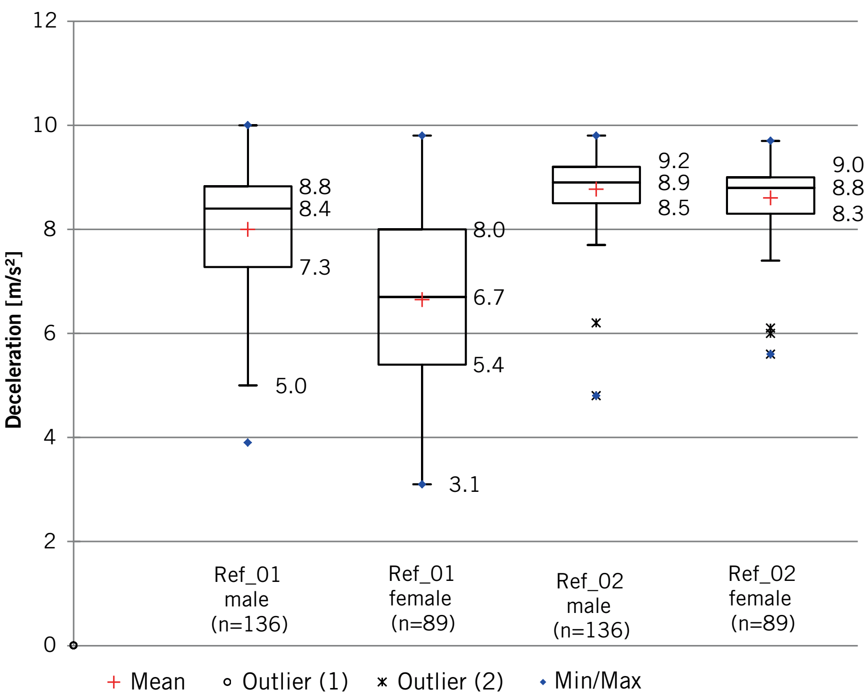

FIGURE 2 Development of the deceleration rate at the beginning (Ref_01) and after completing (Ref_02) the driver safety training (results based on own data collection)

AVOIDANCE OF ADJUSTING TOO SMALL GAP-IN-TIME VALUES

One will apply that the distance control is under the responsibility of the driver, because an ACC system only performs as a comfort function of a assistance system [2]. Basically, this is right. The question, which arises in this context is, if the driver can perform this responsibility task. If the results in [3] are combined with the models in [8], the following statement can be made: According to the lack of information, based on the manual and the instrument cluster (bar graph without decimal values) it should not be assumed that the driver can perform this task. The reason for this statement is based on the fact that his not-compliant StVO distance behaviour is positive anchored. His behaviour can be changed by negative experiences. Based on the fact that this experience stays away the driver feels assured in his behaviour positively onwards because the ACC system gives him gaps of time, which fit to his behaviour.

CHANGING IN THE CONTROLLABILITY WITH AND WITHOUT THE ASSISTANCE

To get an idea of the controllability differences between assisted driving and driver only, the controllability evaluation is done under the same assumptions as the first one. **FIGURE 4** shows that the longest gap in time exists without presence of assistance exclusive of a collision.

Therefore, controllability with and without assistance is identical. The differ-

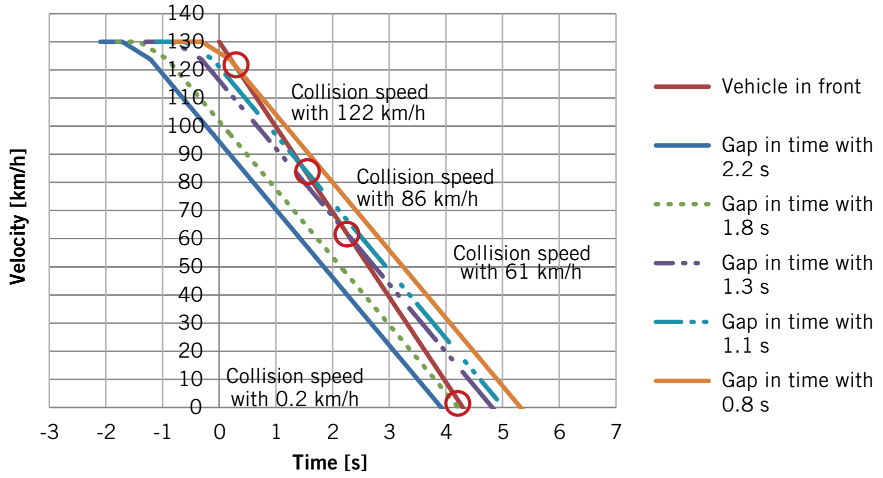

FIGURE 3 Controllability evaluation for the ACC 1 gaps in time for (results based on own calculation)

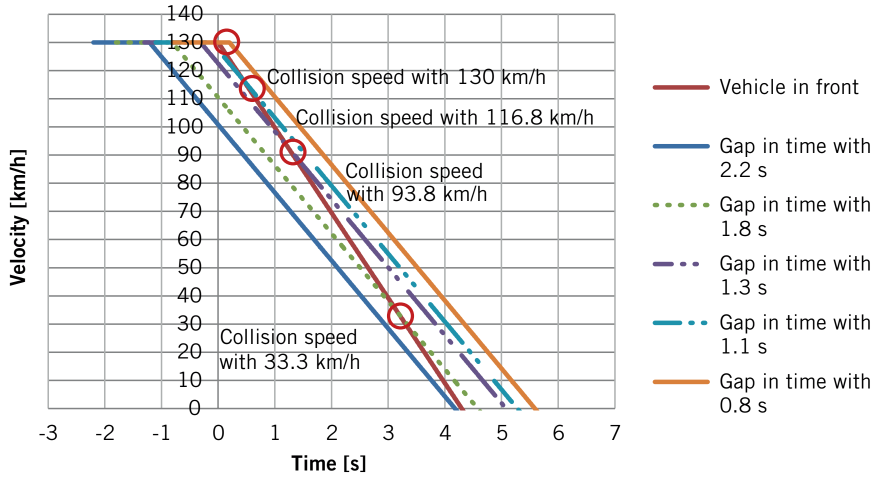

FIGURE 4 Controllability test without ACC

ing point is the height of collision speed, which cannot be confused with the controllability factor. Strictly speaking it has an effect only on the severity factor (in ISO 26262). It could be demonstrated why it makes sense to orientate not at StVO regulation specifications but at the specifications, which result from the driver. Consequently the system transfers the driver from a measure of damages with potentially high value to a lower one.

CONCLUSION

The article has shown the deficiencies in the representation of the gap in time values of ACC systems in the manuals and instrument clusters. It was also demonstrated how to prevent false positive results in the controllability evaluation. For the distance parameters of the ACC the results show that neither the German StVO regulation nor the controllability for all gaps in time are given.

In spite of the identified problems and after the controllability evaluation of non-assistance, it can be demonstrated why the ACC parameters are not conform to StVO regulation. Such a result will arise only, when the driver find a gap in time value in the ACC parameters, which will be the same as his subjective gap in time value. Only under these conditions he will primally activate the assistance system when he finds gap-in-time values, which deliver a positive feedback to him for his own behaviour. Just at this point the ACC system is able to reduce an accident from high severity to a low measure of damages.

Due to the fact that the parameters of the ACC system are not compliant to StVO regulation it unfolds its protective effect and thus reduce collision speed. If the ACC system only supports StVO compliant gaps in time, it could not realise its potential.

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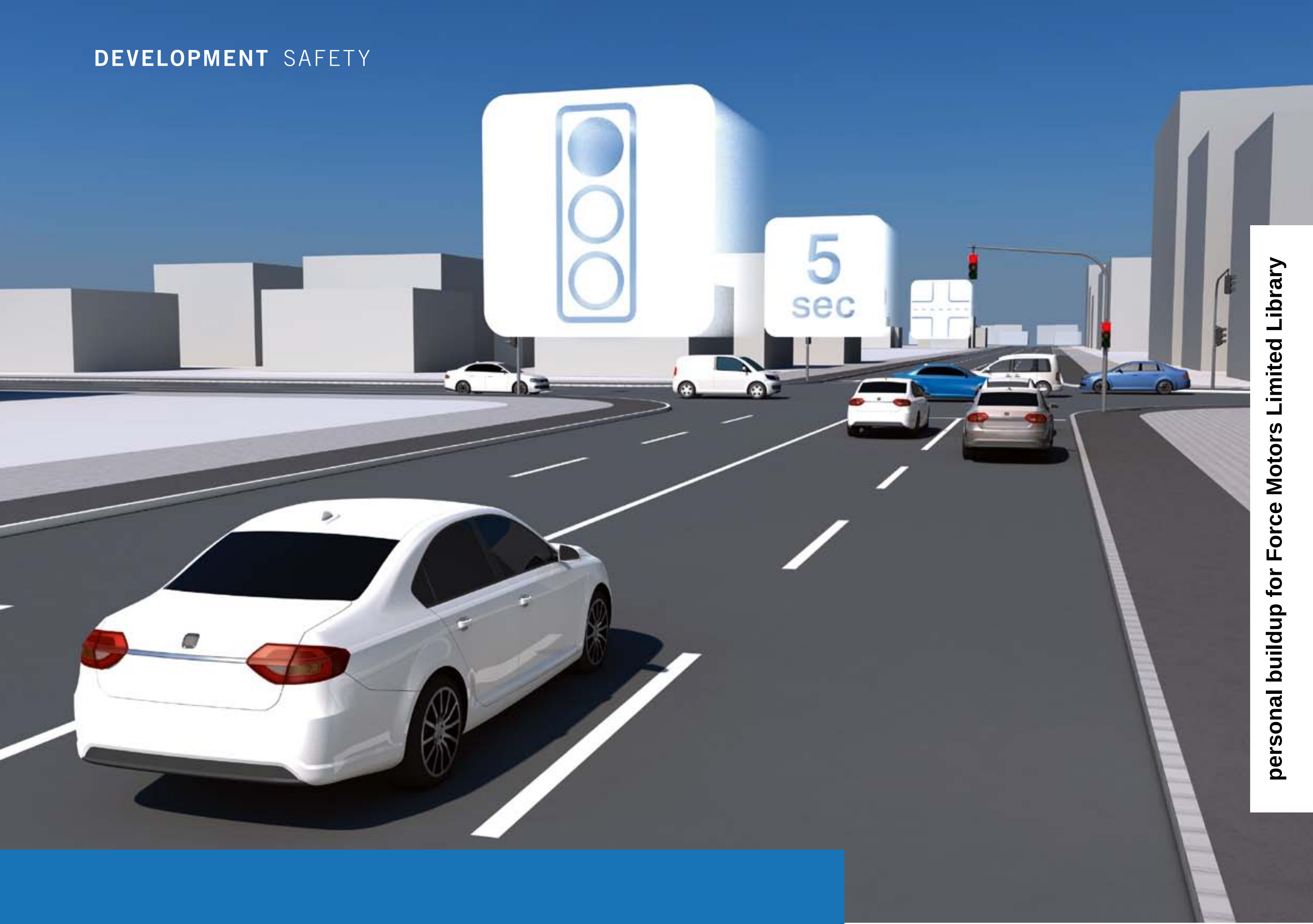

AIM Test Facility for Validating Cooperative Functions

In the future, assistance systems will mainly run on vehicle-to-vehicle and vehicle-to-infrastructure communication. But functions such as warnings about construction areas or status the display of traffic lights have to be designed in a safe manner. Therefore, DLR developed the new test facility Application Platform for Intelligent Mobility (AIM): a route that is about 11 km long and which is implemented into local public road network of city of Braunschweig (Germany). IAV is one of the first users there.

COOPERATIVE SAFETY FUNCTIONS

Vehicle manufacturers, suppliers and research institutions are currently developing functions for exchanging standardised messages between vehicles and traffic infrastructure elements to avoid crashes or reduce the severity of crashes. Interaction between vehicles and infrastructure is based on Wi-Fi hardware and a communication protocol adapted to vehicle-to-vehicle and vehicle-to-infrastructure communication (V2X communication). The communication protocol has been harmonised by the IEEE in the

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802.11p standard all over the world. In Europe, the Car-to-Car Communication Consortium has also defined application messages necessary for communication.

Possible functions include, for example, warnings about construction areas or hazards or information on traffic light status supporting the driver on reaching green lights. In addition, in the future it might also be the case that emergency braking assistant prevents drivers from running a red light.

These cooperative safety functions place particular demands on new test infrastructures. Adequate testing of the functions needs a test environment embedded in flowing traffic, such as the Application Platform for Intelligent Mobility (AIM).

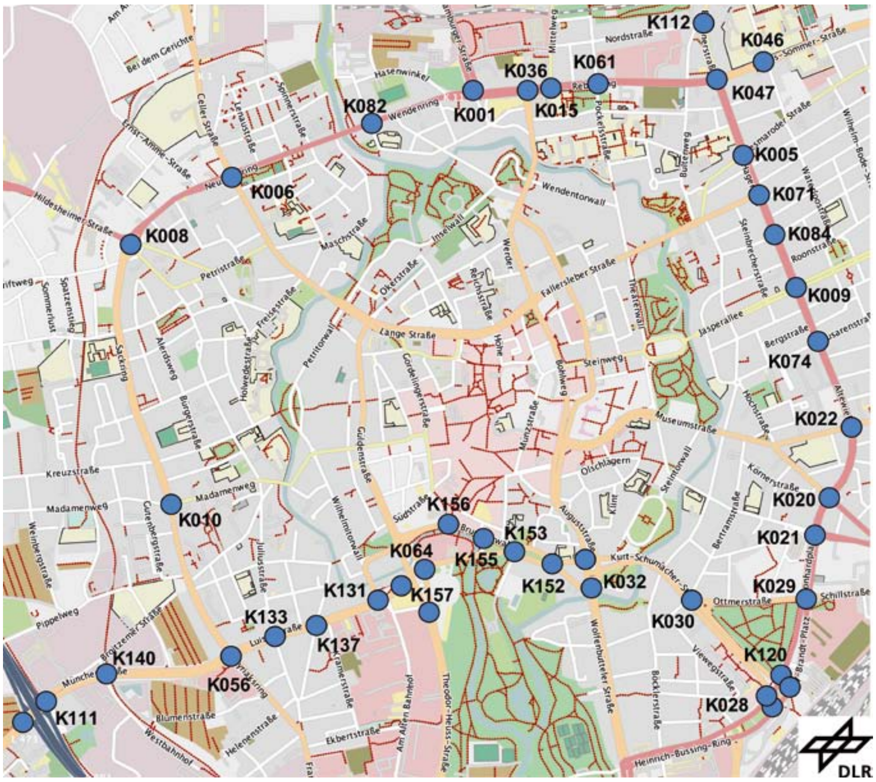

FIGURE 1 Route of the AIM test facility and installed roadside units (RSU), marked in blue (source: Open Street Maps, www.openstreetmaps.org)

THE APPLICATION PLATFORM FOR INTELLIGENT MOBILITY TEST FACILITY

In the city of Braunschweig (Germany), the German Aerospace Center (DLR) operates a large-scale research facility called Application Platform for Intelligent Mobility (AIM) [1]. Together with an efficient simulation infrastructure and a large number of other vehicle laboratories and test infrastructures, this also includes a test facility for cooperative vehicle functions based on V2X communication. In July 2014, this test facility was opened for research purposes in the field of traffic research. Implemented in the public road network, AIM stretches over 11 km (6 miles) of length circular around the city centre of Braunschweig.

The route includes among others two highways, an emergency detour for the A2 motorway and a road leading into the city centre. Hence it carries high volumes of traffic and it can be said to be of major significance in the context of transport. Altogether 35 traffic light systems are installed along the route, equipped with so-called roadside units (RSU) [2]; the term roadside ITS station is a frequently used synonym.

The equipment level in the North-Western part of the test route reflects a possible roll-out scenario. Here only major intersections are equipped with RSUs: Although communication with the infrastructure takes place, it is not possible to obtain a constant flow of information via the traffic infrastructure. This constitutes a great challenge particularly at the start of a roll-out. In contrast, all traffic lights in the South and East of the test route have been fully equipped. Here it is possible, for example, to simulate a high-load scenario that entails transferring particularly large data volumes because of the many communication partners involved. **FIGURE 1** shows the test route and the stations installed along it.

The individual sites of the test facility are connected by Wi-Fi and linked into the DLR IT infrastructure by ADSL at

FIGURE 2 V2X transmission and receiver units in the AIM test facility, also called RSU

selected points. This way, DLR can remotely monitor the current state of the test facility. New software and protocol data can be imported into the system as well.

RSUs receive continuous information on the current status. Together with other traffic-relevant information (for example intersection topology) the status can be transferred via V2X communication, **FIGURE 2**. Additional information can also be transmitted at any time in standardised message formats as defined by ETSI/CEN and in the German project SimTD [3]. In this national project, a proprietary communication protocol was defined that represents the basis of standardisation done by the European standardisation bodies ETSI and CEN. Moreover, proprietary messages can also be defined and used in the test facility.

AIM TEST FACILITY AS EMITTER OF V2X MESSAGES

Current cooperation between IAV and DLR focuses in particular on the traffic light systems equipped with IEEE 802.11p communication units. These are capable of sending the following V2X messages:

- topology of an intersection (Topo)
- signal phases and timing (SPAT) of a traffic light system located at the intersection
- relevant messages related to the surrounding of a vehicle (decentralised environmental notification messages, DENM).

The Topo information is defined for every equipped intersection and is comparatively static. The dynamic contents of the SPAT messages are defined mainly by the switching algorithm of the traffic light system. Adjusting the duration of the red, amber and green phases can be static by controlling the fixed times, or dynamic based on an algorithm, for example depending on traffic density (traffic-dependent control). Both control variations are available in the AIM framework.

SCENARIOS FOR TRAFFIC LIGHT SYSTEMS IN THE AIM TEST FACILITY

Only as an exception to the rule it is allowed to intervene with traffic. The person in charge of the AIM test facility needs to apply for a special permission with the City of Braunschweig. For example, without a permission it is not possible for existing traffic signal plans to be changed for test purposes. However, the V2X messages on the test route may be adapted as required, so that the SPAT and Topo contents of studies may differ from the physically apparent attributes of a traffic light junction. This way, users of the AIM test facility such as OEMs and suppliers involved in developing the V2X hardware and functions can either use the real-life traffic light signals and intersection topologies in form of SPAT and Topo for their test scenarios, or specify their own traffic scenarios. The latter may contain any number of complex, physically non-existent intersection topologies and traffic light configurations that are encapsulated in SPAT and Topo. For example, V2X messages from public transport vehicles with special or priority rights may be simulated.

In addition to SPAT and Topo, traffic lights within the AIM test facility can also send DENMs. Scenarios that simulate safety-critical incidents (for example a crash or break-down of another vehicle) in the surrounding of a vehicle can be implemented. The complexity and depth of a specific application can be configured in a flexible manner offering a high variability for integrated simulated infrastructure-based scenario components. If this process reaches its limits, AIM also offers the alternative possibility of reverting to simulation-based environments or a mobile traffic light module for use on testing grounds.

FUNCTION SPECIFICATION IN THE RECEIVER

For validation of the safety functions, these have to be specified precisely so as not to allow any undefined function state. Therefore, the function specification has to consider the greatest possible number of applications and external influences on the system.

Journeys on the AIM test facility while specifying the functions help collecting information about environmental influences on V2X-based functions. Rain, snow and leaves can impair the range of the radio signals or be detrimental to satellite-based geolocation.

FIGURE 3 shows the influence of faulty direction sensing on the safety function "Warning of red light violation". The ego vehicle is within the reception range r of the SPAT message sent by the traffic light. But the deviation from the actual direction is too large, so that the relevance cone specified by the opening angle α does not include the traffic light. As a result, the system fails to detect the critical area and the desired safety effect of potentially warning the driver is not diminished. This means that either the safety function has to be adjusted or more reliable geolocation is required, for example, by using vehicle distance and direction as well (dead reckoning).

The information gathered on journeys through the AIM test facility can subsequently be evaluated, prioritised and used, as not all situations are relevant for all safety functions. Consequences can include displaying warnings about hazardous areas, for example, with the following information:

- point in time (time or distance to the incident)
- duration of the display
- updating interval
- level of detail of the information
- priority when several incidents are relevant at the same time.

TESTING COOPERATIVE SAFETY FUNCTIONS IN THE AIM TEST FACILITY

The AIM test facility can be used for various applications in the test and validation process. The following features a few applications as examples such as sensitivity analyses, calibrations and reference journeys.

Sensitivity analyses: The calibration of cooperative safety systems entails knowing the relevant influencing parameter. This includes, for example, possible ranges depending on weather, traffic volume, roadside structures or the number of active network nodes. In order to perform the analyses, a catalogue of criteria is defined and a certain route selected within the test facility. The relevant data are then acquired.

Calibrations: Vehicle functions are often developed with a higher degree of freedom that are defined for a specific vehicle in the calibration process. Calibration can be carried out within the test facility by driving along a defined calibration route. It is thus possible to compare the behaviour of the cooperative safety functions in the development vehicle with a reference vehicle. Another option is to administer calibration based on expert knowledge.

Reference journeys: Reproducibility of behaviour is an important criterion for the quality of safety functions. Reproducibility is usually validated inter alia by defining reference routes and driving along them with the development vehicle. For the specific calibration case, a fixed route can be defined within the test facility and driven repeatedly under defined conditions. The journeys can be evaluated using data from the vehicle and from the test facility.

Ensuring the accurate operation of safety functions in all traffic situations requires a lot of effort with regard to planning, setting up, conducting and evaluating tests. Providing the standardised function for sending V2X messages in AIM, only reception and safety functions have to be tested in the test vehicle. This way, the time invested in setting up the test infrastructure is significantly reduced.

OUTLOOK

The AIM test facility is being maintained by DLR for the purpose of extensive research. The DLR uses its facility for a wide range of research projects including their own research as well as government funded projects or industry funded projects. The large-scale research facility is constantly improved and new features are implemented in order to keep pace with state-of-the-art engineering and to fulfil the research needs of the DLR and its partners.

The cooperation between IAV and DLR described here illustrates the effective collaboration of a research institution in supporting the industry with the roll-out of cooperative functions. In particular, testing and validating cooperative safety functions has a high priority and testing these functions within a suitable test infrastructure is an essential prerequisite before introducing new technologies. The launch of the AIM test facility and its integration in IAV's test environment for cooperative safety functions fulfils the requirements for the needed infrastructural test site.

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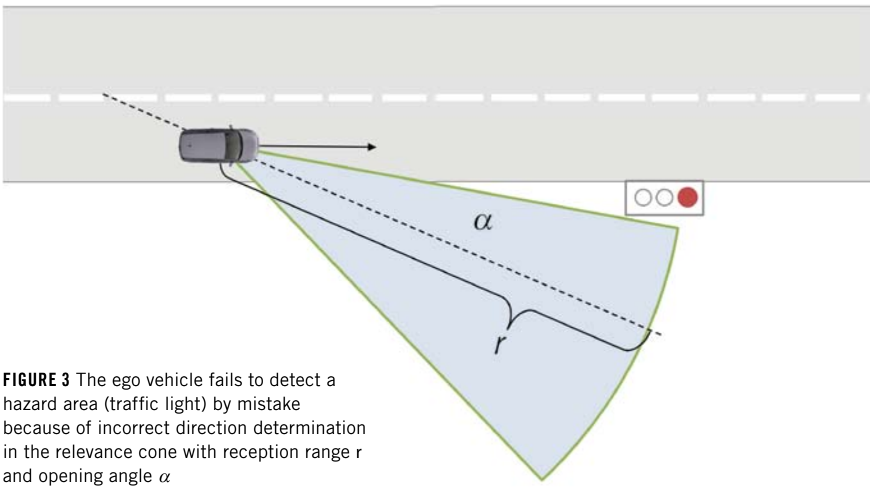

FIGURE 3 The ego vehicle fails to detect a hazard area (traffic light) by mistake because of incorrect direction determination in the relevance cone with reception range r and opening angle α

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In 2008, the peer review process utilised by ATZ and MTZ was presented by the WKM (Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik e. V./German Professional Association for Automotive and Motor Engineering) to the DFG (Deutsche Forschungsgemeinschaft/German Research Foundation) for official recognition. ATZelektronik participates in the Peer Review since 2011.

Automatic Metamodelling of CAE Simulation Models

There are many applications for CAE simulation models in the automotive industry. Simulations are usually less expensive and faster than conducting the real experiment, but still in some applications the simulation run times exceed several days. If the CAE simulation models could be replaced by metamodels, then a drastic runtime reduction would be achieved. divis intelligent solutions has developed reliable metamodels of CAE simulation models within a FAT research project.

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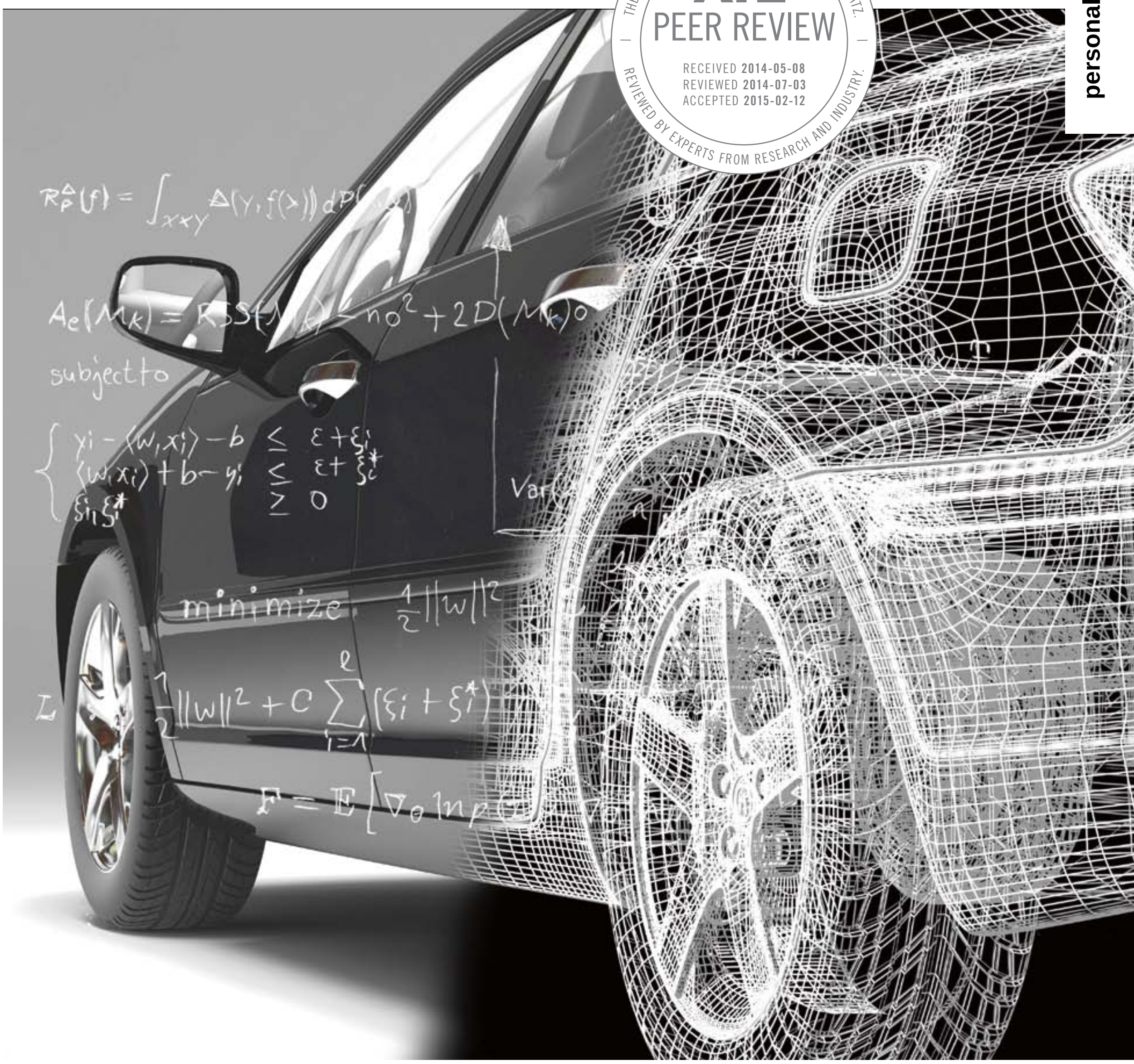

1 MOTIVATION

CAE simulations used in the automotive industry may have long runtimes, for example simulations of crash tests run for several days. If it is possible to replace a simulation run with a metamodel, then the runtime could be reduced drastically. This motivated the research project "Development of methods for reliable metamodelling of CAE simulation models" initiated by the FAT. Two aspects of the research project will be presented in this article. Firstly, benchmarks of modelling methods were conducted on real automotive data sets. Secondly, several model selection criteria were compared through an empirical analysis. Before we present the results, we introduce the concepts of metamodelling and its terminology.

2 METAMODELLING

A metamodel is a mathematical approximation model that should replace a time-consuming CAE simulation. Metamodels are learned with data stemming from simulation runs. After a metamodel is created successfully it can be used to predict the results of a simulation. The quality of a metamodel is derived from prediction errors. The so-called generalisation error measures how well a metamodel predicts all possible observations. In applications, the generalisation model can only be approximated, because the output is not known for all possible observations. However, the so-called training error can be calculated. It is the prediction error that the metamodel makes on the learning data set. Exclusively minimising the training error can yield a model that performs badly for new observations, thus having a bad generalisation error. This situation is called overfitting and should be avoided.

There are a lot of metamodelling techniques in the field of supervised learning, an overview with introduction to machine learning is given in [1, 2]. For our benchmarking experiments we used the techniques which are implemented in the software ClearVu Analytics. They cover the range from relatively simple methods like linear models to more complex ones like Support Vector Machine (SVM). The complete list is: Linear Models, Decision Trees (CART) [3], Random Forests [4], Fuzzy Models [5-9], Neural Networks [10, 11], SVM [12, 13], Kernel Quantile Regression (KQR) [14], Partial Least Squares Regression (PLSR) [15], Principal Component Regression (PCR) [15] and Gaussian Processes [16].

Metamodelling methods share the common feature that their fitting behaviour can be controlled by a set of parameters. The parameters have to be adjusted to the data set at hand. Doing this manually is a time-consuming task and can be replaced by an automatic model optimisation. As described before, only minimising the training error may lead to overfitting. So, in order to conduct a model optimisation we need a selection criterion to choose amongst fitted metamodels the one that yields the lowest generalisation error. There are two approaches for model selection criteria. One is a parametric approach derived by the analysis of linear models, the other non-parametric approach is cross-validation (CV) which uses validation data sets retained during the learning process.

CV is applicable to arbitrary modelling methods, and neither any assumptions have to be made, nor any knowledge about the internals of the modelling method is needed. With a k-fold cross-validation the learning data set is partitioned into k preferably equally sized parts, with $1 < k \leq n$. Each of the k partitions serves as a validation data set for a model that is fitted on the union of the remaining $(k - 1)$ partitions. So, in CV modelling takes place k times. Then error measures can be calculated based on the predictions and the true output values of the validation sets. Since the validation data was not seen during the learning process, error measures derived from CV are better estimates for the generalisation error than the training error. Concerning the choice of k, a good compromise is $k = 10$, an empiric analysis [17] even showed that CV with $k = 10$ estimates the generalisation error better than leave-one-out ($k = n$).

The parametric model selection criteria were developed for linear models. Their calculation is based on measures derived from a fitted model. In detail, they are the residual sum of squares (RSS), that is to say the quadratic prediction error made on the training data set, and the degrees of freedom (DF) which is a complexity measure for linear models. The Akaike Information Criterion (AIC) [18] is defined as

Eq. 1	$AIC := 2 \cdot DF + n \cdot \log(RSS/n)$

the Bayesian Information Criterion (BIC) [19] as

Eq. 2	$BIC := n \cdot \log(RSS/n) + DF \cdot \log(n)$

and the Generalised Cross Validation (GCV) [20] as

Eq. 3	$GCV := (RSS/n)/(n - DF)^2$

In order to apply these three model selection criteria to other modelling techniques than linear models, their DF values have to be known, respectively a complexity measure for arbitrary modelling techniques equivalent to DF has to be used. Ye [21] developed such a complexity measure, called generalised degrees of freedom (GDF) which is defined for a fitted model M as

Eq. 4 $$GDF(M) = \sum_{i=1}^{n} \frac{\partial E[\hat{y}_i]}{\partial y_i}$$

The sum over the partial derivatives measures the sensitivity of the expected value of a prediction $E[\hat{y}_i]$ in terms of an original output y_i. Application of GDF to linear models yields the same value as DF. To calculate the partial derivatives, [21] uses a Monte-Carlo approach. In the following they are calculated numerically with a two sided variation. Thus $(2 \cdot n)$ models have to be fitted to calculate GDF.

The software tool ClearVu Analytics offers automatic model optimisation. It uses 10-fold CV as model selection criterion to determine the best parameter set for any of the modelling technique. Furthermore, we compare the best models found by each modelling techniques to determine a best model. For this purpose we conduct nonparametric statistical tests on the prediction errors from the 10-fold CV to find significant differences between the best parameterised metamodels. The optimisation is conducted by an Evolution Strategy [22, 23].

3 BENCHMARKS WITH AUTOMOTIVE DATA SETS

The FAT provided 41 data sets, **TABLE 1**. The data is mostly derived from crash simulations. In order to avoid giving away internal knowledge of the automotive companies involved, the names of input and output variables were anonymised. In total there are 861 output variables, all of them real valued, for which a metamodel has to be fitted. The size of the data sets ranges from 36 to 708 regarding the number of observations and the amount of input variables varies between 5 and 142.

An automated model optimisation with the software ClearVu Analytics was conducted for each of the 861 output variables. To summarise the metamodel quality over all data sets, the correlation between the true output value and the predicted value is used. A correlation value greater than 0.95 indicates a very good model, for a correlation value greater than 0.9 the model can be considered good and the quality of a model with a correlation value greater than 0.8 is still acceptable. According to this classification 455 out of 861 output variables were modelled very well. Furthermore, for 88 output variables good metamodels and for 116 output variables acceptable metamodels were found. **FIGURE 1** shows a graphical summary of these results. **FIGURE 1** (right) shows which modelling method yielded the best metamodel. Despite its relatively simple structure generalised linear models are the best modelling method on the automotive data sets. In almost 200 cases decision trees and SVM prevailed.

That leaves 202 out of 861 output variables where no suitable metamodel could be found by automated model optimisation. For those output variables the metamodels could be enhanced by enlarging the amount of observations or by variable transformations. As an example for a very good metamodel, a screenshot of ClearVu Analytics shows the validation scatter plot of the metamodel, **FIGURE 2**. A scatter plot visualises the metamodel quality by plotting the true output values against the predicted values. With a perfect metamodel all points would be located on the bisecting line.

Company	Data set count	Output variable count
Behr	2	13
Bosch	1	67
Ford	21	645
Opel	9	55
Porsche	6	55
TRW	1	19
ZF	1	7

TABLE 1 Overview of the delivered data sets

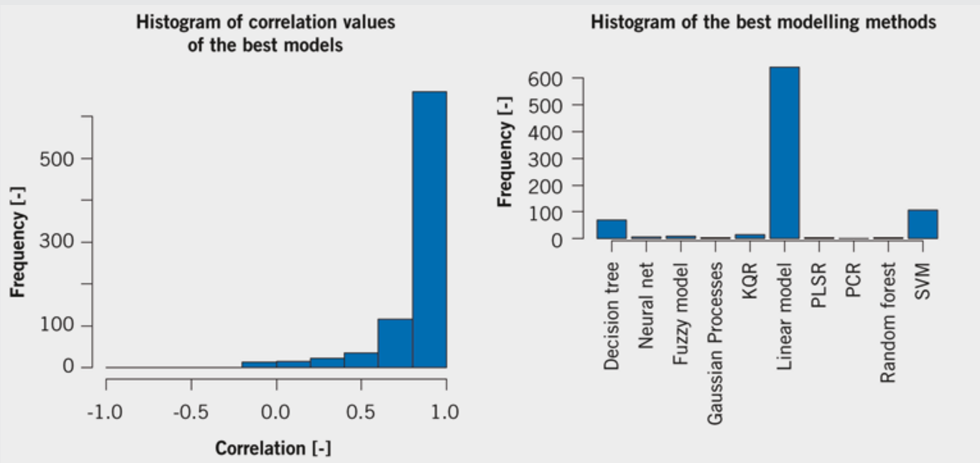

FIGURE 1 Correlation values of the best models and the best modelling methods

4 EMPIRICAL ANALYSIS OF MODEL SELECTION CRITERIA

For model optimisation different selection criteria can be used. Chapter 3 introduced the model selection criteria CV, AIC, BIC and GCV. An empirical examination shall show which of these criteria leads to well generalising models. As mentioned in the previous chapter, the calculation of the generalisation error is not possible except for constructed examples. To estimate the generalisation error reasonably well a huge amount of data is required. Neither the data provided by the team members nor the data from the UCI machine learning repository [24] is available to such an extent. Therefore, test functions of the black box optimisation are used to generate datasets. These are particularly the functions Katsuura, Rastrigin and Rosenbrock as used for the Blackbox Optimisation Benchmark (BBOB) [25]. They are nonlinear and except for Rosenbrock have many local optima. This is advantageous for this experiment because a dataset which is difficult to model is likely to show an extensive Pareto front between complexity and training error during the model optimisation. From this Pareto front the selection criteria can select a model. The test functions are used with two input variables from the design space [-5, 5]×[-5, 5]. The validation data set for estimating the generalisation error is given on a grid with a distance of 0.01 in the design space by evaluations of the test function. So the validation dataset contains more than one million observations. A learning dataset of one hundred random observations is drawn from of this dataset. With this learning dataset five model optimisation runs are performed for each model selection criterion. The created models are applied on the validation dataset and the resulting prediction error is used as an estimator for the generalisation error of the model.

For the evaluation the generalisation errors of the specific model selection criteria are examined pairwise with a non-parametric test, the Student-t test, to find significant differences. In case of a significant difference the model selection criteria showing the lower generalisation error wins, otherwise the comparison is evaluated as undecided. This approach is run with 30 different learning datasets for the modelling methods support vector machine, linear models, decision tree and neural networks. The choice of the modelling methods is motivated by their good performance on the automotive data sets.

For each test function and each modelling method a model selection criterion competes with three other model selection criteria in 30 runs, so it may reach at most 90 wins. The win count is presented in **TABLE 2**. The cases, where only a few wins were counted due to few significant differences, that is neural networks with all test functions and SVM with test function Katsuura, do not designate a superior model selection criterion. However, in the remaining eight scenarios ten-fold CV is the best model selection criterion. In five of these eight cases CV clearly wins. From these results we conclude that ten-fold CV should be used as model selection criterion during model optimisation.

5 SUMMARY

One aspect of the research project is to benchmark metamodelling methods on real automotive data sets. 41 data sets with 861 output variables were provided by the members of the FAT group. The automatic metamodelling approach of ClearVu Analytics yielded for 659 out of 861 output variables acceptable metamodels, for 455 of them even very good ones.

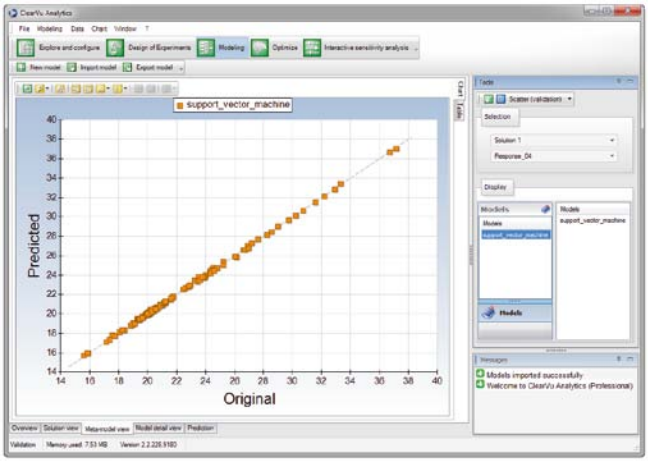

FIGURE 2 Screenshot of ClearVu Analytics showing the scatter plot of a very good metamodel

Another aspect of the research project is the evaluation of several model selection criteria. For this purpose an empirical analysis on constructed data sets was conducted to identify the model selection criterion which generalises best. For some of the criteria a complexity measure for arbitrary modelling methods is needed and GDF is identified and is implemented as a plausible complexity measure. Ten-fold CV is superior to the criteria AIC, BIC and GCV according to our comparison.

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Function	Modelling method	CV	AIC	BIC	GCV
Katsuura	Linear Model	90	0	0	0
	Support Vector Machine	1	2	3	3
	Neural Networks	2	0	0	0
	Decision Tree	63	4	20	5
Rastrigin	Linear Model	33	24	17	24
	Support Vector Machine	85	1	0	0
	Neural Networks	3	0	0	3
	Decision Tree	14	11	10	11
Rosenbrock	Linear Model	79	13	3	13
	Support Vector Machine	88	2	3	1
	Neural Networks	4	2	1	2
	Decision Tree	26	17	11	16

TABLE 2 Results of the comparison of model selection criteria

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Vibrations in All-wheel Drives

The charging of internal combustion engines leads to a higher rotational irregularity of the torque output. This nonuniformity can stimulate the downstream drivetrain vibrations. This is, particularly rotational oscillations have been found to be relevant to the acoustic behaviour inside the vehicle. Now at FEV, the resulting from the interconnection of front and rear drivelines all-wheel drivetrain was tested for its vibrational properties for rotary stimulation.

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1 MOTIVATION

The trend of high-load downsizing to reduce CO_2 emissions from car engines could prevail against the high-speed downsizing in recent years. As high-load downsizing is achieved by supercharging the engine‘s load change, the resulting torque fluctuation is changed. Especially in lower speed ranges an increase of the engine's rotational irregularities can be observed, which may excite the driveline and cause NVH issues [1-4]. As a combination of front- and rear-wheel drivetrains, the all-wheel drivetrain is more complex concerning rotational vibrations. This can be explained by the increased rotational degrees of freedom.

The aim of this work is to investigate a four-wheel drivetrain with a four-cylinder diesel engine , which is mounted longitudinally in the front of a vehicle in terms of its vibrational properties with rotatory stimulation. With the application of a virtual holistic approach the effects of rotational irregularities at the crankshaft on the vehicle interior are calculated additionaly. For this purpose, a full vehicle model is created with the usage of a three-dimensional multi-body simulation programme and coupled with a vibro-acoustic transfer path synthesis. In addition to the virtual tests, the vehicle is measured on a test track for the calculated operating points. The measurement results are used to validate the virtual model. By comparing the real interior noise measures (which include all real excitation mechanisms in driving mode) with the calculated interior measures, the share of noise and vibrations inside the vehicle which are caused by rotational irregularities are presented. By varying the parameters of the rotating components in the calculation model, factors and trade-offs can be identified in the design of the examined four-wheel drivetrain.

2 VARIANTS OF THE ALL-WHEEL DRIVE

Mass produced passenger cars that use all-wheel drivetrains with mechanical coupling of both driving axles can be divided into two groups. Based on the basic drivetrain one can distinguish between front and rear drive-based all-wheel drive. The permanent torque-transmitting base drive is supplemented by an additional drive to the second axle. The mechanical coupling of the partial drivetrains is usually realised by an all-wheel transmission. Adjustable clutches are often used in addition to influence the power distribution between the two driving axles. The investigated powertrain in this article is a rear drive-based all-wheel drivetrain with longitudinal front-engine and fixed drive to the rear axle. With an all-wheel transmission after the main transmission, the front part of the drivetrain can be switched in by closing the clutch in the all-wheel transmission, so that the power flow is divided in two parallel paths to the front and rear axle. The ratio of the all-wheel transmission is 1.0 to both axles. Front and rear differential have the same ratio. The use of identical tyre dimensions on both axles result in a symmetrical all-wheel drive, which does not wind up while driving without load and without wheel spin on road. The resulting static torque distribution between front and rear axle is 50 : 50.

3 CALCULATIONS OF DRIVETRAIN VIBRATIONS

3.1 PROCEDURE

For an evaluation of rotational induced drivetrain oscillations and its impact on the vehicle's interior noise and vibrations, a holistic virtual approach is used. A multi body simulation (MBS) model is built up, which can be expanded with other software tools in a co-simulation, if necessary. For the calculation of the drivetrain vibrations a 3D full vehicle model is designed with a rigid body in multi-body simulation software. Besides the drivetrain, the chassis is modelled with subframe and all existing rubber and hydraulic bearings. The calculation is performed on the basis of the cylinder internal pressure via the drivetrain and its connection points to the vehicle interior.

For the frequency range below 30 Hz, the calculation was performed with an impulsive excitation. Below 30 Hz, the examined body structure proves to be almost rigid in the vehicle longitudinal direction (x-direction), so that the acceleration at the driver's seat rail in x-direction is determined directly in the MBS model. Above 30 Hz this is not the case. The consideration of the body properties is mandatory, which is why the MBS model is extended by a transfer path analysis. The body properties are determined by the transfer path analysis tool FEV-VINS (Vehicle Interior Noise Simulation) [5-7] on the actual vehicle. For determining the interior noise shares the transfer path functions are combined with the results of the multi body simulation. The calculated internal measures are the airborne sound at driver's ear and vibrations in the vehicle vertical direction at the forward end of the outer driver's seat rail. For both, the calculation of the interior noise shares and the interior vibrations the transfer path functions of all existing structure borne noise coupling points between powertrain, chassis and body are used.

For the frequency range of 30 to 200 Hz, the vibration calculation is based on a periodic excitation. To determine the isolated noise and vibration shares which are induced by rotational irregularities, dynamic torque fluctuations at the crankshaft are used for

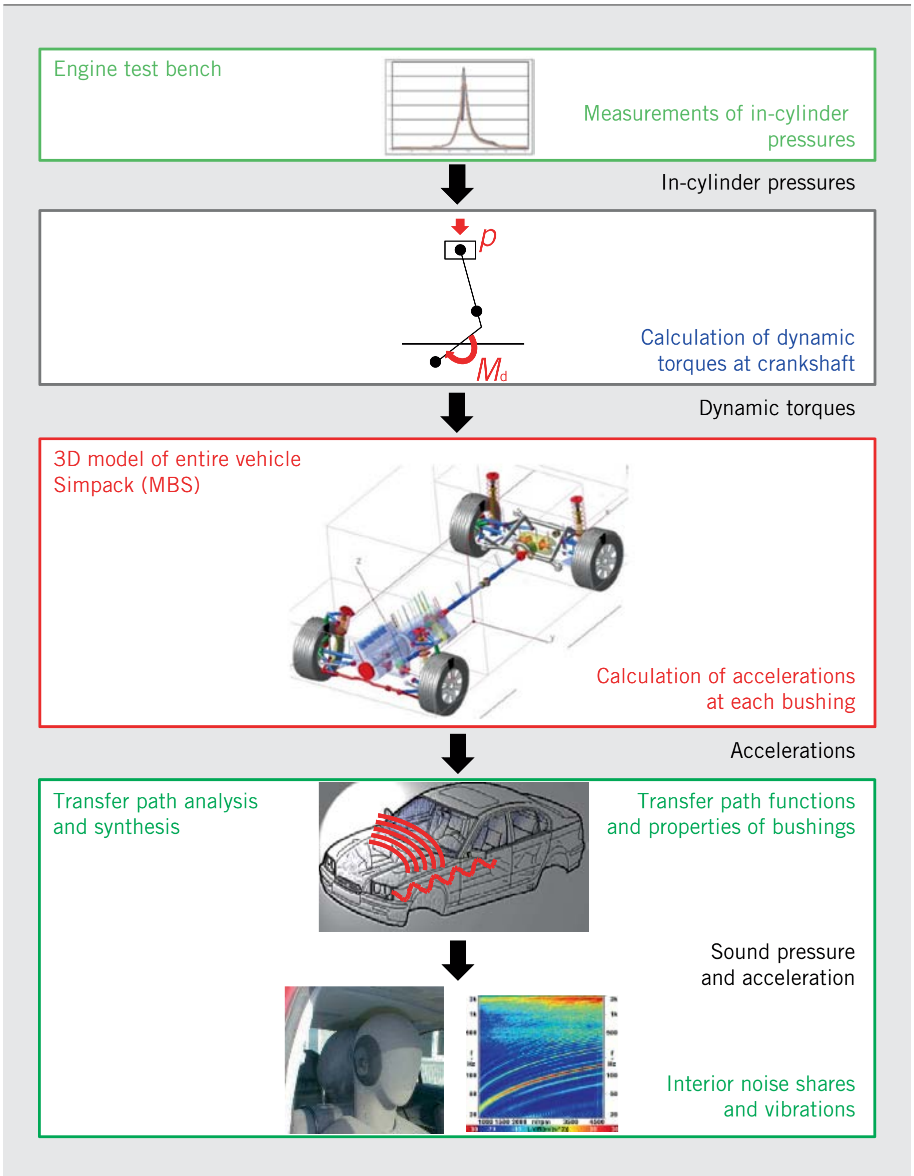

FIGURE 1 Procedure of running mode analysis with a holistic view from in-cylinder pressure to interior noise shares and vibrations in the passenger

the excitation of the drivetrain. **FIGURE 1** shows the procedure for the case of periodic excitation.

3.2 EXCITATION AND OPERATING POINTS

For the examination of the frequency range below 30 Hz pulse the necessary impulsive engine torque was determined in road tests and is shown in **FIGURE 2** (left). Coming from coasting operation a sudden load change into full load at 1250 rpm in second gear is performed. The frequency range between 30 and 200 Hz is examined by a periodic excitation. For this the excitation of combustion and crankshaft mass forces is used. A speed sweep from 1000 rpm to 4000 rpm in full load conditions is calculated in sixth gear. In a first step, the cylinder pressures are determined in quasi-static operating points using engine bench tests of an identical engine. The measurements are carried out between 1000 and 4000 rpm with a speed increment of 250 rpm and summarised in a cylinder pressure map. The cylinder pressure is then calculated by the crank mechanism properties (mass and geometry) to a map of the dynamic crank shaft torque which is used as an excitation in the MBS model. Between the measured engine speeds a linear interpolation is performed within the MBS model. **FIGURE 3** shows the dynamic torque at the crankshaft via a working cycle in full load conditions at 2000 rpm after combining gas and mass forces. Between two firings, the dynamic torque lowers to negative torque values and has a maximum torque difference of about 1800 Nm.

3.3 RESULTS

The investigations of the drivetrain are carried out using modal analysis and running mode analysis. Based on the solution of the eigenvalue problem of the homogeneous differential equation, the eigenvalues and eigenvectors of the vibration system are determined. By applying the principle of superposition and the representation of the eigenmodes an easier inspection of the linear differential equation system is possible. The evaluation of

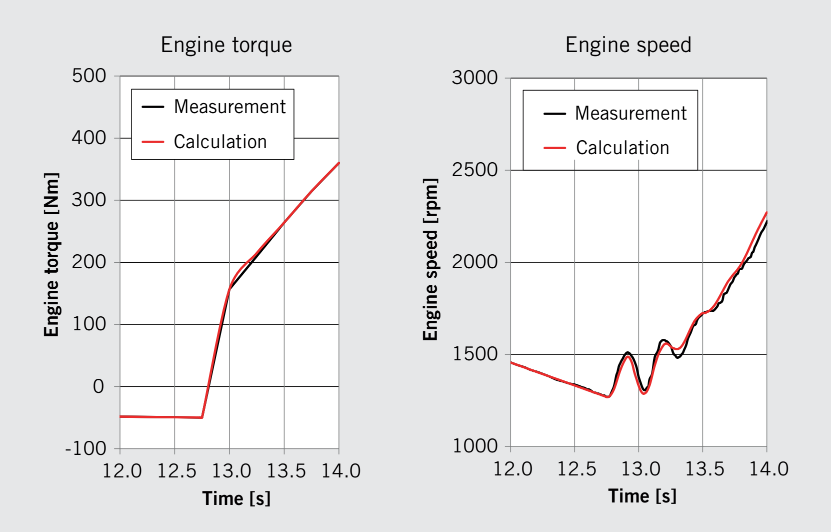

FIGURE 2 Validation with impulsive excitation, sudden load change from coasting in full load conditions in second gear, engine torque (left) and engine speed (right) at the engines crank shaft

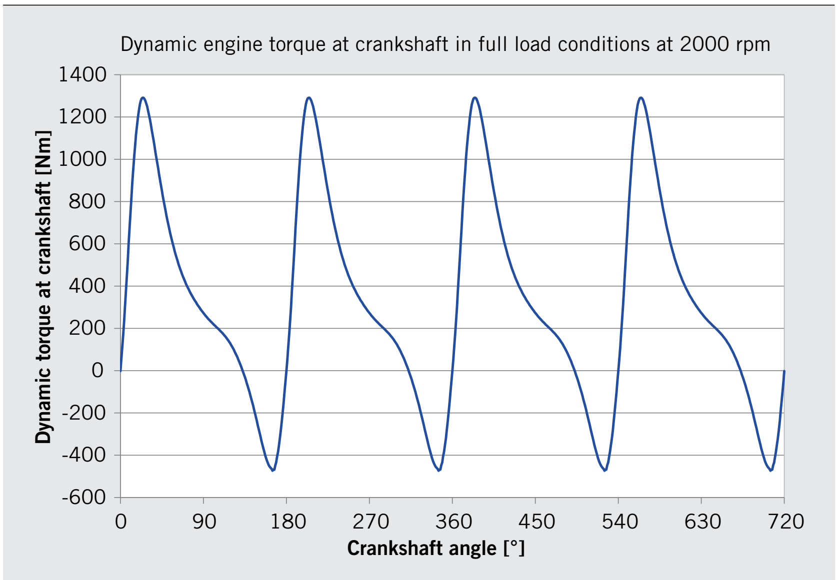

FIGURE 3 Dynamic torques at crankshaft for a working cycle in full load condition at 2000 rpm

the modal analysis for the frequency range of 1 to 200 Hz shows a higher modal density at the all-wheel drive with eleven rotational eigenmodes as the front-wheel drive with seven or rear-wheel drive with six rotational eigenmodes. In particular, the occurring eigenmodes do not correspond to a superposition of the individual powertrains. On the other hand the running mode analysis is the particular solution of the inhomogeneous differential equation, which can be defined by considering the external constraint forces. In this case, the external constraint forces in the two investigated operating points are the described "impulsive" and "periodic" excitation.

The dynamic torque to the cardan shafts to the front and rear axle are used for the model validation and as drivetrain internal evaluation measures. **FIGURE 2** (right) shows the resulting engine speed during the operating point with impulsive excitation. **FIGURE 4** shows the calculated torque fluctuation of the two cardan shafts during this driving manoeuvre (diagrams on the left and in the centre) and the acceleration on the driver's seat rail in vehicle longitudinal direction (right). The engine speed, the torque fluctuation of the both cardan shafts, and the acceleration inside the car oscillate in phase with a frequency of 3.5 Hz and can be observed in the measurement and calculation results. Unlike expected from the ratios, the resulting torque distribution between two drive axles is not 50 : 50. This can be attributed to the fact that the drivetrain to the rear axle with respect to the drivetrain to the front axle has a higher rotational stiffness by a factor of two. **FIGURE 5** shows the results of the modal analysis of the rotating drivetrain. The vibration at 3.5 Hz can be attributed to a global rotational eigenmode of the drivetrain. The entire drivetrain oscillates in phase and is tightly clamped at one end by the tyre-road contact, **FIGURE 5** (left). The state of vibration in the passenger compartment can be determined directly in the MBS model, despite the use of a rigid body structure, **FIGURE 4** (right). The body turns out to be approximately rigid in this direction below 30 Hz.

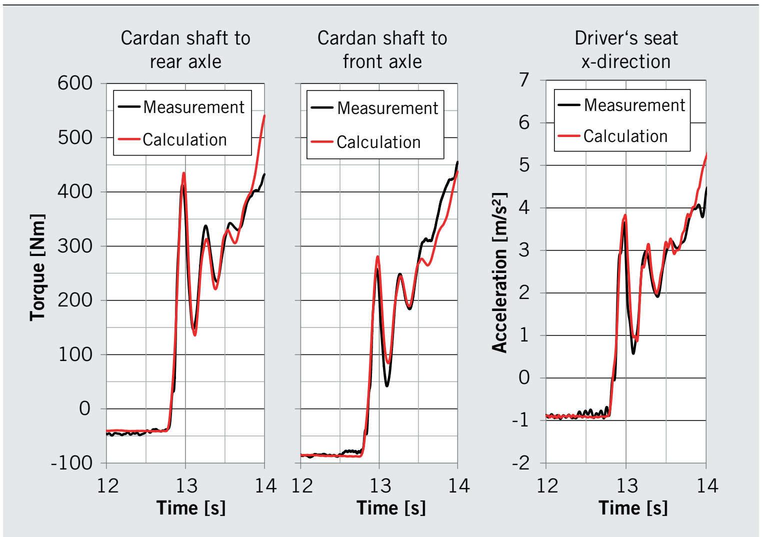

FIGURE 4 Validation with impulsive excitation with sudden load change from coasting in full load conditions in second gear

FIGURE 6 shows the order analysis of the cardan shaft torque fluctuation in firing order after periodic excitation. Clearly visible is the maximum dynamic torque fluctuation at 1150 rpm (38.3 Hz in the second engine order) on both cardan shafts, whereas the amplitude of the cardan shaft torque fluctuation to the rear axle is higher. Despite a static torque split of 50 : 50 between the two drive axles, both parts of the driveline have different torque fluctuation amplitudes because of the different rotational stiffness of both parts. The amplitude maximum at 1150 rpm can be attributed to a concatenation of different powertrain properties. On the one hand the modal analysis of the drivetrain shows a torsional eigenmode at 27.8 Hz, **FIGURE 5** (right). On the other hand, the modal analysis of the elastically mounted rear axle shows a rigid body eigenmode, **FIGURE 7**, since the rear axle bounce mode of 39.2 Hz is also within the frequency range of the maximum amplitude at 1150 rpm. The dynamic torque fluctuation in the cardan shaft to the rear axle, in addition have a local maximum at 1560 rpm and an amplitude increase starting from 3500 rpm. The local maximum at 1560 rpm (corresponding to 52 Hz in the second engine order) can be attributed to the pitch mode of the rear axle

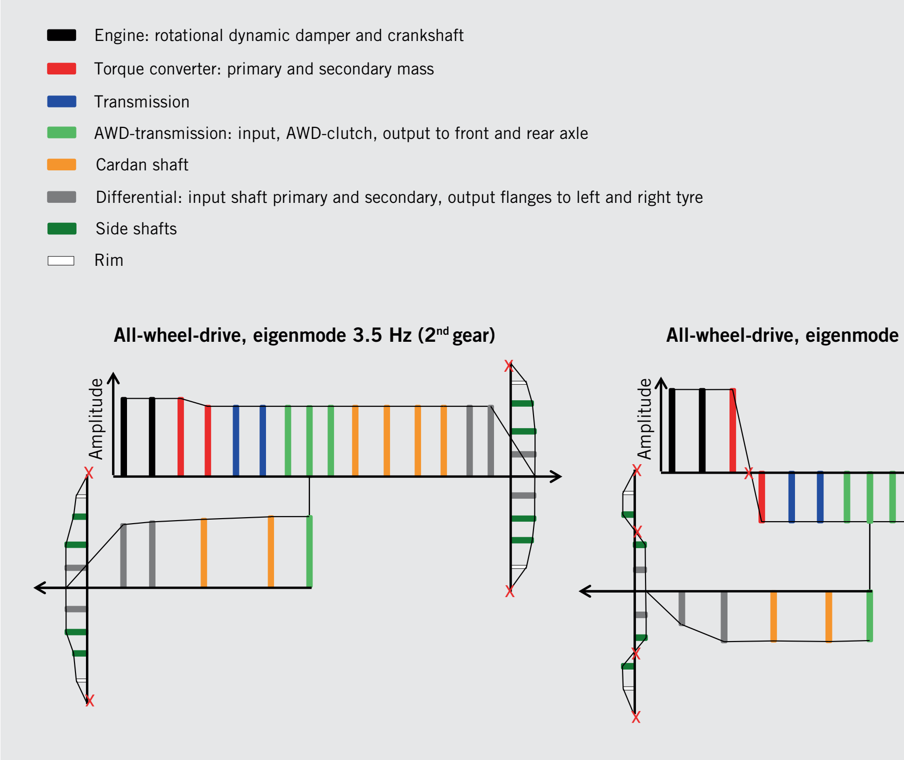

FIGURE 5 Results of modal analysis of the rotating drivetrain

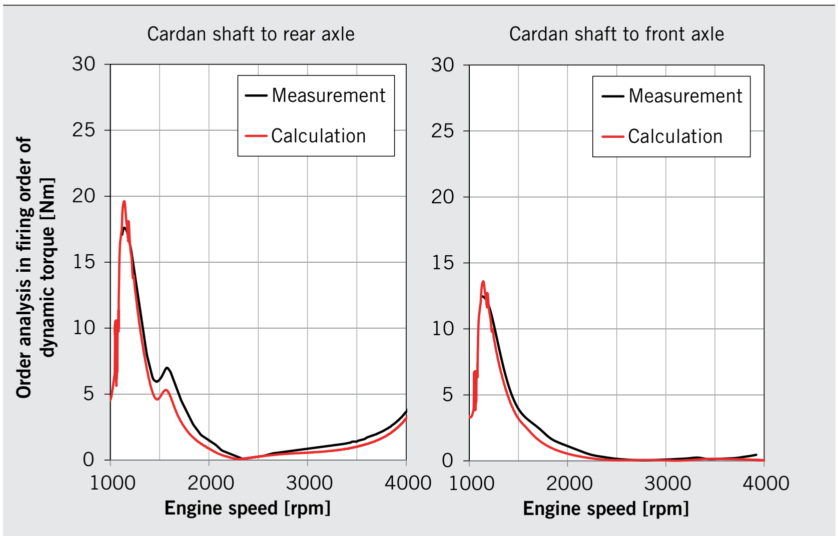

FIGURE 6 Validation with periodic excitation in full load engine speed run up in sixth gear – order analysis in firing order of dynamic torque fluctuation in cardan shaft to rear (left) and front axle (right)

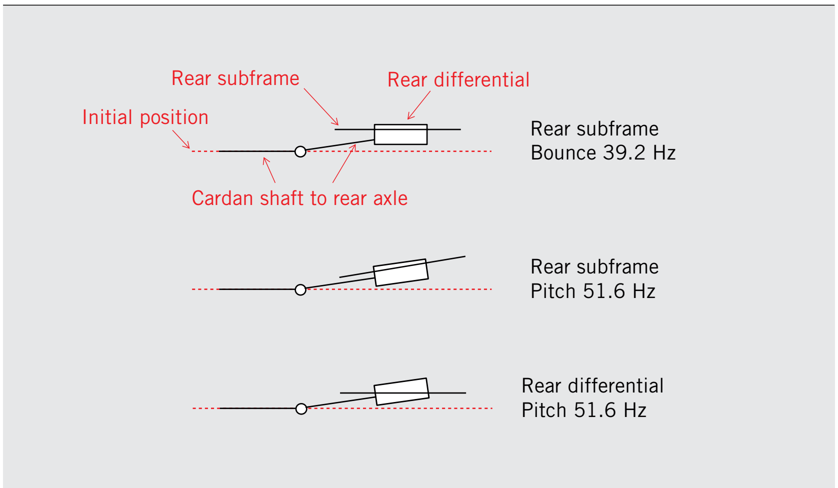

FIGURE 7 Results of modal analysis of the rear axle

at 51.6 Hz, **FIGURE 7** (centre). The amplitude increase at high engine speeds can be attributed to the pitch mode of the rear differential at 146.9 Hz (corresponding to 4407 rpm). The translational eigenmode shapes of the rear axle react back on the rotating system and can be seen within the cardan shaft to the rear axle.

FIGURE 8 and **FIGURE 9** show the interior noise shares and interior vibration in the vehicle's vertical direction as Campbell diagrams for the operating point of periodic excitation. In each figure the overall measurement signals are displayed on the left side, on the right side the calculation results representing the noise shares due to rotational excitation are shown. In the frequency range below 100 Hz the interior noise and vibrations are dominated by rotationally excited oscillations. In particular, the high amplitudes in firing order are largely caused by rotationally excited vibrations. Since the vehicle measurement in contrast to the calculation model includes noise shares of all existing noise sources in the vehicle, the Campbell diagrams of the vehicle measurements also contain non-rotationally excited noise shares. In **FIGURE 8**, this concerns for example the sound pressure rise in the fourth engine order at 100 Hz. In particular, since the intake and exhaust systems are not included in the calculation model, all real noise components cannot be predicted by the calculation. Vehicle inspection with led away exhaust system identified the airborne noise of the exhaust system as the dominant noise source in the case of level increase in the fourth engine order at 100 Hz.

4 PARAMETER VARIATIONS OF THE ROTATIONAL DRIVETRAIN

The validated calculation model was used to perform a sensitivity analysis by varying single parameters. A systematically variation of all rotating components in the vehicle, concerning their rotational inertia and the rotation stiffness, was performed separately by 25 %. In addition, the ratio of the main transmission and the differential ratios on the front and rear were varied by the same amount. The variations were evaluated based on running mode analysis with the periodic and impulsive excitations which were used previously. **FIGURE 10** shows the effects on the drivetrain by a gear ratio variation of 25 %. A reduction of gear ratio by 25 % affects a decrease of amplitude after impulsive excitation, **FIGURE 10** (left). However, at the same time this component varia-

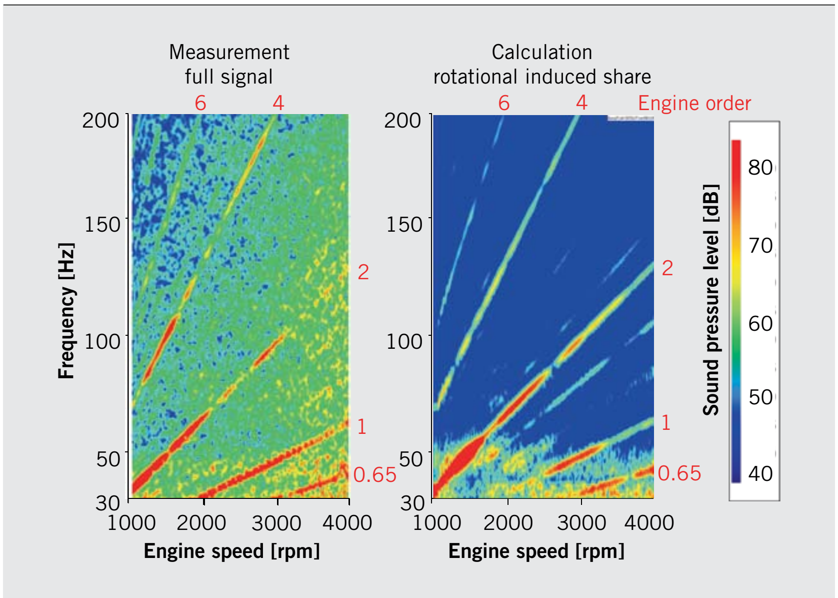

FIGURE 8 Measured sound pressure level at driver's ear (left) and its calculated rotational induced noise share (right) at full load engine speed run up in sixth gear

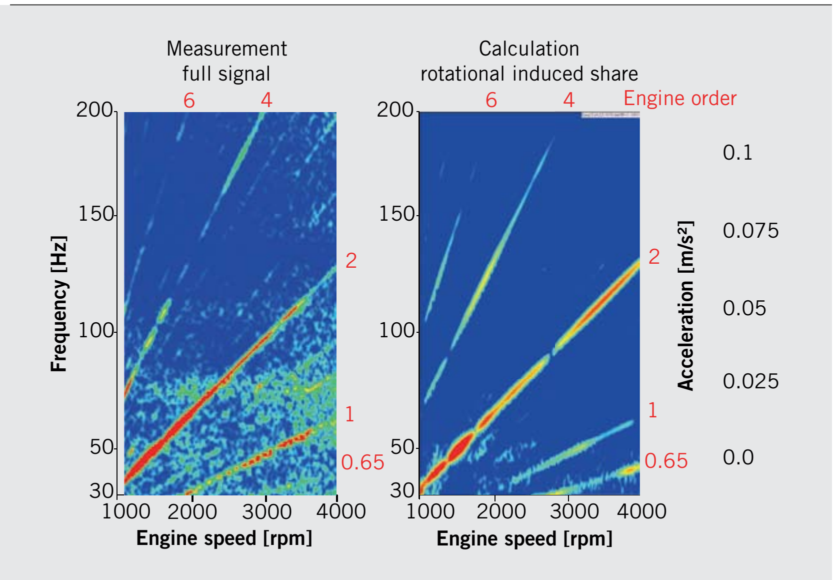

FIGURE 9 Measured acceleration at driver's seat rail in z-direction (left) and its calculated rotational induced noise share (right) at full load engine speed run up in sixth gear

tion means an increase in the oscillation amplitude with periodic excitation, **FIGURE 10** (right). This relationship identifies a general trade-off within the powertrain design of the examined four-wheel drive with the following component parameters:
– moment of inertia of rotating parts from crankshaft to first transmission ratio
– rotational stiffness of rotating parts between differentials and tyres
– ratio of main transmission
– ratio of differentials.

An increase of inertia between the crankshaft and the first transmission ratio causes an increase in the vibration amplitudes at impulsive excitation and a decrease at periodic excitation. An increase of the rotational stiffness of components which are located between the differential ratio and the tyre or a reduction of main transmission and differential ratio cause the same effect.

5 SUMMARY

With the use of a co-simulation that contains a multi-body simulation model and a transfer path analysis, the entire functional chain from rotational irregularities at the crankshaft which excite the driveline to its impact on the total vehicle on the driver's seat is considered. The all-wheel drive has a higher modal density than the front or rear-wheel drive, especially do the eigenmodes of the all-wheel drive not correspond to a superposition of front and rear-wheel drive eigenmodes. Despite a static torque distribution of 50 : 50 between the two drive axles due to the symmetrical drivetrain configuration, significantly different torque fluctuation amplitudes occur in both partial powertrains due to their different rotational stiffness. Below 100 Hz for the investigated four-wheel drive with supercharged four-cylinder

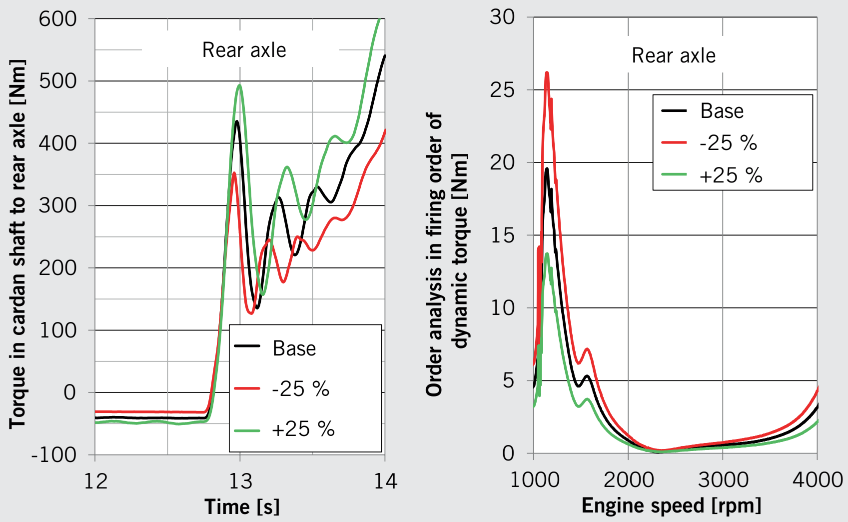

FIGURE 10 Drivetrain oscillation after parameter variation of main transmission ratio by 25 % with impulsive excitation (left) and periodic excitation (right) at the dynamic torque at cardan shaft to the rear axle

diesel engine, the interior noise shares and vibrations in the passenger cabin are dominated by rotational irregularities. By varying the parameters of the individual drivetrain components separately in running mode analyses optimisation potentials, but also trade-offs of powertrain design regarding impulsive excitation (sudden load change) and periodic excitation (rotational irregularities caused by combustion) can be identified. The trade-off parameters are mainly the inertia of all parts between the crankshaft and the first ratio of the transmission, the rotational stiffness of parts which are located between the differential and tyres and the ratios of the main transmission and differential gears. Moreover, the rigid body eigenmodes of the elastically mounted rear axle are partially responsible for the interior noise shares and vibrations in the passenger cabin on the one hand, but do react back on the rotating system of the drivetrain on the other hand.

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