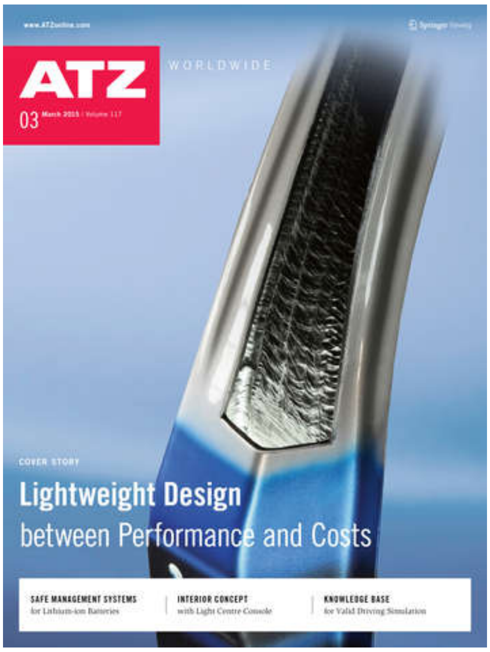
personal buildup for

Force Motors Limited Library



atzw 3/2015, as epaper released on 16.02.2015
http://http:www.atz-worldwide.com

content:

www.ATZonline.com

Springer Vieweg

ATZ WORLDWIDE

03 March 2015 | Volume 117

COVER STORY

Lightweight Design between Performance and Costs

SAFE MANAGEMENT SYSTEMS for Lithium-ion Batteries

INTERIOR CONCEPT with Light Centre Console

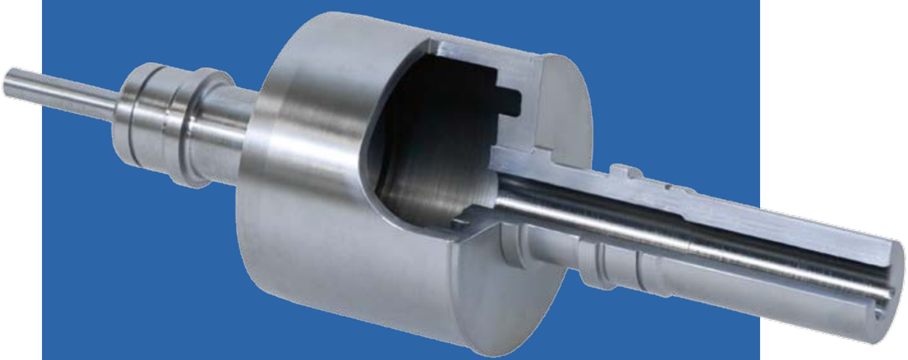
KNOWLEDGE BASE for Valid Driving Simulation

CONTENTS

COVER STORY

Lightweight Design between Performance and Costs

The ambitious targets for reducing fuel consumption and emissions are making lightweight design increasingly important. Although new lightweight materials offer better performance, they are often more expensive. Designers are also spoilt for choice when faced with up to 30 different grades of steel, complex composites or polymers which can be used to exploit lightweight potentials in bodies, roofs and B-pillars.



COVER FIGURE © Edag
FIGURE ABOVE © ThyssenKrupp

Material Concepts

Dear Reader,

Emission levels of less than 90 g of CO_2 per km are hardly possible without electrification, alternative fuels or lightweight design. The latest Shell Passenger Car Scenarios forecast a fleet of 10.1 million electric vehicles by 2040, while the number of petrol- or diesel-powered vehicles will fall to 30.7 million. McKinsey expects that only around 5 % of vehicles will have an internal combustion engine in 2050. The 2011 EU White Paper on transport policy predicts that the use of conventionally fuelled cars in urban transport will halve by 2030.

There are therefore no unanimous forecasts for the number of electric cars in the future. Electric mobility is not predictable. Customers need to be convinced – both emotionally and economically. At the same time, the need for mobility is falling, and mobility is still strongly determined by emotions. So what are customers looking for and what price are they prepared to pay for an energy-optimised vehicle?

In addition to applying suitable measures to the powertrain, lightweight design is an effective means of reducing vehicle weight and emissions. In automotive engineering, there is huge potential not only in the vehicle body but also in load-bearing or safety-relevant components, especially if composite materials are used. The key point, however, is the cost-effectiveness of lightweight design concepts, particularly when we need to consider not only the additional costs of lightweight construction of up to 5 Euros/kg but also the added cost of an electrified powertrain, as well as the fact that the use of different materials will mean that repairs might become more complex and therefore more expensive.

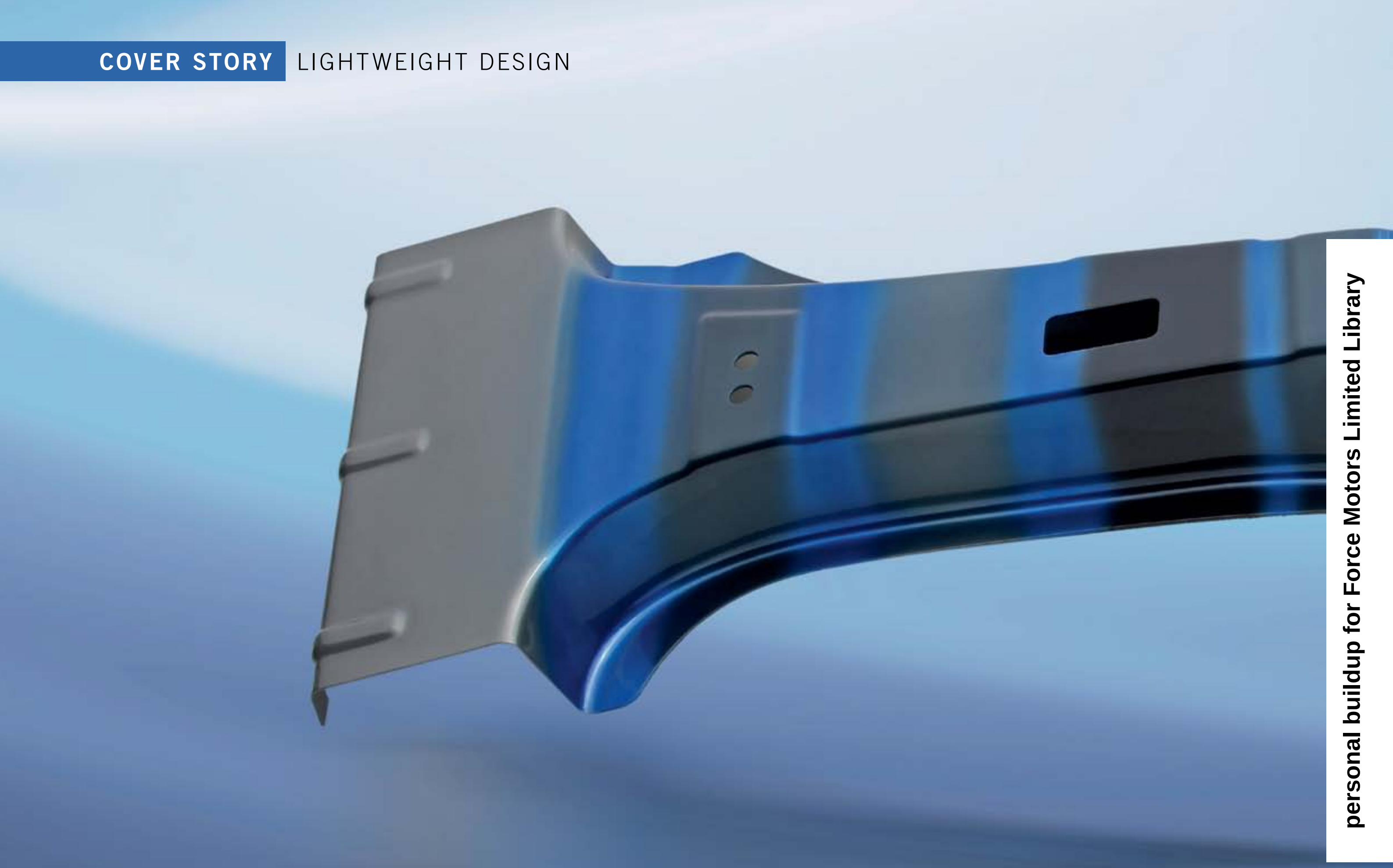
These questions were reason enough to make the subject of lightweight design the leading topic of this issue of ATZ.

Recent innovations in components and materials are evidence of significant progress in aspects of energy and weight efficiency, safety, functionality, design and comfort. This topic is an ideal complement to the latest issue of our magazine lightweight design (lwd), which, in the first edition of 2015, turns its attention to chassis components, and shows how ZF combines material substitution and lightweight design in a wheel-guiding transverse spring made of GRP.

Choosing the right material at the right place is an ongoing challenge for developers and design engineers. It involves enabling new material concepts to be put into production from an economic perspective, while at the same time also addressing life cycle issues. The focus remains on the efficient use of energy and therefore the sustainable protection of resources. In modern automotive engineering, the entire process chain must remain visible at all times.

Best regards,

Dr. Alexander Heintzel, Editor in Chief
Wiesbaden, 22 January 2015



Economically Viable Lightweight Design Concept for a Hybrid B-pillar

Edag and Mubea Carbo Tech were searching a best-in-class solution to manufacture hybrid B-pillars economically. The result is a lightweight design concept that permits a weight reduction of approximately 20 %. The success factors are tailor rolled blanks, an automated fibre reinforced plastics manufacturing process and load specific design.

AUTHORS

Dr.-Ing. Thomas Muhr
is General Partner of the Mubea Group in Attendorn (Germany).

Johannes Weber, B. Eng.
is Project Leader at the Mubea Carbo Tech GmbH in Salzburg (Austria).

Dipl.-Ing. (FH) Andreas Theobald
is Team Leader within the CAE at the Edag Engineering AG in Fulda (Germany).

Dr.-Ing. Martin Hillebrecht
is Head of the Competence Center Lightweight Design, Materials and Technologies at the Edag Engineering AG in Fulda (Germany).

CONCEPT APPROACH

Car manufacturers are currently working under high pressure on the development of new vehicles due to go into production between 2015 and 2020. The vehicle bodies are to weight considerably less, provide high stiffness and fulfill ambitious crash load cases. Intelligent lightweight design should make vehicles up to 100 kg lighter, depending on which segment they belong to [1].

As far as weight, stiffness and eigen frequency are concerned, the B-pillar is one of the most challenging vehicle body components. Side impact requirements continue to be a constant challenge for vehicle manufacturers. In order to develop an innovative solution, it was decided that the key aspect of the project would be the B-pillar.

Mubea Carbo Tech, a supplier of carbon fibre-reinforced structural and visible automotive components of varying degrees of complexity, cooperated with Edag Engineering AG to develop a hybrid part for high-volume production, taking its structural integration in the vehicle body into account in the process. Also involved in this cooperation was the Mubea (Muhr und Bender, Attendorn) Body Division for components made of flexible tailor rolled blanks (TRB).

The objective of the cooperation was to demonstrate the feasibility and economic viability of a hybrid B-pillar based on steel and fibre-reinforced plastic (FRP) and examine the technical design.

CONCEPT ENGINEERING AND CAE DESIGN

In order to create realistic basic conditions, the CAE model of a generic basic vehicle was defined first. It was decided that the IIHS side impact crash test, a US consumer protection measure that is regarded as a critical load case, was to be of significant importance in this project. To serve as a reference, a Mubea TRB B-pillar with standard crash performance in side impact tests (IIHS rating good) was installed in the vehicle.

At the beginning of the concept development, the main focus was on the analyse of tensile and compressive stress distribution in the B-pillar for the load-case IIHS. The result of the analyse showing the zones in which the use of FRP would be effective. Due to the load-specific alignment of the fibres, stresses can be transferred most effective. On account of the deformation, the greatest tensile stress occurs on the B-pillar inner, and the greatest compressive stress on the B-pillar reinforcement, **FIGURE 1**. Bearing in mind the fact that FRP has only very slight elastic and almost no plastic properties, this result helped to identify the zones for the most promising use of a FRP reinforcement.

Various layouts of different FRP reinforcements with regard to topology, layer structure and fibre alignment in interaction with gradually optimised sheet thickness profiles in the steel sheet metal outer shell were subsequently examined and assessed by means of simulation in numerous iteration loops. It was also necessary to examine how the FRP reinforcement would perform in peak stress areas.

Simulation indicated that an FRP hollow profile structually bonded with the B-pillar above the hinge areas would give the best results. Working on the sheet thickness profile in the sheet metal components, it was possible to deduct weight from the upper area and channel the weight into the lower section of the B-pillar. By applying a very high fibre volume content and optimum fibre orientation, this made it ideal for use in the FRP reinforcement. A conscious decision was made to position the end trims outside of the highly deformed areas, to prevent any failure of the steel plate components as a result of stress peaks, **FIGURE 2**.

In the FEM, CAE tests were carried out using a LS-Dyna solver. Energy absorption until start of damage was shown in the material card. Breaking behaviour (delamination in the material) was not modelled. As a result the statements regarding the time of failure tend to be conservative. In reality later failure and higher energy absorption are expected.

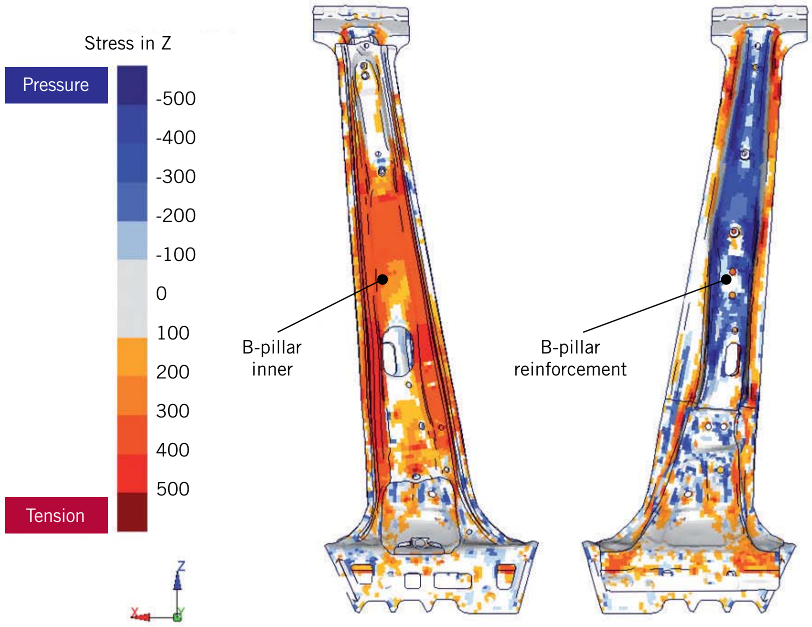


FIGURE 1 Distribution of tensile and compressive stress on the TRB B-pillar in the basic vehicle for IIHS side impact load case

PRODUCTION OF PROTOTYPE FOR COMPONENT TESTING

Following concept development, detailing and simulation, the next challenge was to produce prototypes as close-to-serialproduction as possible. The most important things here were to validate the manufacturing process, collect new insights and validate the FEM analysis.

The hybrid design first of all calls for a differentiation between the combined material groups. On the one hand, the production of the sheet metal parts, and on the other, the FRP reinforcement in the form of a hollow profile.

The steel sheets were produced by the Mubea Tailor Rolled Blank GmbH in Attendorn. Two standard processes in the automotive industry were used in the

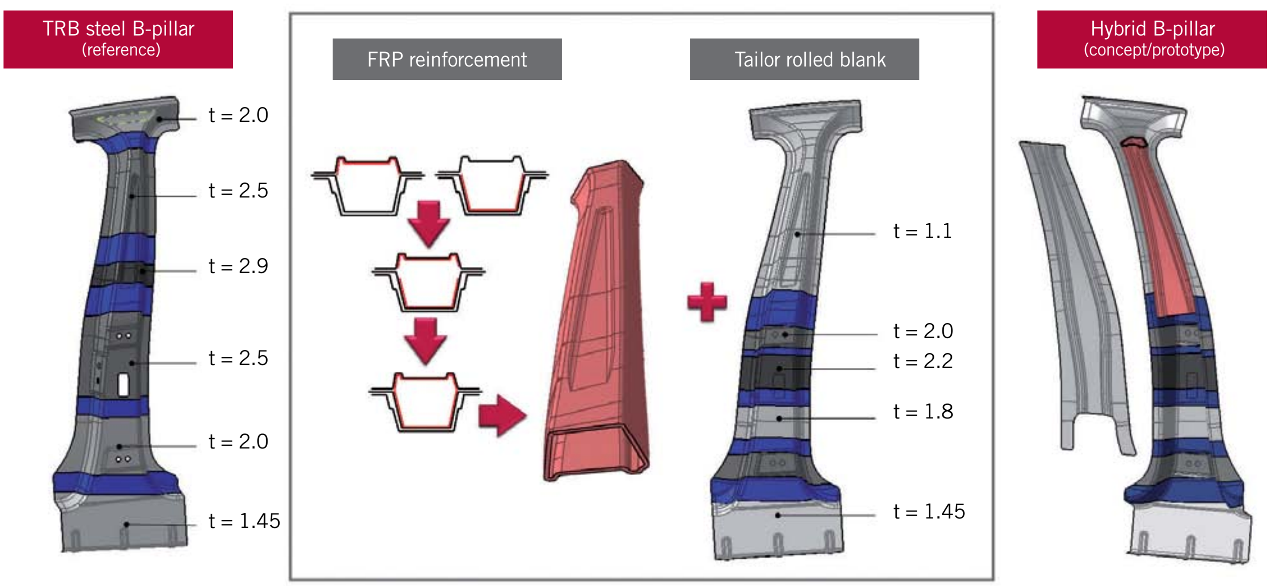


FIGURE 2 Due to the FRP hollow profile adhesive bonded into the TRB B-pillar, the sheet thickness can be reduced to bring about a weight saving of 20 % if the IIHS load case is fulfilled

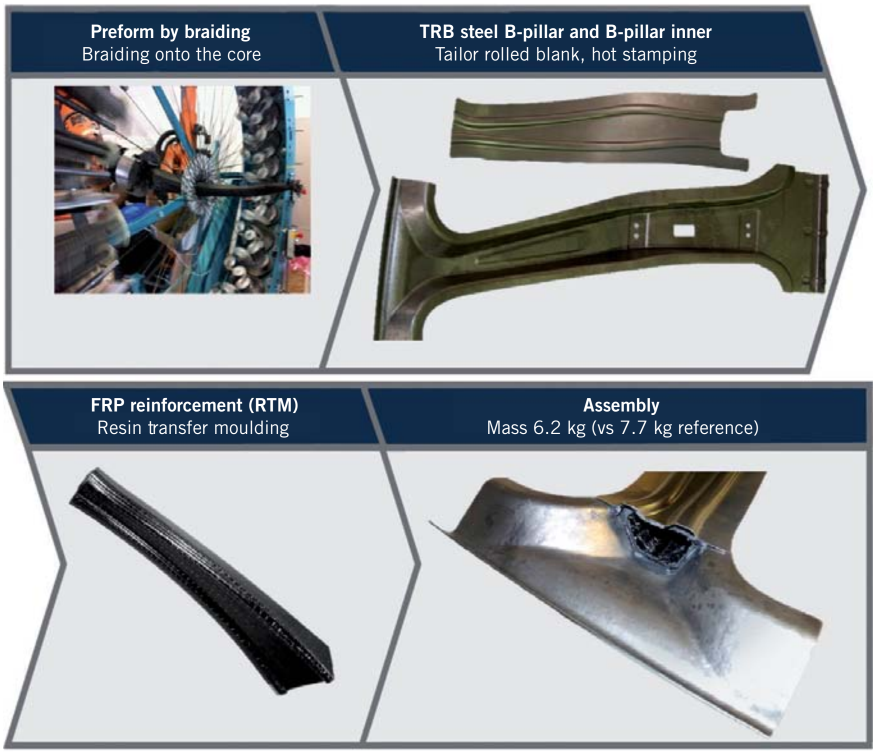


FIGURE 3 Production process chain from raw material to component; all processes were selected and analysed to ensure their suitability for series production

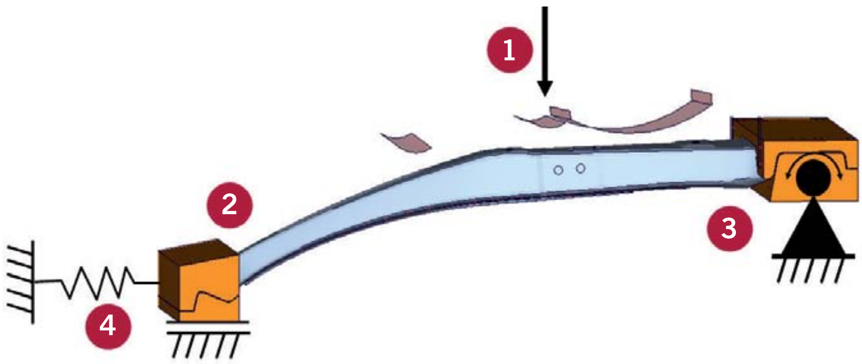


FIGURE 4 Drop tower simulation in CAE: upper mounting point (2) can transfer the translation with a defined stiffness (4); lower mounting point (3) can only transfer the rotation with a defined stiffness; the impactor goes into free fall towards (1) on the test vehicle

production of the semi-finished products and the final products. The established technology for the flexible rolling of raw material and blanks made of this (TRB), using the sheet thicknesses defined in the development, and supplemented by hot forming of the component were used for the B-pillar outer. The method used for the B-pillar inner was conventional deep drawing of a blank with a constant sheet thickness.

With a view to a mass production scenario, automated braiding was used for the creation of the FRP preforms. The advantages of this method are that very little fibre is wasted and complex preforming work during production is eliminated. To create the hollow prototype, a foam core was used as a support element, around which carbon fibres were braided in a robot-controlled process. This process enables fibres to be applied in layers and at defined angles, to create a kind of sleeve. Low-pressure RTM (resin transfer moulding) was used for the core process. This process involves resin impregnation and curing in the RTM tool; a blown core is used to ensure that the material is fully adjusted to the specified geometry. This blown core can subsequently be demoulded with very little effort. To achieve a suitable glass transition temperature, a further tempering process was carried out after the profile ends had been trimmed by corundum blasting, before preparing the part for gluing into the steel component, **FIGURE 3**.

Next to this, the individual components were adhesive bonded, and in addition the steel components joined by conventional spot welding. In order to avoid corrosion of the steel component the adhesive layer also helps as electrical insulator, hence corrosion protection. For the concept selected, this would also be the delivery status, alternatives in the order in which parts are joined are possible.

VALIDATION

Following production of the hybrid B-pillar, a crash test should be carried out to confirm the positive CAE results. As it was not possible to validate the complete vehicle, a drop tower test was developed instead. For the IIHS load case, this was required to produce the same deformation pattern of the hybrid B-pillar as the CAE model of the complete vehicle. In close coordination with the test institute conducting the test, the drop tower test equipment was defined in the virtual model. This ensured that it would be possible to transfer the CAE settings to the test equipment, **FIGURE 4**.

The test component moved translationally in the upper bearing, and rotationally in the lower bearing. In order to be able to roughly simulate the overall vehicle performance, bearing stiffness was also taken into account in the test set-up. The impactor was geometrically coordinated to produce buckling behaviour comparable with that in the complete vehicle crash test. Once the virtual reference model with the conventional steel TRB B-pillar corresponded with the deformation in the complete vehicle and drop tower test, the final development status of the hybrid B-pillar was implemented and simulated in the drop tower CAE model.

In pilot tests, the stiffness was coordinated in the drop tower so that it was at the same level as that of the CAE model. Various subsequent test runs showed that the test and CAE corresponded very closely, **FIGURE 5**.

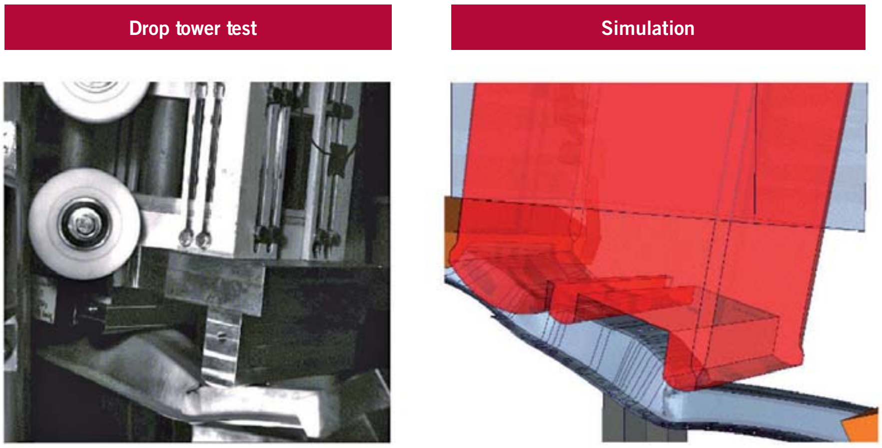


FIGURE 5 Hybrid TRB B-pillar in drop tower at maximum deformation; it shows how closely deformation in CAE and the drop tower test correspond

	Benchmark (advanced state-of-art)	TRB steel B-pillar (reference)	Hybrid B-pillar (hybrid concept)
Part list	B-pillar outer Reinforcement B-pillar inner	B-pillar outer (TRB) B-pillar, inner	B-pillar outer FRP reinforcement B-pillar inner
Manufacturing process	Tailor rolled blank (option), cold forming or hot forming Tailor tempering (option)	Tailor rolled blank, hot forming	Tailor rolled blank, hot forming Braiding/RTM adhesive bonding
Weight	7.7 to 9.5 kg	7.9 kg	6.2 kg
IIHS rating (intrusion distance to centre of seat)	Not examined	Good (160 mm)	Good (127 mm)

TABLE 1 Comparison of design variants

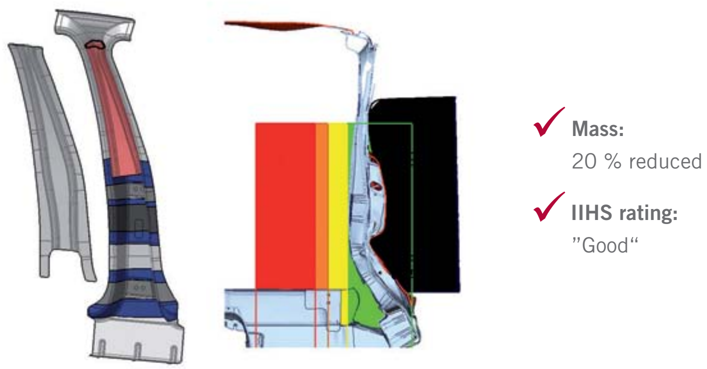


FIGURE 6 CAE simulation of the IIHS load case

The difference between the two concepts meant that there was no reason to expect the same degree of deformation for the hybrid B-pillar and the conventional TRB B-pillar. The degree of deformation of the CAE model and of the final drop tower test with the hybrid B-pillar prototypes did correspond closely.

SUMMARY AND CONCLUSION

As specialists in the composite sector, Mubea Carbo Tech is keen to further the idea of lightweight design: this motivated them to develop a project centring on hybrid lightweight construction for high-volume production. The tests decribed above have shown that an intelligent material mix is a good choice, even in high-stress areas such as the B-pillar, where extremely heavy demands need to be met. In the correct design and position, FRP reinforcements can support the function of a metal structure, and help to make tried and tested concepts even more efficient and lightweight.

From a point of view of weight, the hybrid B-pillar is a best-in-class solution which cannot be achieved using conventional manufacturing methods, and which also offers an additional weight saving of approximately 20 % compared to the highly optimised TRB B-pillars, **TABLE 1**. Modern, automated manufacturing methods help to keep the high material costs involved in FRP volumes to a reasonable level, **FIGURE 6**.

The results underlines the technical feasibility of the project, and serves as the starting point for further developments in which vehicle and manufacturer-specific requirements, material values and developments can be in focus.

It is now the declared intention of Mubea Carbo Tech to take this construction method into serial production and support the vehicle manufacturers in pre-development activities.

REFERENCES

[1] Hillebrecht, M.; Begert, M.; Reul, W.; Kiel, B.: Technik für Mischbauweisen ab 2020. In: ATZ 116 (2014), No. 5, pp. 48-51

[2] Carhs Safety Companion 2014, Wissen für die Fahrzeugentwicklung von morgen. Carhs, Aschaffenburg 2014

[3] Schmitz, S.: Hybrid vehicle structures CFRP/Steel Carbon Tailor Rolled Blank B-Pillar. FutureCarBody, Bad Nauheim, 3 June 2014

THANKS

The authors thank Dr.-Ing. Sebastian Schmitz and Florian Strobl from the Mubea Carbo Tech GmbH, Salzburg (Austria), and Dr.-Ing. Philip Beiter, Benedict Göddeke, M. Sc., and Niklas Klinke, M. Sc., from the Mubea Tailor Rolled Blanks GmbH, Attendorn (Germany), for the qualified technical support within the project.

Trends in Lightweight Construction of Roofs

The bodywork is a major factor in the total weight of a vehicle, making up approximately 35 to 40 %. Its potential for reducing weight an CO_2 emissions is great. Working with innovative technologies ranging from polycarbonate to cellulose, Webasto is developing trendsetting roof systems that help meet the targets for lightweight car body construction.

AUTHOR

Matthias Arleth
is Deputy Chairman of the Board
of Webasto Roof & Components SE
in Stockdorf (Germany).

MOTIVATION

The lighter the better – is the formula for success in automotive construction. Every gram counts in the struggle to achieve lower fuel consumption amid the global demand for emission reduction. The rule of thumb is: 100 kg less weight lowers the fuel consumption of a vehicle by about 0.15 l. To achieve these goals, super lightweight materials have been developed. They include titanium, magnesium or carbon fiber composites, all of which feature a combination of extremely low weight and high stiffness. But they also come at a high price. One that is generally too expensive for automotive mass production.

That notwithstanding, at Webasto these materials are brought up again and again. For visions do produce innovations. Based on the lightweight construction study of a panorama roof, a development team explored what would be technically feasible – without consideration of costs and mass production suitability. The result: the current weight was cut in half. Admittedly only with individual components that were in part very expensive and not appropriate for series production. Yet some of the innovations emerging from this study will still find their way into car lines. The value derived from such prototypes is the opportunity to gain know-how and accumulate experience in the practical implementation of visionary concepts. It all comes down to the distinction between what is technically feasible and that which is economically reasonable.

LIGHTWEIGHT TECHNOLOGIES IN THE ROOF SECTOR

In its drive to develop forward-looking solutions that associate lightweight construction with safety and comfort, the automotive supplier works closely with car manufacturers around the world. Polycarbonate (PC) has been conquering car construction for decades. The pioneering lightweight developments in the roof segment include the use of plastics and a super lightweight paper honeycomb material, copied from the beehive. Paper honeycomb (PHC) in conjunction with reinforcing fiberglass facilitates innovative lightweight construction solutions – and that includes the outer shell of the car body. The thermoplastic is characterised by good mechanical, thermal and optical properties. It was most notably these features that paved the way for its use in the automotive industry.

Glass also remains an essential material in the automotive industry. Webasto developed the safety glass Webasto Glas Protec for use in the roof area. The weight advantage of the glass-plastic composite as compared to conventional composite safety glass is around 10 to 15 %.

This paper presents innovative processes, technologies and materials geared towards weight reduction. They are:
- PU composites for roof elements
- Polycarbonate for roof windows and panels
- glass and plastic composite: Webasto Glas Protec.

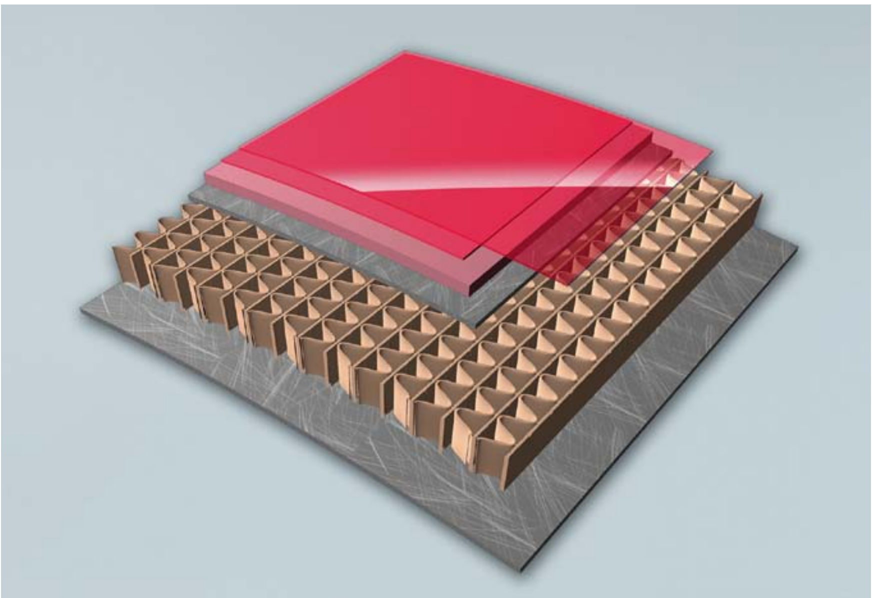


FIGURE 1 Structure of a PU composite with paper honeycomb core

PU COMPOSITES: STABLE, LIGHTWEIGHT, ECONOMICAL

PU composites are generally noted for their high degree of stiffness with low weight, good 3-D moldability and acoustic as well as heat-insulating properties. They are constructed in a symmetrical or asymmetrical sandwich structure and in exterior components consist of a structural outer layer (shell), fiber/PU matrix and a core. In addition, fastening elements or other comfort-enhancing features can be integrated.

The stiffness of the material is essentially achieved by the fibers embedded in the matrix and the sandwich thickness. Depending on the stiffness requirements, these are composed of inorganic fibers (e.g. fiberglass), organic reinforcing fibers (e.g. carbon fibers) or natural fibers (hemp, flax, etc.).

Depending on the requirements and intended area of application, the core can consist of particle foam (e.g. polystyrene) or cellulose (paper). Foam cores have advantages with regard to the specific weight and heat-insulation, but have disadvantages in terms of temperature stability and costs. Cores made of paper honeycombs are manufactured from cellulose fibers that are predominantly obtained from recycled waste paper. The individual paper layers are joined together by means of ultrasonic technology, creating a complex honeycomb structure that can absorb high compression forces. The insensitivity to moisture is ensured by the waterproof outer shell or the fiberglass/matrix composite.

The load impacting the component is absorbed by the fibers. The matrix, e.g. polyurethane (PU), bonds the fibers, thus enabling load input and output, preventing buckling under pressure that is parallel to the grain. Moreover, the matrix Protects the fibers from environmental influences.

What's more: PU composite materials are lightweight, which puts them among the important ingredients for future

FIGURE 2 Jeep New Renegade: two roof panels that can be quickly removed from the roof system with just a few simple steps

lightweight formulas. Due to their great stiffness these materials are well suited for body shell parts of up to 2 m^2. Thanks to the low tooling costs, especially for order volumes with small to medium unit numbers, PU composites are also economically interesting materials.

In the new Jeep Renegade, for the first time Webasto introduces a two-piece roof system that can be opened and whose elements can be completely removed and stored in the trunk of the car. The core consists of paper honeycomb encased in a mixture of polyurethane and reinforcing fiberglass, **FIGURE 1**. The exterior surfaces are covered with a grained, thermoformed and weatherproof film, while the inside surfaces are flocked to match the interior décor.

The special challenge posed by this roof system involved the compensation of the curvature change. The asymmetrical sandwich construction creates a so-called bimetallic effect, which results in different curvatures in varying temperatures. By means of FEM calculation, this dynamic was taken into consideration in the sealing design. The result: a tight seal under all conditions, no wind noises and a harmonious curvature shape, **FIGURE 2** and **FIGURE 3**.

The weight savings of this PU composite development versus steel are about 50 %. Moreover, it is the first use of Paper Honeycomb (PHC) in the exterior shell of a vehicle undertaken in serial production. Up to now PHC was used primarily as a lightweight material for headliners of sunroofs.

POLYCARBONATE ROOFS

Plastics such as polycarbonate are suitable for use as lightweight materials. The material is transparent, extremely impact resistant, neither splintering nor breaking on impact. And yet it is very lightweight. With a density of 1.20 g/cm^3, polycarbonate components weight up to 50 % less than identical parts made of glass. The extremely high impact resistance is particularly relevant for application in the roof area. Protection of the passengers in case of an accident or falling rocks is always ensured, even when the vehicle rolls over. In addition, an appropriate varnish coating provides scratch resistance as well as resistance to weather-related effects and UV radiation.

Automobile designers appreciate the freely moldable material that offers them multi-faceted design options that go far beyond traditional sliding and panorama roofs. Polycarbonate allows for creating very large roofs and just as visionary ideas like boldly curving windows.

The first polycarbonate roof system for the smart fortwo rolled off the production line at the Webasto Schierling plant in 2007. The latest generation of the city car is also equipped with a panorama roof made of polycarbonate. The roof window size is 1.20 m^2, it has a thickness of 5.25 mm and weighs 9.80 kg. But the real technical highlight is its capacity to absorb solar energy and thus to keep the interior of the car from heating up. That means that the infrared radiation stays where it belongs – outside. The technology that enables this: The infrared absorbers integrated into the polycarbonate – and that already in the granulate material of which the panes are manufactured. The new smart marks the first time use of the product called Makrolon AG2677 in the color and temperature-stable, heat absorbing color 771079.

Also taking ecological aspects into consideration, the infrared absorption has benefits. If the interior heats up less, the need for using the air-conditioner for cooling decreases. That further reduces fuel consumption.

PC PANELS

In addition to glazing components in a Class-A-look, Schierling produces lightweight panels made of polycarbonate for various automakers. That includes 14 models alone for the Volkswagen brand universe. These panels border the tilt/slide sunroofs in the front and at the sides, creating a seamless transition to the vehicle's roof. This gives the entire roof surface a high-quality solid glass appearance. Such panels in 3-D shapes are not feasible in glass, **FIGURE 4**.

Currently, the proportion of polycarbonate used in automobile construction is about 15 %. Experts assume that within the next five years that share will increase to about 20 %. For the potential of polycarbonate has by no means been fully exploited as yet. For instance, fixed rear side and rear windows, windshields, spoilers with integrated taillights and even movable (hinged) side windows are conceivable. Additional functions can also be integrated into PC parts, such as heating wires. Webasto is already working on developments on these subjects.

WEBASTO GLAS PROTEC

That being said, glass remains an essential material for the automotive industry – provided that the high requirements for a further weight reduction can be met. Because the customer appreciates light in his car interior, and the brightness engendered by a transparent roof system creates a feeling of well being. There is another reason for the growth of the proportion of glass in the car: Cars currently have approximately 4.60 m^2 glass surface, while in 1985 it was only 3.50 m^2.

But glass is heavy. Another lightweight alternative is called Webasto Glas Protec.

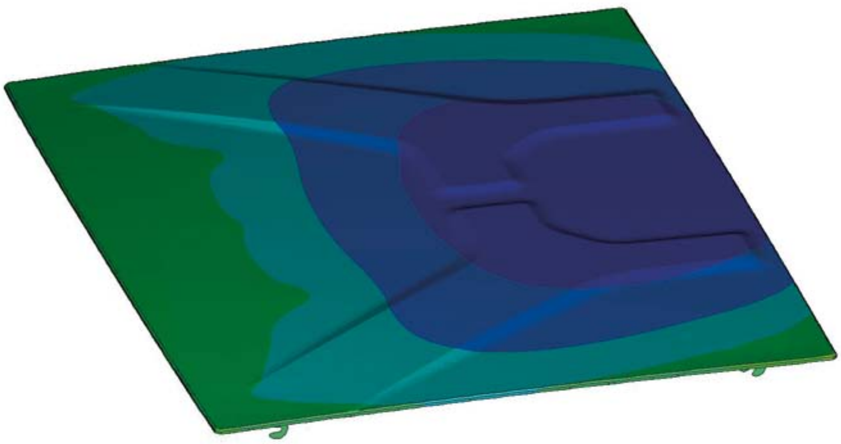


FIGURE 3 FEM simulation of the Jeep New Renegade roof elements

This safety glazing, a glass-plastic composite, enables the achievement of 10 to 15 % weight savings as compared to conventional laminated safety glass. A highly tear-resistant PET film (polyethylene terephthalate) is applied to the inner surface of convex single-pane safety glass (ESG). In the event of glass breakage, the film holds the fragments together, thereby Protecting passengers from injuries from flying glass splinters. The protective effect of the film allows for the usage of very thin (< 3 mm) and thus lighter weight glass panes. The secure anchoring of the glass pane in the roof system is ensured by the patented perforation of the film. Roof systems made of Webasto Glas Protec can be manufactured in lengths of up to 1.60 m, **FIGURE 5**.

Then again, weight isn't everything when it comes to innovative roof systems. Ecological aspects play an ever greater role here, especially with a view to e-mobility. Additional comfort features, as for example, with Webasto Glas Protec a tint in the film or the absorption of infrared radiation thanks to a special coating can contribute to reduce consumption.

As it were, radiation of cold in the area of the head could be fended off. As is already common in building glazing, a thin metal coating can produce the effect of having the thermal radiation of passengers' own bodies reflected onto the inner surface of the pane. This lowers the heating requirements – an energy topic primarily relevant for electric vehicles. The developers are also working on the use of organic photovoltaics in conjunction with Webasto Glas Protec.

This safety glazing is being installed in series production since 2005. Current models include the Range Rover, Mercedes R-Class and Ford Lincoln. The Jaguar XJ sedan features a large two-part panorama roof made of Webasto Glas Protec as standard equipment.

FIGURE 4 Tilt/slide sunroof for Golf VII: panel made of polycarbonate in Class-A look

FIGURE 5 Quality check of the PET film for the Webasto Glas ProTec glazing technology

MULTI OPTIONAL ROOF

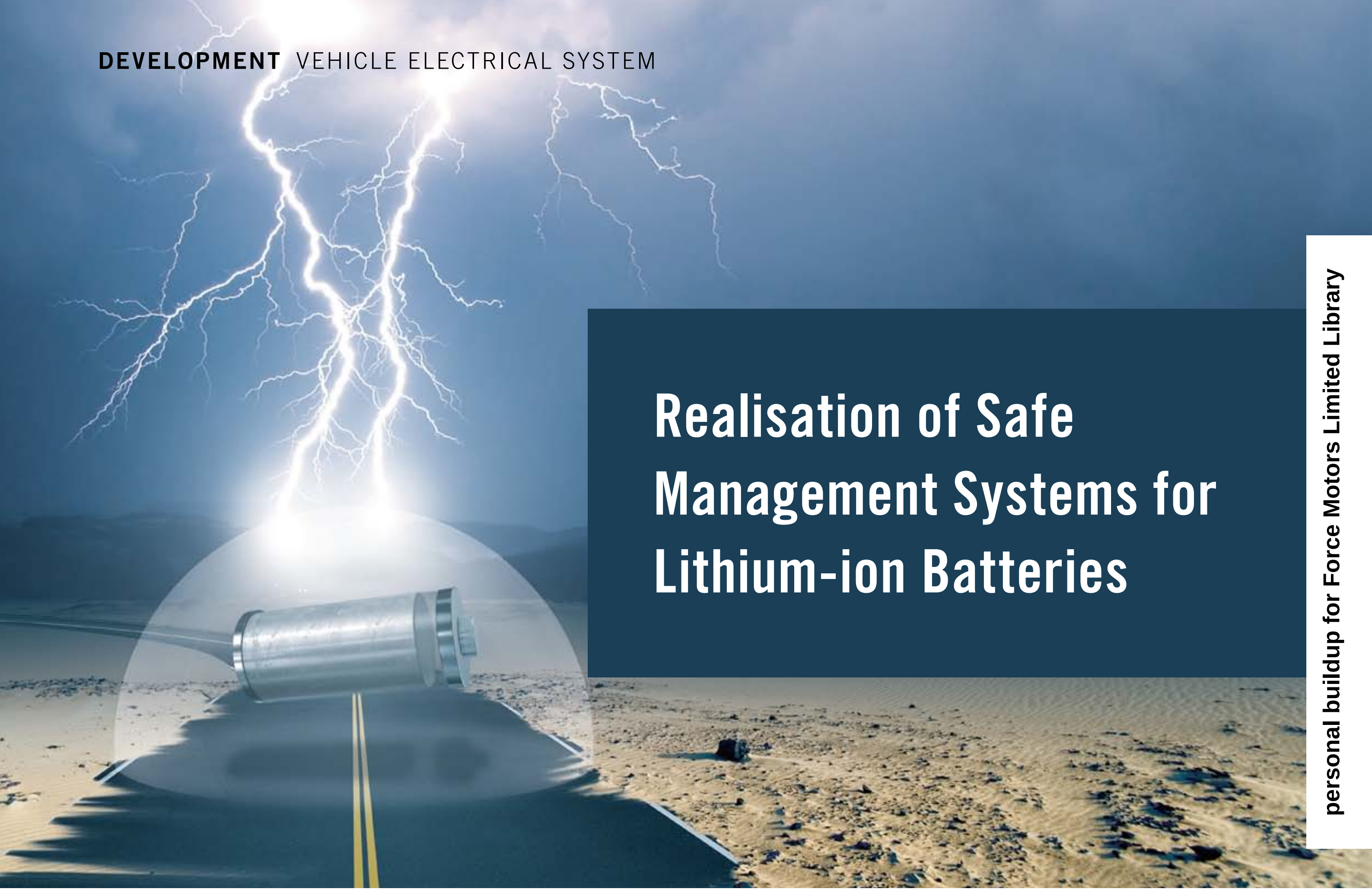
The Multi Optional Roof (MOR) is a completely new dimension in lightweight car body construction. The idea: One vehicle interface – multiple roof versions. What this means is that different roof systems can be fitted onto one vehicle shell version. The installation interface is identical for all roof variants. The roof modules are delivered on demand, ready to install and are then built in on the assembly line. The great advantage: The automotive manufacturer does not have to decide early in the construction stage which roof system should be installed on later models of a vehicle. This provides enormous flexibility that allows for rapid reactions to market trends or for upgrading facelifts with attractive roof systems. And it reduces complexity, since the number of vehicle shell constructions is brought down, **FIGURE 6**.

Webasto consolidates all it lightweight construction technologies in the MOR. It is also conceivable that the surface of the hardtop element could be equipped with solar cells. The solar power thus generated can be supplied directly to the battery. This results in a drop in fuel consumption. That is why solar roofs are listed as an Eco Innovation by the European Union. The CO_2 savings potential of solar roofs is more than respectable: An Otto engine emits an average of 2.3 g/km less CO_2, a diesel vehicle about 1.6 g/km less when equipped with a solar roof for charging the battery.

FIGURE 6 Multi optional roof: multiple roof versions on one shell construction version

OUTLOOK

Fuel savings and CO_2 reduction will remain one of the predominant issues in the automotive industry for some time to come. Therefore, lightweight construction technologies – and that also includes the roof area – continue to gain in significance. As an innovative supplier, the development and implementation of sustainable solutions is an obligation. That is something we have succeeded in accomplishing with our lightweight panes made of polycarbonate, Webasto Glas Protec and creative ideas in the area of PU composites. But progress demands ongoing further development. That is why the tradition-rich Bavarian company continues to invest in these technologies. Above all, it is the electrification of the automobile that poses great new challenges for lightweight construction.



Realisation of Safe Management Systems for Lithium-ion Batteries

AUTHORS

Dr.-Ing. Marc Nalbach
is Director of Design & Development Energy Management at Hella KGaA Hueck & Co. in Lippstadt (Germany).

Dr.-Ing. Christian Wagner
is System Engineer for Battery Management Systems at Hella KGaA Hueck & Co. in Lippstadt (Germany).

When developing high-voltage traction batteries for electric vehicles, the focus is not only on the costs but also on the safety of lithium-ion cells and the protection of occupants and other people touching the car against electric shocks. Secure system architecture for the battery monitoring electronics, customised on every vehicle, is an important variable for complying with safety objectives. Hella presents how the system architecture of a battery management system can be developed sustainably and cost-effectively with the support of model-based methods and in compliance with the ISO 26262.

DEVELOPMENT OF LITHIUM-ION BATTERY TECHNOLOGY

Due to the future worldwide CO_2 emission targets, the distribution of electric and hybrid vehicles in the coming years will steadily increase. The system costs will be reduced and the evolution of the electric drive systems must proceed quickly [1].

Today traction batteries with a cathode material of lithium-nickel-manganese-cobalt oxide are used in automotive applications. In particular, the so-called third-mix NMC cells with a mixing ratio of one to one to one (1-1-1) are a common technology. The influence of the individual components are: manganese increases the intrinsic safety of the chemical, cobalt increases the life time and nickel increases the energy density. Nevertheless, the 1-1-1 NMC technology must be strictly protected against overcharge and deep discharge to avoid a thermo chemical accident. With emphasis on longer ranges the proportion of nickel has to increase significantly in the future. Today mixtures in the ratio 6-2-2 are already in development. By 2020, a ratio of 8-1-1 is forecasted for automotive applications. The last one is already in development for consumer electronics.

However, the chemical safety of the high-energy compositions will decrease significantly. Therefore the monitoring of the battery cells becomes increasingly crucial [2]. In addition to the electrical management, the thermal conditioning of the many cells for the traction battery equally emerges as a challenging task. For this, the demanding cooling and even heating systems were and are integrated in the battery, they are electronically controlled to keep the battery chemistry in an optimal working range.

Besides, the voltage level of a high voltage battery requires additional safety mechanisms. The focus is on measures to protect the vehicle passengers as well as external staff against electric shocks. The high-voltage (HV) monitoring circuit (High Voltage Interlock) ensures the proper connection and protection of all high-voltage components. Furthermore, a constant monitoring of the insulation level of the high-voltage system is implemented by active and passive measurement methods in current and future systems [3]. In summary, different electronic components are necessary for monitoring and conditioning of the battery chemistry and the protection against high-voltage.

BATTERY MANAGEMENT SYSTEM

The electronic monitoring devices are summarised as Battery Management System (BMS). As shown in **FIGURE 1**, the BMS consists of several system components. Typical tasks of the BMS are guaranteed achievement of safety goals, providing accurately measured data for the battery application and realisation of established vehicle functions such as diagnostics or network management.

One challenge in developing a secure architecture for a BMS is the functional separation of safety-critical and non-safety-critical parts, for example for system functions, vehicle functions or communication data as well as interaction between different BMS control units among each other and their interfaces to the system context.

SECURE SYSTEM ARCHITECTURE

In this context, a secure architecture is defined as the hierarchical and functional break down of safety goals into system functions. The structured distribution of these functions on system components (control units) and the further refinement down to the hardware component level is part of a reliable system design in terms of security and robustness. Additionally, all functions which are non-safety related but necessary for operation of a BMS must be incorporated in the consideration area.

For dealing with the complexity arising from this context, the ISO 26262 defines a specific process model including work products and applied methods. The aim of the ISO standard is to document the traceability and verifiability of the development with the current state of the art methods.

The standard includes recommendations on requirements management as well as for the description of system architectures [5]. The requirements management is therefore the basis of a secure system architecture. The ISO 26262 places special emphasis on traceability not only between system requirements and customer requirements (including

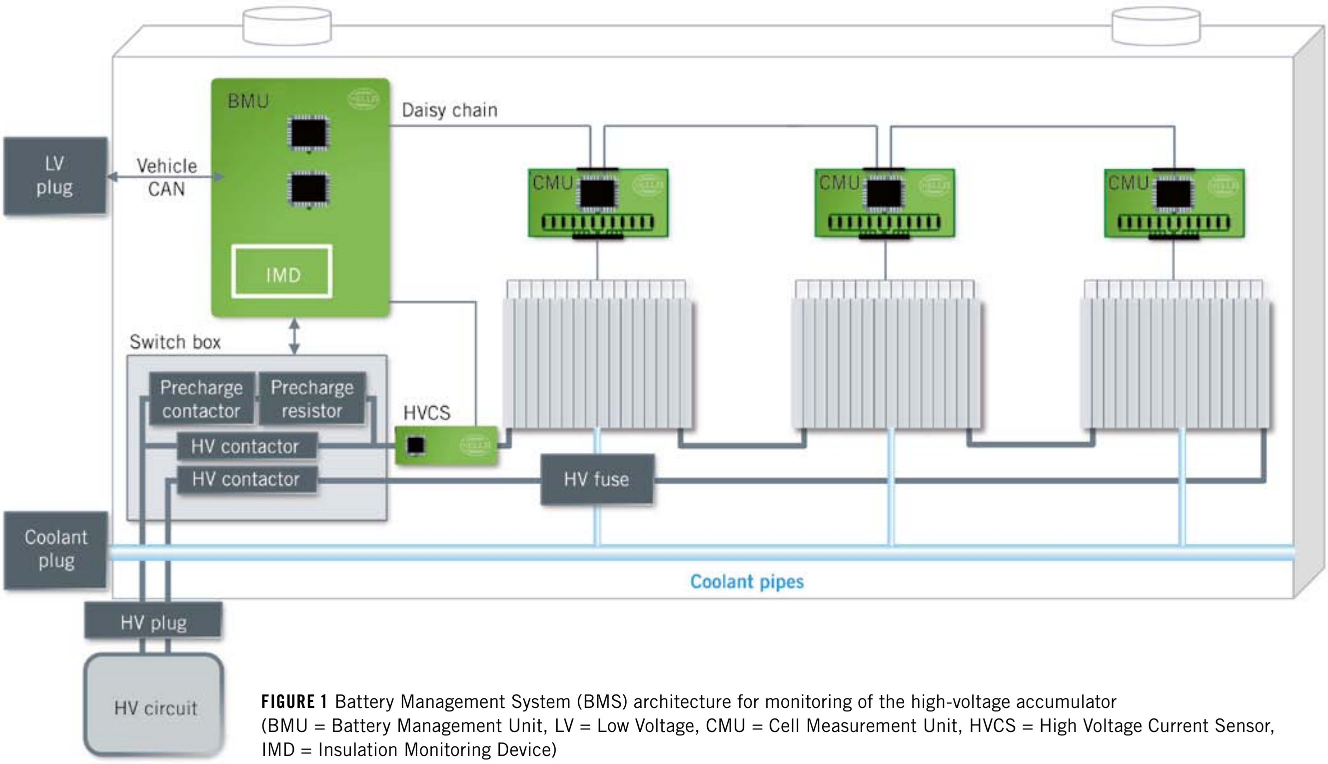


FIGURE 1 Battery Management System (BMS) architecture for monitoring of the high-voltage accumulator (BMU = Battery Management Unit, LV = Low Voltage, CMU = Cell Measurement Unit, HVCS = High Voltage Current Sensor, IMD = Insulation Monitoring Device)

the functional safety concept), but also demands a strict link between system architecture and system requirements. Considering this, the influence of requirements on the architecture and vice versa is comprehensible.

The BMS safety goals are usually rated with ASIL B or ASIL C level. Therefore, a semi-formal notation for describing the design, **TABLE 1**, is recommended by the ISO standard. Model-based description languages like SysML are one characteristic of semi-formal notation. The inherent structuring of the development approach and its associated mastering of complexity are advantages of model-based methods. Furthermore, the use of graphical modelling languages supports the intuitive understanding of the relationships within the system.

For high voltage batteries, the monitoring of the cell chemistry is often classified as ASIL C due to a high exposure and low controllability. In contrast, the protections of passengers is usually rated slightly lower with ASIL B.

MODELLING CONCEPT

Due to the amount of options offered by SysML (over 200 language elements), it is necessary to develop a modelling concept which restricts the variability. It describes the purpose and the application of specific modelling language elements in the development process [6].

In **FIGURE 2**, the general aspects of such a modelling concept are illustrated. The vertical separation between functional and technical architecture is important. Both aspects are also represented in the ISO 26262 standard as functionally (FSC) and technically safety concepts (TSC). The horizontal separation is used to describe the BMS at different abstraction levels. On top level L1, the BMS is considered as an overall system. Below, further layers include detailed elements such as associated control units on level L2 and hardware components in level L3. This structure enables a systematic function break down of the overall system down to individual system elements. By linking the architectural elements to corresponding requirements the traceability required by the ISO standard is fulfilled including FSC and TSC.

In detail, a solution-independent model of the system is described by the functional architecture. The first step in the development process is the creation of use case diagrams (point ① in **FIGURE 2**). The protection of passengers against electric shock is a common use case of the BMS. The subsequent refinement with activity diagrams (point ② in **FIGURE 2**) describes the sum of all functions that must be covered by the BMS. The just mentioned use case can be refined in the following functions:
- measurement of insulation resistance
- comparison of the insulation resistance against a threshold values
- warning of the driver in case of an error.

Thereafter, the functional architecture (point ③ in **FIGURE 2**) contains groups of all identified systems. The functions of the use case that protect against electric shock are grouped into a function block insulation measurement and a communication block. The preliminary architecture will not provide a concrete solution, but can be evaluated against the requirements in the FSC. Thus inadequacies in the design can be discovered and resolved at a very early stage. Additionally, each function can be ASIL classified into a safety level by the linkage of the FSC. This allows an efficient design of the function blocks and a separation of safety-critical and non-safety critical functions.

In contrast to the functional architecture, the technical architecture describes a specific solution. At the top level L1, the system context is the reference point of the technical domain.

The distribution of functions and function blocks to the control units are realised in the next L2 abstraction level. Basically, the technical architecture distinguishes two characteristics of modelling methods. The static modelling describes the interfaces and the distribution of functions (point ④ in **FIGURE 2**). The dynamic modelling is used to describe the behaviour of the system (point ⑤ in **FIGURE 2**). The interaction with external and internal control units is detailed in L2. For the behavioural aspects, sequence and state diagrams are the preferred modelling notation. The individual elements of the architecture are in turn linked with the requirements (point ⑥ in **FIGURE 2**) to justify the design decision and maintain the traceability.

The modelling of the underlying layer (L3) differs only in the degree of abstraction from layer L2. Here the hardware modules of a control unit are the element under study. The functional blocks of the previously introduced example are allocated to one control unit, the BMU (L2). The insulation measurement is allocated to a dedicated controller (L3) and the communication of the warning message is operated via CAN bus. The resulting interfaces, the CAN interface and the voltage measurement interface to calculate the insulation resistance, could be aligned with the system context (L1).

Due to this process model it becomes automatically a constant interaction between requirements and architecture. Usually new requirements arise during system modelling. These must be taken into account and incorporated back into the existing requirements. This process is not a negative one – in contrast it shows systematically specification gaps and closes them. This process is also known as “zig-zag” pattern [6]. Moreover the model-driven structured approach reduces design errors and promotes cost-effective development.

CONCLUSION

The seamless integration of a battery management system into a vehicle is a complex task. The interplay of system

Three methods	ASIL level			
	A	B	C	D
1. Informal notation (description languages with a weakly defined syntax, for example diagrams, sketches)	++	++	+	+
2. Semi-formal notation (languages with formally described syntax, but semantics is not completely and unique specified, for example UML)	+	++	++	++
3. Formal notation (both syntax and semantic are completely defined, for example Z, VDM, PVS)	+	+	+	+

TABLE 1 Process model with three methods according to ISO 26262, volume 6, page 18 (++ = highly recommended, + = recommended) [4]

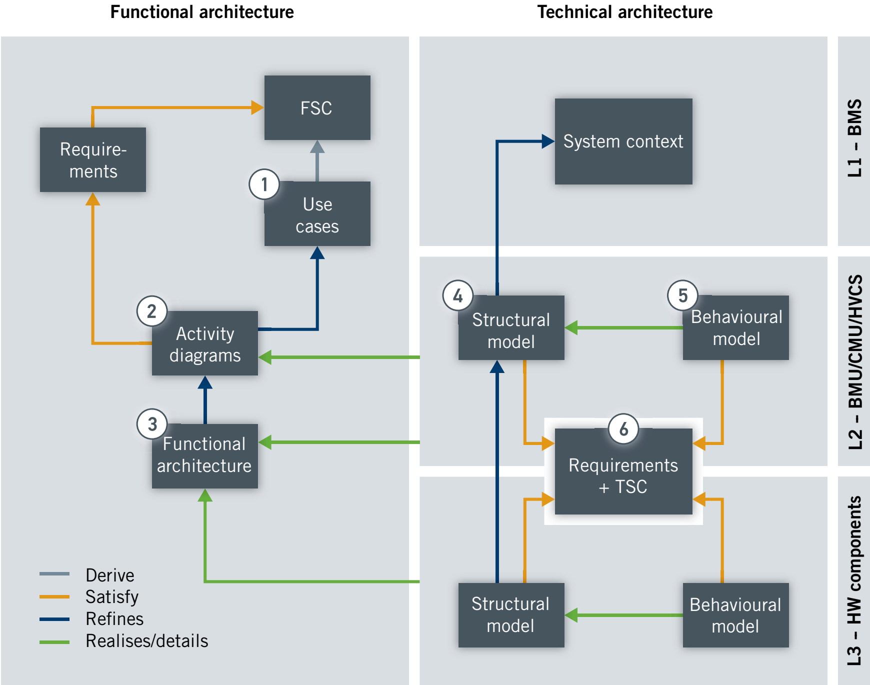


FIGURE 2 Overview of the modelling concepts for functional and for technical architecture

functions, safety goals and a plurality of control units require a structured approach to control complexity as cost driver. The described procedure model for the development of secure architectures has been successfully applied and optimised [7]. The mentioned requirements of ISO 26262 are met and the necessary work products to demonstrate compliance with the safety goals are made directly within the process. In addition, the efficiency of this methodology results from a change from a document-based to a model-based approach.

REFERENCES

[1] Schulte, A.: Market Study E-Mobility: Market Development, Infrastructure, Costs and Regulations. In: Elektrik/Elektronik in Hybrid- und Elektrofahrzeugen und elektrisches Energiemanagement V (2014), pp. 201-213, Renningen: Expert-Verlag, 2014

[2] Theis, C.; Hackmann, M.: Die Zelle zu unterschätzen, könnte fatale Folgen haben. Interview. In: ATZelektronik 9 (2014), No. 3, pp.16-18

[3] Nalbach, M.; Mehling, F.: Isolationsfehler in Bordnetzen erkennen. In: Hanser eMobility 1 (2014), pp. 18-20

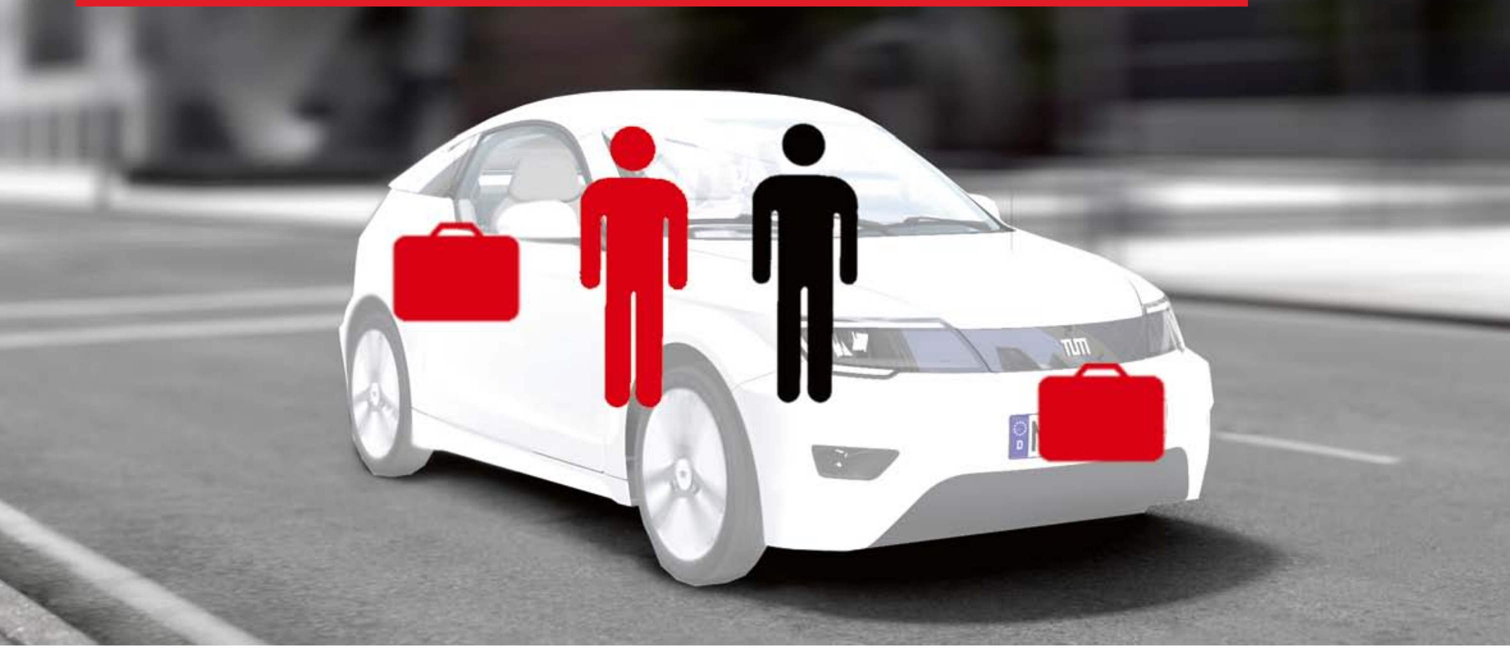
[4] ISO 26262, Volume 6

[5] ISO 26262, Volume 4

[6] Weilkins, T.: Systems Engineering with SysML/UML. Modeling, Analysis, Design. 1st edition, The MK/OMG Press, February 12, 2008

[7] Wagner, C.; Meyer, J.: Erfahrungen mit dem modellbasiertem Systementwurf am Beispiel des automobilen Steuergerätes Battery Management System (BMS) I. In: Maurer, M.; Schulze, S.-O.: Tag des Systems Engineering (12.-14.11.2014), pp. 215-224, München: Hanser, 2015

Potential of Online Model Identification for Vehicle Dynamics Controls of Load Sensitive Lightweight Vehicles



AUTHORS

Dipl.-Ing. Florian Kohlhuber
is Research Associate at the Institute of Automotive Technology at the Technische Universität München (Germany).

Elias Schneider, B. Sc.
is Master Student in the course Vehicle and Motor Technology at the Technische Universität München (Germany).

Prof. Dr.-Ing. Markus Lienkamp
is Director of the Institute of Automotive Technology at the Technische Universität München (Germany).

Future efficiency-focused vehicle concepts with curb weights around 500 kg suffer from a high influence of everyday load on vehicle dynamics characteristics. Currently, researchers at the TU München work on driving-synchronous estimation methods to determine valid vehicle parameters for each trip to improve the quality of chassis control systems.

PROBLEM OF LOAD SENSITIVITY

In order to achieve ambitious efficiency improvements for future automobiles, a trend towards design and production of lightweight vehicle concepts has started. With about 500 kg, these cars have considerably lower curb weights than nowadays cars, which usually range from 900 up to over 2000 kg. Examples are the Nils (Volkswagen, 430 kg), the Urban Concept (Audi, 500 kg) or the Twizy (Renault, 480 kg). But, on the other hand, new challenges for passive and active driving dynamics arise in this new vehicle class.

These challenges result from the fact that the reduction of a vehicle's unloaded weight leads to an exponential increase of the influence of load, meaning passengers as well as luggage, on a vehicle's physics, **FIGURE 1**. Regarding conventional nowadays cars, a typical load with driver and co-driver (80 kg each) rarely represents more than 15 % additional weight, whereas for lightweight vehicles the ratio is around 1:3. Assuming a maximum load of 210 kg by adding 50 kg of luggage, the load to curb weight ratio of lightweight vehicles can easily double or triple compared to conventional cars. This, in turn, leads to an increasing load influence on the overall parameters of the loaded vehicle, both on the inertial values like the centre of gravity (COG) location and moments of inertia as well as on chassis parameters like axle loads or tyre characteristics. In this way, vehicle dynamics differ considerably between trips depending on varying loads that are transported. This problem is called load sensitivity.

VARIANCE OF VEHICLE AND TYRE PARAMETERS

To investigate the impact of different everyday loads on the driving dynamics of lightweight vehicles and to derive the possible spectrum of values vehicle and tyre parameters can attain, the exemplary load scenarios in **TABLE 1** have been analysed. For this, the electric vehicle concept of the Technische Universität München, which has been presented at the International Motor Show 2011, has been used as a reference. This vehicle has a curb weight of 500 kg, a yaw moment of inertia of 500 kgm², an axle load distribution of 45:55 and a wheel base of 2100 mm. Different weights for passengers as well as luggage in the front and rear trunk were combined to seven load scenarios, each representing a maximum for a characteristic physical property.

In this way, the variance of the most important physical vehicle properties can be observed. These are for the overall vehicle the total mass, the yaw inertia, the longitudinal COG position and the relative front axle load. Basic axle behaviour as a combination of suspension and tyre (dimension: 115/70 R16) behaviour is represented by three parameters, namely the mean axle cornering stiffness, the mean lateral relaxation length and the mean pneumatic trail. For each of the three overall vehicle parameters and for the three values of the rear axle, **FIGURE 2** shows the minimum and maximum value as well as the relative deviation based on the seven setups.

One can clearly observe that all relevant physical parameters underlie trip individual deviations of around 30 %. Furthermore, it should be pointed out, that the longitudinal COG position can vary by more than 200 mm which is almost 10 % of the wheel base. In combination with the corresponding total masses, axle load distributions between 39:61 and 49:51 are possible. Although, one could state, that these high parameter deviations can occasionally occur for conventional cars as well, very high loads of several hundred kilograms would be necessary. With respect to lightweight vehicles, just little everyday loads can cause the same effect.

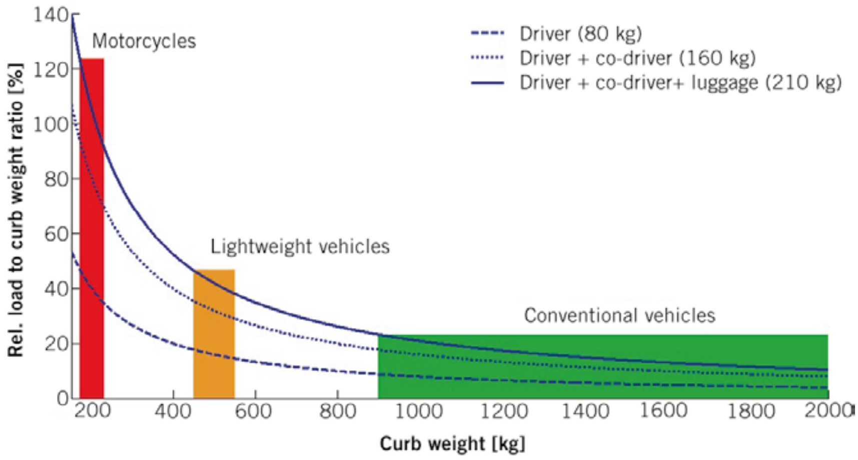


FIGURE 1 Load influence with respect to different vehicle classes

Setup	Driver [kg]	Co-driver [kg]	Rear luggage [kg]	Front luggage [kg]	Total mass [kg]	Annotation
S550	50	0	0	0	550	Minimum load with light female driver
S580	80	0	0	0	580	Standard, most-likely setup
S585	50	0	0	35	585	Maximum relative front axle load
S610	50	0	30	30	610	High yaw inertia with low load
S695	80	80	0	35	695	High absolute and relative front axle load
S730	80	80	35	35	730	Maximum of yaw inertia
S740	90	90	60	0	740	Overload with maximum of rear axle load

TABLE 1 Analysed everyday load scenarios

LOAD INFLUENCE ON PASSIVE DRIVING DYNAMICS

In order to demonstrate the effect of the presented parameter deviations on the passive vehicle behaviour, step steer manoeuvres have been simulated for all setups in a multi-body simulation (Adams/Car). **FIGURE 3** presents the lateral accelerations and yaw rates of the setups S695, S740 and the most likely "driver-only" scenario S580. As steering wheel step input an amplitude of 20° was chosen at a vehicle speed of 120 km/h. Regarding the maximum amplitudes, the transient overshoots and the eigenfrequencies of the measured outputs, the vehicle setups' responses are very different. For example, setup S695 reaches a maximum yaw rate of 10 °/s, whereas the "driver-only" setup´s yaw rate maximum is at almost 15 °/s. Concerning the maximum lateral acceleration, the bandwidth of all setups ranges from 0,4 to almost 0,6 *g* representing an obviously high difference in vehicle reaction, too.

A more detailed analysis of the vehicle's parameter variation and the effect on the passive driving behaviour can be found in [1]. In summary, it can be stated that already small differences of masses or positions of daily loads have a high effect on the agility and the self-steering behaviour as well as the threshold between stable and instable driving behaviour.

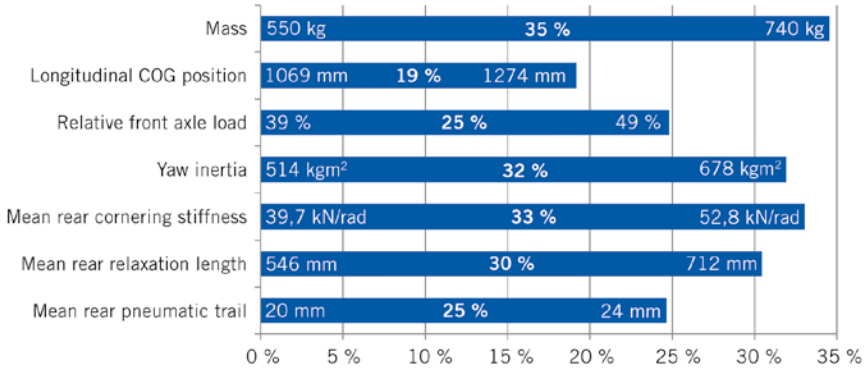


FIGURE 2 Load dependent variance of basic vehicle parameters

POTENTIAL OF ONLINE MODEL IDENTIFICATION FOR VEHICLE DYNAMICS CONTROLS

Model-based vehicle dynamics controls normally rely on constant values for the internal model parameters. It was shown that for lightweight vehicles these parameters differ on a wide range for each trip. Therefore, the standard values used in the controller are not valid for most of the trips. To solve this problem, those parameters have to be determined online for each trip to update the internal model. The potential of such an online model identification is presented in the following based on a Torque Vectoring (TV) feed-forward control.

In advance to that, a vehicle model has to be chosen, that is used in the feed-forward control as well as in the online identification algorithm. On the one hand, this model should work with a small set of parameters and, on the other hand, it should be able to represent the dynamic vehicle behaviour very well within limits of everyday driving. A good choice for a model matching these requirements is based on the single-track model which is extended for several aspects. To simplify estimation of total mass, longitudinal dynamics are incorporated into the model. To account for the typical narrow tyre decrease of lateral stiffness already at low wheel lateral slip angles, a nonlinear forming parameter is added to the linear stiffness factor. In addition, the delayed lateral force buildup is incorporated through mean lateral relaxation lengths. In total, only

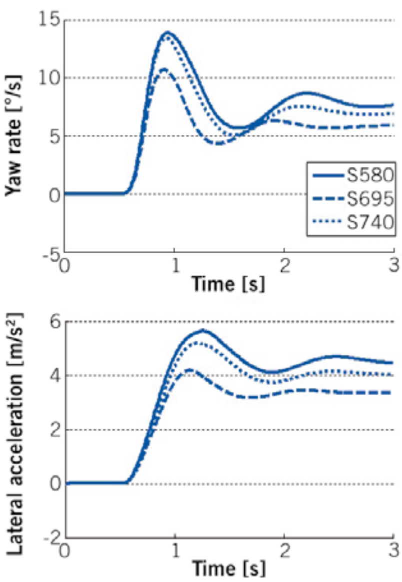


FIGURE 3 Responses of differently loaded vehicles

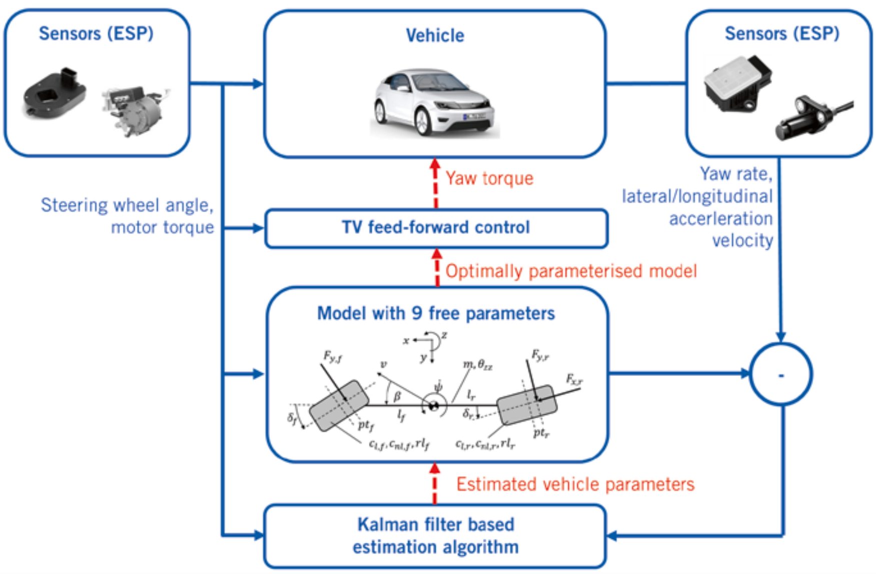


FIGURE 4 Torque Vectoring (TV) feed-forward control and online model identification

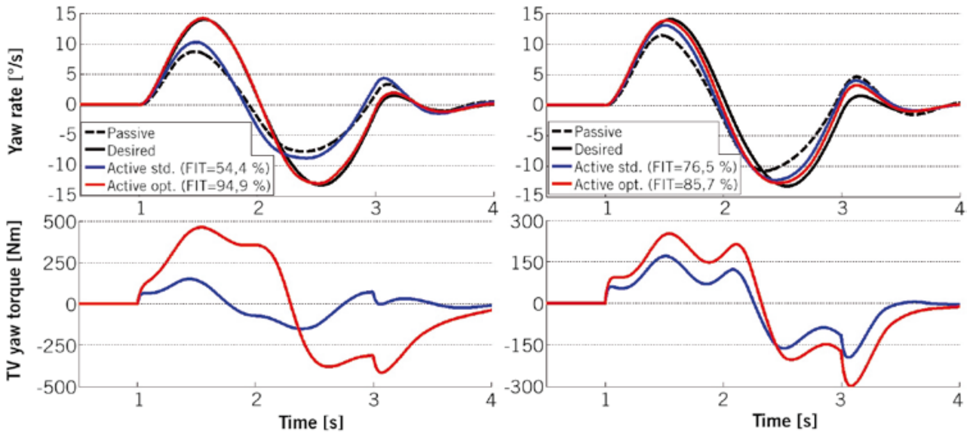


FIGURE 5 Single lane change manoeuvres without and with standard as well as optimal feed-forward control

three parameters are used to model each axle's suspension/tyre system. Together with the three overall vehicle parameters mass, yaw inertia and longitudinal COG position, the vehicle model in total can be parameterised by nine parameters. If those are chosen physically correct, the model is able to represent real vehicle behaviour in terms of lateral forces, side slip angle, lateral acceleration and yaw rate very well.

Similar to [2] the feed-forward algorithm uses this model and calculates -without any feed-back loop an additional yaw torque based on velocity, desired yaw rate and axle steering angles, that is needed to make the vehicle follow the desired yaw rate trajectory. This is shown in the upper half of **FIGURE 4**.

To determine the possible improvement of the feed-forward control by using trip-optimal parameters, lane change manoeuvres at a velocity of 100 km/h have been simulated in multi-body simulation with all setups. Each setup was driven without control and twice with feed-forward control, once with the controller values set to the standard, most-likely S580 case and in a second simulation set to the values that fit the corresponding setup. In this way, the vehicle response with a non-adaptive standard feed-forward control can be compared to the behaviour of an optimally parameterised controller.

FIGURE 5 shows the results for the setups S695 and S740. In both cases the vehicle with a correct parameterised control (red) is able to follow the desired yaw rate trajectory (black) very well even without a feed-back control. If the TV controller just uses the standard S580 set of parameters (blue), results are poor. The requested yaw torques as output from the different feed-forward controls differ much. The TV torque is applied via an active differential on the rear axle of the vehicles. The example shows that the quality of feed-forward controls of load sensitive cars can be considerably increased if the internal model is updated to the trip individual correct parameter set.

APPROACH FOR ONLINE PARAMETER ESTIMATION BASED ON CUSTOMER RELEVANT DRIVING

An algorithm that is able to estimate this set consisting of nine parameters has been presented in [1] and further developed in [3]. Without the need for additional measurement hardware other than ESC sensors (steering wheel angle, motor torque, velocity, yaw rate, lateral/longitudinal acceleration) a recursive filter identifies the described nine-parameter model within the first minutes of random customer relevant trips. The lower part of **FIGURE 4** shows that the optimal parameter set is found comparing the model outputs to the measurement of the real vehicle. Therefore, an Unscented Kalman Filter (UKF) is applied which uses a priori known suspension kinematics and delivers accurate values for the three chassis and the six axle parameters. Compared to related work, there is no need to know certain values like COG position in advance [3] or to make use of standardised driving manoeuvres [5], which would not be applicable for the given case anyway. Regarding the estimated parameters, relative accuracies of far more than 90 % have just been achieved after 5 to 7 min journey time in multi-body simulation. This results are based on real customer relevant inner and outer city driving cycles with velocities ranging from 0 to 120 km/h and lateral accelerations up to 0,3 *g*.

REFERENCES

[1] Kohlhuber, F., Lienkamp, M.: Load problem of lightweight electric vehicles and solution by online model adaption. 5th International Munich Chassis Symposium, 24/25 June 2014, Munich, pp. 281-302
[2] Obermüller, A.: Modellbasierte Fahrzustandsschätzung zur Ansteuerung einer aktiven Hinterachskinematik, München, Technische Universität, Dissertation, Cuvillier-Verlag, Göttingen, 2012
[3] Kohlhuber, F., Büchner, S., Lienkamp, M.: Tripsynchronous parameter estimation of vehicle and tire model parameters as virtual sensor for load-sensitive lightweight vehicles. In: IEEE International Conference on Vehicular Electronics and Safety (ICVES), 16-18 December 2014, Hyderabad/India, accepted paper
[4] Best, M. C.: Identifying tyre models directly from vehicle test data using an extended Kalman filter. In: Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility 48 (2010), No. 2, pp. 171-187
[5] Hon, S. et al.: Vehicle inertial parameter identification using extended and unscented Kalman filters: In: Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems, The Hague, 2013, pp. 1436-1441

Interior Concept with Light Centre Console

Dräxlmaier Group's new X² centre console architecture opens up great potential for lightweight design. Thanks to its integral design, this innovative product weighs 30 % less than typical centre consoles generally installed in mid-size vehicles today. Numerous studies confirming series production readiness have already been completed.

AUTHORS

Dr. Isabella Schmiedel
is Director of Interior Advance Development for the Dräxlmaier Group in Vilsbiburg (Germany).

Dipl.-Ing. Manfred Winklbauer
is Department Head of Light and Product Innovations in Interior Advance Development for the Dräxlmaier Group in Vilsbiburg (Germany).

Lion Pfeufer
is Online Editor of the Corporate Communications department in the Dräxlmaier Group in Vilsbiburg (Germany).

COMBINATION OF TWO ARCHITECTURES

Companies today face wide-ranging challenges in the area of sustainability. Car makers and automotive suppliers operate within a complex environment with high expectations regarding social responsibility that opens up new potential, economic aspects such as rising fuel prices and increasing resource scarcity, and strict statutory requirements for the reduction of CO_2 emissions. Products with low environmental impact and reduced weight make an important contribution to overcoming these challenges.

Against this backdrop, the Dräxlmaier Group spent three years developing a centre console that opens up new potentials in lightweight design thanks to the combination of two typical architectures [1]. Thus, the new X² centre console combines a shell design with a support element design, resulting in a noticeable reduction in weight.

THE STATUS QUO

Two centre console architectures currently dominate the market: the shell design and the support element design. With regard to the former, the outer skin is largely formed by the shell itself (shown in red), which is generally manufactured with a grain texture or painted, **FIGURE 1**. Reinforcing interior elements provide additional support for loads. Thus, the disadvantage is that the strength required of the centre console has to be provided by separate internal structural components. These must be manufactured in addition and installed, leading to more processes and increased investment in tooling. Additionally, the injection moulding production process allows for only slightly contoured, plain console sides, placing limits on styling options such as patterns or ornaments.

The support element design offers greater design freedom, but this is achieved with numerous panels that enclose the structural component – shown here in red, **FIGURE 2**. The large number of panels in different shapes need to be manufactured separately as well as requiring many assembly steps, since the panels must be fastened using screws, clips or other joining methods.

ADVANTAGES OF THE NEW INTEGRAL DESIGN

The “integral design” described here refers to the supporting, structure integrated into the console sides. This new X² centre console, **FIGURE 3**, combines the two typical centre console architectures, improving their common advantages while largely dispensing with their disadvantages. Of particular note is the lightweight design: The integral design and the centrally divided support element both significantly reduce the number of components needed to achieve the required strength. For example, most of the panels are elimi-

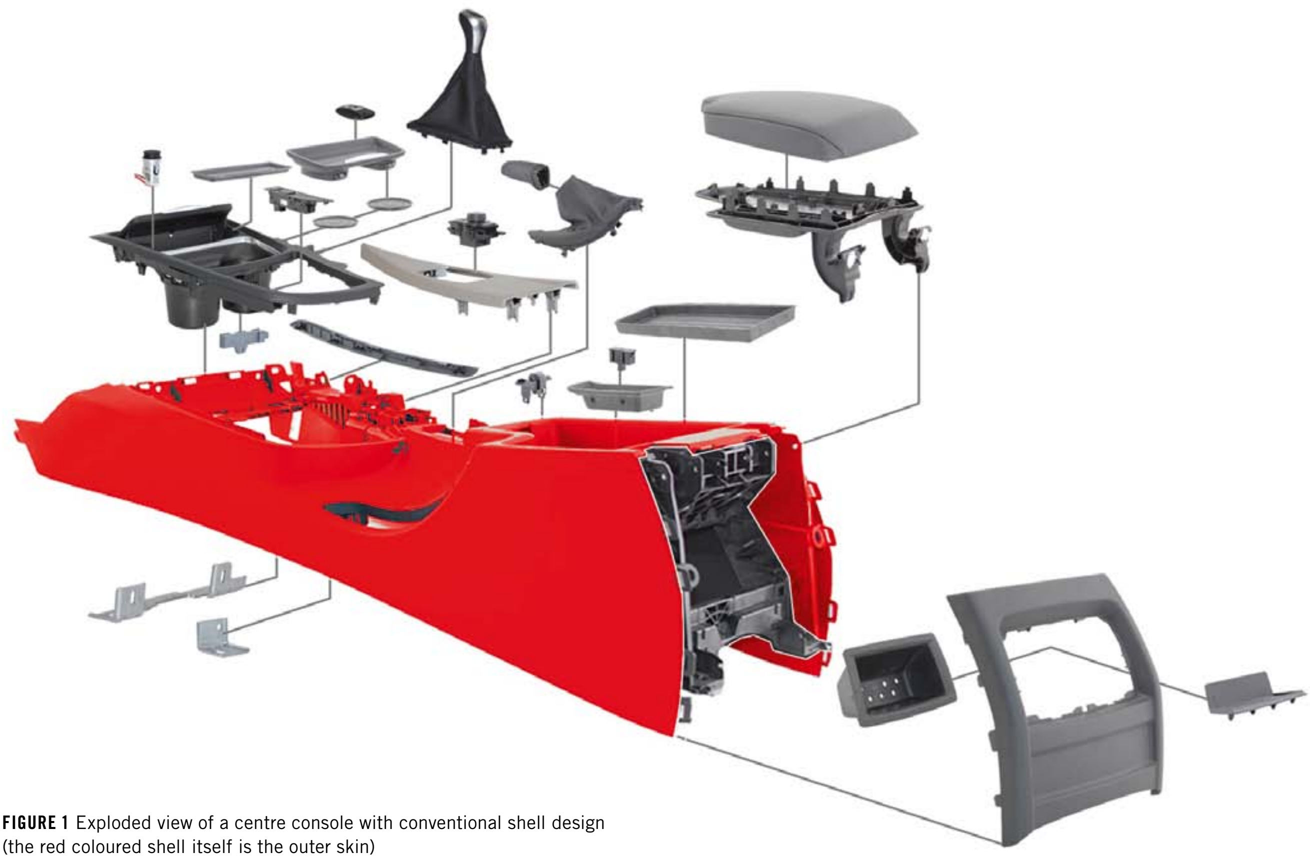


FIGURE 1 Exploded view of a centre console with conventional shell design (the red coloured shell itself is the outer skin)

FIGURE 2 Exploded view of a centre console with conventional support element design (structural component shown in red)

nated, and the reinforcing interior elements can be reduced to a single component, **FIGURE 3**.

The closure on the armrest is also eliminated, which further supports the principle of lightweight design. This is replaced by an innovative opening concept driven by a special spring. The base configuration, which is the lightest, can be upgraded with an armrest height adjustment feature, if desired. The modularity of the X² centre console comes into play here: The upgrade only requires two easily installed additional parts on the console sides.

LIGHT MATERIALS

Another important aspect is the use of lightweight materials in the X² centre console. For example, the two lightweight design side support elements are produced using a Thermoplastic Foam Moulding (TFM) process. Plastics reinforced with natural and glass fibres are also used. The storage compartment and the panel are made, for instance, of the light, sustainable composite material Natural Fibre Polypropylene (NFPP). Overall, the interior concept is roughly 30 % lighter than a conventional centre console currently found in mid-range vehicles. This corresponds to weight savings of around 1.5 kg. The new laminated design and the the centre console's tool-free installation help optimise costs.

STYLING POSSIBILITIES

At the same time, the X² centre console permits alterations according to customer requirements. For example, side padding can be subsequently installed in the knee area. The styling of decorative elements and the decorative panel can also be varied. Decorative styling of plastic, aluminum or wood is possible. Special features such as applications or decorative designs on the armrest covering as well as premium leather stylings are conceivable. In other words, this is a huge leap towards maximum styling freedom. However, the lightweight design potential is best achieved in the entry-level variants.

SERIES REQUIREMENTS SATISFIED

The goal is to ready the X² centre console for series production. The simulations required for this goal have already been completed. These include testing of warping properties, filling pressure, crash behaviour and stiffness load cases. For the latter, the forces acting on multiple locations of the X² centre console were determined using the finite element method, **FIGURE 4**. The result: All values comply with the standard. The same is true of the other simulations mentioned, all of which satisfy all OEM requirements.

The ease of assembly was also tested for series production compatibility. For this the developers focused on clip assembly ensuring efficient production without compromising on crash or stability requirements. An interlocking clamp mount enables screw-free fastening in the vehicle.

SUMMARY

Lightweight design offers huge potential. This is especially true when applied inventively as is the case with the integral design approach of Dräxlmaier Group’s X² centre console. It is a good example of systematic lightweight design, thanks to a combination of the surface and structure by merging the shell and support element design approaches. In conjunction with topology optimisation of the components in the interests of constructive lightweight design and the use of light materials, it is possible to achieve weight savings of roughly 30 %. In its base configuration, the X² centre console is roughly 1.5 kg lighter than centre consoles currently installed in mid-size vehicles.

Numerous analytical studies for confirming the series production compatibility of the interior concept have been completed, and several patents have already been granted. A number of OEMs have already shown interest.

FIGURE 3 Exploded view of the new X² centre console with an integral design that combines the outer surface and formative structural elements into a single unit with little parts

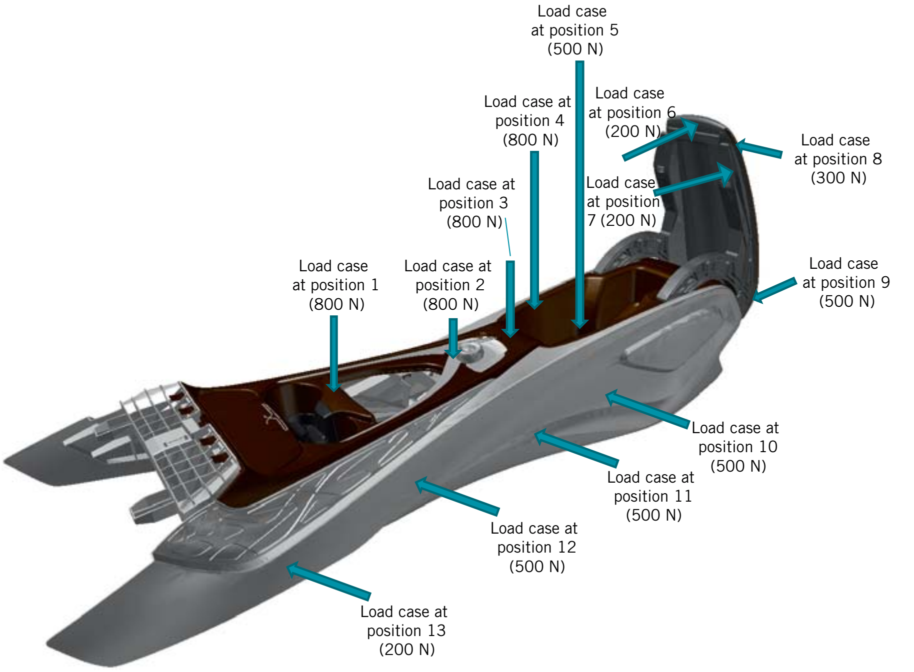
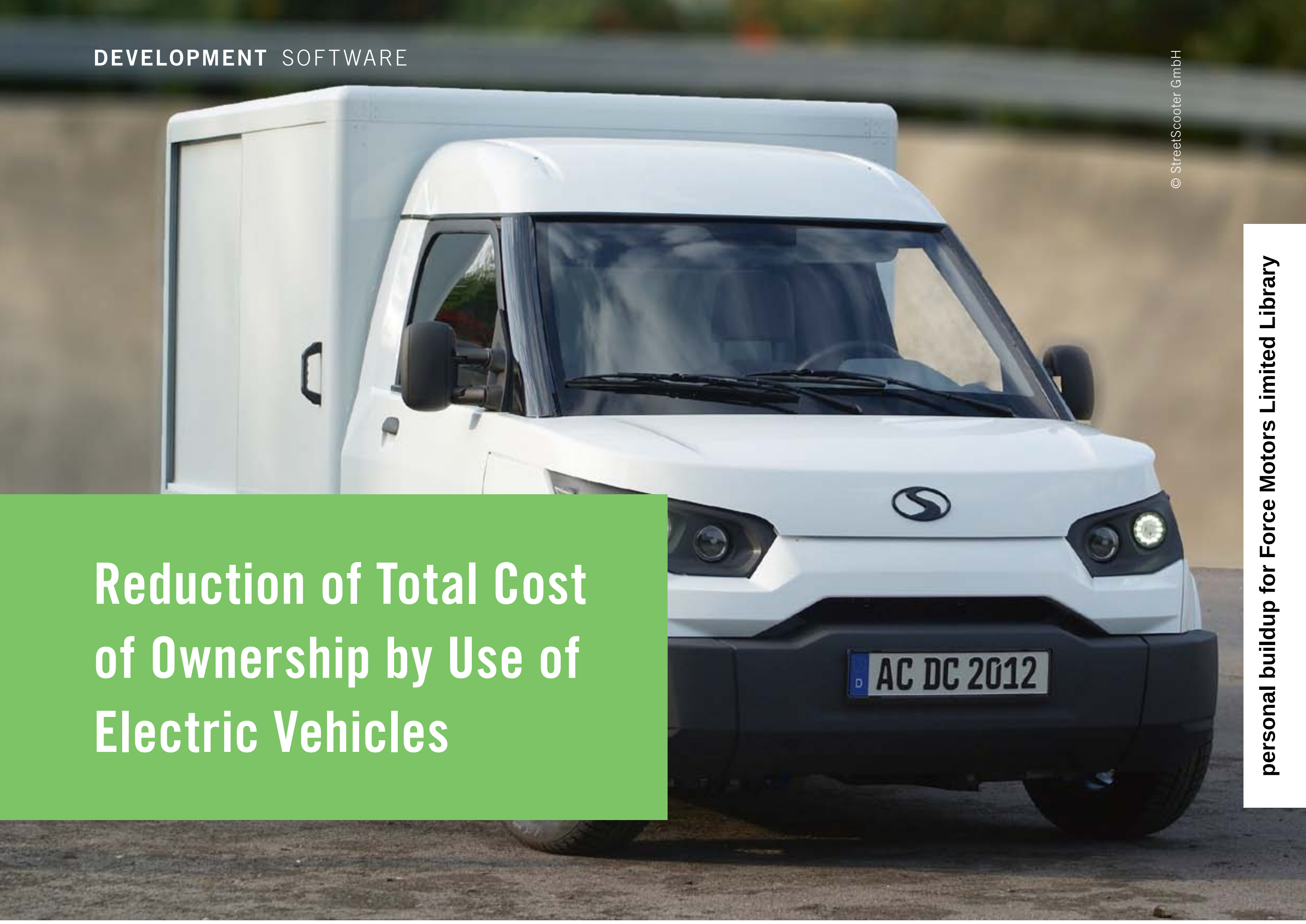


FIGURE 4 FEA load case simulation – pressure was applied to the X² centre console with a piston to simulate load cases; the result: the measurement values in N exceed the required values at all 13 positions

REFERENCES

[1] N. N.: Mittelkonsolen – Aktuell Produkte. In: ATZ 116 (2014), No. 11, pp. 30

[2] Hofacker, A.: Leichtbau: Mit integraler Bauweise spart Dräxlmaier Gewicht im Innenraum. [Lightweight Design: Dräxlmaier Saves Weight in the Interior with an Integrated Design.] In: Springer für Professionals, http://www.springerprofessional.de/mit-integraler-bauweise-spart-draexlmaier-gewicht-im-innenraum/5302332.html, access date: 25 November 2014



Reduction of Total Cost of Ownership by Use of Electric Vehicles

Today in the commercial sector vehicles with internal combustion engines come overwhelming to use. To convince the fleet operator that electric vehicles can also be economically attractive, a new software was developed by the Department of Production Engineering E-Mobility Components of the RWTH Aachen, which can be determine the optimum combination from conventional and electric vehicles in vehicle fleets.

AUTHORS

Prof. Dr.-Ing. Achim Kampker
is Head of the Chair of Production Engineering of E-Mobility Components at the RWTH Aachen University (Germany).

Dr.-Ing. Christoph Deutskens
is Chief Engineer of the Chair of Production Engineering of E-Mobility Components at the RWTH Aachen University (Germany).

Philip Müller, M. Sc.
is Research Assistant at the Centre for International Automobile Management at the RWTH Aachen University (Germany).

Dr. rer. nat. Thomas C. M. Müller
is Post-Doctoral Researcher at IEK-5 Photovoltaics at the Forschungszentrum Jülich (Germany).

MOTIVATION

Electromobility is still in its starting phase. In 2013, the Federal Motor Transport Authority recorded a total of 6051 initial registrations of electric vehicles in Germany. While this makes Germany one of the leading countries in the field of electromobility in Europe, this figure represents merely 0.2 % of all newly registered cars [1]. The lack of customer acceptance is still a crucial problem. How can it be achieved, that by experiencing significant growth in quantities electromobility will be established as a main factor in mobility? One promising strategy for transforming this niche product into a mass product is the use of electric-powered vehicles in corporate vehicle fleets. According to the association of brand-independent vehicle fleet management companies (VMF) there are approximately 1.6 million corporate vehicle fleets in Germany, consisting of about 4.4 million corporate vehicles (passenger vehicles and vans) [2]. For companies it is the cost of the new technology that mainly drives the decision whether to invest in electromobility or not. The new software Dynamic Fleet Optimizer (DFO) developed at the Chair of Production Engineering of E-Mobility at RWTH Aachen University shows that electromobility can be an economically attractive choice for companies. Hence, implementing electric vehicles in the company's vehicle pool can be rationally justified instead of being a solely emotional decision.

FORESIGHTED RATIONAL DECISIONS CONCERNING ELECTROMOBILITY

When deciding on a drive technology for the company's vehicle fleet, the fleet manager is ultimately responsible for the incurred costs. Several comparisons of total cost of ownership (TCO) of competing drive concepts reveal, that these costs are anything but trivial [3-8]. This concept compares the total costs of operating a certain kind of vehicle summed over its entire lifecycle. When applied to an entire vehicle fleet consisting of different types, however, the decision becomes much more complex: What are the impacts of adding a number of electric vehicles to an existing fleet, which reliably operates a fixed set of routes in its current configuration?

It is the capacity of the battery that often limits the operational range of an electric vehicle. In a corporate fleet with calculable routes, however, this does not have to be an elimination criterion. Batteries that cannot be used in vehicles for common ranges due to decreased capacity can then be used in vehicles operating on shorter routes. Such an approach – combined with a selective use of initial battery capacities (number of battery modules) – leads to a reduction of the total cost of ownership of a vehicle fleet despite persistently high battery costs.

The objective decision criterion has to be the minimisation of total cost of ownership. The Chair of Production Engineering of E-Mobility Components at RWTH Aachen University has developed a computer algorithm that allows for this minimisation problem to be solved for any arbitrary composition of any vehicle fleet. This dynamic and high-dimensional algorithm for calculating an investment plan is specially fitted to vehicle pools operating on calculable route profiles. Interdependencies in operating times of vehicles as well as numerous modelling parameters for possible combinations are considered. Simply speaking, the software aims at providing cost minimal mobility for a given commercial route profile. The obtained investment plan also accounts for the findings of the latest research on this topic. One example is the decreasing capacity of a battery over its lifetime depending not only on the operation profile but also on the battery technology in use [9]. Finally, scenarios on how residual values of electric vehicles develop over time and usage are considered.

FUNCTIONING OF THE SOFTWARE

Initially, the software is supplied with the direct and indirect costs of the different types of vehicles in operation. Then, all the vehicle models that are considered by the decision maker are selected. Macroeconomic factors can be adjusted in order for country-specific conditions to be considered. Examples for these factors include revenue tax rates, main refinancing rates as well as developments in the prices of liquid fuels and electric energy in the respective country.

DFO works with the entire range of occurring direct costs such as price of the vehicle, taxes, residual value of the vehicle, periodic duties, as well as all relevant indirect costs such as cost of energy, capacity of the battery, maintenance costs, vehicle taxes, and CO_2 taxes. Furthermore, the software allows the user to choose whether battery replacements shall be allowed or not and to include vehicles with varying battery configurations (different capacities) in the algorithm. Based on the extensive dataset combined with the mileage and route profiles of the fleet operator, cost-optimal decisions concerning the implementation of electric vehicles are made by the software. The time horizon can be freely selected and it is only limited by comput-

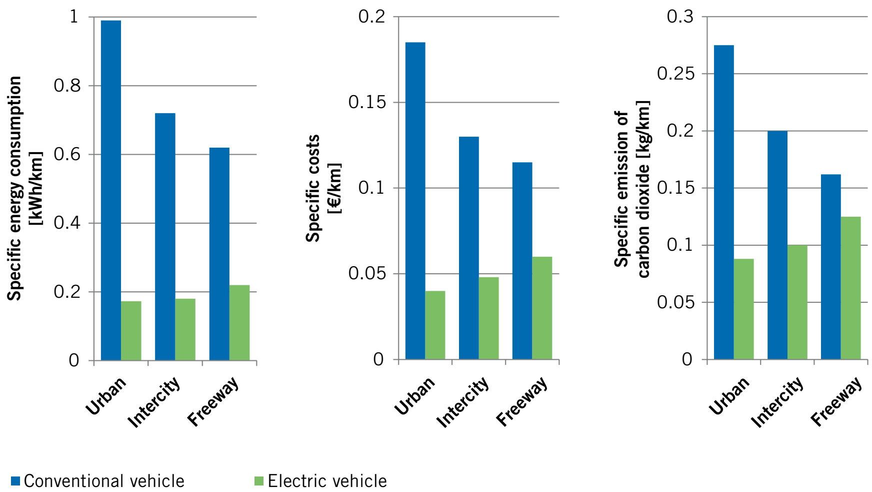


FIGURE 1 The individual route profile has to be considered: while an electric vehicle is particularly advantageous in urban areas, this advantage becomes less important for intercity or freeway routes; a conventional vehicle shows an opposing trend

ing power. The derived decisions might concern sales of current vehicles, purchases of new vehicles, as well as battery replacements. The dynamic calculation under consideration of arbitrary risk factors therefore offers a cost-optimal vehicle combination fulfilling the operator's route profile at all times, **FIGURE 1**. Free parameterisation of all variables, scientifically founded scenarios, and the possibility to include guarantees for residual battery capacities and leasing models facilitate very high resolutions of reality when compared to competing methods of optimisation.

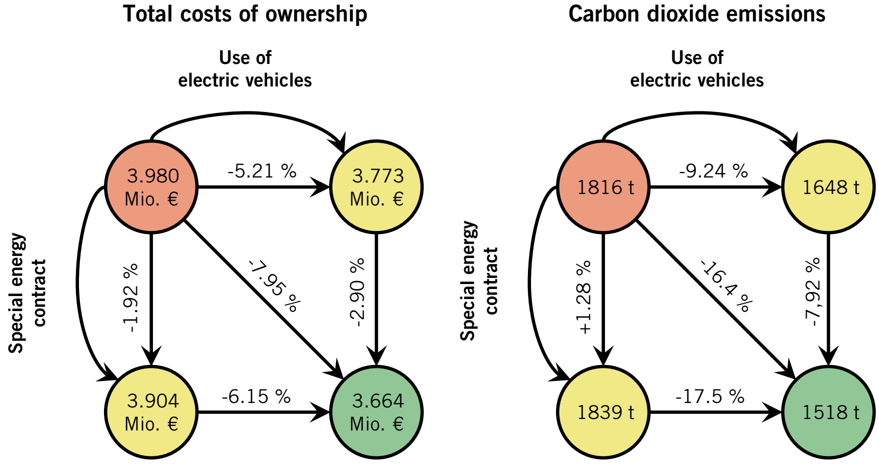


FIGURE 2 Possible savings in total cost of ownership as well as carbon dioxide (left: potential reduction of total cost of ownership by use of electric vehicles – further reductions may be possible if special contracts with energy suppliers can be negotiated; right: potential reduction of total cost of ownership by use of electric vehicles with simultaneous implementation of special contracts with energy suppliers)

REDUCTION OF TOTAL COST OF OWNERSHIP IN FLEETS IS POSSIBLE

The purpose of this software is to examine whether including electric vehicles in corporate vehicle fleets can lead to cost savings and if so, which investment plan is optimal. Based on this algorithm's results, portfolio-optimisation in former customer projects leads to calculated cost savings of 5 to 10 %, **FIGURE 2**. Another effect – besides the reduction of total operating cost – is the decreased emission of CO_2 by up to one-fifth. Depending on the price of electric energy the optimal share of electric vehicles in a fleet varies between 30 and 50 %, **FIGURE 3**. In **FIGURE 3** the electric vehicle StreetScooter Compact of the StreetScooter GmbH and the model Polo of the Volkswagen AG, with a 1.2-l engine for both cases (petrol engine or diesel engine), are compared. The results show that even in the very short term an addition of electric vehicles of 58 % in the fleet is optimal. Special contracts with energy suppliers were assumed to be in effect. The conducted calculations show that in a framework of fleet scenarios electromobility is indeed an economically viable option. It is not necessary to show that a given electric vehicle is able to cover any route, but only that it is able to cover a specific part of all routes at significantly lower cost. This fundamental realisation suffices to grasp the full potential of electromobility in commercial fleets.

SUMMARY

Still, not only the vision of the decision maker is crucial, but electromobility also has to be recognised as a viable option in the first place. In a survey carried out by the Corporate Vehicle Observatory Platform in 2013 only 18 % of the 3,652 responding enterprises stated that the future use of electromobility was an option for them at all [10]. When making a decision about electric vehicles in corporate vehicle pools, an objective evaluation of quantifiable factors using the latest findings from research as well as from practical application is essential. The combination of conventional and electric vehicles calculated by the DFO software, allows for an optimal use of the specific advantages of all possible alternatives. When it comes to corporate vehicle fleets, electromobility is not a yes or no decision.

REFERENCES

[1] www.kba.de/cln_031/nn_124832/SharedDocs/Publikationen/PM/2014/pm__02__14__fahrzeugzulassungen__12__2013__pdf: Fahrzeugzulassungen im Dezember 2013. Kraftfahrt-Bundesamt, balance sheet, 24.3.2014

[2] www.vmf-fuhrparkmanagement.de/branche.html: Markt Deutschland: Überschaubar und mit wachsender Bedeutung. Verband markenunabhängiger Fuhrparkmanagementgesellschaften e. V., 24.3.2014

[3] Al-Alawi, B. M.; Bradley, T. H.: Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. In: Applied Energy 103 (2013), pp. 488-506

[4] Ernst, C.-S.; Hackbarth, A.; Madlener, R.; Lunz, B.; Sauer, D. U.; Eckstein, L.: Battery sizing for serial plug-in hybrid electric vehicles: A model-based economic analysis for Germany. RWTH Aachen, FCN Working Paper 14/2010, Aachen, 2011

[5] Neubauer, J.; Brooker, A.; Wood, E.: Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies. National Renewable Energy Laboratory, Golden, USA, 2012

[6] Plötz, P.; Gnann, T.; Wietschel, M.: Total Ownership Cost Projection for the German Electric Vehicle Market with Implications for its Future Power and Electricity Demand. Fraunhofer-Institut für System- und Innovationsforschung, Karlsruhe, 2012

[7] Redelbach, M.; Propfe, B.; Friedrich, H.: Competitive Cost Analysis of Alternative Powertrain Technologies. Institut für Fahrzeugkonzepte, Deutsches Zentrum für Luft- und Raumfahrt e. V., Stuttgart, 2012

[8] Sharma, R. et al.: Conventional, hybrid and electric vehicles for Australian driving conditions – Part 1: Technical and financial analysis. School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia, 2012

[9] Ecker, M.; Nieto, N.; Käbitz, S.; Schmalstieg, J.; Blanke, H.; Warnecke, A.; Sauer, D.: Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithiumion. In: Journal of Power Sources 248 (2014), pp. 839-851

[10] N. N.: CVO Fuhrpark-Barometer 2013. Arval Deutschland GmbH, Kirchheim, 2013

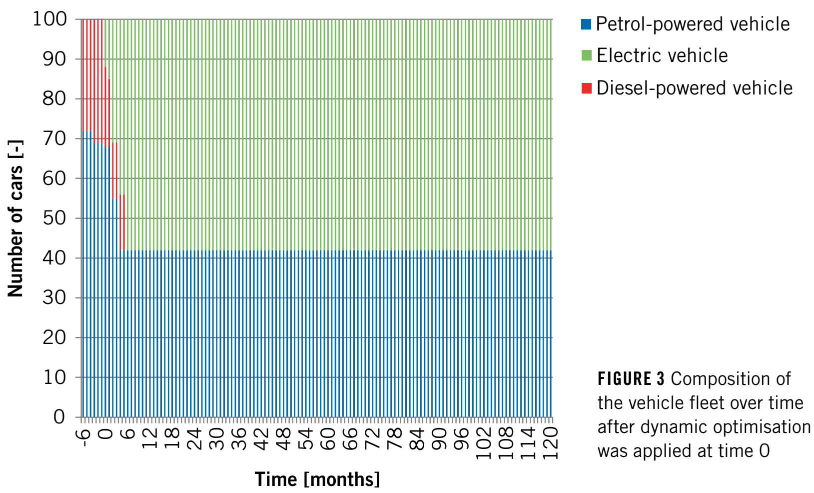


FIGURE 3 Composition of the vehicle fleet over time after dynamic optimisation was applied at time 0

Lignin Powder as a Filler for Thermoplastic Lightweight Design Components

The use of the wood material lignin as a filler instead of ash, talcum or glass fibres in thermoplastics offers an enormous lightweight potential. Additionally, life cycle analysis, sustainability and CO_2 emissions improve when using this organic nature product. Volkswagen, the TU Dresden and the Faserinstitut Bremen investigated the effect of lignin powder as filler in polypropylene (PP) with different weight fractions. Here, the safe-guarding of the mechanical properties of the new compound is essential also for series production.

INTRODUCTION

In recent years, lightweight design has gained enormous importance in the automotive industry. Especially, renewable and sustainable low-density materials are in the focus for applications. The low density of these materials allows reducing the structural weight of end products, which can help to save energy and thus CO_2 emissions.

To reduce the weight and the cost of polymers, different fillers are used. Currently, inorganic materials like glass fibres or balls, soot, talcum, aluminum oxides and silicate but also organic materials like wood powder and cellulose are applicable as filler [1, 2].

The low cost and abundant availability makes lignin attractive as filler in automotive industry. Lignin is the second most abundant polymers from biomass in nature after cellulose. The three dimensional structure consists of p-hydroxyphenyl, guaiacyl and syringyl. These are cross-linked differently again [3, 4]. Lignin is obtained just as by-product in the paper and biofuel industry and serves for energy generation. Though in the recent years, many researches were published [5-7] about lignin as filler material.

Lightweight design is an essential part of the overall Volkswagen strategy reducing the CO_2 emissions. The use of the wood material lignin as a filler in thermoplastics like polypropylene (PP) offers an enormous lightweight potential. Here, a PP/lignin compound filled with up to 30 % lignin powder offers a 20 % weight reduction compared to traditional filled PP compounds assuring the same mechanical performance. Furthermore, in comparison to unfilled thermoplastics a potential cost reduction potential of up to 30 % by using lignin as filler seems possible. Today, the use of lignin as filler for thermoplastic materials in automotive components in series production applications is unknown.

The central subject of this study are the mechanical properties of PP/lignin compounds with up to 30 weight %. They were measured with tensile, three-point bending and impact strength test.

Key aspects for the investigation of novel lignin based fillers are: the examination and quantification of lignin, the optimisation of the manufacturing processes, the characterisation and quantification of the mechanical properties of the novel lignin filled thermoplastics within an established material pre-validation process as well as a final economic efficiency and sustainability analysis.

Furthermore, the process ability of the new products as well as the suitability for high volume production of the developed processes are investigated as main issues for successful implementation in future vehicle concepts.

EXPERIMENTAL SETUP AND PROCEDURE

In this study hardwood lignin from a bio refinery was used. PP with high crystallinity for automotive injection moulding with a Melt Volume-flow Rate (MFR) of 15 g per 10 min was used for blending with lignin at 230 °C and 2.16 kg load.

The lignin powder was dried for 24 h at 50 °C before extrusion process. Polymer and powder were compounded using a Leisteritz ZSE 40 DL co-rotating twin-screw extruder. PP and PP resin (MAPP), which is grafted with maleic anhydride (MAH) adhesion promoter, were weighted and dry-mixed to be added to feeder 1. The lignin powder was added to a separate feeder 2. Feeding of the materials was performed by K-tron gravimetric feeders. The screw speed was 100 rpm and the temperature at the extruder die varied between 175 and 190 °C. Afterwards the extruded material cooled down and was shredded to pellets.

Producing PP/lignin resin with and without MAH adhesion promoter, the same parameters were used. The different material formulations of the seven charges are shown in **TABLE 1**. The amount of lignin powder in the composites is given in weight per cents. All results in the figures and tables are given as mean values.

It is essential for all tensile, three-point bending, and notch impact as well as

Charge/sample	PP [%]	Lignin [%]	MAH [%]
1	100	–	–
2	89	10	1
3	78	20	2
4	67	30	3
5	90	10	–
6	80	20	–
7	70	30	–

TABLE 1 Composition of the seven PP/lignin charges with and without MAH adhesion promoter

AUTHORS

Dipl.-Ing. Hendrik Mainka
is Project Engineer in the Materials and Manufacturing Processes Division at the Volkswagen AG in Wolfsburg (Germany).

Maria Laue
is Graduand at the Institute of Textile Machinery and High Performance Material Technology (ITM) at the TU Dresden (Germany).

Univ.-Prof. Dr.-Ing. habil. Dipl.-Wirt.-Ing. Chokri Cherif
is Director of the Institute of Textile Machinery and High Performance Material Technology (ITM) at the TU Dresden (Germany).

Prof. Dr.-Ing. Axel S. Herrmann
is Director of the Faserinstitut Bremen e. V. in Bremen (Germany).

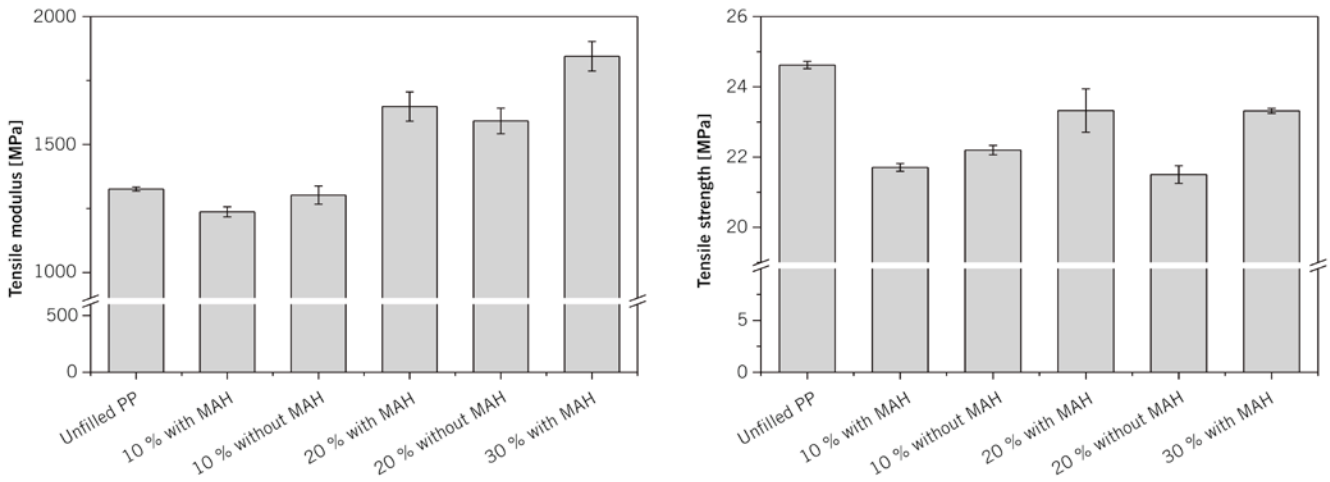


FIGURE 1 Tensile moduli and tensile strength of all PP/lignin compounds: tensile moduli (left) and tensile strengths (right)

hardness tests: Before testing, all specimens were conditioned for at least 72 h at a temperature of 23 °C and a relative humidity of 50 %.

The extruded material was compression moulded into samples for different mechanical testing. Compression moulding was performed at 185 °C with 350 bar pressure using an Arburg Allrounder 420 C. It was worked with a dwell pressure at 260 bar for 20 s.

Tensile properties were measured on a tensile test machine from ZwickRoell. 15 specimens of each blend were tested. The measurement of the strain changes were detected optical.

All three-point bending tests for flexural properties were tested on the Zmart.pro static material testing machine from the ZwickRoell company. Ten specimens of each blend were tested.

Impact strength of notched samples was tested on a ZwickRoell instrument with a 2-joule pendulum. Ten specimens of each blend were tested.

The hardness of all samples was determined with Shore D in the tests.

MEASUREMENT RESULTS AND DISCUSSION

To compare and assess the mechanical properties of all blended materials with each other different methods like tensile, three-point bending and impact strength test were performed.

The results of tensile strength properties are shown in **FIGURE 1**. It becomes obvious that the tensile moduli values increase with increasing lignin content. Furthermore there is no significant enhancement of strength with addition of MAH. Also, the increasing lignin content causes high standard deviations. This indicates an inhomogeneous distribution of the lignin in the PP melt. The tensile and break stress values of all material blends are nearly similar with some exceptions.

However, the elongations at break decrease with increasing lignin content. Just 10 % lignin causes a deterioration of strain by almost 80 %. With 30 % lignin weight blend the elongation at fracture is 3.4 %, which is only 0.67 % of the starting value. 10 % lignin content without addition of MAH shows a similar decreasing of the value.

The MAH adhesion promoter seems not to influence the homogeneity in the specimens because the standard deviations are stable.

Matrix	Lignin content [weight %]	Tensile modulus [MPa]	Tensile strength [MPa]	Strength at break [MPa]	Elongation at break [%]
PP	0	1326	24.6	19.6	508.3
PP and MAH	10	1237	21.7	13.1	98.6
PP and MAH	20	1648	23.3	13.8	13.8
PP and MAH	30	1845	23.3	19.1	3.4
PP	10	1302	22.2	13.5	94.5
PP	20	1592	21.5	9.0	53.0

TABLE 2 Mechanical properties of all PP/lignin compounds

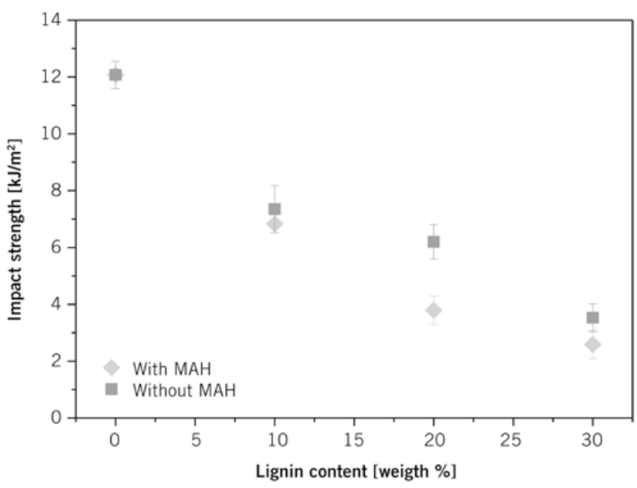


FIGURE 2 Impact strength of all PP/lignin compounds

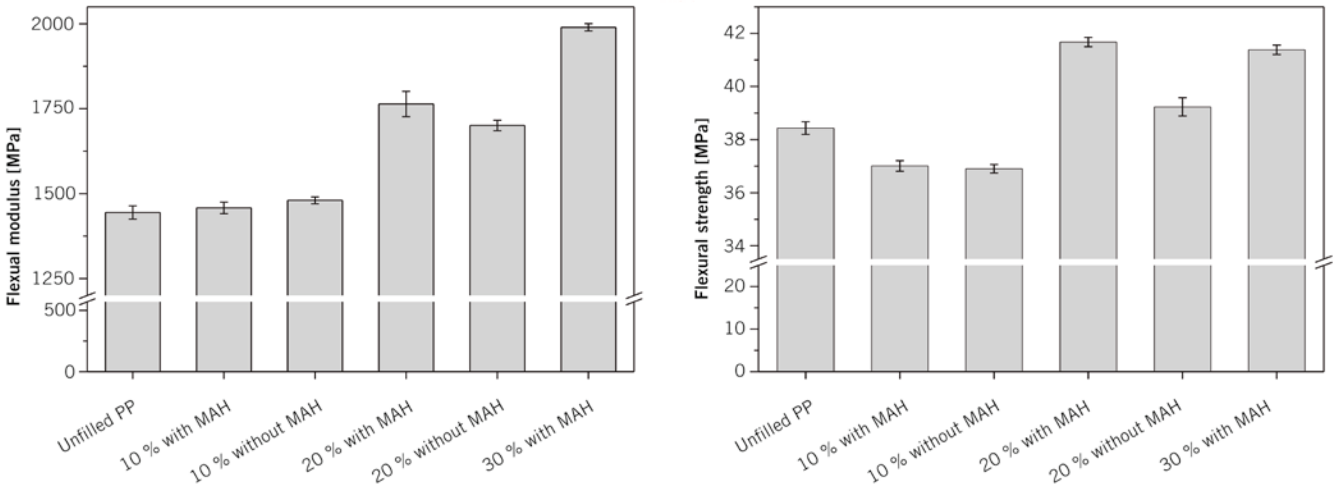


FIGURE 3 Flexural moduli (left) and flexural strengths (right) of all PP/lignin compounds

In summary, lignin has a positive effect on the tensile moduli. However, the tensile strength values decrease compared with unfilled PP. It is conceivable to use lignin as filler for cost reduction. **TABLE 2** shows the results of the mechanical properties.

The results of the impact strength tests are shown in **FIGURE 2**. The values of the impact strengths with and without MAH continuously decrease with increasing lignin content. But without addition of MAH the deterioration is considerably lower. It can be concluded that the function of MAH as adhesion promoter have a negative effect on the impact strength of the compound of PP and lignin.

The flexural moduli increase with increasing lignin content, which was noted already in the tensile strength test, **FIGURE 3**. The flexural strength varies to a lesser extent whereas noticeable that the value with 20 % lignin and 2 % MAH is higher than the measured strength with 30 % lignin.

Based to flexural strain, you can see also that the materials are brittle with high lignin content because the values decrease. The decrease is less for the tensile tests. Unfilled PP shows the highest value with 6.3 % flexural strain. In contrast, the sample with 30 % lignin content has just 3.6 % flexural strain.

In summary, the addition of lignin has a increase effect on the flexural moduli. However the strength values decrease with 10 % lignin compared to unfilled PP. With 20 % filler or more the flexural strength increases. Therefore the statements so far support this results and it is conceivable to use lignin as filler for cost reduction.

The hardness of the different blended polymers was measured with shore D. The values are shown in **FIGURE 4**. It can be seen that there is no significant increase of hardness with addition of MAH.

SUMMARY

In this study Volkswagen, TU Dresden and Faserinstitut Bremen investigated the effect of lignin powder as filler in polypropylene with different weight fractions. Furthermore there were strong improvements of the mechanical properties if the MAH adhesion promoter is added.

In general the properties of the different PP/lignin compounds are influenced by the lignin content. If filler was included the materials were stiffer. The best values were measured with 20 % lignin content and MAH. However, the scope of applications still has to be defined for the automotive industry. Moreover it has to be investigated if lower values without adding MAH are acceptable for the final utilisation, so that further cost can be reduced.

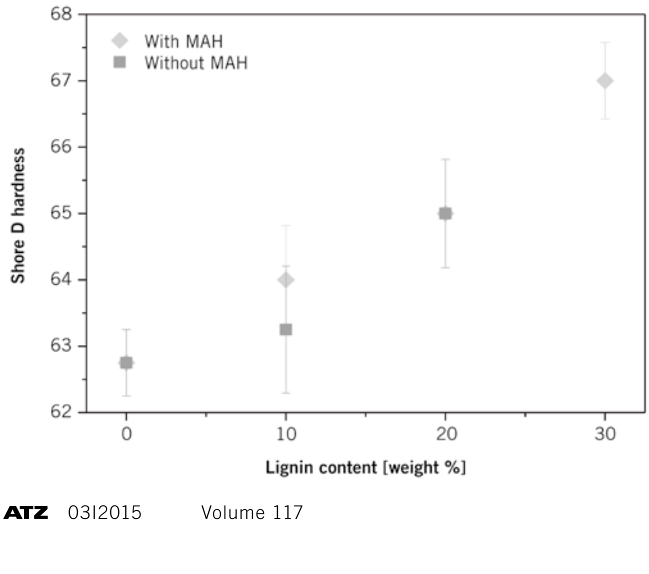


FIGURE 4 Results of Shore D hardness determination for PP/lignin compounds with and without MAH adhesion promoter

REFERENCES

[1] Myer Kutz (Ed.): Applied Plastics Engineering Handbook: Processing and Materials. London, Amsterdam, New York: Elsevier, 2011
[2] Baur, E. et al.; Saechtling, H. (Hrsg.): Saechtling Kunststoff-Taschenbuch. München: Carl Hanser, 2013
[3] Laurichesse S.; Avérous, L.: Chemical Modification of Lignins: Towards Biobased Polymers. In: Progress in Polymer Science 39 (2014), No. 7, pp. 1266-1290
[4] Hatakeyama, H.; Hatakeyama, T.: Biopolymers. pp. 1-63, Berlin, Heidelberg: Springer, 2010
[5] Morandim-Giannetti, A. et al.: Lignin as Additive in Polypropylene/Coir Composites: Thermal, Mechanical and Morphological Properties. In: Carbohydrate Polymers 87 (2012), No. 4, pp. 2563-2568
[6] Sailaja, R. R. N. et al.: Mechanical and Thermal Properties of Compatibilized Composites of Polyethylene and Esterified Lignin. In: Materials & Design 31 (2010), No. 9, pp. 4369-4379
[7] Nitz, H. et al.: Influence of Lignin Type on the Mechanical Properties of Lignin Based Compounds. In: Macromolecular Materials and Engineering 286 (2001), No. 12, pp. 737-743

IMPRINT

ATZ

WORLDWIDE

www.ATZonline.com

Founded 1898 as „Der Motorwagen“

Organ of the VDI-Gesellschaft Fahrzeug- und Verkehrstechnik (FVT)
Organ of the Forschungsvereinigung Automobiltechnik e. V. (FAT) and of the Normenausschuss Automobiltechnik (NAAutomobil), formerly known as FAKRA, in the DIN Deutsches Institut für Normung e. V.
Organ of the Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik e. V. (WKM)

03I2015 _ Volume 117
Springer Vieweg I Springer Fachmedien Wiesbaden GmbH
P. O. Box 15 46 · 65173 Wiesbaden · Germany I Abraham-Lincoln-Straße 46 · 65189 Wiesbaden · Germany

Amtsgericht Wiesbaden, HRB 9754, USt-IdNr. DE811148419
Managing Directors Armin Gross, Petrus W. J. Hendriks, Joachim Krieger

Managing Director Marketing & Sales Armin Gross I **Director Magazines** Stefanie Burgmaier I **Director Production** Olga Chiarcos

EDITORS IN CHARGE
Dr. Johannes Liebl, Wolfgang Siebenpfeiffer

EDITOR IN CHIEF
Dr. Alexander Heintzel
phone +49 611 7878-342 · fax +49 611 7878-462
alexander.heintzel@springer.com

VICE-EDITOR IN CHIEF
Dipl.-Ing. Michael Reichenbach
phone +49 611 7878-341 · fax +49 611 7878-462
michael.reichenbach@springer.com

MANAGING EDITOR
Kirsten Beckmann M. A.
phone +49 611 7878-343 · fax +49 611 7878-462
kirsten.beckmann@springer.com

EDITORIAL STAFF
Dipl.-Ing. (FH) Richard Backhaus
phone +49 611 5045-982 · fax +49 611 5045-983
richard.backhaus@rb-communications.de
Dipl.-Ing. (FH) Andreas Fuchs
phone +49 6146 837-056 · fax +49 6146 837-058
fuchs@fachjournalist-fuchs.de
Dipl.-Ing. Ulrich Knorra
phone +49 611 7878-314 · fax +49 611 7878-462
ulrich.knorra@springer.com
Roland Schedel
phone +49 6128 853-758 · fax +49 6128 853-759
roland.schedel@text-com.de
Stefan Schlott
phone +49 8726 967-572
redaktion_schlott@gmx.net
Markus Schöttle
phone +49 611 7878-257 · fax +49 611 7878-462
markus.schoettle@springer.com
Martina Schraad
phone +49 611 7878-276 · fax +49 611 7878-462
martina.schraad@springer.com

PERMANENT CONTRIBUTORS
Andreas Burkert, Prof. Dr.-Ing. Stefan Breuer, Harmut Hammer, Detlef Krehl, Prof. Dr.-Ing. Fred Schäfer

ENGLISH LANGUAGE CONSULTANT
Paul Willin

ONLINE I ELECTRONIC MEDIA
Portal Manager Automotive
Christiane Brünglinghaus
phone +49 611 7878-136 · fax +49 611 7878-462
christiane.bruenglinghaus@springer.com
Editorial Staff
Katrin Pudenz M. A.
phone +49 6172 301-288 · fax +49 6172 301-299
redaktion@kpz-publishing.com

SPECIAL PROJECTS
Managing Editorial Journalist
Markus Bereszewski
phone +49 611 7878-122 · fax +49 611 7878-462
markus.bereszewski@springer.com
Editorial Staff I Coordination
Dipl.-Reg.-Wiss. Caroline Behle
phone +49 611 7878-393 · fax +49 611 7878-462
caroline.behle@springer.com
Christiane Imhof M. A.
phone +49 611 7878-154 · fax +49 611 7878-462
christiane.imhof@springer.com

PROJECT MANAGEMENT I ASSISTANCE
Yeliz Konar
phone +49 611 7878-180 · fax +49 611 7878-462
yeliz.konar@springer.com

ADDRESS
Abraham-Lincoln-Straße 46 · 65189 Wiesbaden
P. O. Box 1546 · 65173 Wiesbaden, Germany
redaktion@ATZonline.de

ADVERTISING

SALES MANAGEMENT
Volker Hesedenz
phone +49 611 7878-269 · fax +49 611 7878-78269
volker.hesedenz@best-ad-media.de

KEY ACCOUNT MANAGEMENT
Rouwen Bastian
phone +49 611 7878-399 · fax +49 611 7878-78399
rouwen.bastian@best-ad-media.de

DISPLAY AD MANAGER
Susanne Bretschneider
phone +49 611 7878-153 · fax +49 611 7878-443
susanne.bretschneider@best-ad-media.de

AD PRICES
Advertising ratecard from October 2014.

MARKETING I OFFPRINTS

HEAD OF MARKETING MAGAZINES + EVENTS
Jens Fischer

PRODUCT MANAGEMENT AUTOMOTIVE MEDIA
Jens Fischer
phone +49 611 7878-340 · fax +49 611 7878-407
jens.fischer@springer.com

OFFPRINTS
Martin Leopold
phone +49 2642 907-596 · fax +49 2642 907-597
leopold@medien-kontor.de

PRODUCTION I LAYOUT
Kerstin Brüderlin
phone +49 611 7878-173 · fax +49 611 7878-78173
kerstin.bruederlin@springer.com

SUBSCRIPTIONS
Springer Customer Service Center GmbH
Haberstraße 7 · 69126 Heidelberg, Germany
phone +49 6221 3454-303 · fax +49 6221 3454-229
Monday to Friday, 8 a.m. to 6 p.m.
springervieweg-service@springer.com
www.my-specialized-knowledge.com/automotive

SUBSCRIPTION CONDITIONS
The eMagazine appears 11 times a year at an annual subscription rate 199 € for private persons and 333 € for companies. Special rate for students on proof of status in the form of current registration certificate 98 €. Special rate for VDI/ÖVK members on proof of status in the form of current member certificate 172 €. Special rate for studying VDI members on proof of status in the form of current registration and member certificate 71 €. Annual subscription rate for combination ATZworldwide (eMagazine) and ATZ (print) 399 €. All prices include VAT at 7%. Every subscription comes with access to the online archive. However, access is only available for the individual subscription holder. To obtain access for your entire company/library/organisation, please contact sales@springerprofessionals.de or phone +49 611 7878-686. The subscription can be cancelled in written form at any time with effect from the next available issue.

YOUR HOTLINE TO ATZ

Editorial Staff
☎ +49 611 7878-341
Customer Service
☎ +49 6221 3454-303
Advertising
☎ +49 611 7878-269

HINTS FOR AUTHORS
All manuscripts should be sent directly to the editors. By submitting photographs and drawings the sender releases the publishers from claims by third parties. Only works not yet published in Germany or abroad can generally be accepted for publication. The manuscripts must not be offered for publication to other journals simultaneously. In accepting the manuscript the publisher acquires the right to produce royalty-free offprints. The journal and all articles and figures are protected by copyright. Any utilisation beyond the strict limits of the copyright law without permission of the publisher is illegal. This applies particularly to duplications, translations, microfilming and storage and processing in electronic systems.

PEER REVIEW

Peer Review Process for Research Articles in ATZ, MTZ and ATZelektronik

STEERING COMMITTEE

Prof. Dr.-Ing. Lutz Eckstein	RWTH Aachen University	Institut für Kraftfahrzeuge Aachen
Prof. Dipl.-Des. Wolfgang Kraus	HAW Hamburg	Department Fahrzeugtechnik und Flugzeugbau
Prof. Dr.-Ing. Ferit Küçükay	Technische Universität Braunschweig	Institut für Fahrzeugtechnik
Prof. Dr.-Ing. Stefan Pischinger	RWTH Aachen University	Lehrstuhl für Verbrennungskraftmaschinen
Prof. Dr.-Ing. Hans-Christian Reuss	Universität Stuttgart	Institut für Verbrennungs-motoren und Kraftfahrwesen
Prof. Dr.-Ing. Ulrich Spicher	MOT	
Prof. Dr.-Ing. Hans Zellbeck	Technische Universität Dresden	Lehrstuhl für Verbrennungsmotoren

ADVISORY BOARD

Prof. Dr.-Ing. Klaus Augsburg	Dr. Malte Lewerenz
Prof. Dr.-Ing. Michael Bargende	Prof. Dr.-Ing. Markus Lienkamp
Prof. Dipl.-Ing. Dr. techn. Christian Beidl	Prof. Dr. rer. nat. habil. Ulrich Maas
Prof. Dr. sc. techn. Konstantinos Boulouchos	Prof. Dr.-Ing. Markus Maurer
Prof. Dr. Dr. h.c. Manfred Broy	Prof. Dr.-Ing. Martin Meywerk
Prof. Dr.-Ing. Ralph Bruder	Ao. Univ.-Prof. Dr. Gregor Mori
Dr. Gerhard Bruner	Prof. Dr.-Ing. Klaus D. Müller-Glaser
Prof. Dr. rer. nat. Heiner Bubb	Dr. techn. Reinhard Mundl
Prof. Dr. rer. nat. habil. Olaf Deutschmann	Prof. Dr. rer. nat. Peter Neugebauer
Prof. Dr.-Ing. Klaus Dietmayer	Prof. Dr. rer. nat. Cornelius Neumann
Dr. techn. Arno Eichberger	Prof. Dr.-Ing. Nejila Parspour
Prof. Dr. techn. Helmut Eichlseder	Prof. Dr.-Ing. Peter Pelz
Prof. Dr. Wilfried Eichlseder	Prof. Dr. techn. Ernst Pucher
Dr.-Ing. Gerald Eifler	Dr. Jochen Rauh
Prof. Dr.-Ing. Wolfgang Eifler	Prof. Dr.-Ing. Konrad Reif
Prof. Dr. rer. nat. Frank Gauterin	Prof. Dr.-Ing. Stephan Rinderknecht
Prof. Dr. techn. Bernhard Geringer	Prof. Dr.-Ing. Jörg Roth-Stielow
Prof. Dr.-Ing. Uwe Dieter Grebe	Dr.-Ing. Swen Schaub
Dr. mont. Christoph Guster	Prof. Dr. sc. nat. Christoph Schierz
Prof. Dr.-Ing. Holger Hanselka	Prof. Dr. rer. nat. Christof Schulz
Prof. Dr.-Ing. Horst Harndorf	Prof. Dr. rer. nat. Andy Schürr
Prof. Dr. techn. Wolfgang Hirschberg	Prof. Dr.-Ing. Ulrich Seiffert
Prof. Dr. techn. Peter Hofmann	Prof. Dr.-Ing. Hermann J. Stadtfeld
Prof. Dr. rer. nat. Peter Holstein	Prof. Dr.-Ing. Karsten Stahl
Prof. Dr.-Ing. Volker von Holt	Prof. Dr. techn. Hermann Steffan
Prof. Dr.-Ing. habil. Werner Hufenbach	Prof. Dr.-Ing. Wolfgang Steiger
Prof. Dr.-Ing. Armin Huß	Prof. Dr.-Ing. Peter Steinberg
Dr. techn. Heidelinde Jetzinger	Dr.-Ing. Peter Stommel
Prof. Dr.-Ing. Roland Kasper	Dr.-Ing. Ralph Sundermeier
Prof. Dr.-Ing. Prof. E. h. mult. Rudolf Kawalla	Prof. Dr.-Ing. Wolfgang Thiemann
Prof. Dr.-Ing. Tran Quoc Khanh	Prof. Dr.-Ing. Dr. h.c. Helmut Tschöke
Dr. Philip Köhn	Prof. Dr.-Ing. Georg Wachtmeister
Prof. Dr.-Ing. Ulrich Konigorski	Prof. Dr.-Ing. Jochen Wiedemann
Prof. Dr. Oliver Kröcher	Prof. Dr. rer. nat. Gerhard Wiegleb
Prof. Dr.-Ing. Peter Krug	Prof. Dr. techn. Andreas Wimmer
Dr. Christian Krüger	Prof. Dr. rer. nat. Hermann Winner
Prof. Dr. techn. Thomas Lauer	Prof. Dr. med. habil. Hartmut Witte
Prof. Dr. rer. nat. Uli Lemmer	Dr.-Ing. Michael Wittler

Scientific articles of universities in ATZ Automobiltechnische Zeitschrift, MTZ Motortechnische Zeitschrift and ATZelektronik are subject to a proofing method, the so-called peer review process. Articles accepted by the editors are reviewed by experts from research and industry before publication. For the reader, the peer review process further enhances the quality of the magazines‘ content on a national and international level. For authors in the institutes, it provides a scientifically recognised publication platform.

In the Peer Review Process, once the editors has received an article, it is reviewed by two experts from the Advisory Board. If these experts do not reach a unanimous agreement, a member of the Steering Committee acts as an arbitrator. Following the experts’ recommended corrections and subsequent editing by the author, the article is accepted.

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.

THE SEAL OF APPROVAL FOR SCIENTIFIC ARTICLES IN ATZ.
ATZ PEER REVIEW
REVIEWED BY EXPERTS FROM RESEARCH AND INDUSTRY.

AUTHORS

Dipl.-Kffr. techn. Katrin Mutter
is Project Coordinator in the Team Testing Management of the Daimler AG in Sindelfingen and PhD at the Institute of Machine Components at the University of Stuttgart in the field of Reliability Engineering (Germany).

Dr.-Ing. Axel Röder
is Manager of the Team Testing Management in the Mercedes-Benz Cars Development Corporate Unit of the Daimler AG in Sindelfingen (Germany).

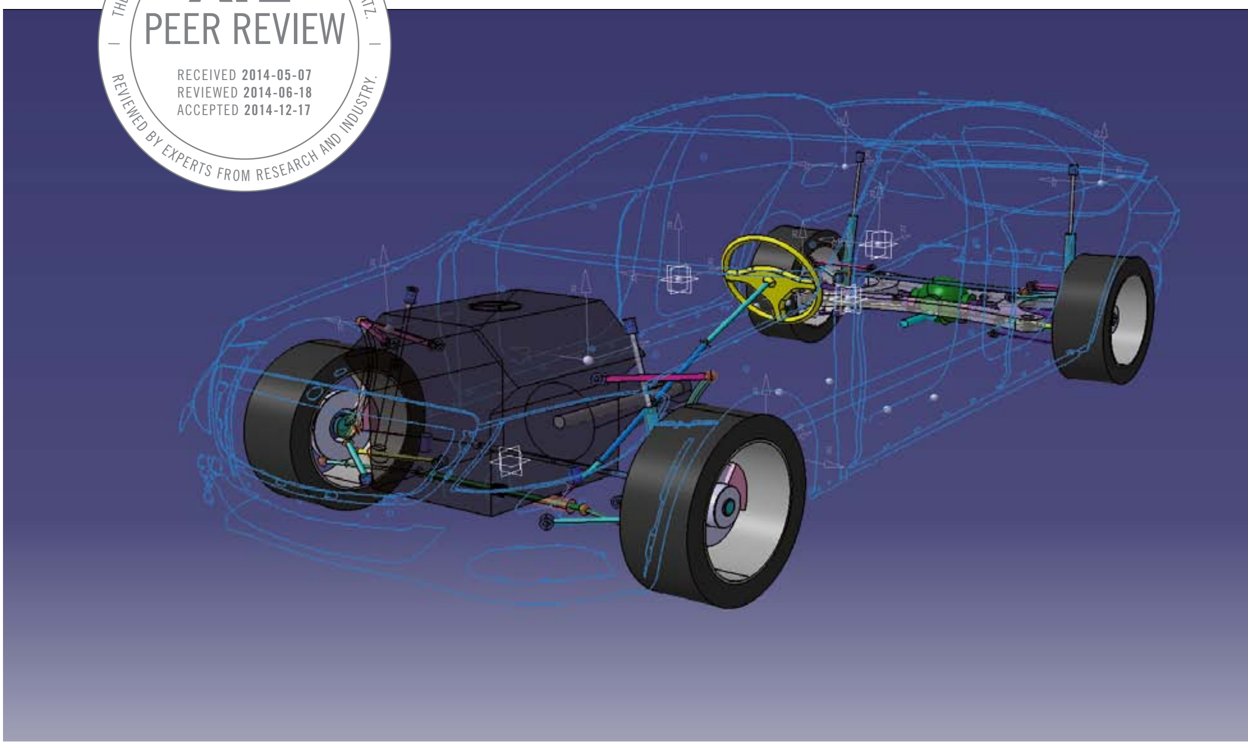
Prof. Dr.-Ing. Bernd Bertsche
is Head of the Institute of Machine Components at the University of Stuttgart (Germany).

Dipl.-Betriebswirt Jörg U. Brünis
is Head of Overall Testing Management in the Mercedes-Benz Cars Development Corporate Unit of Daimler AG in Stuttgart (Germany).

Simulating Reliability with Respect to Ride Comfort

Key potential areas for optimising the efficiency during vehicle development process are therefore rigidly aligned with safeguarding activities of customer oriented overall vehicle functions in early phases of development. Based on this, the Institute of Machine Components, field of Reliability Engineering, University of Stuttgart, applied in cooperation with the Mercedes-Benz Cars Development as a part of Daimler an advanced reliability concept. With this concept, the numerical simulation methods used are capable for the first time of evaluating and assessing the long-term quality and reliability of a vehicle's ride comfort.

THE SEAL OF APPROVAL FOR SCIENTIFIC ARTICLES IN ATZ.
ATZ
PEER REVIEW
RECEIVED 2014-05-07
REVIEWED 2014-06-18
ACCEPTED 2014-12-17
REVIEWED BY EXPERTS FROM RESEARCH AND INDUSTRY.



1 MOTIVATION

In the automotive industry, ever shorter development times, increasing levels of customisation and options for products, and the resulting boom in the number of variants available, together with rising cost pressure, have led to a reduction in the number of trial testing vehicles developed. At the same time, the requirements pertaining to the functional quality and reliability of end products are at an all-time high. Key potential areas for optimising the efficiency with which vehicle design work is safeguarded are therefore rigidly aligned with the digital, test stand and street phases. This approach also forms the basis for targeted front loading to shift safeguarding activities back to early phases of development.

Functional short-term safeguarding based on digital prototypes has already become established in the development processes practised by manufacturers [1, 2]. Safeguarding reliability in the long term, however, remains very much a manual activity, as computers have not yet been fully integrated and current component and system-related reliability techniques still do not offer a comprehensive concept for evaluating the durability of overall vehicle functions such as ride comfort and vehicle dynamics. In this context, reliability as defined in [3] refers to "the probability of a product not failing within a defined time window under specific operating and ambient conditions". Target reliability must be adapted accordingly where it applies to overall vehicle functions (see section 4).

2 OVERALL VEHICLE FUNCTIONS IN THE DIGITAL PROTOTYPE

The entire product development process can be divided into two basic phases: one digital and one physical, **FIGURE 1**. Initial safeguarding measures are implemented in the digital phase by making calculations and running simulations only. In the physical development phase, safeguarding occurs on test stands as well as on the road using available parts, components and trial testing vehicles. During street testing, globally distributed testing grounds and public roadways are used. Digital safeguarding is also practised throughout the physical development phase to ensure plausibility and validate the trial testing results obtained in addition to gaining important information about how the simulation methods can and should be developed further.

From a customer perspective, it is not the parts, components or systems of a vehicle that matter so much as the overall functions offered when it comes to perceiving the vehicle. These functions pertain to thermal development, driving performance, consumption, vehicle dynamics and ride comfort, for example, whereby the latter two are associated with the category of ride and handling, **FIGURE 2**. Overall vehicle functions are the result of the coordinated interaction of various components and systems as well as the complex effects they produce when using the vehicle. It is in this context that Mercedes-Benz leverages the concept of the digital prototype. **FIGURE 2** shows separate overall vehicle functions [2, 4]. In the digital prototype environment, corresponding overall vehicle simulation models are introduced to assess and evaluate a standardised, uniform state of development across all overall vehicle functions to obtain consistent and clear results for one and the same vehicle.

3 STRUCTURE OF AN END-TO-END SAFEGUARDING PROCESS

In the past, overall vehicle functions were divided, classified and safeguarded in the digital development phase only. To this end, standardised, functional safeguarding tasks in the form of load scenarios exist to safeguard the digital prototype [1, 2]. By applying these load scenarios, designers can compare the simulation results for different model series as well as for varying stages of development within the confines of the development process for a particular model series. Standardised test descriptions are also in place to safeguard exercises carried out in the test stand and

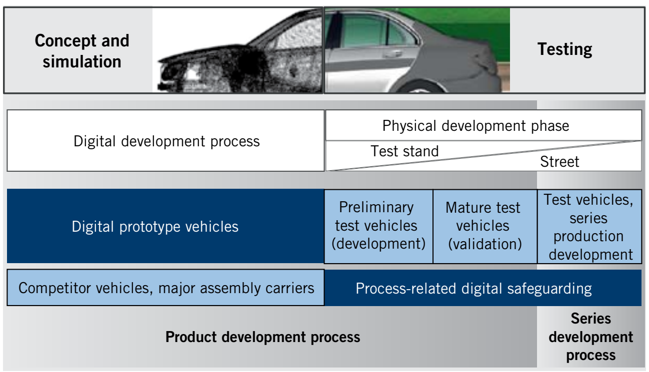


FIGURE 1 Digital and physical safeguarding in the product life cycle

street environments but are not directly comparable with those of the digital trial testing phase. This, in turn, makes it more difficult to hand over the safeguarding results in a binding, confidential manner as well as track the state of development of the safeguarding exercises throughout the overarching safeguarding process. Redundancies in the content of the safeguarding programme are also much more difficult to identify.

In striving to improve the efficiency of the safeguarding process, Mercedes-Benz has extended the application content within the structure of the overall vehicle functions from the digital prototype to the physical development phase that includes the test stand and street sub processes. In the target objective state, these sub processes encompass standardised, clearly defined safeguarding scopes that are assigned to the phases in a well-defined manner, whereby the scopes permit, or allow, an ideal mix of the trial testing methods available. The only preliminary requirement in this context is that the methods applied have attained an appropriate level of maturity in the three phases.

To achieve the target state described, the first step is to analyse and compare the test descriptions across all trial testing specialist departments, **TABLE 1**. Doing this makes it possible to determine which part or aspect of the overall safeguarding scope is currently being processed and how activities should be divided and assigned in future. In a further step, a target-actual comparison is drawn to identify redundancies, which must then be alleviated. Inadequacies or deficiencies can also be detected to prevent safeguarding scopes from transitioning to other phases to ensure a complete and seamless integration of methods in the simulation, for example. Currently, action is required to safeguard the reliability of overall vehicle functions by carrying out numerical simulation exercises.

In view of the fact that long-term quality as it pertains to ride comfort has previously not been safeguarded in the digital phase, the following concept was devised for the overall vehicle function of ride and handling. When this concept is applied, the simulation methods used are capable of evaluating and assessing the long-term quality and reliability of a vehicle's ride comfort. Digital reliability is assessed by applying the constraints and evaluation criteria that originally applied to the physical development phase in carrying out trial testing exercises on test stands and on roadways.

4 SIMULATING RELIABILITY WITH RESPECT TO RIDE COMFORT

The design requirement of shifting the need to make clear, binding statements about the reliability of the overall vehicle to the digital phase as a preliminary step to avoid provisioning expensive trial testing vehicles led to the development of an advanced reliability concept for overall vehicle functions [5]. Based on the definition of reliability as explained by Bertsche [3], the reliability of overall vehicle functions was clarified as the probability of the performance criteria for the overall vehicle function not exceeding the limits of a defined target area, or range, under a given set of environmental and usage conditions up to a certain vehicle mileage figure.

4.1 THE FIVE STEPS OF THE CONCEPT

The concept introduced in this article attempts to characterise the stochastic scatter present at a mileage figure of 0 km as well as quantify the divergent degradation behaviour of the components that influence the overall vehicle function. Degradation in this context refers to the change in characteristic component properties across the fictitious vehicle lifespan and serves as a basis for determining real-world reliability over the entire mileage spectrum. Examples of degradation include aging and fatigue of rubber bushes and mounts in the form of hardening or changes in dampening elasticity. To this end, five steps were defined, **FIGURE 3**, and are explained in terms of ride comfort in the following sections.

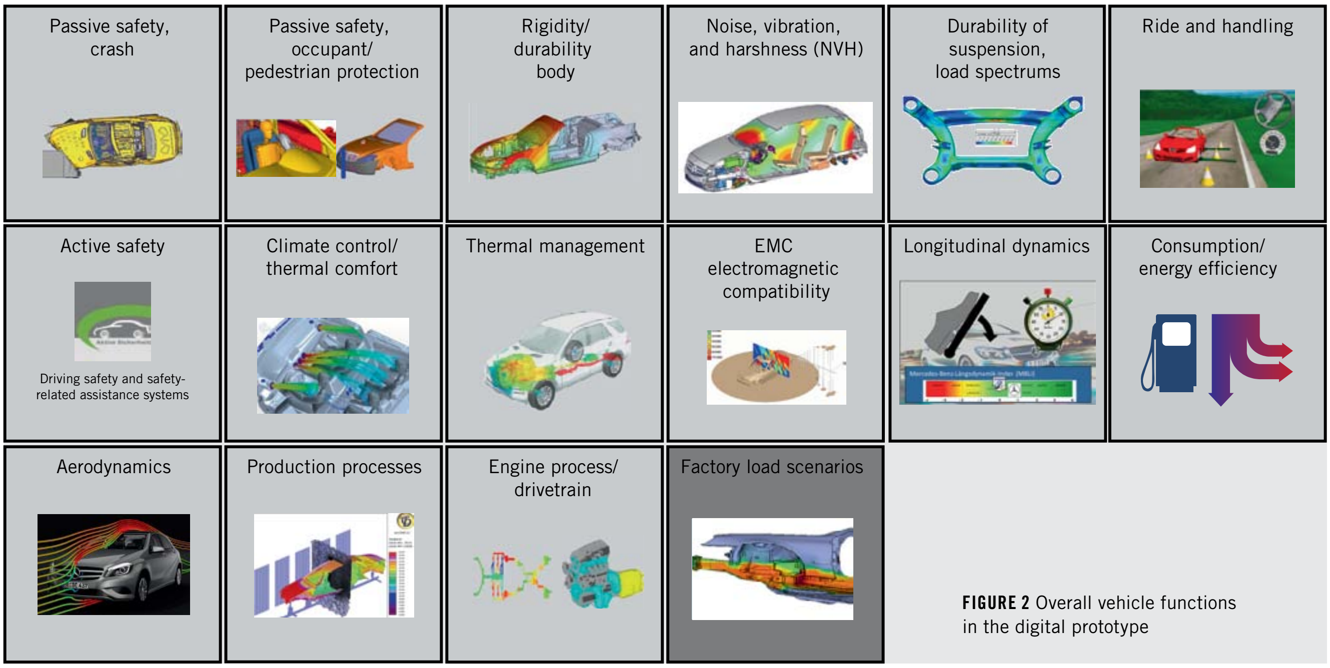
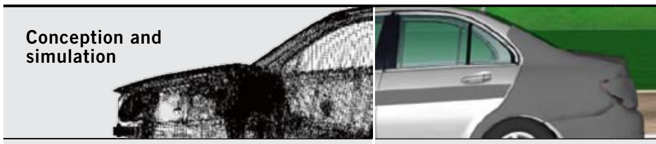


FIGURE 2 Overall vehicle functions in the digital prototype



		Digital development phase [D]	Physical development phase: Test stand (P)	Physical development phase: Street (S)
Passive safety, crash 	Safeguarding task A_1	Safeguarding scope, digital (D) for A_1	Scope P for A_1	Scope S for A_1
	Safeguarding task A_2	Safeguarding scope, digital (D) for A_2	Scope P for A_2	Scope S for A_2
	...	...	...	...
	Safeguarding task A_m	Safeguarding scope, digital (D) for A_m	Scope P for A_m	Scope S for A_m
Passive safety occupant/ pedestrian protection 	Safeguarding task B_1	Safeguarding scope, digital (D) for B_1	Scope P for B_1	Scope S for B_1
	Safeguarding task B2	Safeguarding scope, digital (D) for B_2	Scope P for B_2	Scope S for B_2
	...	...	...	...
	Safeguarding task B_n	Safeguarding scope, digital (D) for B_n	Scope P for B_n	Scope S for B_n
Rigidity durability body 	Safeguarding task C_1	Safeguarding scope, digital (D) for C_1	Scope P for C_1	Scope S for C_1
	Safeguarding task C_2	Safeguarding scope, digital (D) for C_2	Scope P for C_2	Scope S for C_2
	...	...	...	...
	Safeguarding task C_o	Safeguarding scope, digital (D) for C_o	Scope P for C_o	Scope S for C_o
...	...	...	...	...
	...	...	...	...
	...	...	...	...
	...	...	...	...

TABLE 1 End-to-end safeguarding scopes for the digital, test stand and street phases

4.1.1 QUANTIFYING RIDE COMFORT

Vibration or ride comfort encompasses all mechanical and acoustic vibrations that the occupants in a vehicle are subjected to [4]. The term NVH, which is frequently used in literature and in practice in this context, distinguishes between noise (audible > 100 Hz), vibration (perceived by touch or sight < 25 Hz) and harshness (intermediate range that is perceived differently depending on age and constitution, approximate 25 to 100 Hz) in relation to the range of frequency to which humans are sensitive [6, 7].

Ride comfort is evaluated based on different phenomena that occur on varying road surfaces and in specific driving situations. In the digital prototype, the phenomenon known as stuttering, or vibration, is viewed as part of standard procedure [8], whereby several definitions for the vibrational effect have been derived from literature and practical applications. Most of the time, engine vibrations are what is being referred to and upset the otherwise smooth control and stability of the front end of the vehicle as a result of the engine block starting to resonate with the body at a coupling frequency [8]. The term can also be expanded in scope, however, to cover the vibrations exhibited in the chassis and suspension, engine and detachable parts. When this definition is applied, the vibrational effect encompasses frequencies ranging from approximately 4 to 25 Hz. Ride comfort and the phenomena associated with it are evaluated primarily in a subjective manner. When vibration is very noticeable, for example, it is perceived as an unpleasant hopping of the vehicle as it travels down the road.

To realise a numerically-based simulation exercise, however, objective characteristic variables must be derived that accurately represent, or characterise, the subjective evaluation. An overview of the different processes and procedures for objectively assessing perceived vibration is provided in [9].

Many automakers evaluate vibrational performance by targeting the driver seat console or seat assembly under maximum vehicle acceleration to define an objective criterion, as the main area in which forces are transferred from the vehicle to its occupants is the seats they sit on. Maximum acceleration continues to be used as an objectivity variable within the scope of the reliability analysis. The limits for the design criteria can be set in variable fashion, depending on the market position of the vehicle and manufacturer, and are specified in relation to the target design state for a vehicle in the vehicle technical specifications. These limits directly

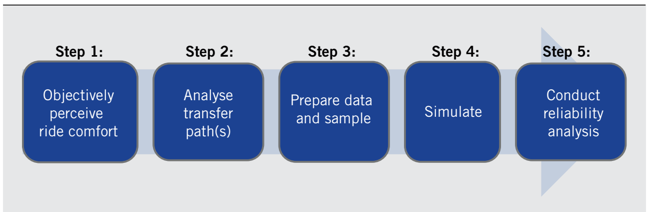


FIGURE 3 Five steps for simulating ride comfort reliability

correlate with the levels of tolerable acceptance on the part of the vehicle occupants and are routinely validated with customers. In the context of reliability engineering, exceeding the defined limits can be viewed as an active occurrence of the phenomenon and compromise the overall operative function of the vehicle as a result.

4.1.2 TRANSFER PATH ANALYSIS

Within the confines of traditional reliability engineering, the durability of the overall system hinges on the reliability performance of each individual component. Those combinations of component failures that can cause the overall system to fail are depicted in a Boolean model [3]. Due to the complex interactions between the components, however, a comfort phenomenon cannot be represented at the overall vehicle level using the classic Boolean theory. Constellations can be conceived whereby the requirements defined for vibrational response are maintained even though the individual components perform outside the window of tolerance specified. This is the case when degradation effects mutually oppose, or counteract, each other. Conducting a transfer path analysis can prove beneficial in this regard, as it allows the process by which the vibration phenomenon starts to be traced and analysed. In this scenario, a detailed transfer path analysis was conducted by experts and validated using trial-testing vehicles. A simplified version is illustrated in **FIGURE 4**. The transfer path maps the chain of events from the point at which road vibrations occur and are transmitted to the seat. Road bumps place the wheels of a vehicle in a state of vibration. The wheels then transfer these vibrations via the wheel carriers and steering guide assemblies to the suspension struts and from there on to the body up to the seat. The longitudinal members also act as a transfer path that connects with the engine mountings and the engine and transmission assembly. These vibrations are likewise routed along the body to the seat and are perceived there by the vehicle occupant. At this time, not only the dampers and damper head bearings, but also the suspension mountings and seat respond to minimise vibration levels.

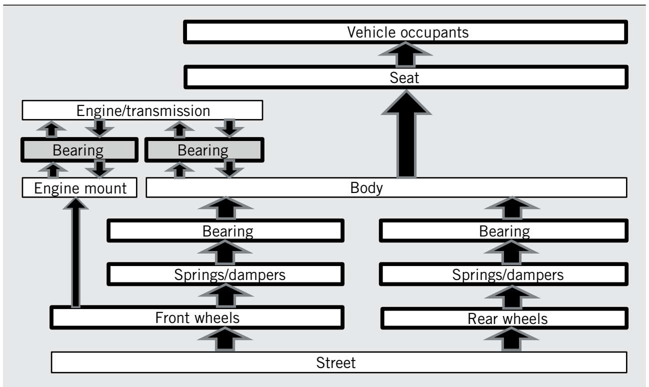


FIGURE 4 Sample transfer path of a vehicle model for the vibration phenomenon

4.1.3 DATA PREPARATION AND SAMPLING

The transfer path analysis also points to the minimum scope of components that must be tested in the simulation model. The response variable, however, still does not exhibit an identical, consistent reaction to a change or modification to the individual componentry and, thus, to its degradation. This is why a sensitivity analysis is conducted by drawing on a design-of-experiments exercise [10], for example, to investigate the effects of each component parameter on the characteristic vibration value. For this purpose, the component parameters are varied individually within a specific window of parameters and the intensity with which they influence the simulation output is analysed. To ensure that the outlay expended on the simulation is also compatible or compliant with future applications, only those components should be degraded in the long-term investigation that are significant with respect to the initial parameters or yield a comparably high level of degradation for less significant relevance. Reducing or restricting focus to critical components also minimises simulation exercise times and reduces the outlay required to accumulate and prepare the output data.

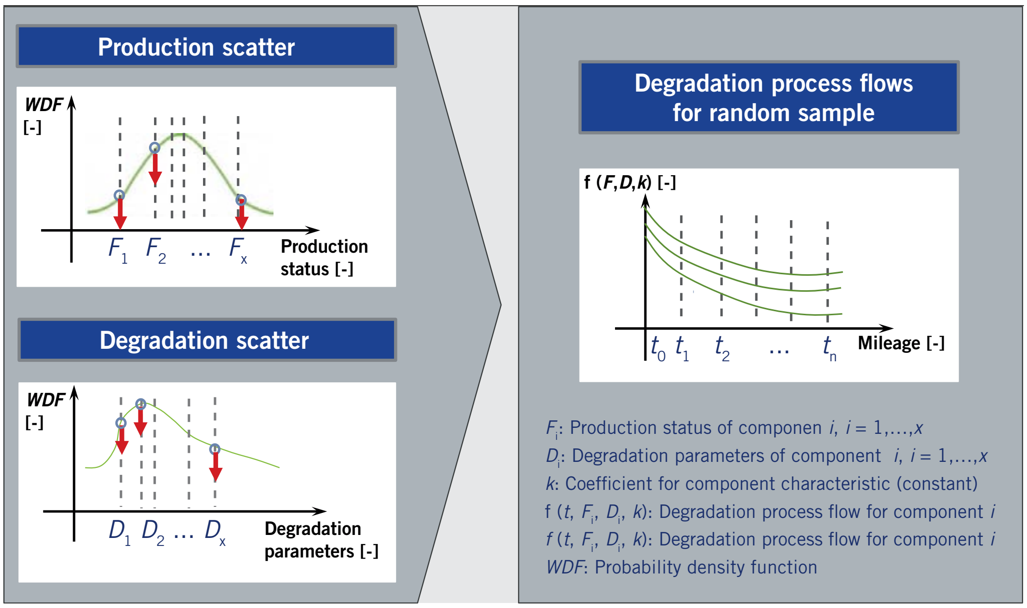


FIGURE 5 Statistical preparation of the input data for a component

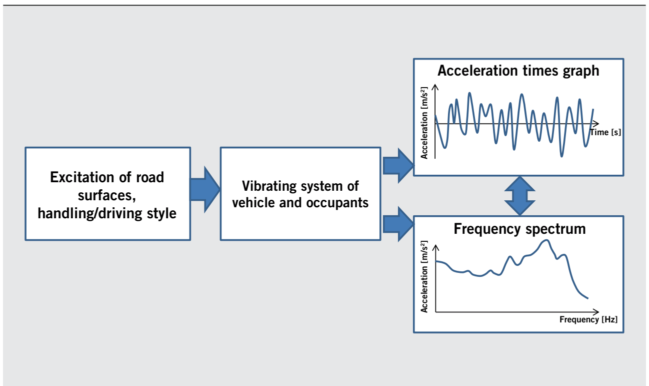


FIGURE 6 Inputs and outputs of the dynamic simulation

When vehicle random checks are carried out during the simulation, the scattering effects associated with the new parts and those that relate to degradation performance are taken into account by way of statistical distributions. In real-world trial testing vehicles, various different combinations of these parameters can be encountered. To map this information accordingly in the simulation exercise, the first step taken is to quantify a random initial state or condition for each component by referring to the distribution that maps the production scatter for the component in question, **FIGURE 5**. This can be a specific parameter such as the static rigidity of an elastomer bearing or a mathematical function such as the characteristic damper curve or dynamic rigidity. The combination of the values extracted characterises the first vehicle targeted by the random sample check. All additional vehicle samples are generated in the same fashion. The second step involves assigning a characteristic degradation curve to each vehicle. Here, too, a random generator is used for this purpose. To this end, statistical distributions must first be defined for the degradation scatter. The result of the sampling process is a digital random sample that accurately represents the physical vehicles.

4.1.4 Simulation An MBS model is typically used to simulate shaking and vibrational response [11]. The vehicle samples generated serve as input data in this context, **FIGURE 6**. As carrying out a dynamic simulation that spans the entire lifecycle of the vehicle is still unrealistic at present, a limited number of time windows is simulated for the random sample as permitted by available computing power, and the incremental progressions are quantified by applying regression techniques. Vibrational excitation is characterised in amplitude trend displays that are derived from plotting a road surface that offers typical levels of vibration or an amplitude spectrum of stochastically generated signals. The simulation output at any respective point in time is initially depicted in a trend display for the acceleration exhibited at the seat which, via the fast Fourier transform algorithm, can transition to a frequency spectrum that quantifies the acceleration level with respect to the given frequency [12]. The target characteristic vibration value can then be determined based on this spectrum.

4.1.5 RELIABILITY ANALYSIS

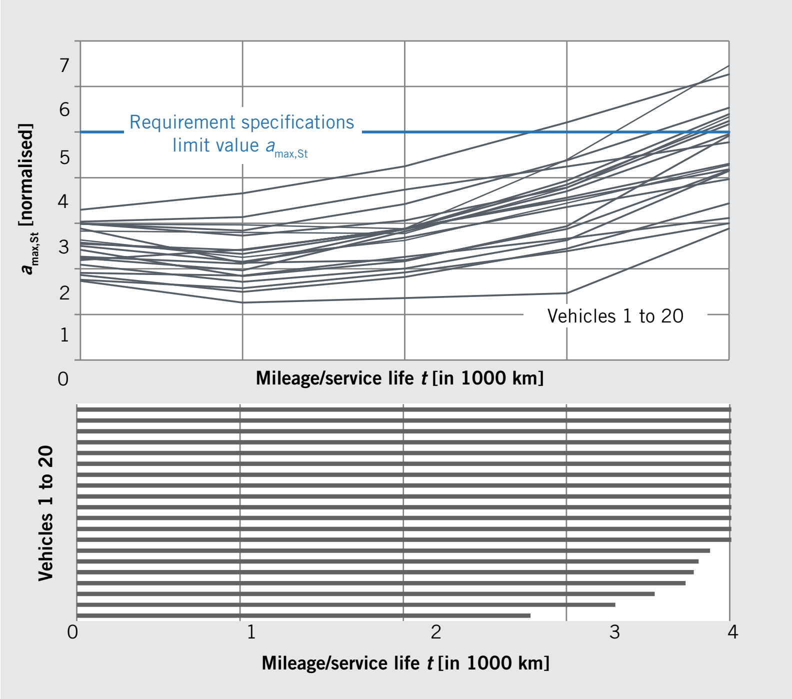
The reliability analysis for the vibration phenomenon is depicted in the following section by referring to a simulation exercise carried out for the current S-Class. In fact, the vibration phenomenon did not reach the described vehicle specifications limit carried out during the analysis of the observed mileage. The resulting high reliability is given by the fact that the simulation was based on already near-series, optimised components. However, to demonstrate the application of the method in the practical example, the limit has been changed so that failures were recorded. This allows a theoretical replication of a previous stage of development. The following remarks and conclusions are based on the reduced value.

The characteristic vibration value determined from the acceleration frequency spectrum is normalised across a vehicle mileage figure of 300,000 km in **FIGURE 7**. This value corresponds with the amplitude of the maximum vibrational respectively stuttering acceleration $a_{max,st}$. **FIGURE 8** also shows the normalised limit value (red line) for $a_{max,st}$ as defined in the requirement specification. If an occurrence of the vibration phenomenon is defined as any point in time at which the limit value defined in the requirement specification is initially exceeded, the times of non-compliance can be derived from the intersecting points of the characteristic and limit value curves. These are also plotted in the illustration.

Statistical reliability analyses in the context of mechanical engineering are typically conducted by leveraging the Weibull distribution [3]. In the process, the times of non-compliance are used to determine the Weibull straight line with its shape parameter b and location parameter T. In so doing, the Weibull straight line depicts the characteristic median lines, meaning that 50 % of the non-compliance events occur to the left of the straight line, while the other 50 % are found at the right of this line. The shape parameters of the Weibull distribution indicate the slope of the straight line and thus correlate with the scatter, or spread, of the non-compliance incidents. Location parameter T specifies at which mean or average point in time 63.2 % of the vehicles tested failed. A confidence bound is also generally defined for the Weibull straight line that indicates the percentage of values that lie within the bound.

The dual-parameter Weibull straight line (with 90 % confidence bound) determined for the maximum stuttering acceleration $a_{max, st}$ of the S-Class is depicted in **FIGURE 8**. This line corresponds with a time-censored evaluation, meaning that all incidents of non-compliance that have not yet taken place after a fictitious vehicle lifecycle (here: 300,000 km) has been run through are incorporated as intact units in the non-compliance data analysis. With respect to the random sample this article focuses on, seven incidents of non-compliance were registered over 300,000 km, while three vehicles remained intact throughout this time frame due to their compliant vibrational response.

Shape parameter $b = 7.3$ of the Weibull straight line points to the type of wear-related failures (compare bathtub curve [5]). This was anticipated as such for the ride comfort, as it represents the result of the interactions among and between degrading components. The value $b = 7.3$ also indicates that the non-compliance incidents are all within close proximity to each other. Location parameter $T = 4.5$ lies over the fictitious service life of a vehicle, which is consistent with later failures caused by wear in conjunction with the shape parameter determined. In addition to the shape and location parameters, the Weibull curve can be used to read characteristic service life value B10, which commonly applies to preventive quality assurance. This value is 3.3 and indicates the time by which 10 % of the vehicles (with respect to $a_{max,st}$) have failed, or exhibited non-compliance. In light of the fact that all non-compliance values lay within the confidence bound of the Weibull straight line, it can be con-



Vehicle	04	06	11	13	16	17	20
Failure time t	3.88	3.54	2.78	3.81	3.73	3.78	3.3

FIGURE 7 Failure data for vibration phenomenon

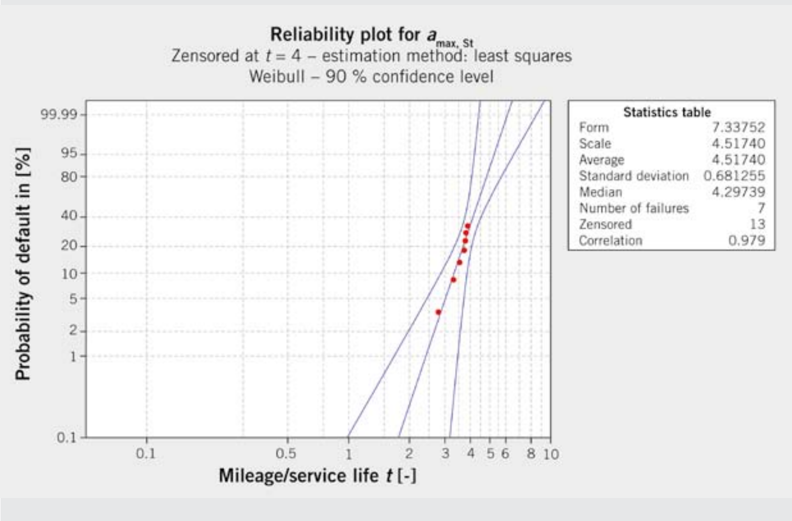


FIGURE 8 Results of the reliability analysis on the vibration phenomenon

cluded that each individual incident of non-compliance reveals the same behavioural pattern. This deduction is supported by the high correlation (98 %) of the non-compliance times with the Weibull straight line. The reliability analysis for the maximum vibrational acceleration $a_{max,st}$ has shown that the non-compliance values simulated correspond to the failure behaviour anticipated for this characteristic value with respect to wear and that the failure incidents only occur when the vehicle has achieved a high mileage figure.

5 SUMMARY AND OUTLOOK

In relation to the target objective of implementing an end-to-end safeguarding process that covers the digital, test stand and street phases, the concept outlined in this article highlights the efficiency potentials that be achieved by implementing digital safeguarding practises to ensure long-term quality. To this end, digital safeguarding makes use of the evaluation criteria that were previously reserved for the physical development phase.

The digital validation process described for safeguarding the reliability of overall vehicle functions such as ride comfort thereby gives rise to trial-testing scopes transitioning from test bench or road-based environments to a digital validation system. This transition process ultimately leads to a reduced number of trial-testing vehicles and, in light of new knowledge obtained during the digital development phase, to a shorter physical or real-world development phase.

The comfort phenomenon analysed merely represents one of the elementary and relevant comfort aspects based on a selected objectivity variable.

It is on this basis that additional comfort phenomena can be analysed and digitally safeguarded in future so that further potentials can be realised.

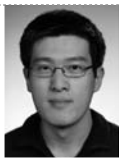
REFERENCES

[1] Breitling, T.; Großmann, T.; Zöller, A.: Digitale Prototypen unterstützen Entwicklung. In: ATZextra (2009), No. 1, pp. 162-171
[2] Wattenberg, K.; Mahler, K.; Wiehe, L.; Breitling, T.; Dragon, L.; Bauer, W.: Ohne Prototypen schneller zum Ziel. In: ATZextra (2012), No. 4, pp. 92-96
[3] Bertsche, B.; Lechner, G.: Zuverlässigkeit im Fahrzeug- und Maschinenbau. Berlin: Springer, 2005
[4] [4] Heißing, B.; Brandl, H. J.: Subjektive Beurteilung des Fahrverhaltens. Vogel, 2002
[5] Koller, O.; Mutter, K.; Uhl, M.; Zeiler, P.; Bertsche, B.: Simulation-Driven Reliability Analysis in Automotive Applications. ARS 2013
[6] Morello, L.: The automotive body. Dordrecht: Springer, 2011
[7] Hieronimus, K.: Anforderungen an Schwingungs- und Akustikberechnungen aus Sicht der Fahrzeugentwicklung. VDI-Bericht Nr. 186, Düsseldorf, 1990
[8] Mitschke, M.; Wallentowitz, H.: Dynamik der Kraftfahrzeuge. Berlin: Springer, 1997
[9] Zeller, P.: Handbuch Fahrzeugakustik. Vieweg & Teubner, 2009
[10] Siebertz, K.; van Bebber, D.; Hochkirchen, T.: Statistische Versuchsplanung: Design of Experiments (DoE). Springer, 2010
[11] Rill, G.; Schaeffer, T.: Grundlagen und Methodik der Mehrkörpersimulation. Vieweg & Teubner, 2010
[12] Jörißen, B.: Objektivierung der menschlichen Schwingungswahrnehmung unter Einfluss realer Fahrbahnanregungen. Duisburg-Essen, Universität, Dissertation, 2012

AUTHORS

Ilka Zöller, M. Sc.
is Scientist in the Research Group for Vehicle Ergonomics, Institute of Ergonomics and Human Factors at the Technische Universität Darmstadt (Germany).

Nicole Mautes, B. Sc.
is Master's Course Student of Mechanical Engineering and Student Assistant at the Institute of Ergonomics & Human Factors at the Technische Universität Darmstadt (Germany).



Wen Ren, M. Sc.
is Master's Course Graduate in Computational Engineering at the Technische Universität Darmstadt (Germany).

Dr.-Ing. Bettina Abendroth
is Research Group Leader for Vehicle Ergonomics and Deputy Manager of the Institute of Ergonomics & Human Factors at the Technische Universität Darmstadt (Germany).

Knowledge Base for Valid Driving Simulation

Driving simulators are being used increasingly as part of the vehicle research. In this regard, the validity of a driving simulator represents a necessary condition in order to facilitate the transfer of the results to reality. The Institute of Ergonomics & Human Factors (IAD) of the Technische Universität Darmstadt addressed this topic of validation of driving simulators, as part of a two-year DFG project.

THE SEAL OF APPROVAL FOR SCIENTIFIC ARTICLES IN ATZ.
ATZ PEER REVIEW
RECEIVED 2014-07-14
REVIEWED 2014-09-10
ACCEPTED 2014-12-09
REVIEWED BY EXPERTS FROM RESEARCH AND INDUSTRY.

1 MOTIVATION

The use of driving simulators as a study environment for driving tests has become a common practice. This is mainly due to the fact that the influence of disturbance variables can be controlled in a driving simulator [1] and a secure testing environment is ensured for the subjects [2]. Nevertheless, a simulated test environment has certain disadvantages too. Driving simulators can never reflect the reality to 100 % [3]. To examine if the results obtained in a driving simulator are all the same transferable to reality, it is necessary to validate the driving simulator. The aspects of validity can be differentiated into two [4, 5], namely into physical and behavioural correspondence. Physical correspondence describes the differences in the physical characteristics and the external form between the driving simulator and the real vehicle, whereas the behavioural correspondence refers to the balancing of the driver behaviour in simulated and real investigation environment and is assumed to be present, provided that no statistically significant difference exists [6].

2 BENCHMARKS FOR SELECTED DESIGN PARAMETERS

There is a range of different driving simulators, which are different with regard to their design parameters. The equipment quality contributes directly to the physical validity [7]. In the literature, there are benchmarks for each of the parameters which are presented as excerpts in the following. What is particularly important is the visual perception. The horizontal viewing angle (field of view, FOV) affects visual perception significantly. According to [8] an angle of 50° horizontally is acceptable as the minimum FOV; however, depending on the driving situation, a FOV of 180° may be advisable [9]. For a correct perception of speed, at least 120° is required [10]. The vertical FOV plays a lesser role; in this respect, [8] considers 40° to be adequate [9]. The physical validity of a driving simulator, besides the visual, inter alia, is also influenced by the proprioceptive perception. For driving simulators, there are several possibilities of simulating motion, for example hexapod, rail system, turntable, and vibration actuators. A 100-% representation of acceleration in a driving simulator is usually not possible; therefore, it is reduced by a scaling factor. For lateral movements, according to [11], a value of 0.5 to 1.0 and for longitudinal movements the order of less than 0.05 is possible.

The benchmarks presented provide design suggestions for a physically valid driving simulation. The driver behaviour related correspondence is not necessarily achieved by the fact that the components of a driving simulator indicate a high quality and therefore physical reality. In the research, derivation of design recommendations from a driving simulation valid for driver behaviour is mostly yet to be achieved.

3 VALIDITY OF DRIVER BEHAVIOUR AS A RESEARCH FIELD

At the IAD, the question of validity of driver behaviour in driving simulators has been explored in detail. Besides study of the literature, the project included the implementation of new series of investigations in the field and in the simulator as well as ultimately derivation of essential design recommendations for a valid (in the following, the term validity refers to, unless explicitly contradicted, the driver behaviour related correspondence between real und simulated environment of investigation) driving simulation.

The analysis of reference literature shows that are already some studies which are dedicated to the validation of driving simulators [2, 12]. The research efforts to date, however, raise critical points that are essential for further investigation [13]. Validation studies lack a clean methodology and presentation of results. So as to exclude the influence of individual performance requirements, it is important to have recourse to different series of experiments on identical group of subjects; however, this is still absent. In addition, there is often a lack of a complete presentation of the results, together with important statistical test values. Due to this fact, it is hardly possible to compare the findings of different studies. Also, there is a gap with regard to the objectives of the investigations considered in the validation studies. Thus, only two studies are known [13] that examined the suitability of driving simulators as a study environment for functional analysis of driver assistance systems. However, this question turns out to be important if particularly for such study objectives mostly experiments are conducted in simulated environment. Also the validation of driving simulators for night driving has rarely been conducted, although under such adverse visibility conditions high accident rates prevail which accordingly results in a need for research.

As part of the project, corresponding driving tests were conducted in the field and in the static IAD driving simulator (180° FOV horizontally, sound simulation, force feedback). It is found that partially valid results can be achieved [14] with a driving simulator of this equipment in investigations under night vision conditions. When testing critical braking manoeuvres with active brake intervention, however, a static driving simulator has its limitations [15] due to lack of vestibular feedback. In this regard, an acoustic feedback could create a more realistic impression and provide essential stimuli for the perception of the acceleration forces.

Also a systemic study of the influence of independent variables on the validity remained until now largely incomplete. [13] provide an overview of the main influencing factors: task-related and environment-related stress factors and individual conditions of performance. In a study, mostly a specific driving simulator is examined with regard to validity. What remains disregarded is the fact that the individual design components of a driving simulator as well as the investigation scenario have an impact on the results. Accordingly, a study was conducted at IAD, which examined the influence of motion simulation and the FOV horizontally with respect to validity. For this purpose, the dynamic driving simulator belonging to the Fraunhofer IGD was used. The test section consisted of city, highway and rural road passages. In the literature there are already few studies that explore the influence of FOV horizontally or also of motion simulation [10, 16] in more detail. However, a comprehensive study that considers systematically varied both design parameters and also a wide range of validity parameters in various scenarios, is not available till now. Mostly seen was a significant influence of design parameters on the subjective perception of reality of the subjects. The results of the objective characteristics of this study are integrated into the software tool described later and elaborated there systematically.

4 MODEL DEVELOPMENT

From the previous observation, it is not clear how the design parameters affect the driver behaviour and thus the validity depending on a scenario. This will be explained in more detail in the following. **FIGURE 1** shows a model-based analysis of the interdependency between the independent variables of scenario and hardware/software and the dependent variables of action, stress and subjective evaluation. According to the methodology of [17], the validation of a simulator involves a comparison this same dependent variables in the field and in the simulator. The aim of the model is to explain the relationship between dependent and independent variables based on the information processing of humans. The scenario of a driving test series goes down as an environmental variable in the man-machine interaction; it is modelled in the simulator software. The hardware design parameters of the driving simulator pass on this scenario information, for example, about the imaging medium to the human. The human receives the stimuli through his senses and processes them. According to [18] the information processing can be divided into steps of detection, recognition, decision and action. In the processing of information, there is a balancing with the sensory memory as well as the short and long-term memory [19]. In this, there is also a comparison of the stimuli presented in the simulator with reality. This closeness to reality of the simulated environment as perceived by the subject acts indirectly on his decision and action and thus on the validity. This validity aspect can also be referred to as fidelity of a driving simulator [20] and, according to [7], in analogy to driving behavioural validity. At the end of information processing is the action of man. It is directly related to stress [21]. In the area of action as well as in the area of stress, there are various validity parameters that allow a comparison of driver behaviour between the field and the driving simulator and provide evidence for the driver behaviour validity. In addition to action, also the other phases of information processing act on the stress a [1, 22] because they "demand a workload" from the human. The detection leads, on a long-term basis, to a stress in the form of a fatigue effect, since it only involves the direct reception of stimuli by sense organs and does not result in memory balancing or processing. The phases of cognition and decision-making, however, act quickly on the stress. There is also a backlash of the stress on the phase of detection [1], since a high stress affects the stimulus perception negatively seen from a long-term point of view. Besides the human-related effect of action on the stress, there is also a backlash of action on the environment (scenario) as well as the driving simulation itself (hardware). Therefore, the subject can defuse the dangerous situation, for example, by pressing the brake pedal (hardware) in case of a critical rear-end collision and thus influence the scenario. As is evident in this model, the design parameters of the driving simulator (hardware/software) as well as the scenario selection will influence the validity. Therefore, it is important to adapt the design of a driving simulator and its components to the respective target of investigation.

5 SOFTWARE TOOL

The software tool SimuVal was developed at the IAD to provide assistance to researchers in the configuration of a driving simulator, so that it is optimally suitable for the respective target of investigation. Since the optimal form of the design parameters depends on the considered characteristic values as well as the investigation scenario, a guide in the classical sense was out of the question. In order to meet this complexity, the systematised findings were combined into a software tool. The software tool was developed in C++. The tool offers the possibility to systematically look for study results concerning driver behaviour validity through a graphical user interface, to add new entries or modify existing ones, **FIGURE 2**.

6 SUMMARY

In summary, it can be said that the DFG project at IAD has delivered a comprehensive insight into the question of the validity of driver behaviour validity, systematised previous study results in this context, revealed key factors affecting the driver behaviour validity and quantified their effect on a number of validation char-

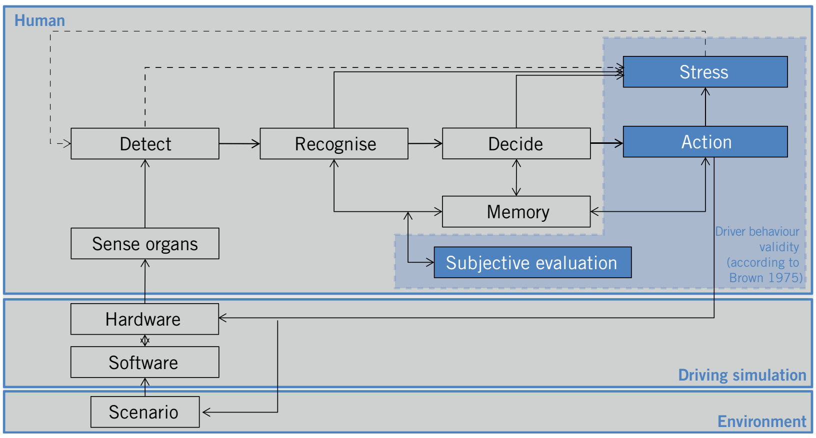


FIGURE 1 Relationships of effect between independent and dependent variables of the driver behaviour validity (solid arrows = short-term effect; dotted arrows = long-term effect)

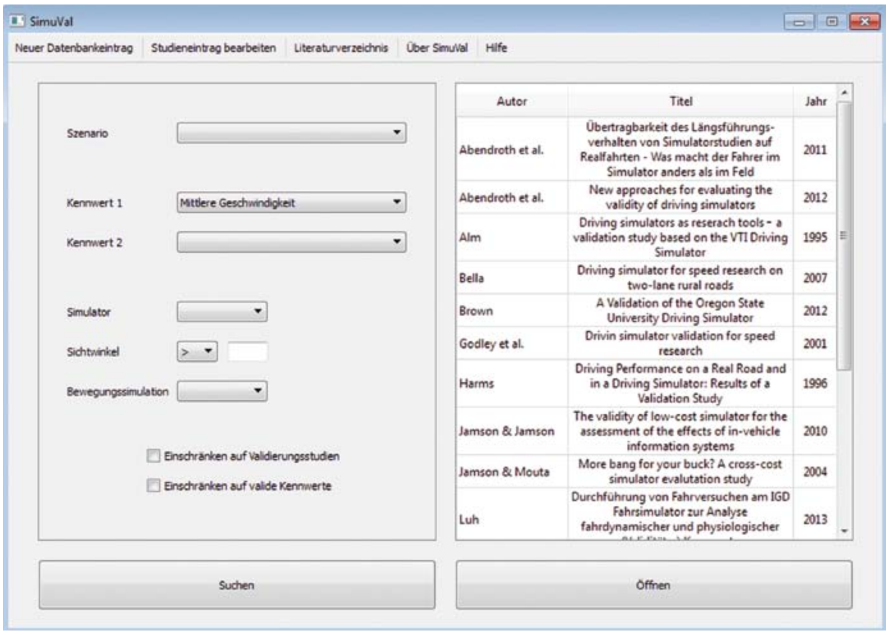


FIGURE 2 Screenshot of the software tool SimuVal

acteristics in the context of a comprehensive study. The results from the trials as well as from the literature are systematically processed in the software tool SimuVal according to the influencing factors and shown graphically to the user.

REFERENCES

[1] Vollrath, M.; Schießl, C.: Belastung und Beanspruchung im Fahrzeug – Anforderungen an Fahrerassistenz. In: VDI-Berichte (2004), No. 1864, pp. 343-360
[2] Blana, E.: Driving simulator validation studies: A literature review. Institute for Transport Studies, University of Leeds, Vol. Working Paper 480, 1996
[3] Knappe, G.: Empirische Untersuchungen zur Querregelung in Fahrsimulatoren. Vergleichbarkeit von Untersuchungsergebnissen und Sensitivität der Messgrößen. Erlangen-Nürnberg, Universität, Dissertation, 2009
[4] Mudd, S.: Assessment of the Fidelity of Dynamic Flight Simulators. In: Human Factors 10 (1986), No. 4, pp. 351-358
[5] McCormick, E.: Human Factors Engineering. New York: McGraw-Hill, 1970
[6] Blaauw, G.: Driving Experience and Task Demands in Simulator and Instrumented Car: A Validation Study. In: Human Factors 24 (1982), No. 4, pp. 473-486
[7] Godley, S.; Fildes, B.; Triggs, T.: Driving simulator validation for speed research. In: Accident Analysis and Prevention 34 (2002), pp. 589-600
[8] Haug, E.: Feasibility study and conceptual design of a national advanced driving simulator. Iowa City: University of Iowa, College of Engineering, Center for Simulation and Design Optimization of Mechanical Systems
[9] Padmos, P.; Milders, M.: Quality criteria for simulator images: A literature review. In: Human Factors 34 (1992), No. 6, pp. 727-748
[10] Jamson, H.: Image characteristics and their effect on driving simulator validity. In: Proceedings of the International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design (2001), Colorado
[11] Greenberg, J.; Blommer, M.: Physical fidelity of driving simulators. In: Handbook of Driving Simulation for Engineering, Medicine, and Psychology, Boca Raton, Florida, CRC Press, 2011
[12] Mullen, N.; Charlton, J.; Devlin, A.; Bédard, M.: Simulator validity: Behaviors observed on the simulator and on the road. In: Handbook of Driving Simulation for Engineering, Medicine, and Psychology, Boca Raton, Florida, CRC Press, 2011
[13] Zöller, I.; Diederich, C.; Abendroth, B.; Bruder, R.: Fahrsimulatorvalidität – Systematisierung und quantitative Analyse bisheriger Forschungen. In: Zeitschrift für Arbeitswissenschaft 67 (2013), No. 4, pp. 197-206
[14] Zöller, I.; Yang, N.; Abendroth, B.; Bruder, R.: Zur Validität des Blickbewegungsverhaltens unter Nachtsichtverhältnissen in einer Fahrsimulatorstudie. In: 60. Kongress der Gesellschaft für Arbeitswissenschaft, 12-14 March 2014, Munich
[15] Zöller, I.; Betz, A.; Mautes, N.; Scholz, L.; Abendroth, B.; Bruder, R.; Winner, H.: Valid representation of a highly dynamic collision avoidance scenario in a driving simulator. In: Transportation Research Part F [accepted for publication]
[16] Colombet, F.; Reymond, D. M. G.; Pere, C.; Merienne, F.; Kemeny, A.: Motion cueing: What is the impact on the driver's behavior? In: Proceedings Driving Simulator Conference (2008), pp. 171-182
[17] Brown, J.: Visual elements in flight simulator. In: Report of Working Group 34 (1975), Washington DC: Committee on Vision, Assembly of Behavioural and Sociel Sciences. National Research Council, National Academy of Sciences
[18] Luczak, H.: Untersuchungen informatorischer Belastung und Beanspruchung des Menschen. Darmstadt, TU, Dissertation, 1975
[19] Schlick, C. M.; Bruder, R.; Luczak, H.: Arbeitswissenschaft. Heidelberg: Springer, 2010
[20] Blana, E.; Golias, J.: Differences between vehicle lateral displacement on the road and in a fixed-base simulator. In: Human Factors 44 (2002), No. 2, pp. 303-313
[21] Rohmert, W.: Das Belastungs-Beanspruchungs-Konzept. In: Zeitschrift für Arbeitswissenschaft 38 (1984), No. 4, pp. 193-200
[22] Handschmann, W.; Voss, M.: Informationsaufnahme und -verarbeitung durch den Kraftfahrzeugführer. Teil 2: Beanspruchung durch Informationsbelastung. In: ATZ 81 (1979), No. 2, pp. 67-70

THANKS

The authors would like to thank the Institute of Automotive Engineering of Technische Universität Darmstadt (Professor Hermann Winner) and the Fraunhofer Institute for Computer Graphics Research (IGD) in Darmstadt (Professor André Stork) for providing the test vehicle and the driving simulator respectively within the DFG project Determination and Quantification of Design Features of a Realistic Driving Simulation.