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DESIGN of Electric Vehicles with Reduced Background Noise

NEW Roof Concept for the Porsche 911 Convertible

CONSUMPTION Reduction of Commercial Vehicles by Aerodynamics

LIFE CYCLE ASSESSMENTS FOR CARS

Springer Vieweg

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LIFE CYCLE ASSESSMENTS FOR CARS

4, 10 I From the perspective of a life cycle assessment, the growing popularity of alternative powertrains and their electric motors is shifting a large proportion of the vehicle's emissions from the use phase to production and recycling. An electric car itself produces virtually zero exhaust emissions. At Volkswagen, the implementation of a life cycle concept is the basic precondition for the targeted execution of eco-friendly vehicle development. At BMW, life cycle analyses make it possible to achieve a better assessment of the materials and components used.

COVER STORY

DEVELOPMENT

RESEARCH

RUBRICS I SERVICE

CLOSE TO THE WIND

Dear Reader,

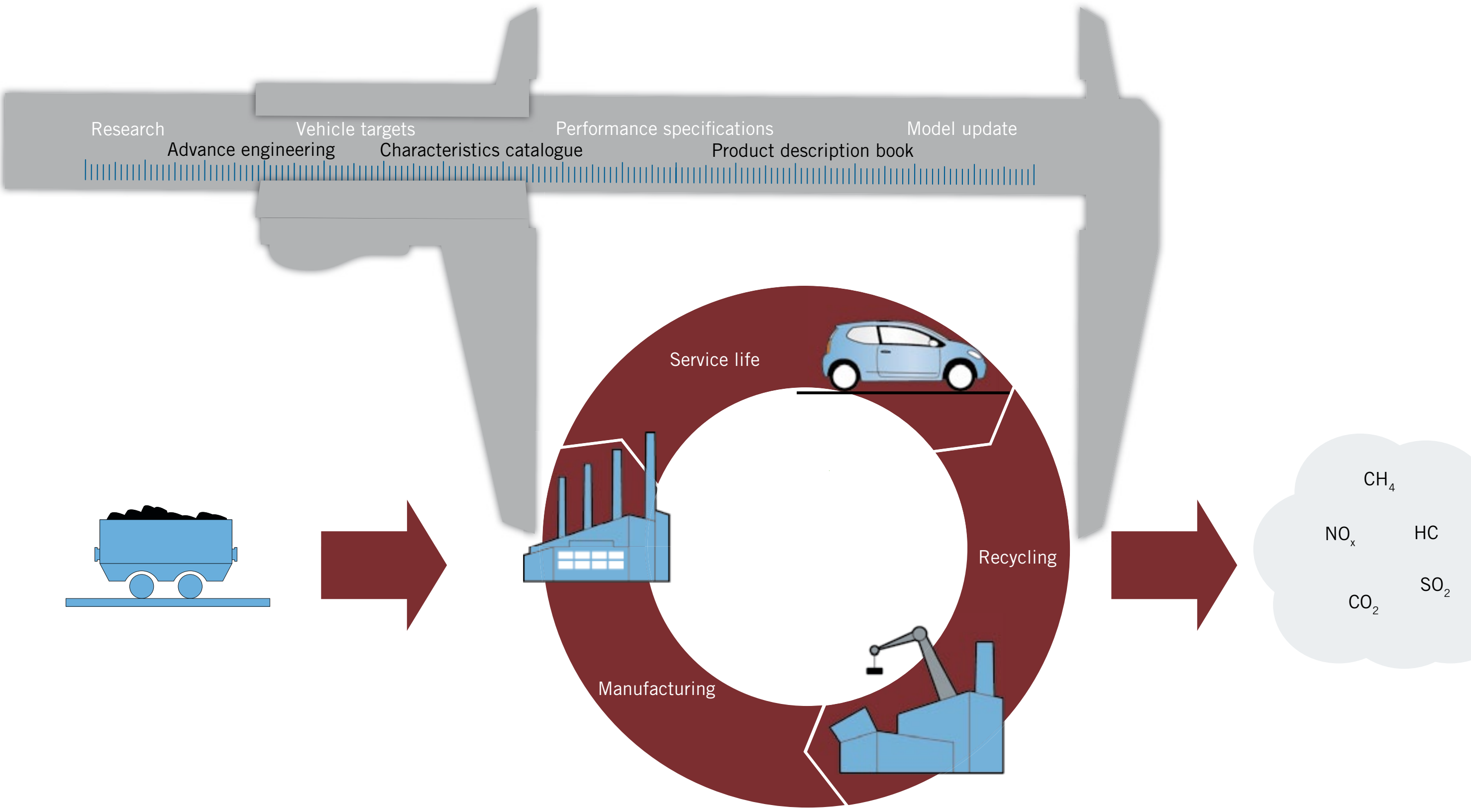
When a new captain steps onto the bridge of a flagship like ATZ/MTZ, he is met with curiosity and high expectations. The previous captains, Wolfgang Siebenpfeiffer and Johannes Winterhagen, steered ATZ/MTZ onto an excellent course, keeping it well ahead of its competitors. The aim is to consolidate this course and further extend our lead. In doing so, ATZ/MTZ must never merely follow developments but must always act from a leading position. Its objective is not only to include new topics in its portfolio and to focus on the latest developments, both in domestic brands and among importers. It also has to further develop the electronic availability of our media, which is one of the greatest challenges of the immediate future. Our editorial team will be working extremely hard to ensure that ATZ/MTZ, ATZelektronik and ATZproduktion continue to have an outstanding presence as electronic media.

Innovation is not an end in itself but is a cocktail of quality and continuity, with a dash of enthusiasm for everything new and garnished with a tasty slice of "esprit". A sense of proportion is called for, because a development can only lead to success if it is based on what has already been accomplished. The recipe must therefore be a well-balanced one, with a blend of subtle tastes that whet your appetite for more. You may have noticed that I love cooking, especially Italian food. Applied to a magazine, this means that the readers must above all enjoy what they are reading and gain benefit from it. ATZ/MTZ has always understood how to do this in an excellent manner, and the new digital contents at "Springer für Professionals" will soon be offering even more information and topicality.

Accompanying automotive and engine technology and the very latest electronic developments in a journalistic form means being constantly open to innovation. There are few industries that are developing and changing so rapidly. At present, this sector is dominated by environmental and transport policy issues. But beyond this, we must never forget the sheer fascination that comes from cars and their technology. Only with a generous portion of "petrol in our blood" we will be able to continue sailing close to the wind – and therefore go faster than the rest.

Best regards,

DR. ALEXANDER HEINTZEL, Editor in Chief
Wiesbaden, 4 June 2012



THE LIFE CYCLE APPROACH AT VOLKSWAGEN

Although reduced fuel consumption is an important priority, it is just one side of a larger coin. Environmentally sustainable vehicle development is a comprehensive task that demands a holistic approach. From the outset, appropriate tools must be made available. For Volkswagen, the tool of choice is the life cycle assessment. This assessment of the entire product life cycle focuses on more than just driving emissions, thus helping the company to achieve the environmental targets that it has set itself.

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MOTIVATION

The car industry is facing new challenges. It must not only make its cars ever more comfortable, faster and safer, but must at the same time improve their environmental performance. In the past, this was usually achieved by reductions in fuel consumption (and, correspondingly, emissions) during the service life of the vehicle.

Today, reduced vehicle emissions and fuel consumption remain an important priority. However, the development of sustainable mobility requires a more comprehensive approach. After all, a vehicle begins to generate environmental impacts long before the customer first drives it. The raw materials from which it is built first have to be extracted, and production materials and components have to be manufactured. These are processes that take place long before a new car eventually takes to the road.

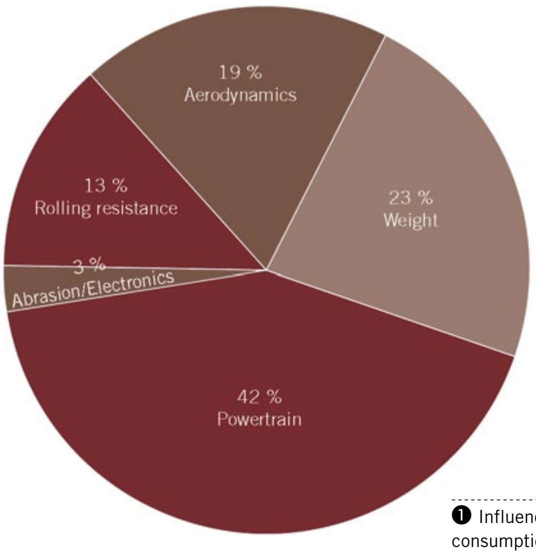
Therefore, efforts to minimise the environmental impacts of the vehicle must focus on the entire product life cycle. This means that the potential environmental impacts of new vehicles, components and materials must be assessed before they have even left the drawing board, looking at all aspects from the initial concept and design sketches to the production process, subsequent vehicle operation and recycling.

Since these different phases are interdependent and interrelated, they cannot and should not be considered in isolation. For example, fuel consumption is affected to a significant extent by the weight of the vehicle, ❶, as defined in the production phase, while high-quality recycling systems generate secondary raw materials for the manufacturing process. A life cycle perspective is therefore key to environmentally sustainable vehicle development. The tool chosen by Volkswagen to implement this approach is the life cycle assessment (LCA) in line with ISO standards 14040 and 14044 [1, 2]. Life cycle assessments allow the company to identify those areas in which improvements will have maximum effect, and to prioritise its innovations accordingly.

IMPLEMENTATION AND INTEGRATION

The life cycle assessment methodology was first developed thirty years ago, and since then the technique has been practised in many different product fields. Volkswagen has been performing LCAs aimed at optimising its products and processes ever since the early 1990s. As early as 1996, the company was the first carmaker to prepare a life cycle inventory (LCI) for the Golf III and to publish it [3]. In the following years, LCIs have been published for various vehicles of the Volkswagen Group [4–7].

That said, implementing and integrating a life cycle perspective into corporate processes on a regular, permanent basis remains a highly challenging task. The key success factors on the way to a successful transformation are:



❶ Influence of vehicle-related variables on fuel consumption (based on Golf VI BlueMotion)

: integration into company policy and processes
: reasonable timeframes
: reliable and quantifiable product development targets
: development of a communication strategy.

ENVIRONMENTAL STRATEGY AND GOALS

The biggest environmental challenges facing the automotive sector are climate change, health/air quality and sustainable resource use. These three areas have therefore been incorporated into the environmental goals for product development at the Volkswagen brand.

The aim of environmental management at Volkswagen is to continuously improve the environmental performance of the company's vehicles. The aim is therefore to develop each new model in such a way that it represents an improvement in environmental performance over the full life cycle compared to the relevant reference vehicle or predecessor model. Thus, the ongoing improvement of our vehicle fleet in terms of environmental impacts and resource conservation forms an integral part of Volkswagen's corporate policy.

INTEGRATION PROCESS

Environmental protection and sustainable mobility must be incorporated into company policy on a regular, permanent basis. Environmental protection is therefore designated as a Group-wide function at Volkswagen. At the same time, the relevant roles and responsibilities are not just confined to upper-level management but are also exercised by many other employees at various hierarchical levels and locations. For example, every Volkswagen site has its own Environmental Officer, with clearly defined functions. The Environmental Officer's tasks are closely focused on reducing emissions, on ensuring the best possible use of resources and on continuously refining and developing the environmental management tools.

To support these efforts, Volkswagen has developed an environmental management structure under which responsibility for the integration of environmental criteria into product development for the Volkswagen brand is borne by the Environment Officer Product.

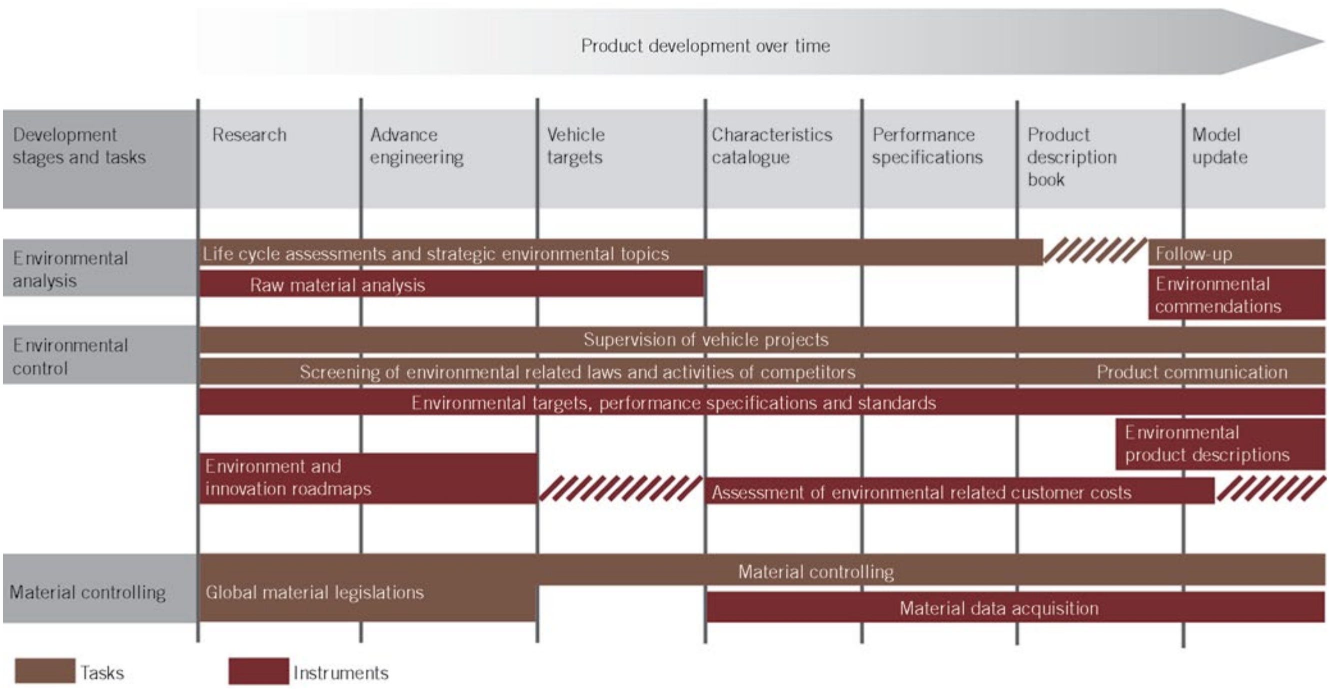
The environmental criteria cut across all stages of the product life cycle. ❷ shows the various environmentally relevant tasks and instruments across the product development process. As the diagram shows, they span all phases of the development process, from research through to mid-cycle facelifts.

REASONABLE TIMEFRAMES

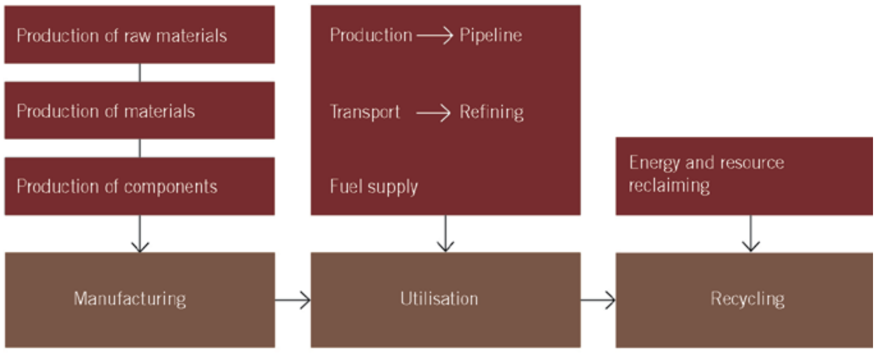
The purpose of a life cycle assessment – not just at Volkswagen – is to analyse and assess in detail all the data on energy consumption, emissions and the other environmental impacts generated during the production of vehicles or technologies and/or during related processes. Preparing an LCA for a complete vehicle involves collecting data for thousands and thousands of parts, as well as for the related upstream supply chains and processes.

Also, bearing in mind that all the components used in the manufacture of a vehicle in turn consist of numerous sub-components and materials, and are manufactured using many different processes – processes that in turn consume energy, consumables and other inputs – one begins to get some sense of the complexity of the LCA modelling process, and the amount of work and time it requires, ❸.

In order to reduce the workload involved, in 2007 Volkswagen introduced the so-called Slim-LCI interface system [8], an automated process which not only significantly reduced the workload required for complete-vehicle LCA modelling, but



❷ Life cycle instruments in the vehicle development process



❸ System boundaries

also further improved the consistency and quality of the results.

RELIABLE AND QUANTIFIABLE TARGETS

One of the major challenges for environmentally sustainable product development based on a life cycle approach is the need to integrate two different worlds or perspectives: that of the LCA modelling expert, who profiles the environmental performance of the product, and that of the engineer who develops the products and technical solutions that actually impact the environment.

The life cycle assessment is an environmental management tool whose methodology delivers scientifically based results, for example the calculation of a carbon footprint for a specific component, or the calculation of comparative footprints for a number of different technologies. In order to integrate the LCA methodology and its results into an environmental management system, it is necessary to translate the results into technical goals. The goals must be expressed in a form that is sufficiently specific and concrete to allow an engineer or planner to apply them to a particular concrete project, even if he/she has no specific knowledge of life cycle assessments and their underlying methodology. Typical examples of LCA-derived goals include a maximum weight for a given component made from a given combination of materials, or the use of particularly efficient production and processing methods for given materials.

COMMUNICATION STRATEGY

In order to publicise the progress being made in developing environmentally compatible vehicles, the Volkswagen brand developed a communication tool known as "Environmental Commendations" (see www.environmental-commendations.com.de). Environmental Commendations document ecological progress in a vehicle or technology in direct comparison with predecessor models and technologies. Volkswagen uses these Environmental Commendations to inform its customers, shareholders and other stakeholders about its successes in developing environmentally friendly vehicles, and how it achieved them.

For this communication to be credible, it is important that, in addition to being transparent, readily comparable and verifiable, the findings and evaluations in the LCAs match up to internationally recognised quality standards. To ensure this, the LCA results are reviewed, verified and certified by independent experts (for example the TÜV technical inspectorate) in line with the requirements of ISO 14040.

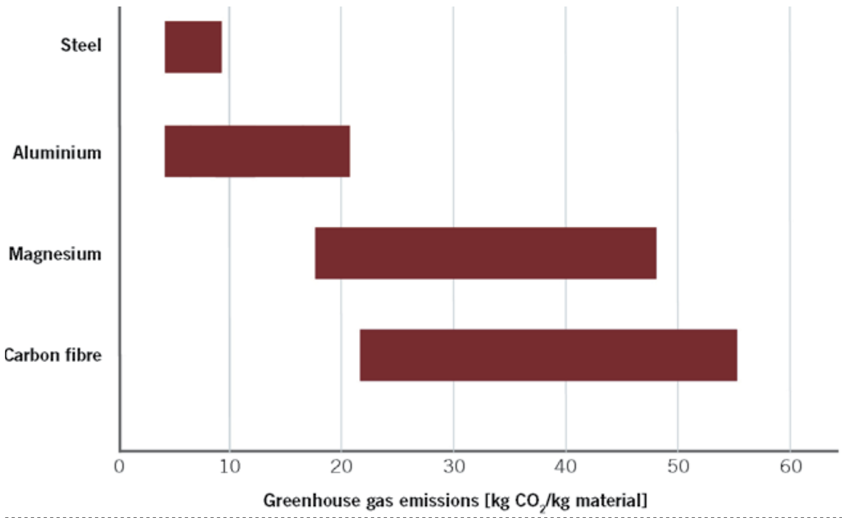
INTELLIGENT LIGHTWEIGHT DESIGN AS AN EXAMPLE

Any steps to influence the environmental impact of the various vehicle-related variables must begin by ascertaining the relative potential of these variables. For example, one of the factors with the biggest influence on fuel consumption is vehicle weight. On average, this factor is responsible for roughly a quarter of fuel consumption, ①. One focus of environmentally sustainable product development is therefore on research and development of lightweight bodies.

Although normally both traditional lightweight materials, such as aluminium and magnesium, and newer materials such as carbon fibre, have more energy- and CO_2-intensive production processes than steel, ❹, it is nevertheless not possible to make general claims along the lines that "material A is always better than or always worse than material B".

Whether a lightweight design measure does actually reduce total life cycle greenhouse gas impact or not depends on further factors, such as:

: the size of the weight saving achieved by use of the materials in question, or of material-adapted design
: whether powertrain modifications can be implemented
: the scope for deriving secondary materials from the end-of-life vehicle.



❹ CO_2 profiles of different materials

Basically, increased CO_2 emissions for lightweight materials and concepts at the manufacturing stage must be outweighed as early as possible by the resulting weight-induced fuel savings in the service-life phase. Only if the earliest possible environmental break-even point is achieved can one speak of "intelligent" lightweight design, ❺.

The use of different materials, resulting in differences in component design and reduced space requirements, can offer potential for developing new improvement strategies – for example involving powertrain modifications. In practice however, it may turn out that one and the same lightweight design measure may allow powertrain modifications to be made on vehicle A but not on vehicle B. Therefore, lightweight design measures must always be considered in the context of the complete vehicle, and not from the perspective of a single component.

One potential action area for reducing complete-vehicle CO_2 emissions is materials manufacturing. The materials manufacturing stage offers the opportunity to reduce specific energy consumption per kg of material produced, for example by using renewable energy sources. The use of secondary materials in particular can help to reduce environmental impacts. For example, some cast aluminium alloys may use up to 90 % recycled aluminium.

On the process side, important measures include the use of climate-friendly shielding gases as a replacement for sulphur hexafluoride, or reducing the amount of metal scrap. In the service-life phase, fuel-efficient vehicle design measures should then be complemented and maximised by fuel economy training for drivers. Finally, at the recycling stage, reprocessing of lightweight materials into high-quality secondary raw materials can increase the scope for use of such materials, with associated benefits for the environment.

EXAMPLE HOT FORMING

One example of successfully applied intelligent lightweight design and environmentally sustainable vehicle development is hot forming of high-strength steels. The technical objective is to produce components that use less material but have the same or even higher strength than components produced using conventionally formed materials. Reduced consumption of materials conserves resources and allows significant weight savings to be achieved, combined with an increase in strength. The low-alloy, specially coated metal is heated to a temperature of around 900 °C, then simultaneously cooled and formed. It follows that hot forming is far more energy-intensive than a conventional forming process, ❻. On the other hand, the reduction in the amount of material used significantly reduces the environmental impacts from the extraction of raw materials, production of manufacturing materials and production of the vehicle itself. At the same time, hot forming also significantly reduces the weight of the complete vehicle. These weight savings allow various types of environmental impact to be reduced over the vehicle life cycle as a whole.

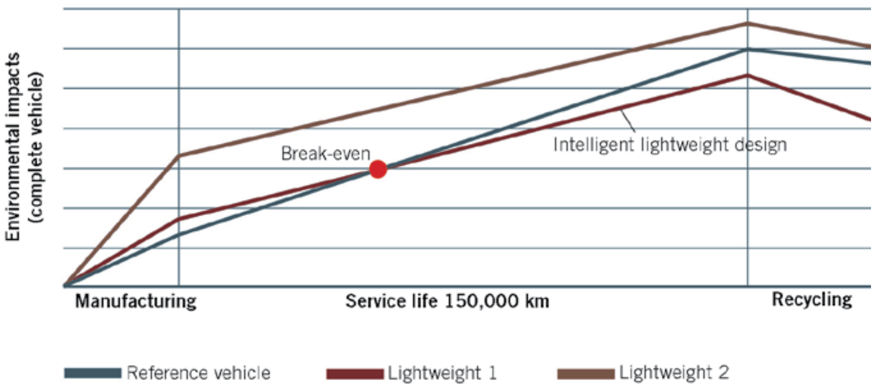
In the context of the total vehicle life cycle, hot forming is the only lightweight design technique which starts paying dividends as soon as the vehicle takes to the road, with substantial potential fuel savings over the course of the service-life phase.

SUSTAINABLE POWERTRAIN CONCEPTS

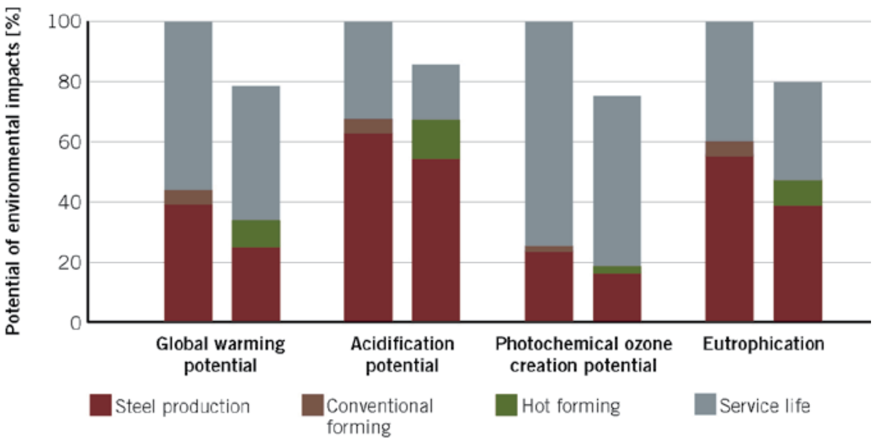
The environmentally sustainable product development measures described above can be applied not only in the production of vehicles and vehicle components but also in the assessment of upstream energy chains and thus in the strategic planning of powertrain and fuel concepts.

A tool for analysing the complete range of environmental impacts attributable to vehicle use is the "well-to-wheel analysis". The well-to-wheel analysis recognises that the efficiency of a vehicle powertrain is not determined just by the efficiency of the engine or motor. Accordingly, it looks at the entire energy chain from resource to road.

Analysis of the well-to-wheel energy chain is taking on increasing significance in the light of resource depletion and the increasing diversity of available powertrains and fuel types.



❺ Environmental impacts of different lightweight design concepts



❻ Environmental impacts of forming processes

One example are Volkswagen's electric vehicles, whose carbon footprints can already be accurately predicted using this technique. That said, a well-to-wheel analysis for battery electric vehicles, for example, is much more complex than for petrol- or diesel-powered vehicles, given that regional factors have a bigger influence on CO_2 and energy footprints for electricity production than for fuel production. For battery-powered electric vehicles, various different regional electricity mixes are therefore taken into account. Sometimes, if operated on a largely fossil fuel-based electricity mix, an electric vehicle can produce higher CO_2 emissions than, say, a petrol-engined vehicle. Well-to-wheel analyses are therefore an appropriate tool for making the environmental performance of (alternative) powertrains and their primary energy sources measurable and strategically plannable [9].

CONCLUSIONS

A life cycle perspective is a key requirement for targeted and effective environmentally sustainable vehicle development. As Volkswagen could demonstrate with the aid of the examples before, the life cycle assessment based on ISO 14040/44 provides an appropriate environmental management tool for quantifying and evaluating the product development process with regard to environmental impacts across the full life cycle of the vehicle. An important requirement for successful use of the LCA tool is that its results must be translated into clear goals and targets for the design engineers.

Only through the translation of LCA findings into quantifiable targets and into practical actions will the life cycle assessments produce genuine environmental benefits. Such benefits can be achieved even for highly complex products made from a wide range of raw materials. Even for a highly complex value chain, the LCA can produce high-quality results in a reasonable timeframe, allowing this methodology to be integrated efficiently into business processes.

Also important for the implementation of life cycle-based product development is the integration of this approach into the company's overall goals. Embedding this thinking into the relevant business processes allows environmentally sustainable product development to be implemented throughout the different sectors of the company and along the entire value chain.

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ENERGY AND SUSTAINABILITY ASPECTS OF DRIVE SYSTEMS

Electric mobility is on the way towards consolidating its place as an established form of mobility in the future. Given the appropriate contextual conditions, with a holistic approach geared to sustainability and good integration into a renewable energy supply system, it offers numerous benefits. According to research by BMW, conventional mobility will, however, continue to be secure in its existence in the long term due to the many benefits that a hydrocarbon-based energy supply has to offer.

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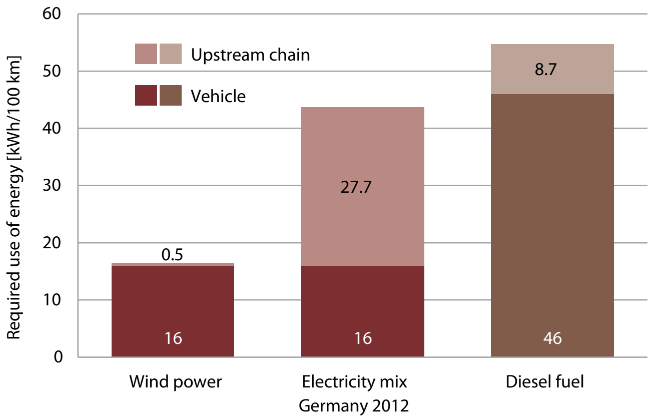
BACKGROUND

The first battery electric vehicles (BEVs) with a plausible claim to series production maturity are currently arriving on the market. The spectrum of reports so far has ranged from overwhelming euphoria at the prospects for the rapid and revolutionary replacement of conventional drive systems to concerns being raised that the electric car is in fact an ecologically senseless consumer of carbon-based power. These reactions are often isolated analyses and do not arise from consideration of the context as a whole.

Electric mobility is, however, a brand new type of transport system that merits and requires a multifaceted analysis. This contribution puts forward some intentionally simple comparative analyses on the energy balance, the tie-in with the energy supply system, and the eco balance in order to identify the basic differences between electric mobility and conventional mobility (internal combustion engine, fossil fuels).

ENERGY REQUIREMENT

In a simplified analysis, a conventional vehicle and a BEV require approximately the same amount of drive power to over-



❶ Comparison of energy requirement for electric mobility to conventional mobility

come driving resistance. The required use of energy in both systems differs significantly due to the difference in conversion efficiency between these types of vehicle. On the assumption that the respective vehicle is a generic C-segment reference vehicle as defined in [1], the BEV requires approximately 16 kWh of energy per 100 km. An equivalent diesel-engined car needs almost three times as much energy, at 46 kWh, produced by diesel fuel (corresponds to 4.6 l). This is because the thermodynamic energy conversion process takes place in the internal combustion engine inside the vehicle, ❶.

Added to this is the energy expended in the energy supply processes in the upstream chains: for electricity, in the power plant and grid; for fuel, during crude oil extraction, transport, refinement and distribution. In the case of fuel, this proportion of approximately 19 % is surprisingly low. This is an initial indication of the benefits and high efficiency of the hydrocarbon-based infrastructure.

Given the high proportion of thermal power stations and their thermodynamic losses, the electricity mix for BEVs entails a very significant proportion of energy use in the upstream chain, the effect of which is that overall energy consumption is brought roughly into alignment with that of the conventional vehicle. Electricity generated from renewable energy sources, such as wind power or photovoltaic (PV) systems, incurs only small transmission and distribution losses, making this the most favourable situation overall.

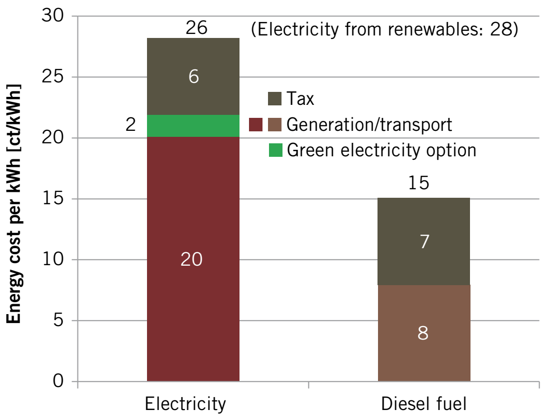
On the cost side and before taxes, the kilowatt hour electricity – the "more refined" energy form – is approximately 2.5 times more expensive than diesel (Germany), ❷ (left). The same is essentially true of green electricity, thanks to the remarkably low mark-up of only around 2 ct/kWh. Before tax, the costs per distance of the BEV and diesel car are more or less equal due to the higher energy requirement, ② (right).

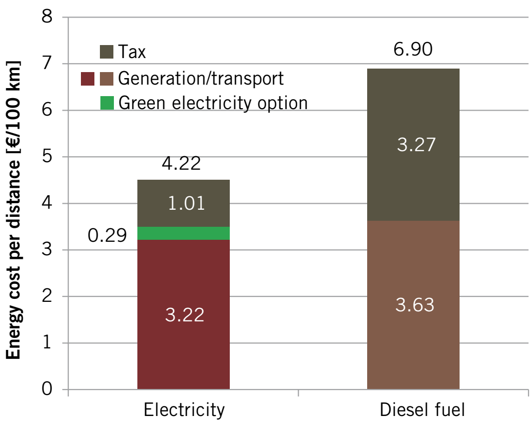
ENERGY AND FUEL SUPPLIES

When we consider the input of energy into the vehicle, we use as our reference one of the many and practically all-accessible filling stations. An average filling station in Germany fills approximately 250 vehicles each day and turns over around 11 m³ of fuel [2], which equates to a "driving distance" of approximately four times around the Earth. The filling technology used is compatible with vehicles from mopeds to HGVs, and is prevalent and available worldwide. A single refuelling process takes only 1 to 2 min and the calorific value flow from the dispensing hose corresponds to 15 MW (PV) to 90 MW (truck) compared with the modest 3 to 8 kW standard charging power of BEVs, ❸.

The filling station has a reserve of over 120 m³ (at approximately 1.1 GWh, this is equivalent to the capacity of the average pumped-storage power station) and decouples the refuelling process from a continuous supply, which considerably increases the robustness of the overall system. All of these properties and possibilities are owed to the high energy density of liquid fuels, which has been central to cars, the supply network and usage potential for 125 years.

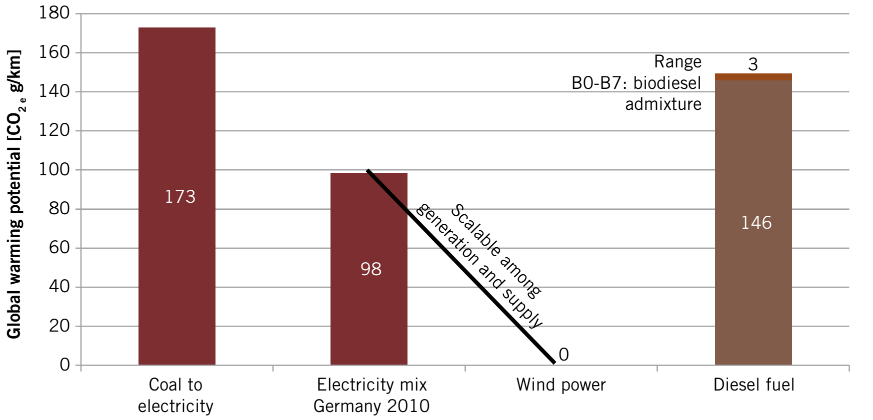
If we wanted to implement the same ratios achieved by the filling station mentioned before in the world of electric mobility and to achieve the same ranges, it would be necessary to charge (as a rough estimate) 1,000 BEVs per 0,5 h each with 50 kW DC at approximately 40 charging stations, making a total of 2 MW. This would be rather problematic to put into practice because of required space and infrastructure integration.





❷ Energy costs per kWh (left) and distance (right) comparing electricity and diesel fuel

❸ Power comparison between conventional refuelling and electric recharging



❹ Greenhouse gas emissions in comparison – electric mobility compared to conventional diesel fuel mobility

As far as energy production is concerned, even large BEV populations would not have a critical impact on the energy supply side. Ten million BEVs would generate only around 3 % extra demand. The provision of power presents a considerably greater challenge because there must be practically 100 % balancing of generation and load everywhere in the grid at all times due to the lack of comparable buffers otherwise available in the liquid fuel system. Preventing overloads and grid instability are the most demanding requirements for grid managers.

The spatially distributed charging in households as predominantly anticipated charging locations is one of the first solutions to arise and, for the customer as well, represents a fundamentally new way of interacting with the vehicle. The trip to the filling station becomes superfluous and, with automated wireless charging systems (presented in conceptual form in various funded projects in 2011 [3]), the vehicle can charge itself at home. This results in a brand new quality of use that, at least partly, compensates for the long charging times and limited ranges.

CO_2 BALANCE IN VEHICLE USE

While fuel customers have only limited scope to make an impact on the overall CO_2 chain as part of fuel standards and compatibility, BEV customers, particularly in liberalised electricity markets, have various opportunities to exert influence over the origin of the power they consume and make a significant impact on the CO_2 footprint of their individual motoring profile. Depending on the assumptions relating to supply, the following situations arise, ❹:

: 173 g/km on the assumption that the use of electricity from renewable sources is already prioritised and that the extra demand from electric mobility is met by inexpensive carbon-based power.
: 98 g/km based on the electricity mix in Germany in 2010 assuming that, physically, all consumers take from the "grey energy pool". The mix improves with the structural change of the electricity sector, with a renewable electricity share of 20 % today compared with 66 % forecast for 2030 [4].
: 0 g/km in the case of renewable generation that can be dedicated specifically to electric mobility demand or resulting from the use of wind and photovoltaic power that cannot otherwise be fed into the grid.

All of these views are valid. The collective interest of customers, OEMs and energy suppliers in terms of the sustainable establishment of electric mobility must be to aim for relevance to the third point through the formation of conducive background operating conditions.

For customers, green energy products, ideally in conjunction with demand-oriented system expansion, become attractive in view of very low mark-ups as a means of ensuring "CO_2 = zero" in the context of the closed usage/origin relationship.

The purposeful use of today's wind energy surpluses, which are also expected to increase considerably in the future – dynamic wind power expansion, worldwide approximately +27 % a year in

❺ Via process optimisation and use of renewable energy: 50 % lower global warming potential in the production process compared to conventional CFRP production

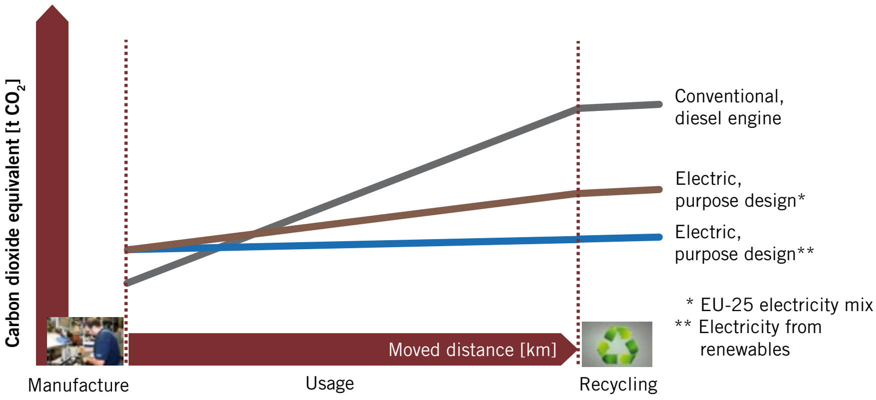
2005 to 2010 – is another option in this context. The concept of a managed charging strategy whereby electric car charging takes place in the wind-power-abundant and low-load hours of night has already proven successful [3]. With the amount of wind-based electricity already available today and as control criteria has remained simple, the share of wind-generated electricity in the charging current mix has increased by 40 %.

Another completely new opportunity for customers is the possibility to run their vehicle on electricity that they have generated at home. Of the million and more energy feed-in systems installed in Germany, approximately 87 % of <30 kW systems are mostly private PV installations no further than 80 km from the nearest major urban centre [evaluations of data from 5]. It can therefore be deduced that hundreds of thousands of systems would already be suitable for running a vehicle partly or completely self-sufficiently if charging took place in the daytime or if electricity for night-time charges were buffered by the home energy management system. With increased use of self-generated electricity under existing feed-in tariff incentive schemes, the customer is presented with attractive options to reduce running costs.

SUSTAINABILITY ASSESSMENT OVER THE ENTIRE LIFE CYCLE

Measuring the environmental impacts of a vehicle or drive concept over the entire life cycle makes it possible to apply the methodology of life cycle engineering. This procedure for life cycle assessments (LCA, ISO 14040/44) encompasses every stage of manufacture (including the entire upstream chain of suppliers through to raw material extraction), use by the customer and end-of-life recycling. All impacts in the environmental impact categories, for example global warming potential (t CO_2 equivalent), are measured with this technique.

Applying this methodology as early as the concept phase is an established part of the sustainability strategy of the BMW Group. It provides transparency throughout all life cycle phases and processes (cradle to grave). In this way, evaluation of the materials and components employed can be used as a basis for actively influencing decision-makers in manufacturing, for example as regards the origin of materials, process optimisation measures, use of secondary material and renewable energy in the manufacturing process. Target values for all life cycle phases are entrenched in the development process.



❻ Vehicle comparison of the global warming potential over the entire life cycle

A notable difference between the life cycle of an electric vehicle and that of a car with a conventional drivetrain is the additional energy expended in the manufacture of the battery pack and the effect of increased energy consumption due to the additional weight.

In the case of electric vehicles, a distinction can be made between two concepts: “purpose design”, where vehicle concepts are designed purely with the focus on electric mobility; and “conversion design”, where concepts are adapted and based on conventional vehicles.

Purpose design makes it possible to compensate for the additional weight of the battery pack by means of an optimised concept and selective use of lightweight materials.

The higher greenhouse emissions caused by the manufacture of lightweight materials, for example carbon-fibre reinforced plastic (CFRP), can be significantly reduced by process optimisation and the use of renewable energy in manufacturing, ❺.

A comparison between a diesel-engined vehicle and an electric vehicle (purpose design) over the entire life cycle shows that global warming potential is reduced by approximately one third, ❻.

Where electrical energy from a renewable source is also utilised in the usage phase, it is possible to achieve a further reduction in global warming potential to 50 %.

SUMMARY

There is therefore a distinct polarity between the conventional hydrocarbon-based transport system, with the tremendous benefits that make it indispensable for many motoring purposes in the long term, and the electrically powered approach, which, although it has its limitations, offers new and essential opportunities for sustainable mobility.

These can be identified if one looks at electric mobility in the overall context of a new energy landscape that adapts to many of the core applications, such as commuter and city traffic, and pushes the main limitations into the background. Hydrogen-fuel-cell vehicles may deliver long ranges and fast refuelling to the electric mobility market in the future but, in the meantime, plug-in hybrids or range-extender BEVs will bridge the gap to the “old world”, which will continue to exist for many motoring needs.

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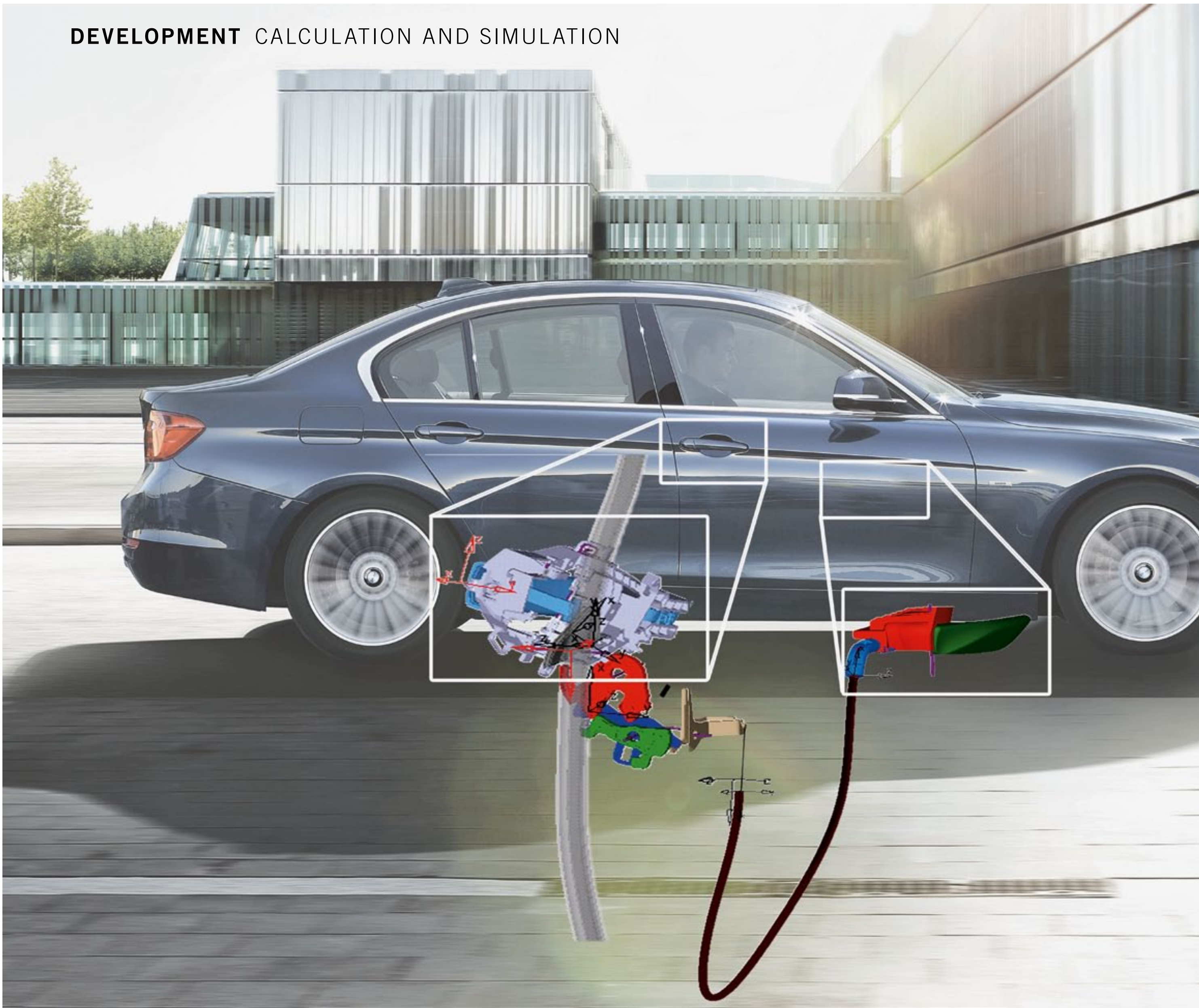

SIMULATION OF BOWDEN CABLES IN THE VIRTUAL ENTIRE VEHICLE

Due to their physical behaviour, Bowden cables pose a particular challenge for simulation technology. In the context of today's product development process at BMW, a lot of issues are discussed by means of virtual vehicles. In most cases flexible parts like hoses, cables and Bowden cables are still simulated as rigid parts. Thereby their forms are deviating from the real ones in some extent. In a joint project BMW and ITI could design a simulation of Bowden cables for the scenarios opening of a bonnet and release of a door lock reflecting the physical behaviour of these parts in a realistic way.

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BEHAVIOUR OF A BOWDEN CABLE

Although Bowden cables are all around in today's vehicles, they remain unnoticed by the user most of the time. A Bowden cable (according to DIN 71986 [1]) is a type of flexible cable used to transmit mechanical movement or (pulling) force by the flexible moveable combination of an inner cable relatively to a hollow outer cable housing. The housing is generally of composite construction, consisting of a helical steel wire, often lined with plastic, and with a plastic outer sheath [2]. The inner cable is most commonly made of steel or stainless steel.

The definition in [2] reveals that the behaviour of Bowden cables is highly dependent on the effective direction. Inside today's cars as well as future ones there are a lot of mechanisms using Bowden cables. Most of them are optically imperceptible by the customer. The following enumeration contains selected applications of Bowden cables in vehicles of the BMW Group:

: release of the bonnet
: release of the door locks by inner and outer door handle
: shift cable to the transmission
: folding down the front seats' backrests in two-door vehicles
: window lift inside the doors
: remote release of the rear seats' backrests.

Despite fundamental similarities between these applications, there is a multitude of varying parameters concerning the Bowden cable itself as well as its structural and functional boundary conditions. For example, Bowden cables can be distinguished by the type of winding. The two most common types have either a gently or a steeply rising winding (the so-called Shimano Bowden cables). Another possibility is the classification by pulling cable or pushing sheath, that means by effective direction [3, 4].

BMW and ITI describe here two application scenarios of different mechanisms handled by Bowden cables and their realisation with the help of the system simulation software SimulationX from ITI. Particular characteristics and their implementation into appropriate models are exemplified for both scenarios.

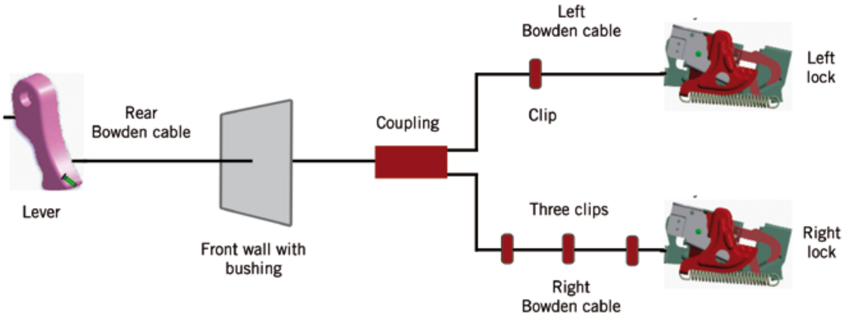
OBJECTIVES OF SIMULATION

The simulation has to show not only the quasi-static form and rest position of the balanced Bowden cable in the coordinate system of the vehicle, but also the forces applied when the user operates the related mechanism. These forces in turn cause changes in form and position of the Bowden cable.

For an accurate projection several aspects need to be taken into account. The model computes the position of the Bowden cable depending on its given length, the clip positions for the anchorage to the body as well as the required acting forces. Furthermore, the friction between the inner cable and the covering sheath is considered in dependence of tensile strength, friction coefficient and curvature radius.

The location of the maximum curvature and its corresponding wrap angle are just as calculated as the forces that are necessary to release a lock or actuate any other mechanism. The simulated changes in form and position can not only be visualised in SimulationX' 3D view, but also transferred into a 3D CAD system.

Of course, the acceptance of simulation results is strongly connected to a comparison to measurements taken from hardware. This was an important aspect when choosing the suitable scenarios that will be explained in the following section. In the first one the opening of a bonnet is described while this is done in the second scenario for the release of a door lock via inner and outer door handles.



❶ Schematic drawing of the Bowden cables for releasing the bonnet

APPLICATION SCENARIO 1: OPENING OF A BONNET

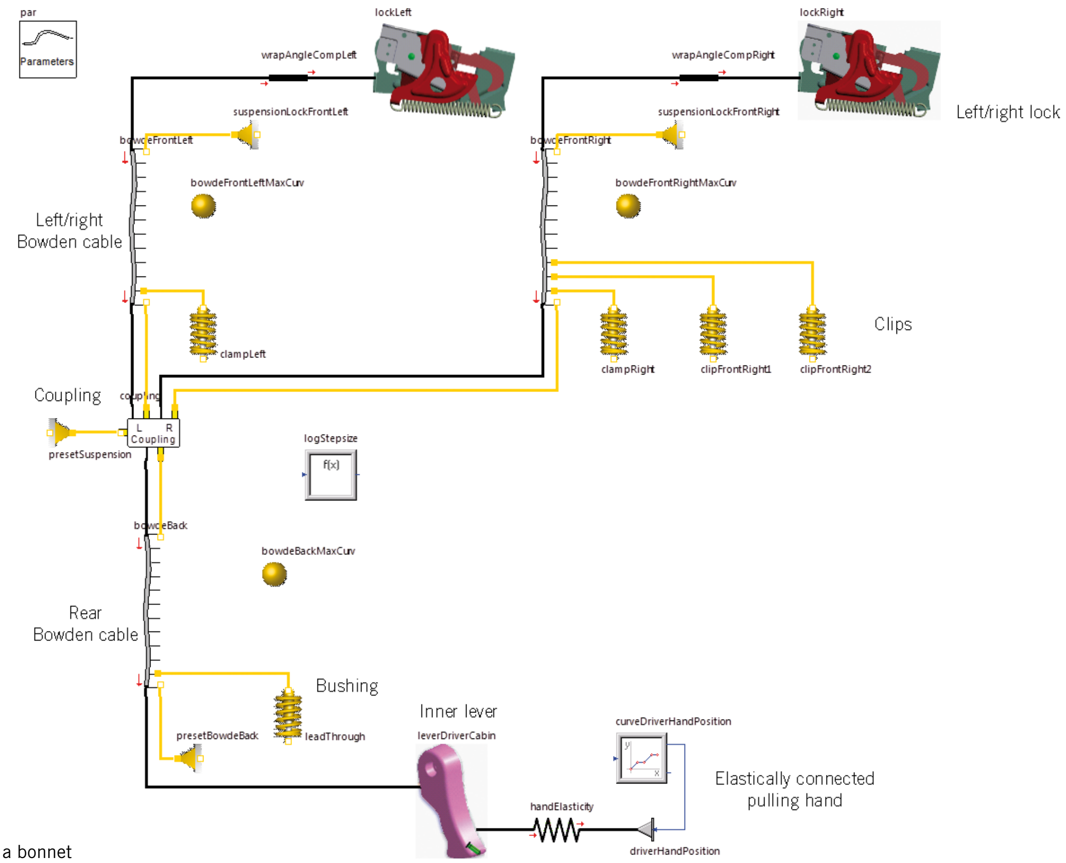
To open the bonnet or front lid, the driver pulls a lever in the leg area beneath the A pillar. The rear Bowden cable, which penetrates the front wall in a bushing, transfers the opening force to a coupling. Two additional front Bowden cables (left and right) connect the coupling with the lock, mounted per clips. This relationship is illustrated schematically in ❶.

In this first scenario, each bonnet lock is represented by a behaviour model based on a single element in SimulationX. Splitting the specific functional parts like pawl and rotary latch is realised not until in the second scenario.

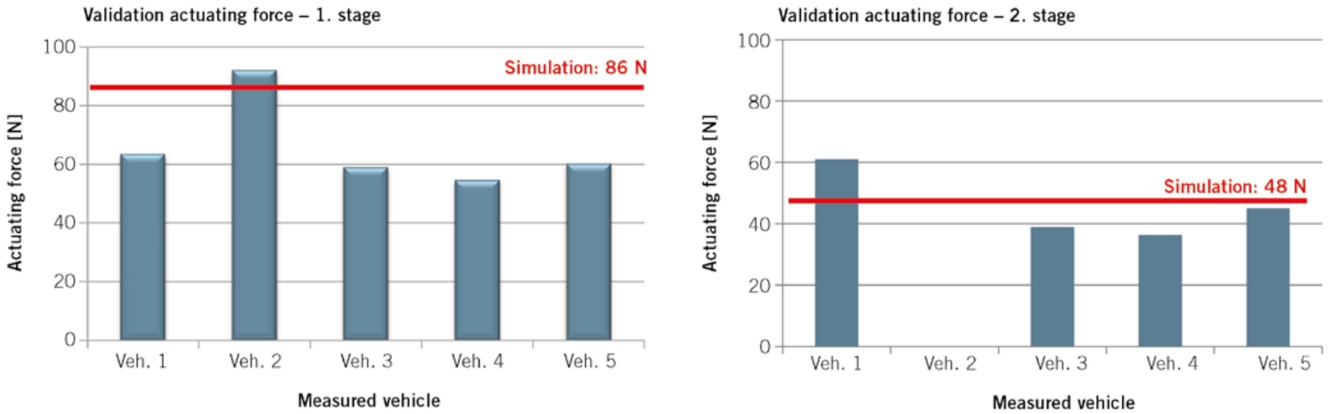
The clips that keep the Bowden cables in place are modelled using spring-damper elements from the multi-body systems library. The set point of a curve element describing the driver's hand position and actuating force is elastically connected to the lever by a one-dimension spring element. ❷ shows the corresponding structure view of the simulation model that consists of masses, spring-damper elements, transfer functions, coupling and Bowden-cable elements including friction between cable and sheath as well as both locks.

The validation of simulated results by reference to measurements is an essential part of a virtual evaluation. It is the confidence base for further modelling activities.

The opening process of the bonnet locks is done in two stages. Within the simulation a force of up to 86 N is set to reach the first stage and a force of only 48 N to reach the second one. Looking at ❸, one can recognise that each of the results is conform with the measurements to a high degree.



❷ Model built of the release of a bonnet



❸ Comparison of simulation results with measurements for actuating forces in two stages (measured for five BMW vehicles)

APPLICATION SCENARIO 2: RELEASE OF A DOOR LOCK

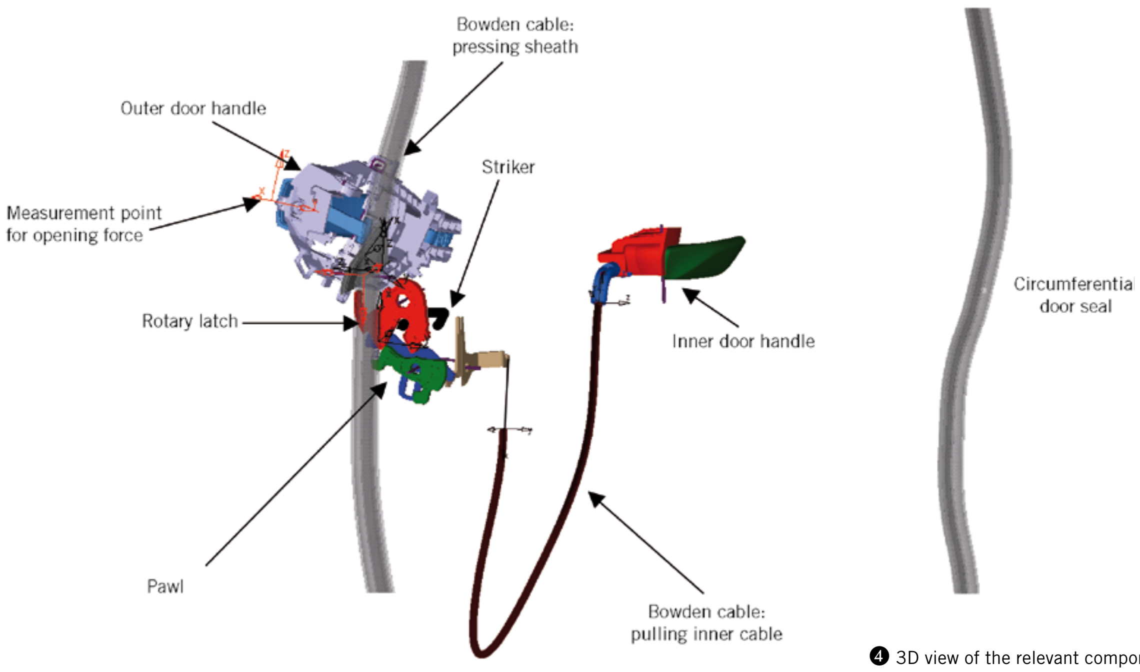
Motivated by the impressive results of the first scenario the level of detail is raised in the second one. Moreover an additional type of Bowden cable comes into play. To open a vehicle door by means of the inner door handle, a Bowden cable with a pulling inner cable is being used similarly to the release of a bonnet lock (compare to scenario 1).

To open a door by the outer door handle, the force is transferred by a Bowden cable with a pushing sheath. The lock is now split into the relevant components like pawl and rotary latch, which are shown in the three-dimensional model view in ❹. Consequently, both standard elements from the multi-body systems library as well as those from the one-dimension mechanics library are combined. As described in the first scenario already, the comparison of simulation and measurement results is an inherent part of the evaluation.

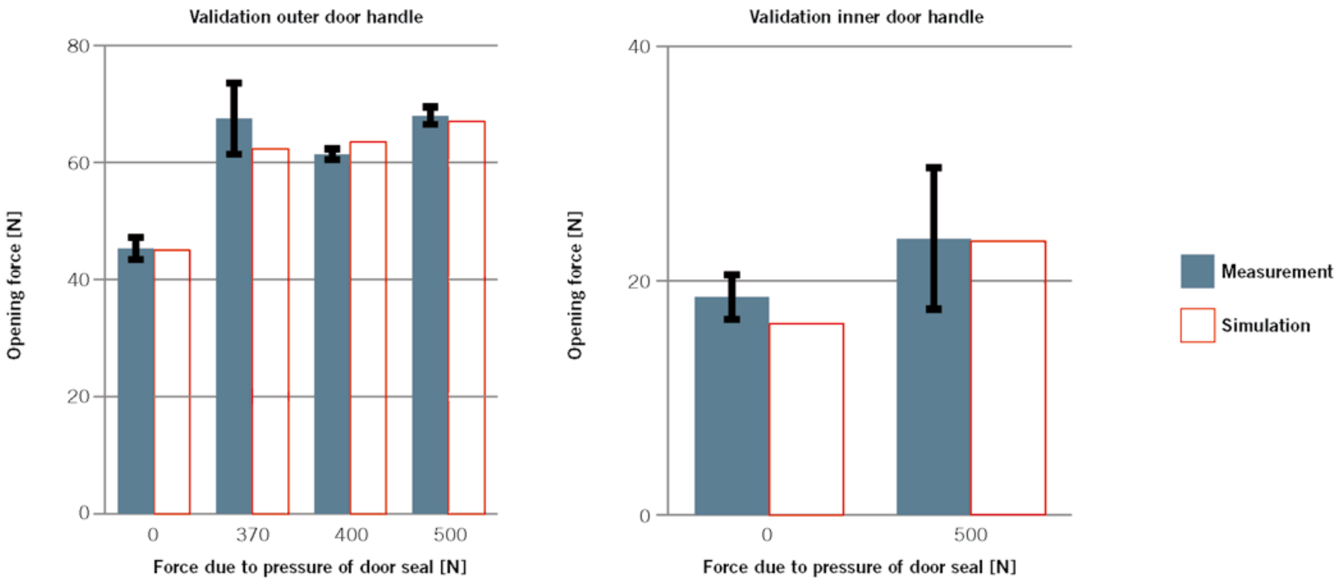
When the vehicle door is locked, the circumferential door seal creates a pressure onto the rotary latch which grasps the striker. The measurements in ❺ of the opening forces were taken for different values of the seal pressure. As this pressure is an important parameter in the simulation model, the opening force can be calculated for every value and both cases – the inner as well as the outer door handle. Although applying two different types of Bowden cables, there is a high correspondence between the simulated and the measured opening forces as recognisable in the confrontation of ⑤.

LAYOUT OF THE SIMULATION

During the project period it became apparent that the simulation time can be shortened to a high degree when the computation is split into two phases.



❹ 3D view of the relevant components to release the vehicle door (starting position: door is closed)



❺ Confrontation of simulation results with measurements for the door opening forces (left: validation for the outer door handle, right: for the inner door handle)

Hence, the results of the pre-simulation are input parameters for the main simulation. The pre-simulation determines the static starting position of the Bowden cables that can be used in many runs of the main simulation.

During the pre-simulation, the form and position of the Bowden cable sheath is being computed without considering the inner cable. Key input data for this part is the dimensions of the Bowden cable like length and diameter, the clip positions (start, end, intermediate) that represent the fixing to the body and the coefficient of friction between inner cable and sheath.

The subsequent main simulation provides the actuation forces, the changes of the Bowden cable's form due to these forces and the time-dependent behaviour of all system components involved.

BMW's expectations towards the deployment of the system simulation software SimulationX based on experiences in the field of finite elements analysis (FEA) and other time consuming simulation methods which often require advanced hardware resources. By contrast, all the scenarios described in this paper can be run on a laptop with a 32-bit operating system. Independently, the advantages of a 64-bit multicore workstation will be investigated in current and future projects.

SUMMARY AND OUTLOOK

In this case study shown by BMW and ITI the development tool SimulationX offers the possibility to map the specific features of Bowden cables to a simulation model, which is very close to reality. This allows BMW to deal with certain issues at a very early stage of development, although there is no hardware available. It is possible to predict the system's behaviour at the early design phase and show the consequences of parameter variations on the handling comfort immediately.

In both scenarios for an opening of a bonnet and a release of a door lock, a high correspondence between simulation results and taken measurements could be achieved. The case study is already of great importance in today's virtual prototype development and will become even more relevant in the future.

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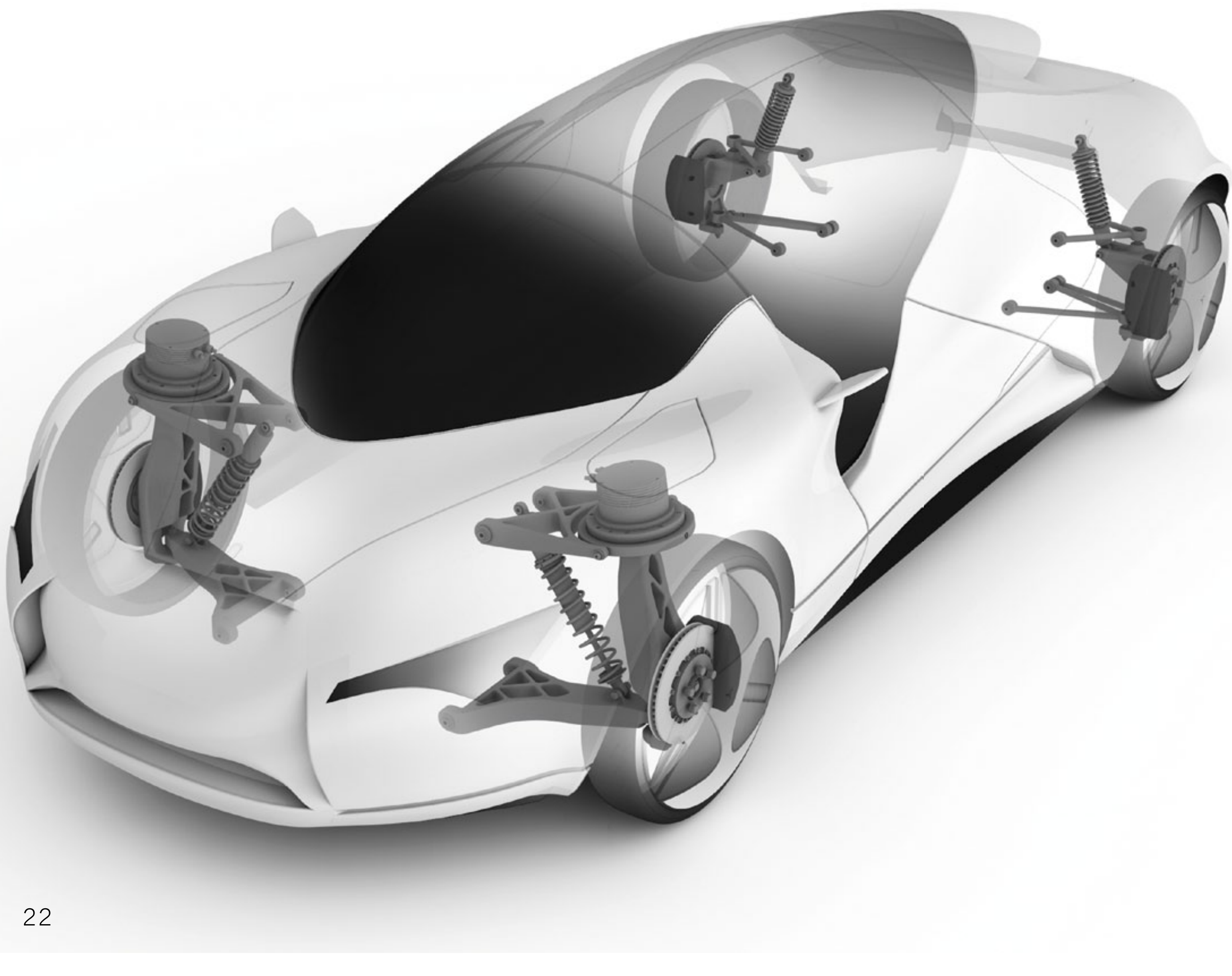
About the Author

He has worked together with international partners to offer numerous seminars preparing students for construction projects abroad.

REAR AXLE LAYOUT FOR THE SPEEDE RESEARCH VEHICLE

For the SpeedE sporty full electric vehicle electric motors positioned near the rear wheels were combined with a steer-by-wire system, which allows high steering angles. To design the rear axle of the three seater optimally the ika at RWTH Aachen University uses the simulation software Aksis, which includes newly developed modules for elasto-kinematics calculation and suspension characteristic optimisation.



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RESEARCH VEHICLE SPEEDE

The Institute for Automotive Engineering (ika) at RWTH Aachen University is currently designing SpeedE, a research platform as a sporty full electric vehicle. The concept combines two electric motors positioned near the rear wheels, an innovative steer-by-wire system controlled by sidesticks and a newly designed front axle allowing exceptionally high steering angles. Together this setup creates a highly manoeuvrable and agile three seater.

During the suspension design process the simulation software Aksis is used among others. Besides the existing functionality for rigid kinematics calculation newly developed modules for elasto-kinematic behaviour determination and automatic suspension optimisation are applied.

By developing the research vehicle SpeedE the ika is advancing a new generation of full electric vehicles. Contrary to earlier drafts the perceivable advantages of electro-mobility are put into the focus of the design process and are aligned with the complex requirements for efficiency and safety.

The concept features innovations such as contactless charging, functional integration of suspension and propulsion systems and revolutionary design of exterior and interior work. The sporty appearing vehicle is the first project of the cooperation between the ika and the School of Design of Pforzheim University. The vehicle accommodates up to three people, with the driver positioned in the centre and in front of the two passengers. The propulsion is realised through two electric motors located near the rear wheels [1].

One focus of the research is the steer-by-wire system of SpeedE, which is made possible by a financial support of the foundation "Hans Hermann Voss Stiftung". The operation of the steering system by the driver is carried out by means of two sidesticks. This type of control system has already been employed successfully in research vehicles [2, 3]. The steering of the wheels is realised using two independent electric actuators, which are integrated into the wheel suspension. This enables large wheel steering angles up to 90° and thus very high manoeuvrability of the vehicle. Additionally, the individual deployment of the wheel steering angles allows innovative functions to increase vehicle safety and efficiency as well as an optimal utilisation of the side force potential of the front axle.

PROBLEM DEFINITION

The foundation of a dynamic as well as safe driving behaviour is, even in combination with modern vehicle control systems, based on the passive set-up of the suspension. Considering the constraints of a powerful rear wheel drive with torque vectoring functionality and centre of gravity position towards the rear of the car, special attention has to be paid to the rear axle layout.

Regarding the kinematics the toe and camber curves are defined after choosing the position of roll and pitch centres. A linear increase of toe-in during bump motion reduces the general tendency towards oversteering of the vehicle. At the same time, toe angle changes during wheel travel must be limited to ensure sufficient directional stability on uneven tracks.

To maximise the forces transmitted by the tyre in longitudinal and lateral directions, the tyre contact patch area must be as large as possible at all times. Thus a progressive increase of negative camber angle in bump motion is desirable to partly compensate the reduction of the contact patch area induced by the roll motion of the vehicle body during cornering. Here, as well, a compromise needs to be found regarding directional stability requirements.

Besides the wheel trajectories the elasto-kinematics, that means the change of wheel alignment due to longitudinal and lateral forces, play an important role while designing the vehicle dynamic characteristics. A tendency towards toe-in at the outer rear wheel in a turn will reduce the oversteering tendency of the vehicle. Under longitudinal braking and propulsion forces only small changes of toe angle are desirable.

CALCULATING RIGID KINEMATICS

Aksis is a software developed by Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka) for calculating rigid kinematics of multi-link independent suspension systems based on the method proposed by Matschinsky in [4]. Mathematically, the suspensions are regarded as five-link systems determining the wheel carrier position. By combining single links to for example a wishbone all established types of independent suspensions from a McPherson strut up to independent multi-link suspensions can be calculated.

The clearly arranged graphical interface design in the basic software allows to easily enter data of any number of axles and to compare their respective properties. Besides a multitude of characteristic values in tabular form it is possible to plot the curves of toe angle, camber angle, track width and roll centre position over wheel travel for several load cases. If spring stiffness are provided the curve of wheel load over wheel travel can be displayed as well.

The very fast computation times allow an immediate display of the impact of parameter changes. This makes it this software a valuable tool especially during early development phases of suspension systems.

The software Aksis has been programmed based on Microsoft Excel. To perform a calculation a license is necessary; the user interface however can be distributed without a license to share calculation results. Additionally, these results can be documented by exporting automatically to a Microsoft Word document.

For the use of the software during the layout of the SpeedE rear axle the tool is extended by two modules. Thus, calculation of elasto-kinematics is introduced and the possibility to optimise suspension characteristics is added.

ELASTO-KINEMATICS MODULE

Using the elasto-kinematics module, it is possible to investigate the response of the suspension system to arbitrary forces and torques at the wheel contact point as well as longitudinal forces at the wheel centre. Initially, the equilibrium of forces and torques at the wheel carrier is set up and the resulting forces at the attachment points are calculated. Considering the provided bushing stiffness allows the determination of the deformation at the attachment points.

Subsequently, the algorithm for the calculation of the rigid kinematics is used to provide the change in wheel alignment. Finally, the equilibrium at the wheel carrier is recalculated. If the error caused by the change of wheel alignment exceeds a certain tolerance threshold, the calculation is repeated. Since the compliance of the attachment points is usually very small, in most cases, a single iteration step is sufficient.

While defining a bushing stiffness, the user may introduce any coordinate system and choose between a linear or non-linear definition. The stiffness can either be specified in three independent directions in space or assume rotational symmetry in radial direction.

OPTIMISATION MODULE

The fast computation times of Aksis qualifies the tool to use it for optimising wheel alignment curves and elasto-kinematic characteristics. When configuring the optimisation problem the user has the option to define the modifiable kinematic points and stiffness, as well as the range in which the parameter can be varied. Additionally the properties that shall be optimised and the corresponding target characteristics are specified. To solve the optimisation problem, the modifiable parameters are varied such that the resulting characteristics match the target as closely as possible. This is done using the optimisation tool "Solver" included in Microsoft Excel.

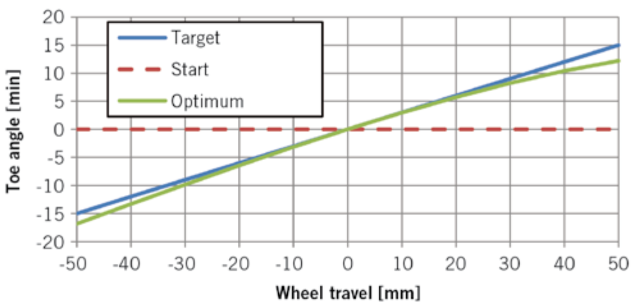
To evaluate the deviation between resulting and target curve the root mean square (RMS) regarding several sample points is determined and used as the quality criterion. If several characteristics are optimised simultaneously, the sum of weighted single RMS values is used.

This method can be used successfully as long as the weighting factors are chosen carefully and not too many properties are optimised at once. Especially with contradicting optimisation targets, this method to reduce the problem to a single criterion reaches its limitations. To allow reliable solutions to these problems, in the future multi-criteria optimisation algorithms shall be implemented.

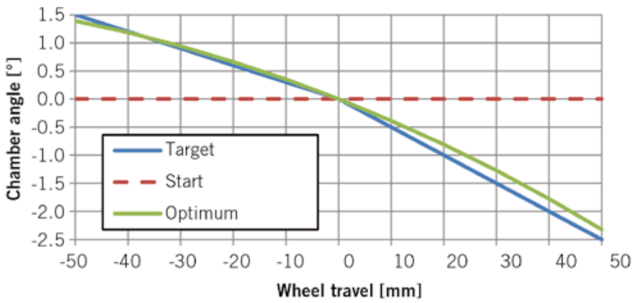
APPLICATION AT THE REAR AXLE DESIGN

The rear axle of the SpeedE, which is driven by two electric motors, is realised as a double wishbone suspension and mounted directly to the body. The concept layout is carried out regarding the relevant wheel alignment curves (here only toe and camber characteristics are displayed) as well as the elasto-kinematic reaction due to longitudinal and lateral forces.

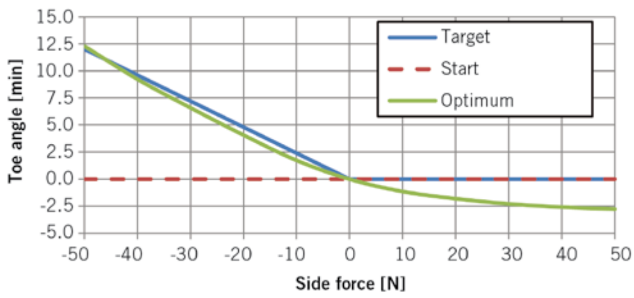
The core design range for the SpeedE wheel alignment characteristics amounts up to ±50 mm wheel travel. Target kinematic characteristics are displayed in ❶ and ❷, target curves of the elasto-kinematic reaction are shown in ❸ and ❹. Additionally a high lateral stiffness of the axle is desired. Furthermore during concept layout roll centre position, track width change as well as anti-dive and anti squat are considered, but cannot be displayed here.



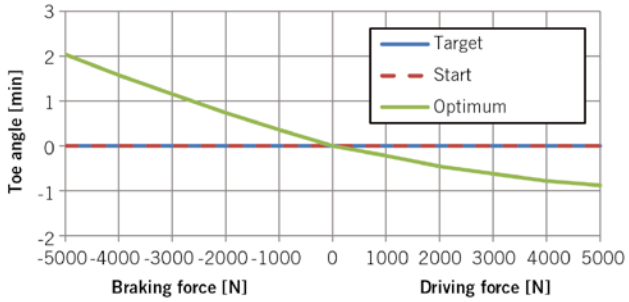
❶ Target kinematic change of toe angle during wheel travel



❷ Target kinematic change of camber angle during wheel travel



❸ Elasto-kinematic change of toe angle under side force



❹ Elasto-kinematic change of toe angle under longitudinal force applied at the contact patch (braking) and wheel centre (driving)

The available design space for the rear axle is derived from the full vehicle packaging plan. Besides the suspension links, body springs and dampers, a stabiliser bar and the drive shafts need to be located within this space. The initial configuration of the axle has two horizontal wishbones of equal length. The tierod is located within the lower wishbone plane.

To optimise the suspension properties an approach in several steps is chosen. In each step one aspect of the characteristic is defined. At first, the inner hard point locations of the wishbones are determined. Within this step the goal is to achieve target roll centre position and camber characteristics during wheel travel while the tierod remains within the lower wishbone plane. During the second step, the lower wishbone plane is rotated around the lateral vehicle axis to adjust anti-dive and anti-squat. Subsequently, the toe characteristic during wheel travel is optimised by varying the inner tierod hard point.

After all hard points are defined, the elasto-kinematic reaction is optimised. This is accomplished in a single step considering all relevant load cases. Bushing stiffness are assumed to be linear with the option to specify asymmetric coefficients for every direction. The final result of the optimisation is also shown in ③ and ④.

SUMMARY AND OUTLOOK

During the development of the research vehicle SpeedE at ika, Aksis, the suspension layout software developed by fka, has been enhanced by two modules to calculate elasto-kinematics and to optimise suspension characteristics. Thus, an effective tool for the preliminary layout for the SpeedE rear axle is available.

Obtaining the hard point positions and bushing stiffness in this way, the layout will be detailed using full vehicle simulations in a next step. In the future, basic investigations and optimisation of full vehicle behaviour is going to be integrated in Aksis.

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DESIGN OF ELECTRIC VEHICLES WITH REDUCED BACKGROUND NOISE

According to statements of politicians, research and industry, e-mobility has got the green light. However, the technical maturity is not yet on an acceptable level in all respects. Apart from the cruising range, which is widely discussed, the focus is on squeak and rattle (S&R). This has, by now, not sufficiently been studied in the context of e-mobility and the lapse of classical powertrain noise. Development service providers such as Bertrandt combine virtual simulation methods with physical test methods to analyse and eliminate annoying noises at an early stage.

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ROLL MOTION, ACTUATION AND WIND SOUND AND THEIR INDIVIDUAL PERCEPTION

The end consumer sets high quality standards for the product. These standards, however, differ from individual to individual. No matter if sub compact or premium car – the customer will judge comfort and quality according to his own definitions.

Driving noise has to match the car according to the customer's individual perception. There is a basic distinction between three kinds of driving noise: roll motion, powertrain and wind sound. They are welcome, as they reflect the car's actual technical condition to the driver. Even the indicator's ticking sound – a so-called functional sound – is being expected inside the car. But as soon as surprising or unknown noise is perceived, this noise is considered unpleasant and disturbing and gives the customer the impression of inferior quality.

E-MOBILITY AS A CHALLENGE

In the first automobiles, S&R was covered by powertrain, roll motion and wind sound. The further cars were developed and optimised, the easier S&R could be heard inside the car. Nowadays, the development of so-called noiseless driving is a central point. The most recent designs, however, do not only focus on reducing annoying noise – they also should reduce probably occurring warranty expenses.

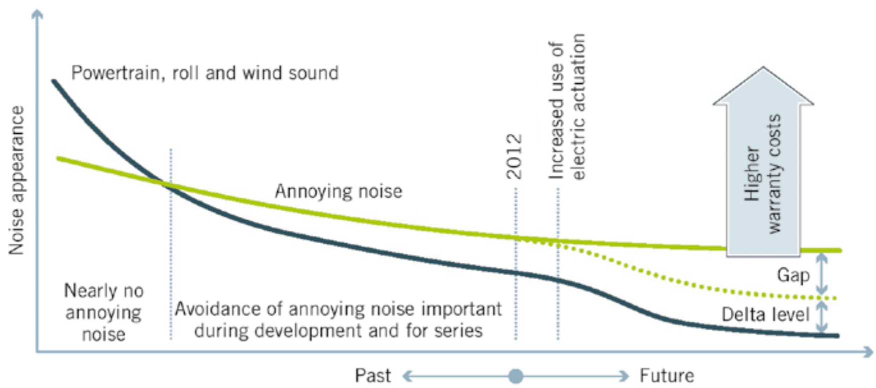
❶ shows the noise appearance related to the development over a period of approximately 30 years. The development of the powertrain, roll motion and wind sound (blue curve) is compared with the annoying noise (green curve). It shows that currently, considerable efforts have to be made to avoid S&R in the interior of the car or to keep them at the present Delta level (see dotted line), respectively. As a result of introducing and developing electric cars, S&R and how to avoid it are, again, at the centre of the developers' attention.

Electric vehicle (EV) passengers perceive annoying noise significantly stronger, as an e-motor does not make any combustion noise. In addition to that, it causes way less mechanical sound which directly affects the noise appearance in the interior of the car. So, engineers have to live up to the challenge of thwarting warranty costs that are risen by a more sensitised customer perception. ❷ shows the total and partial noise in the interior of a modern middle class car at 50 km/h. It becomes clear that the powertrain sound dominates in wide frequency ranges. Rolling noise (below 100 Hz) and wheel noise on the street (approximately 1 to 2 kHz) add noise in smaller frequency bands. At a speed of more than 50 km/h, the perception inside of the car blurs to a random noise caused by the rolling and wind sound.

A speed below 50 km/h is of importance for typical bad road surfaces inside the city and is thus a significant criterion for noiseless driving. That is why many OEMs invest in S&R noise prevention.

NOISE PREVENTION IN DEVELOPMENT

An EV's interior often displays new material combinations, futuristic design



❶ Comparison of powertrain, roll and wind sounds (blue curve) and annoying noise (green curve) during a period of three decades and innovative concepts. Another vital feature of e-cars is the distinctively reduced interior equipment. On the one hand, this is to go harmonically with the mostly innovative and eye-catching exterior design; on the other hand, it contributes to the weight reduction. New connexion concepts or interfaces as well as modern material combinations make experienced virtual developing methods more and more important.

Preventing S&R is already an established part of the car developing process. Even during conceptioning, possible risks need to be considered and countermeasures have to be prepared. At an early stage of the development phase, the experts for disturbing noise then detect and evaluate possible error sources and take steps accordingly. As development periods become shorter and shorter and the cost pressure increases, often the virtual annoying noise is disregarded. This requires expertise, experience and authority as up to today, nearly no objective evaluations – for example, the noise pressure level in the field of passive acoustics – are available for the interior of cars. Distinguishing the S&R as well as correlation to the contact points are up to the experts.

VIRTUAL DEVELOPMENT STAGE

Presently, virtual analysis methods offer the most efficient possibility to determine, evaluate and finally avoid S&R at an early stage of product development. Computer aided design (CAD, for example the Catia software) is being applied to issue the junctions in a component (such as mounting parts of an instrument panel) as well as in interfaces to neighboured component parts (such as the instrument panel to the A-pillar cover). The relevant components may not come below a specified minimum distance which is defined by several parameters such as the connexion concept, the material and the stiffness of the component part. S&R occurs if the specified value is undercut and there is any clearance, contact or clash.

After the contact point has been determined, it will be evaluated regarding their risk by the specialists, based on their experience resulting from former projects and a material data base. For each subsystem, a number of problems can arise for which steps have to be documented and confirmed in the hardware system. Related to the complete car, these problems are already solved by the specialists during the design phase virtually and without significant extra costs. If these points had to be determined during the hardware phase, causing a re-design of tools, considerable costs would arise. In the CAD system, ideally, increasing only one distance is enough to avoid the problem.

As the virtual contact point analysis via CAD software does not provide objective results and is only based on experience and subjective evaluation methods, the simulation of S&R is applied. It is based on the calculation of finite element models and provides objective results. Parameters that are necessary for the calculation are, amongst others, geometry, stiffness, material variables or weight. As there is a lot of time and calculation effort necessary at present, mainly single interior component parts such as instrument panel, centre consoles or door panels are being calculated. The S&R simulation offers the advantage that any changes in the stiffness of the component parts or additional connection points can objectively be evaluated at an early stage and the influence can be visually displayed.

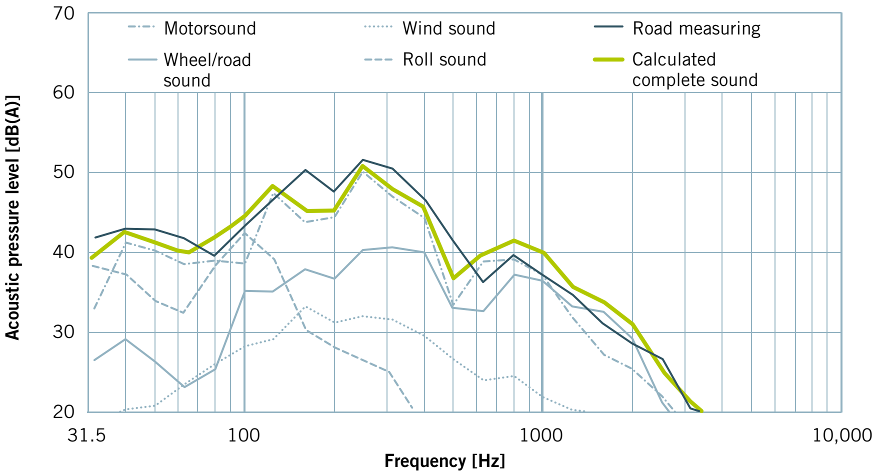
These virtual methods are extended by so-called stick-slip tests that check new material and material combinations objectively, systematically and reproducibly with respect to annoying noise emissions. Two samples each, that might cause squeaking and creaking noise, are being checked under certain conditions. The stick-slip effect can thus be measured and checked on its influence.

❸ shows the installation of a test stand schematically. One sample is fixed on the spring, the other one is fixed at a slide. Both are now brought into contact with each other with an adjustable normal force F_N. By means of a movement of the slide v_S the spring is being deflected as a result of the friction force F_R between both samples. However, if the reset force of the spring exceeds the static friction F_H a contact shot break will occur resulting in kinetic friction. The reset force of the spring is reduced up to a certain point and the friction force accrues again. This process repeats itself periodically and leads to acceleration during the contact shot break which can be realised as squeaking noise.

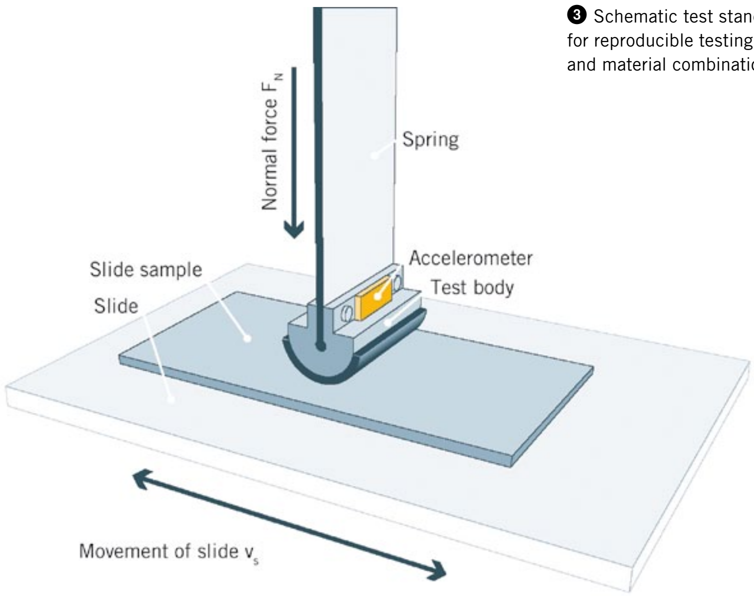
However, not only the material combination but also the stiffness of the component part, the contact geometry, connection concept or surface plating are of importance for evaluating a critical contact point, as a critical combination of material which is not moved does not cause any noise. Based on this experience, the engineers are continuously developing methods that enable a prediction by means of these complex parameters. Developing a database helps to avoid the same mistakes and to understand and actively influence parameters causing the noise appearance.

HARDWARE ANALYSIS OF S&R

After the virtual test phase is finished and first component parts such as doors, instrument panel or centre console have been built, the experts apply the subsystem analysis. In order to have informa-



❷ Exposition of complete sounds and partial sounds in the interior of a middle class car at a speed of 50 km/h



❸ Schematic test stand installation for reproducible testing of material and material combinations

tion regarding the risks of S&R as early as possible, the interior component parts are tested independently from the complete car with respect to annoying noise. The most common test stand to simulate the road animation of a complete car under lab conditions is the four stamp hydropulse device. The force application is made via four hydraulic cylinders on which the wheels of the car are placed. Combined with a climate chamber and sun simulation, even S&R, that only occurs at certain temperatures or after ageing of the car, can be determined. Thus, it is at any time possible to reproduce any annoying noise facilitating the analysis.

An essential additional part is the mobile analysis in the complete car. Compared with the analysis on the test stand, real driving offers the advantage that also excitations and influence of actuation, exhaust-gas system and heating and air conditioning can be checked.

But in most cases, a test stand analysis under reproducible lab conditions without the disturbing noise being interfered by drivetrain, rolling or wind noise is necessary.

SUMMARY AND FUTURE PROSPECTS

Many different edge conditions influence the development of a vehicle that is made out of thousands of parts. Often, design, constructed space, mounting, producibility, costs and other points vary resulting in continuous challenges for the development department. Due to these differences, even similar component parts require different actions for different models. The best solution has to be worked out in a team of experts and component part designers and has to be approved by means of trials and long term tests.

In plain electric vehicles, the problem of annoying noise becomes even more apparent. Apart from traditional protection methods in the hardware system, virtual protection methods to prevent S&R will play a more and more important role.

Two clicking component parts may cause high warranty expenses. It is thus even more important to observe the constructions during product development in cooperation with experts and to work out virtual solutions together with the component part designers, as this will not cause extra costs in most cases. Shorter development periods, decreasing production costs and demanding customers make this step even more necessary in the development of purely electrically actuated cars.

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NEW ROOF CONCEPT FOR THE PORSCHE 911 CONVERTIBLE

With the new 911 Carrera cabriolet, presented at the beginning of the year, Porsche engineers not only save weight while increasing rigidity of the vehicle, but also achieve a coupé-like roof contour with a panel bow top concept for the first time. In addition to the new roof technology, the open top Carrera features enhanced safety and comfort.

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BODY STRUCTURE

Back in 1982, Porsche for the first time presented a 911 cabriolet at the Geneva International Motor Show. Ever since, the convertible version of this classic sports car has become a firm part of Porsche's model range. A new 911 cabriolet was shown to the public at the Detroit Motor Show in January 2012. It is based on the new Carrera coupé of the 991 series which was recently launched.

As in the case of the coupé, extensive weight reduction measures have also been implemented in the new cabriolet. It weighs in at 1470 kg (3.4 l entry-level version with dual clutch transmission). This is 60 kg less than the comparable predecessor model of the 997 series. The weight reduction measures primarily include the lightweight body shell structure. Further weight savings were achieved in the assembly parts.

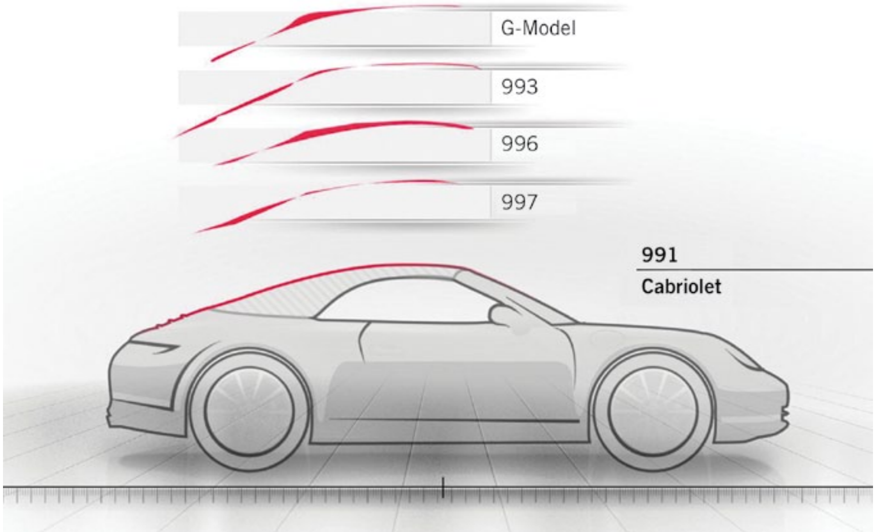
At the same time the new model offers static and dynamic stiffness which surpasses that of the predecessor. The body shell's static torsional stiffness is increased from 9000 to 11,700 N/° and the dynamic natural frequency of the trimmed body to 20 Hz (997: 17 Hz). These increases were achieved through body shell measures in the area of the door sills and in the centre tunnel as well as by means of additional, stiffening assembly parts.

PANEL BOW TOP CONCEPT

In the past, the 911 Carrera cabriolet versions' roof contours deviated from those of the coupé due to the concept. As the convertible top fabric was tensioned by means of individual bows which were discernible on the exterior surface, the result was a cabriolet-specific roof line in each case. With the new panel bow concept, the convertible top roof lines have been successfully matched to those of the coupé for the first time, ❶.

A full two years prior to the start of the actual vehicle project, Porsche's predevelopment department was already working on a new convertible top concept for the future 911 cabriolet.

The objective was the development of a roof concept which offers the familiar advantages of a classic fabric top in terms of weight and package whilst also retaining the typical roof line of the coupé. This necessitated a solid, universal support for the convertible top covering.

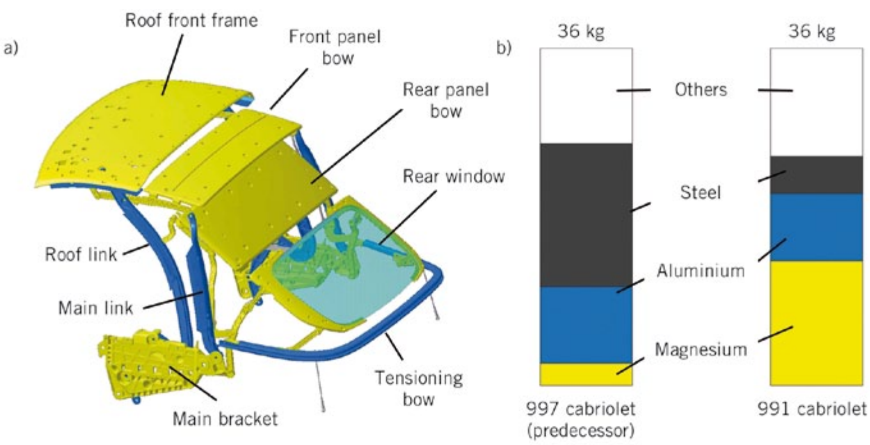


❶ Roof contour of different series

Once the convertible top concept had been defined and extensively tested on the basis of several sample structures in Porsche's pre-development department, further series production development took place together with the supplier Magna Cartop Systems, which also undertakes series production and supply for the convertible top.

To implement the coupé-like roof line, the convertible top covering is supported by panel elements all over the central area: the front roof frame, two panel bows and the rear window with frame, ❷ (a). All of these elements are kinematically coupled via the convertible top linkage. This holds them in their defined positions when the convertible top is closed or open, and enables them to be kinematically controlled when the top is moving. When the top is closed, the panel elements are not secured against each other.

To make the solid roof structure tangible for the customer in the interior of the vehicle as well, the roof frame, the panel bows and the rear window have been equipped with firm roofliner trims. Due to the movement sequence when opening and closing the convertible top, the side areas had to be designed as bowed roofliners. A system consisting of several control cords ensures that the bowed roofliners move to the desired position when the convertible top is being closed. The bowed roofliners are also held in position by the control cords when actuating the convertible top whilst the vehicle is moving, enabling them to reliably reach their storage position.



❷ (a) Assembly of roof; (b) materials in soft top

CONVERTIBLE TOP MOVEMENT AND STOWAGE

The convertible top is designed using the Z-folding principle, ❸. Even when the top is stowed away, the front roof frame lies in the uppermost position, thereby protecting the inner side of the top. Like a sickle, the top compartment lid folds over the rear area of the roof frame. The front section of the folded top remains visible.

The convertible top fabric is only partially connected to the first panel bow by means of a tightening strip. This enables a panel bow storage position which permits an overall folded convertible top package with a length of approximately 550 mm and a height of around 230 mm in the central area. This condition – among others – was crucial to implementing the styling of the vehicle's rear end.

During the development of the convertible top, particular attention was paid to how the fabric folds up. In convertible top specific component endurance tests, the convertible tops were exposed in both the open and closed position to vibration stresses, temperature and humidity fluctuations corresponding to the strain experienced throughout the service life of a vehicle. This enabled specific optimisation of the position of the fabric folds in terms of wear and creasing.

CONVERTIBLE TOP MATERIALS

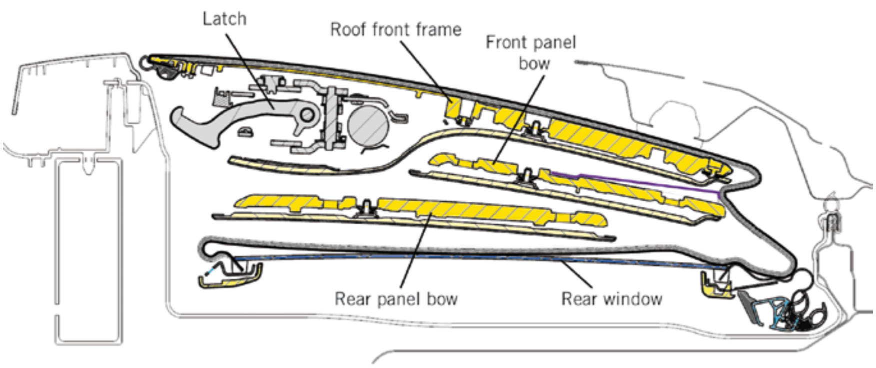
The outer convertible top covering is the Sonnenland A5.3, identical to that fitted in the predecessor model, with a thickness of 1.1 mm and a flamed surface. In contrast, the new convertible top has an all-over insulating layer between the outer covering and the convertible top linkage. In the central area above the bows, it is 5 mm thick and serves primarily to optically conceal impressions in the outer covering as well as being used for acoustic reasons. 10 mm thick insulation, which significantly improves the acoustic characteristics, has been fitted in the lateral area between the rear side windows and the rear window.

To reduce weight the shape-determining elements of the roof frame, the panel bows and the rear window frame are manufactured from magnesium. The majority of the lateral kinematic links and the convertible top support also consist of magnesium. Die-casting and thixomoulding processes are used to manufacture these elements. The main lateral links and the rear tensioning bow are manufactured from aluminium and the use of steel has been reduced to a minimum, ② (b).

MANUFACTURING AND JOINING TECHNOLOGY

The weight optimisations have not only been achieved by using lightweight materials but also through innovative component and joining technologies. Various pivot points of the lateral convertible top links do not have separate shaft bolts. Manufactured using the thixomoulding method, the magnesium links are fitted with shaft bolts integrated into the component. The running surfaces are designed with a draft angle of 0 ° and provide the necessary off-tool diameter tolerances.

A rear window glazing concept which enables a virtually flush transition between the convertible top fabric and the 3.15 mm thick single layer safety glass with a minimal gap was chosen to underline the coupé-like roof line. In a foaming process, the fabric and window are joined together using a polyurethane frame whose main cross-section is not visible below the rear window's screen print. Only a narrow strip, which is recessed, is visible from the outside. Fasteners for attachment to the convertible top kinematics are cast into the polyurethane frame.



❸ Sectional drawing of the stowed top

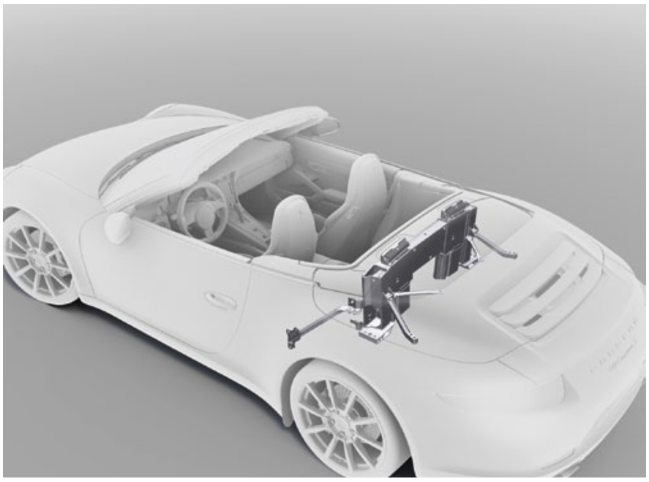
ROLL-OVER PROTECTION

An extendable roll-over protection system guarantees that the occupants are protected. In the event that the vehicle rolls over, this system together with the cowl panel frame ensures that the survival space is maintained, ❹. During a roll-over, the rear roll-over bar is under particular strain due to the vehicle's rear engine concept.

The supporting frame consists of a welded aluminium construction in which the pop-up modules form part of the supporting frame structure. To meet the vehicle's specified geometrical parameters, an overall supporting frame package of approximately 70 mm was achieved in the vehicle's longitudinal direction.

The completely new design of the supporting frame enabled its weight to be reduced by 5.6 kg in comparison with the predecessor vehicle. Due to the flat roof contour, the roll-over protection system penetrates through the rear window on actuation in order to reach the maximum height.

Besides offering protection in the event that the vehicle rolls over, the protection system's supporting frame also stiffens the vehicle as a whole: it is linked forwards to the B-pillar and backwards to



❹ Roll-over protection system

❺ Wind deflector

the convertible top stowage compartment by means of additional struts. Consequently, a diagonal shear connection between the rear end of the vehicle and the B-pillar is created, which contributes to increasing the vehicle's torsional stiffness.

WIND DEFLECTOR

As a new feature, an automatic wind deflector has been developed, ❺. Forming part of the basic equipment, it is firmly integrated into the rear area of the vehicle. At the push of a button, it automatically deploys behind the front seats and, when the roof is down, does an outstanding job of keeping the interior free of draughts up into the top speed regions. Manual assembly of the wind deflector is therefore no longer necessary.

Two pivoted brackets are attached to both the left and right of a mechanical frame. When the wind deflector deploys, the front bracket is pivoted upwards approximately 90 ° into its vertical position. A fabric mesh is secured to the bracket, which is unrolled from a spring-tensioned roller blind shaft. A second deflection bracket swivels approximately 180 ° from its closed to its open position and tensions the fabric in an L-shape in its effective position behind the front seats.

Both brackets are coupled on the left and right by means of countershaft kinematics. A position past top dead centre ensures that the wind deflector remains stable in its end position.

The wind deflector is operated by an electric motor located centrally above the roll-over protection system's supporting frame. The drive force is transmitted to a slide in the lateral kinematics via a push-pull cable. The slide introduces the movement into the wind deflector brackets' countershaft kinematics via a relay lever on both the left and right.

CONCLUSION

Thanks to the early involvement of the pre-development, styling and complete vehicle departments plus strategic suppliers, a significant improvement has been achieved in combining design requirements and function of the sports car's convertible top. New solutions in lightweight design as well as for comfort, customer benefits and top speed strength provide the basis for further developments in other future model lines as well.

The new panel bow top offers significantly more product content than the predecessor model: the panel elements and the new roofliner concept for the roof's coupé-like shape, additional acoustic insulation for more comfort, additional measures for roll-over protection and the increased length of the convertible top due to the vehicle's modified dimensions and styling. Nevertheless, the weight of the convertible top was matched to that of the predecessor model. This was achieved through the increased use of lightweight materials and intelligent component design.

THANKS

Thanks for collaboration and support to Dr. Heinz Soja, Dipl.-Ing. (FH) Stefan Eichholz, and Dipl.-Ing. (FH) Reiner Armbruster.

THE AUTOMATED MANUAL TRANSMISSION FOR THE LAMBORGHINI AVENTADOR

With the new flagship model, the Aventador, Lamborghini ran counter to the industry trend of fitting Dual Clutch Transmissions. Oerlikon Graziano instead developed a tightly packaged customised Automated Manual Transmission which handles 750 Nm of torque and provides shift speeds of just 50 ms.

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REASONS FOR THE AUTOMATED MANUAL TRANSMISSION

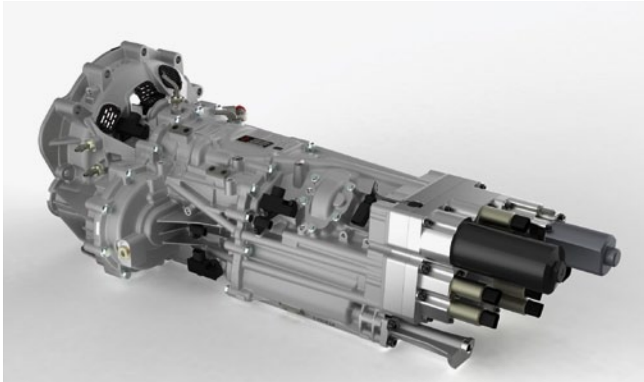
There is a renewed interest in Automated Manual Transmissions (AMT) from sectors of the automotive industry such as supercar and hybrid vehicle manufacturers. The combination of compact packaging, high efficiency, and new evolutions in control strategy means that for some of these applications an AMT is more suitable than a Dual Clutch Transmission (DCT) or conventional manual transmission.

The new 515 kW (700 bhp) Aventador uses a seven-speed AMT with the fastest gear-shift of any synchromesh road vehicle transmission. Designed and manufactured by Oerlikon Graziano, the gearbox weighs just 79 kg and is therefore 20 % lighter than its predecessor applied with the Lamborghini Murcielago. It also uses a novel shift system to achieve the rapid shift time of just 50 ms, ❶.

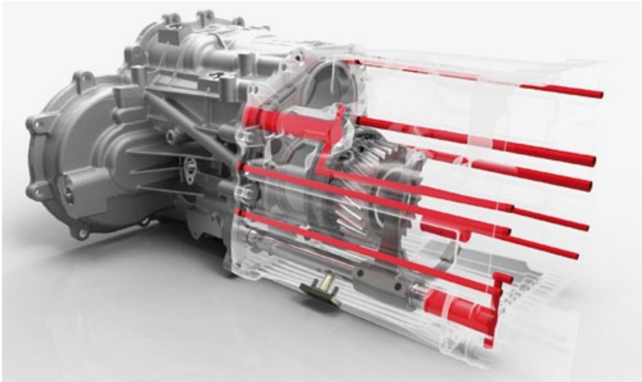
The customer brief for the transmission included very tight packaging requirements, a high level of emotional involvement for the driver and very high input torque and speed. All this was to be delivered without compromising durability and within a demanding project timescale. To achieve these goals, the supplier's engineers worked as a single team with Lamborghini in deep cooperation from day one.

To maximise occupant space, the Aventador features a slim transmission tunnel within its carbon fibre monocoque. The package limitations ruled out the use of a DCT because insufficient space was available for the large dual clutch packs required to handle the input torque of 750 Nm and input speeds up to 9000 rpm. The AMT previously used in the Lamborghini Murcielago would not package within the new car as well.

The compact transmission design was made possible by extensive use of ad-



❶ Seven-speed AMT with the fastest gear-shift of any synchromesh road vehicle transmission



❷ Savings in package size were achieved by integrating the hydraulic system into a compact self-contained unit within the transmission case

vanced analytical techniques, allowing substantially reduced centre distances between the shafts and reduced clearances between the transmission and the vehicle body.

Further savings in package size were achieved by integrating the hydraulic system into a compact self-contained unit without any external pipe runs, all connections being internal through the transmission casings, ❷.

The engineering team was tasked with providing a strong emotional link between the driver and the car. This is reflected in the engineering targets which included unprecedented shift times. The crucial element in faster shifting is the ability to move into the next gear while the system is disengaging the previous one. The transmission applies this principle, well understood from experiences with DCTs, but with the light weight and compact package that is possible with an AMT when no manual option is required.

INDEPENDENT SHIFT RAIL TECHNOLOGY

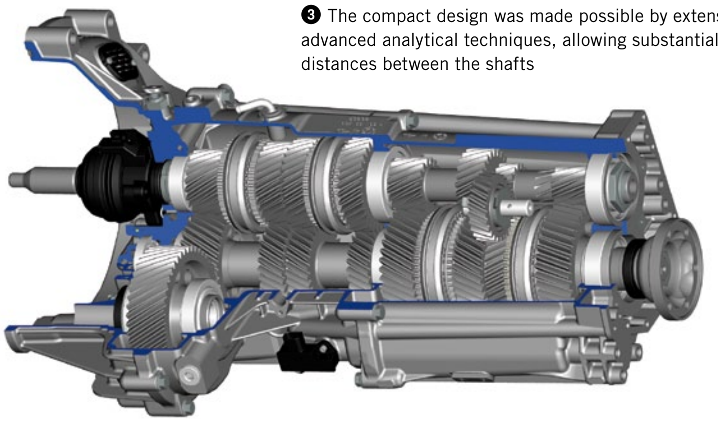
A conventional AMT uses the established H-pattern gearshift of a manual gearbox, in which the various gears are selected by sliding selector rails that lie parallel to each other. The jump from one rail to another corresponds to the dogleg in the middle of the H, called cross-gate movement. Two actuators power the automatic shift; the actuator engaging the desired gear has to wait until the cross-gate actuator has selected the correct rail. Oerlikon Graziano together with Vocis Driveline Controls devised a strategy called Independent Shift Rail (ISR) for the transmission that eliminates this constraint.

In the ISR transmission, there is no cross-gate motion and consequently no cross-gate actuator. Instead, each rail is operated directly by its own actuator, ❸. One rail selects either 1st or reverse, one 2nd or 4th, one 3rd or 5th and one 6th or 7th. This means that no two sequential gears are on the same shift rail until the last change into the 7th, the top gear. As a result, the system can begin to move the rail for the next gear while still withdrawing the previous one, allowing the shift to be accomplished faster.

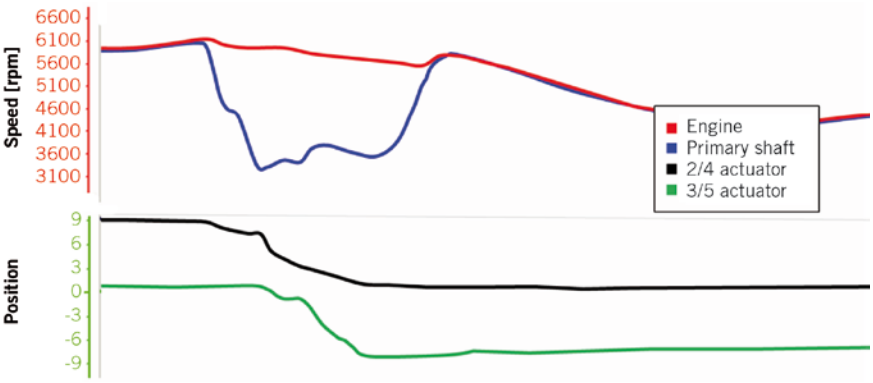
Even with the ISR architecture, ultra-fast shift speeds would not be possible without careful optimisation of the entire system. For example the gear change paddles are hard-wired into the Transmission Control Unit (TCU), eliminating the time required for the Controller Area Network (CAN) bus to poll the system. Furthermore, very accurate measurement and control of the actuation current ensures precise and progressive control of the high-precision hydraulic valves. The valves, specified by Vocis and designed for this application, are critical not just to a fast change but also to shift quality.

To further increase the speed of the shift, the software has to be optimised. Control systems are often designed after the gearbox hardware is frozen and must operate within the constraints of the existing mechanical layout. Simultaneous engineering of the mechanical architecture and the software allowed taking best advantage of the inherent dynamic behaviour of the system. After modelling component elasticities and inertias, the system responses were simulated and optimum strategies for shift execution identified, eliminating much of the compromise inherent in this area.

The algorithms critical for effective high-speed shift control, are based on a core Vocis software platform, tailored for the specific application. The software was developed using software-in-the-loop methods within the model-based devel-



❸ The compact design was made possible by extensive use of advanced analytical techniques, allowing substantially reduced centre distances between the shafts



❹ Although gear shifting takes place in milliseconds, there is a defined sequence of individual operations

opment environment Ascet by Etas, followed by hardware-in-the-loop testing in the Etas Labcar environment for execution and automation of control unit tests. Software change management was controlled using a database to give reliable, secure access to up-to-date revisions during periods of rapid development.

The first ten transmissions used a Vocis TMS20 rapid prototyping controller running Matlab/Simulink executable files. The production TCUs are based on an MPC5567 processor and manufactured to a Vocis specification based on the output of hazard analysis.

ANATOMY OF A SHIFT

Although gear shifting takes place in milliseconds, there is a defined sequence of individual operations, each one scheduled and controlled by the Vocis software. ❹ shows the full sequence for a shift from 4th to 5th gear.

Initially, the engine speed (red line) matches the primary gearbox shaft speed (blue line). The first milestone occurs when the driver requests a shift. Elasticity in the driveline causes the input shaft to break away and slow relative to engine speed (second milestone). At this point, the 2/4 gear selector rail begins move towards disengaging 4th gear. At the third milestone, the actuation system for 5th gear is preloaded. At the fourth milestone, to coincide with torque reversal in the driveline, the 2/4 selector rail disengages 4th gear at the point of lowest mesh load. The primary shaft speed is at its lowest. At the fifth milestone, while 4th gear is still disengaging, the 3/5 selector rail begins synchronisation of 5th gear. At the sixth milestone, 5th gear is fully engaged.

From this point, the primary shaft speed builds up quickly to match engine speed and the 2/4 selector rail continues its travel to take 4th gear into a clearance (neutral) position.

RESULTS

The first prototype transmissions were delivered within 13 weeks of the project start, with the first implementation in a running vehicle just three weeks later. This was partly due to an extensive programme of in-house rig development which included component fatigue testing on dedicated rigs for the gears and synchronisers, hydraulic system fatigue testing in a climatic chamber, and lubrication verification at all attitudes with a rock-and-roll rig, ❺.

Unlike many early prototypes that serve only as proof of concept, the transmissions were fully functioning and sufficiently representative to allow early engineering vehicles to be used for demanding board-level evaluation. The result of this combination of design techniques and operating strategies is a minimum shift time achieved of just 50 ms, making this the world's fastest-shifting transmission with synchronisers. The software is configured to provide three shift modes: Strada, Sport and Corsa. The most refined of these is Strada which provides the smoothest gearshift with minimal engine braking to suit a relaxed driving style. The Sport mode introduces an aggressive throttle blip during downshifts, briefly exceeding the target engine speed to ease the blend into the new ratio and provide a more emotive driving experience. Corsa mode is intended for race track driving. It provides aggressively fast shifts but also keeps the car feeling neutral and stable by providing controlled engine braking.

CONCLUSION

A close working relationship between the development partners ensured that the transmission enjoyed a swift design phase and was able to take advantage of solutions that would not be available within the confines of existing architecture. The AMT is optimised in shift time, feel, packaging and weight. As it was designed specifically for the Aventador application it is not affected by the compromises dictated by an off-the-shelf unit.

❺ Lubrication verification at all attitudes with a rock-and-roll rig

DEVELOPMENT OF AN 800-V ELECTRIC CAR WITH REAR-WHEEL DRIVE

Increasing the voltage level in the traction power network is an evident and reasonable development step in producing sporty and powerful electric cars. Therefore, the engineers at AVL are developing an electric powertrain with 1200-V IGBT technology for the concept electric car Coup-e 800. To prove its suitability for practical application, the system is integrated into the vehicle platform of a Mercedes-Benz C-Class Coupé.

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MOTIVATION

The average traction power of (conventional) new cars sold in Germany in the first six months of 2011 was nearly 100 kW [1]. This customer demand for sporty and dynamic vehicle concepts will still apply even for prospective, fully electric cars. One example of this trend is the Tesla Model S, which offers a maximum traction power of 270 kW [2].

An electric driving performance above 100 kW implies an electric current of more than 350 A in the high-voltage power network (DC) if 600-V IGBT technology is used in the inverter of the traction motor. Notwithstanding extensive progress in the development of high-power battery cells, these currents still remain the limiting factor considering the desired operating life of the high-voltage battery [3].

While battery cells are only one example, resistive power losses in high-voltage cables and power semiconductors as well as the bending radii and weight of the wiring harness also face specific problems with high current loads. Managing the trade-off between customer requests on the one hand and technical practicability on the other, AVL is developing a rear-wheel-drive electric car with 1200-V IGBT technology and a nominal voltage of the high-voltage battery of 675 V.

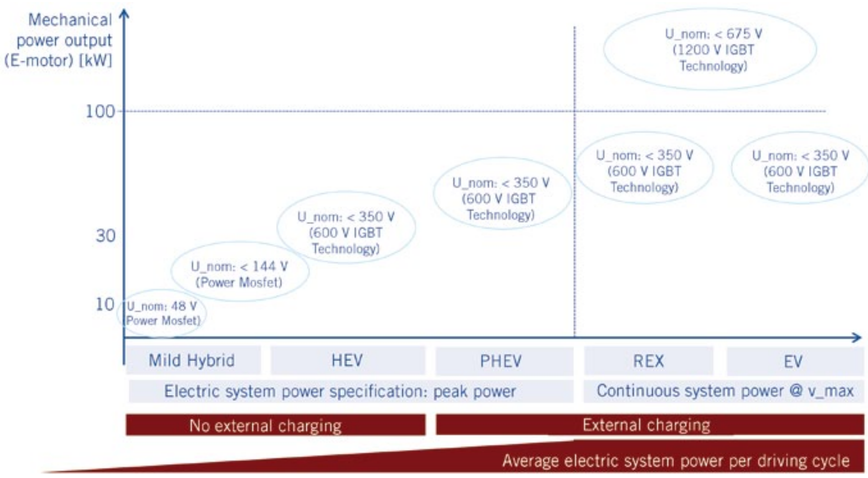
ELECTRIC VEHICLE CONCEPT

Specifying the nominal output power of a conventional car with an internal combustion engine (petrol, diesel and gas) is quite easy. The traction power must be continuously available and is usually correlated with the top speed of the vehicle (at least up to the regulated speed of 250 km/h). This situation changes significantly when specifying the output power of electrified powertrains. Even more specifications of output power differ within the many types of electric powertrain concepts.

Currently, five electric powertrain concepts are emerging in the automotive industry. These concepts can be divided into systems without external charging (mild hybrid and hybrid electric vehicle, HEV) and systems with external charging (plug-in hybrid vehicle, PHEV; range extender vehicle, REX and electric vehicles, EV). According to ❶, the electric power output of the different concepts increases with the requirements of electric driving with regard to pure electric driving situations and the top speed required.

The basic intention of mild hybrid and HEV concepts is the optimisation of fuel efficiency, with the internal combustion engine remaining as the main source of power in the car. Thus, the power specification of the electric system/traction motor in the mild-HEV/HEV segment is usually not a continuous power specification but rather a 1 to 30 s peak power specification, as the electric system is not intended to work continuously but rather to “assist” (during short periods of electric driving, recuperation, etc.). The maximum system power of this vehicle category is still dominated by the maximum output power of the internal combustion engine, which also defines the top speed of the car.

In plug-in hybrid vehicle concepts, the car is designed to operate the first



❶ Correlation between electrical vehicle concepts, electric power required and voltage level approximately 20 to 60 km of the driving cycle exclusively with its electric traction system. After this electric driving cycle, the internal combustion engine is switched on and the vehicle is run almost like an HEV. Nevertheless, the internal combustion engine is available to support the electric system in situations of high power demand or extreme outdoor conditions. Therefore, the electric system power of PHEVs is usually higher than that of HEVs, but the maximum output power of the vehicle is still dominated by the internal combustion engine.

In the two remaining powertrain concepts (REX and EV), the electric system is the exclusive source of traction power. Thus, the output power required to achieve the top speed specified for the vehicle has to be provided by the electric system and therefore has to be available continuously. Depending on basic vehicle parameters such as aerodynamics, rolling resistance, mass etc. for a constant speed of 140 km/h, at least 40 kW of mechanical power is necessary, whereas for 160 km/h at least 60 kW is required, (ignoring auxiliary power and ascending inclines). As every driving situation has to be covered by the electric traction system, the average power output of REX and EV vehicle concepts is significantly higher than that of hybrid concepts.

Electrical system requirements therefore differ strongly between the electric vehicle/powertrain concepts presented. For module conformity and to reduce development effort, OEMs are still trying to transfer the approved technology (600-V IGBT) from hybrid vehicles (HEV/PHEV) to full-electric powertrain concepts (REX/EV). For vehicles with moderate driving performance requirements, this step is reasonable and sufficient. Due to the vehicle performance requirements of the Coup-e 800 – 0 to 100 km/h acceleration in 6 s, top speed of 180 km/h – the decision was made to increase the voltage in the traction power network and use 1200-V IGBT technology. The powertrain shown in ①, top right, in which the Coup-e 800 is positioned, can thus be described as the six-cylinder segment of electric mobility.

ONBOARD POWER NETWORK DEVELOPMENT

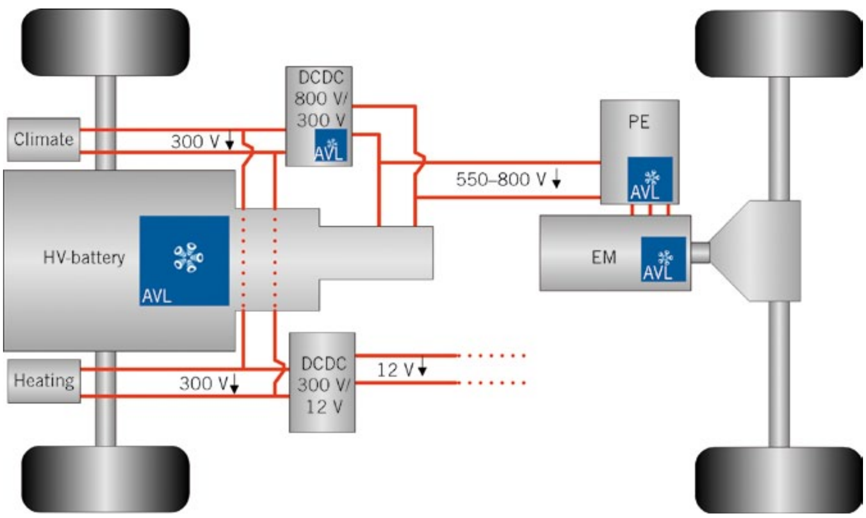
Developing a powertrain with 1200-V IGBT technology currently results in a three-voltage onboard power network, as powerful auxiliaries such as the air conditioning compressor or heaters are barely available on a DC voltage level of 600 to 700 V so far. The corresponding power network architecture developed for the Coup-e 800 is displayed in ❷. With individual battery cell voltage varying from 3.0 V to 4.15 V depending on its state of charge (SOC) and current load etc., the voltage in the traction power network varies between 540 V and 800 V. The traction power network is connected by a DC-DC converter to the interim 300 V power network, which hosts the auxiliaries mentioned above. The 800 V/300 V DC-DC converter is unidirectional and provides a maximum power output to the 300 V power network of 9.5 kW. The conventional 12 V power network is supplied by the 300 V/12 V DC-DC converter with a nominal power output of 2.2 kW.

POWERTRAIN DEVELOPMENT

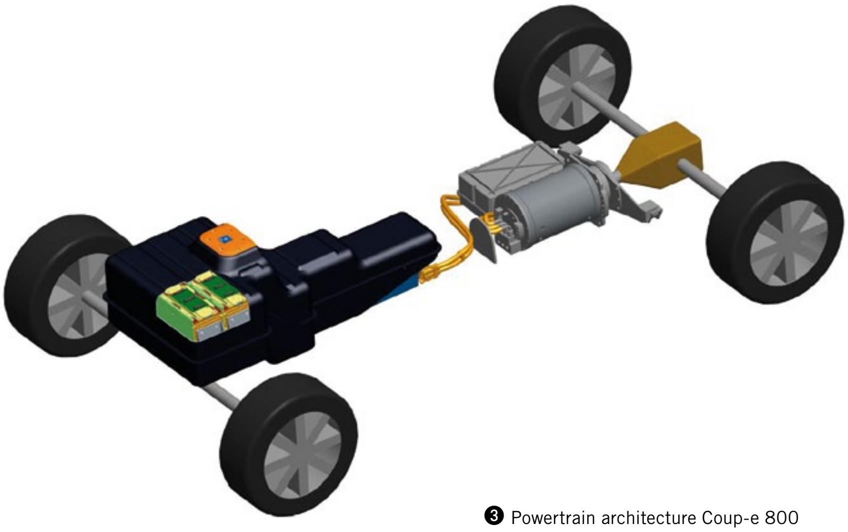
The geometrical integration of the electrical drivetrain components was carried out with the intention of not changing the chassis at all, and especially to retain the passenger and luggage compartment of the Mercedes-Benz C-Class Coupé with modification. The driver impression of retaining a complete vehicle with all accustomed comforts should not be affected by the powertrain electrification. Consequently, the high-voltage battery replaced the conventional internal combustion engine and the gearbox and was integrated partly in the engine compartment and partly in the transmission tunnel. Due to the compact design of the electric motor, an integration concept could be realised directly in front of the rear-axle transmission, with the electric motor being positioned below the rear seat row. With manageable geometrical integration effort, a weight distribution of 53 % (front axle) to 47 % (rear axle) was achieved. The ground clearance of the car was not affected either, and remained on the level of the conventional car. The complete geometrical integration of the powertrain into the base vehicle is shown in ❸.

TRACTION MOTOR WITH DIRECT COOLING OF THE STATOR WINDING

The traction motor of the Coup-e 800 features direct fluid cooling of the stator winding. In order to avoid churning losses, the permanent magnet rotor is not surrounded by the cooling fluid but is dry. The insulation between the stator and rotor is provided by a tube that has been integrated into the air gap of the electric motor. This cooling concept ensures a continuous output power of the traction motor of 140 kW (500 Nm at 2700 rpm) with the electric motor diameter no larger than 245 mm and a total electric motor length of 390 mm. The peak torque (for 10 s) is 750 Nm at 2700 rpm (210 kW). Considering the gear ratio of the rear axle transmission of 3.92 (originally: 3.07), a maximum torque of almost 3000 Nm is developed at the rear axle, which is available up to a vehicle speed of 80 km/h. This powertrain con-



❷ Power network architecture of the Coup-e 800



❸ Powertrain architecture Coup-e 800

cept yields advantages in costs, packaging and efficiency by avoiding the necessity of an additional transmission.

❹ describes the design of the cooling concept in the electric motor housing. The inlet of the cooling fluid enters the electric motor housing at the coil endings, passes the lamination stack of the stator in cooling pipes as well as in stator slots that are not completely filled with windings and exits the electric motor at the opposite housing end.

Thus, heat dissipation is provided by convection directly from the motor windings into the cooling fluid. In this way, the cooling concept permanently enables a high current and flux densities in the lamination stack of the stator, which are available in conventional water jacket cooled electric motors only for a short time (S3 power).

POWER ELECTRONICS

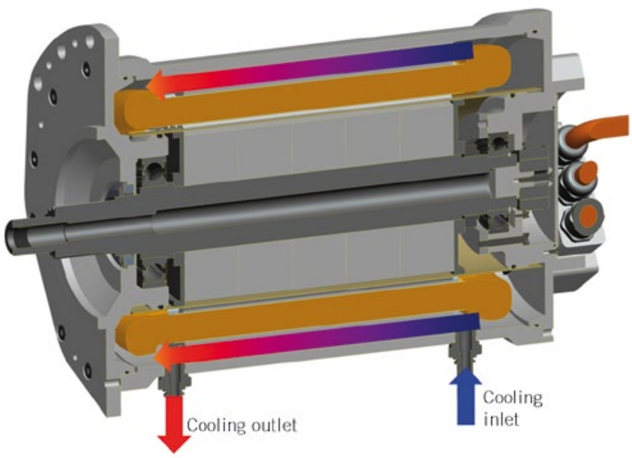
In permanent magnet synchronous machines (PSM), the voltage induced in the stator winding increases proportionally to its rotor speed. Due to the direct coupling between the vehicle speed and rotational speed in this powertrain concept, a voltage is induced into the traction power network (DC) even in the case of inverter malfunction (hardware or software error, no rotating field). Normally in 600-V systems, the maximum voltage induced (at v_max) exceeds the threshold voltage of IGBT modules. In order to prevent further damage to or even destruction of the IGBT, the system has to be switched to a so-called active short circuit (ASC: three-phase short circuit of the stator windings) [4]. However, the ASC results in a defined negative torque on the rear axle [5], which may reduce the driving stability of the car especially when driving on bends or with a low coefficient of road friction. Minimising the arising risks yields restrictions in system and component design.

Due to the higher voltage buffer in the 1200-V system of the Coup-e 800, the ACS can be avoided, as the maximum voltage induced into the inverter does not exceed the threshold voltage of the IGBT modules. Thus, no restrictions in system and component design due to safety requirements are necessary.

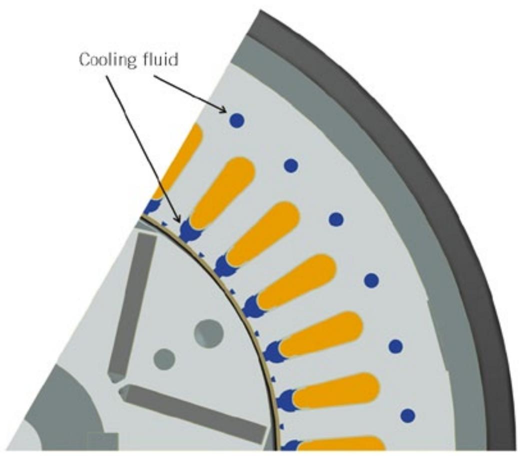
HIGH-VOLTAGE BATTERY

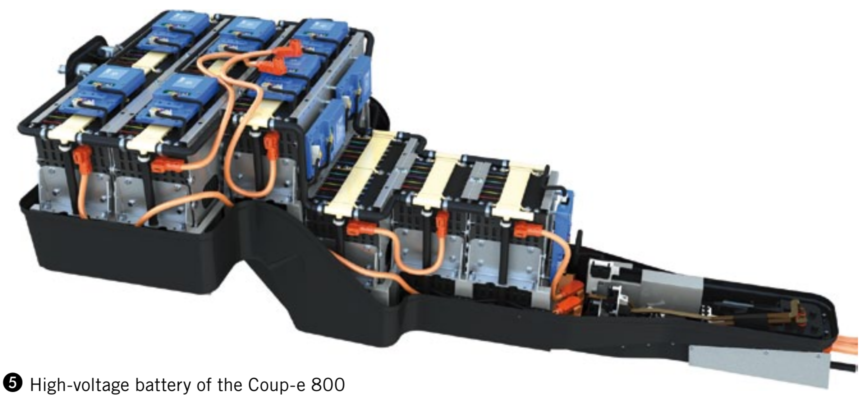
The high-voltage battery of the Coup-e 800 consists of 180 pouch cells connected in series. The 180 cells are arranged in 15 modules, with each module housing 12 battery cells and one module controller. The cells offer a nominal capacity of 41 Ah, resulting in a total energy content of the high-voltage battery of 28 kWh.

The complete battery pack, including the housing, weighs approximately 250 kg, with each battery cell weighing about 1 kg. To provide the cooling concept for the high-voltage battery, conductor cooling was developed where the cooling tube is fixed to the positive and negative pole of each battery cell. Thus, the core of the battery cell is cooled via the positive/negative pole (lead) and the electrode. This cooling method, ❺, is highly efficient, as good electric conductivity is physically correlated with good thermal conductivity [6].



❹ Design of the cooling concept in the electric motor housing





❺ High-voltage battery of the Coup-e 800

DRIVING MANOEUVRE/DRIVING CYCLE	SIMULATION RESULT
Acceleration 0 – 100 km/h	6 s
Elasticity 60 – 100 km/h	3.4 s
Elasticity 80 – 120 km/h	5 s
Driving distance (NEDC)	115 km (19.5 kWh/100 km)
Driving distance (FTP-72)	135 km (16.5 kWh/100 km)

❻ Driving performance and energy consumption of the Coup-e 800

To calculate the vehicle performance and driving distance, the complete vehicle with the respective electric powertrain was built in a simulation environment using AVL Cruise. Apart from the driving performance and elasticity, energy consumption in different driving cycles in particular, for example NEDC and FTP-72, was calculated in order to determine the driving range of the vehicle. ❻ displays the simulated driving manoeuvres.

SUMMARY

The emerging competition regarding improved driving performance and top speeds of (future) electric cars and the requirement to provide the top speed and power continuously are demanding a higher voltage level in the traction power network of future electric cars. With the electric car Coup-e 800, AVL has developed a prototype vehicle that enables the evaluation of all development steps necessary for the qualification of higher voltage levels for the automotive industry to be carried out. Due to the in-house development of all three core components of the electric powertrain (electric motor, inverter, high-voltage battery) including microcontroller intelligence, AVL offers sustainable experience in development of 800-V system and component technology.

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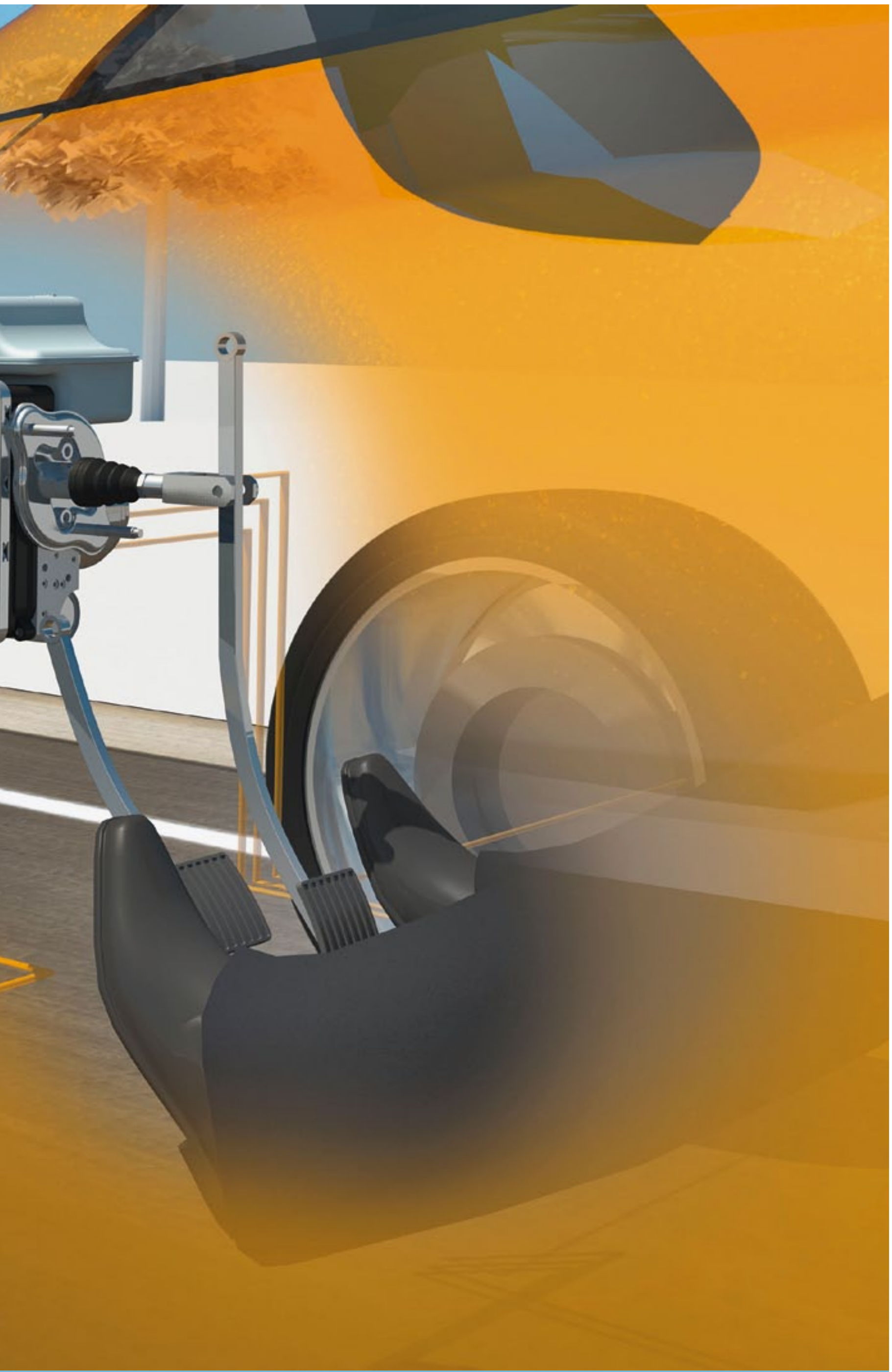
INTEGRATED BRAKE SYSTEM WITHOUT COMPROMISES IN FUNCTIONALITY

The MK C1 integrated brake system from Continental pairs Electronic Stability Control (ESC) with an innovative activation system in one compact, weight-saving unit. In addition to supporting unlimited recuperation in hybrid and electric vehicles, the new development combines high braking force dynamics with precise and quiet pressure control for enhanced comfort and safety functions.



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TASK

The architecture of braking systems in today's passenger cars is a result of historical evolution. Hydraulic modulation of brake force later supplemented the original task of activation. This first made it easier to control braking (ABS), before heightened stability through electronically controlled intervention (ESC) made its appearance. A third component now commonly supplements the two system components above: a vacuum pump works in conjunction with a brake booster because, in the interest of efficiency, modern vehicle engines should not be restricted. Braking systems today consist of two and often three of these distinct components.

Until now, this architecture has served well. However, with the introduction of hybrid and electric vehicles, the situation changed abruptly [1]. One of the main efficiency advantages of this new form of propulsion is its use of the kinetic energy stored in the vehicle to generate electrical current (recuperation), ❶. The transition from mechanically to electrically assisted braking must not distract the driver through a change in the feel of the pedal nor may the transition be audible. The most effective means of accomplishing this is to completely uncouple the brake pedal from the force function. Today's hybrid vehicles accomplish this, albeit with some functional limitations. Based on the experience obtained from producing two generations of electro-hydraulic braking systems for hybrid vehicles, Continental has developed the integrated MK C1 braking system. Plans are currently underway to commence mass production in 2015.

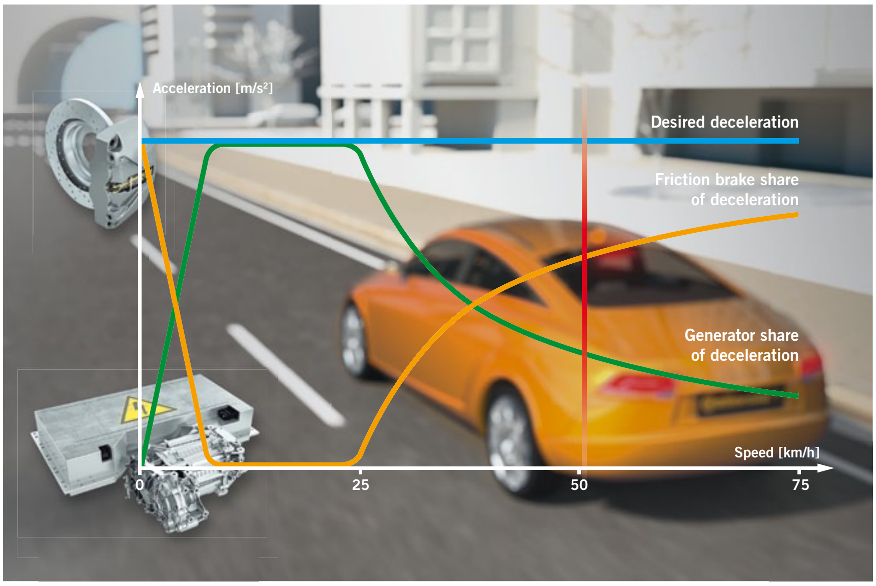
SYSTEM DESIGN

❷ shows the MK C1 brake-by-wire system, consisting of the wheel brakes and pedal. A compact component comprises signal recognition, generation of brake force and modulation (hydraulic block and control device, ECU). It can be mounted on the bulkhead instead of the usual application. The blue system outline in ❸ shows its compatibility to today's vacuum brake boosters. Its abbreviated length is particularly advantageous compared to the conventional arrangement with a brake booster and a master cylinder. Compared to a typical 8"/9" tandem brake booster, this could yield 100 mm and more of deformation zone in a crash situation. An additional benefit to consider is the fact that the MK C1 braking system does not require any vacuum, which means that the vacuum pump previously required is no longer necessary. Because the integrated braking system is considerably more compact than existing systems, it is ideally suited for manufacturers who wish to add a hybrid version to their existing model line-up, since this places additional demands on the braking system.

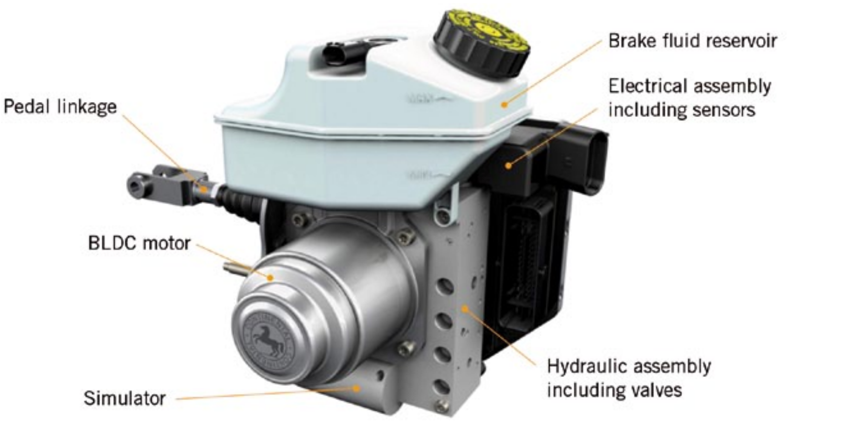
OPERATION

The new electro-hydraulic braking system normally uncouples the driver from the activation process. Attached to the pedal linkage, the brake pedal activates a tandem master cylinder. The cylinder recognises the signal from the driver through electronic sensors, activating a pedal-feel simulator hydraulically.

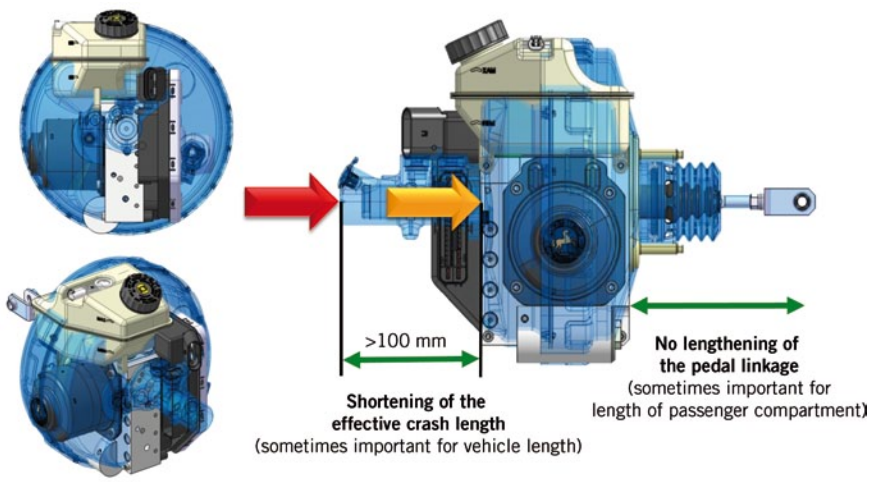
The pressure in the simulator chamber is hydraulically independent of the level of force on the wheel brakes, adjusted by a highly dynamic electric motor, ❹. The driver does not notice any difference in pedal pressure if the ESC or the ABS intervenes because they are uncoupled from the pedal. In contrast to existing systems that work with either an active booster or a vacuum reservoir, it produces better control over the pedal feel. The characteristics of the pedal feel (curve) of the MK C1 are not only adaptable to a specific make or model with regard to pedal effort/travel. The driver or the situation can also influence vehicle deceleration through software parameters. Uncoupling also provides ideal conditions for recuperation in regenerative brake



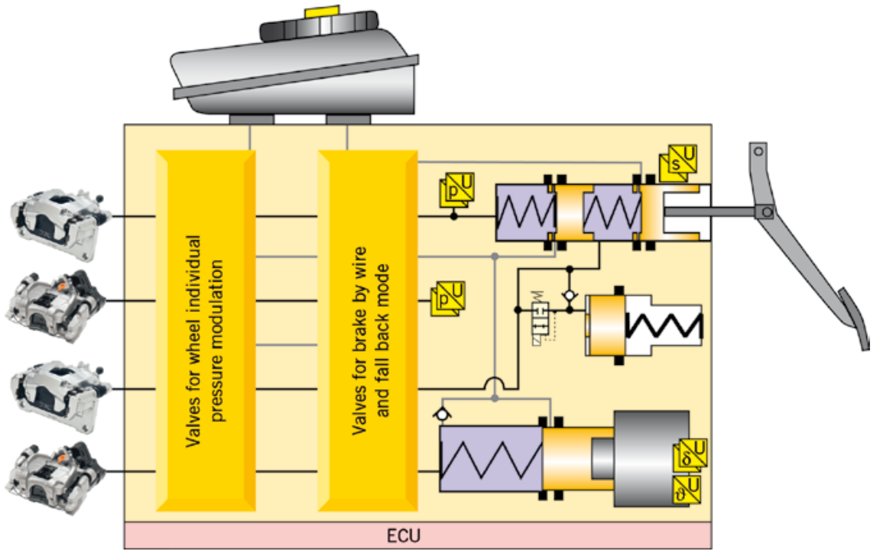
❶ Comfortable recuperation requires uncoupling the pedal but it primarily requires quiet and highly dynamic regulation of braking force



❷ The MK C1 integrated braking system not only combines activation and modulation, but also dispenses with a vacuum pump due to the way it functions



❸ Comparison of the space needed for a conventional braking system with 8"/9" tandem vacuum brake boosters (blue) and an MK C1 electro-hydraulic system (grey)



❹ Schematic drawing of the MK C1 as an electro-hydraulic circuit diagram: above right is the tandem pedal cylinder, in the middle below is the simulation chamber, at the bottom is the working cylinder with the BLDC motor as an actuator

systems. For example, highly dynamic changes are also possible without the driver noticing any lapses in braking.

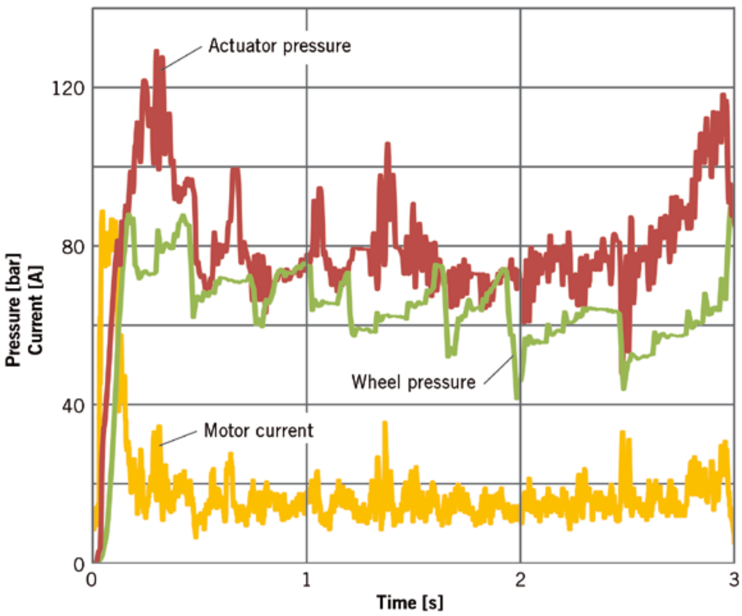
The actuator generates braking force in the integrated braking system. A brushless DC motor provides the drive. Its high efficiency helps to fulfil the requirement of maximum overall demand of ≤100 A. The new braking system fits into the strategy of automotive manufacturers for heightening efficiency because it works according to the power-on-demand principle, thus only requiring current from the car's electrical system during braking, ❺. The electric motor moves the working piston directly via a ball-and-screw spindle. The volume of the working piston is around 50 cm³/s in the current version. Since the load on the ball-and-screw spindle comes from only one direction, it is effectively free of play, something that also makes it possible to calculate the precise position of the working piston. The actuator has been designed to be completely maintenance free in order to ensure high availability. Should the ball-and-screw spindle nevertheless jam, uncoupling from the tandem master brake cylinder means that hydraulic fallback is available without restriction.

Part of the ABS philosophy is that the wheel in need of the highest force is always open to the working piston, which governs it directly. Individual regulation of the force at each of the other wheels occurs with the MK C1, as it does with all of today's governing systems, with one intake valve and one outlet valve per wheel. Compared to conventional ESC systems however, individual force modulation occurs much more quietly and in better doses thanks to a much more precise actuator, sensors and refined valve technology.

The wheel brakes are particularly quiet and easy to adjust, regardless of the ACC force requirements due to all four wheel brakes being hydraulically connected to each other and activated by one single precisely positioned piston. This eliminates the well-known inaccurate pressure points that become visible after a reverse process at the latest, due to the effect of seals rubbing on a circuit-breaking secondary piston.

Compared to conventional hydraulic braking systems, the MK C1 offers greater braking force for safety systems that trigger emergency braking in hazardous situations due to sensor information (stereo camera): even for a heavy vehicle weighing around two tons, full brake force is available within 150 ms.

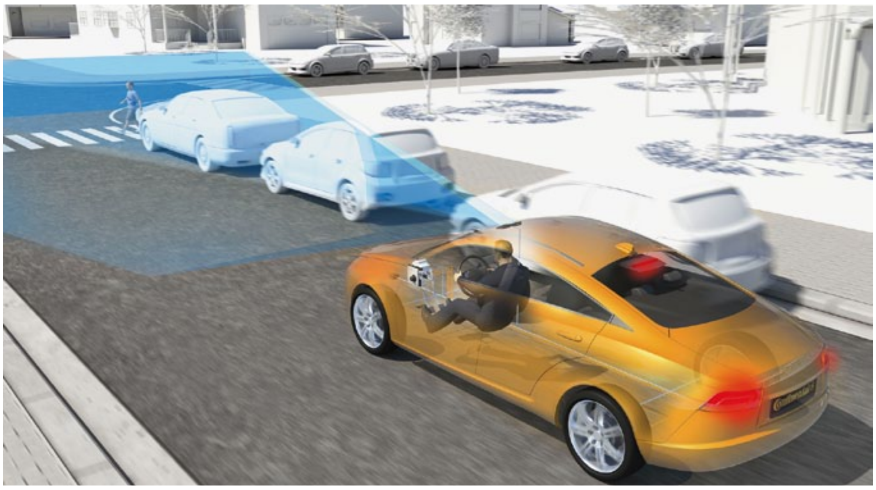
The primary reason for this is that the brake fluid needed to create braking force is already in the cylinder in front of the piston, whereas in a common system, the brake fluid must first be drawn into the cylinder and then compressed. Especially at low temperatures, the difference becomes noticeable due to the heightened viscosity of the brake fluid causing it to be drawn into the cylinder more slowly.



❺ Example of a measurement of the power required during ABS braking with the MK C1 on a dry asphalt road

SENSOR CONCEPT

As soon as the driver steps on the brake pedal, sensors register the pedal travel and pressure. A floating linear-inductive



❻ The dynamic nature of the MK C1 provides an especially good basis for assistance functions such as Advanced Emergency Braking System (AEBS)

sensor senses the motion of the pedal-piston linkage outfitted with a magnetic control. This sensor detects the driver's intention, primarily upon light braking. In this range, which statistically represents up to 80 % of all braking situations, drivers are accustomed to dosing braking force through pedal travel. If the driver wishes more braking power, the sensor sends a stronger signal to the brake force calculation. Both sensors are designed for redundancy and satisfy high standards of safety. In the case of a failure, they report the problem to the built-in electronic control unit (ECU). The ECU controls a linear actuator's electric motor in accordance with the signal emanating from the pedal piston. A sensor likewise senses the force thus generated, comparing it to the first signal. The system also calculates the position of the working piston as measured against the pitch of the ball screw.

HYDRAULIC FALLBACK LEVEL

Without an electric current, the valves that hydraulically uncouple the driver from braking at the wheels remain open, ③. This ensures that the driver maintains a mechanical-hydraulic fallback in the case of an electrical failure. Thanks to its well-designed system and master cylinder diameter, the MK C1 manages the legally mandated minimum deceleration of 6.43 m/s² at $F_{Pedal} = 500$ N (service brake) without electric power, even for a vehicle weighing more than two tons. Depending on local regulations, it may thus be totally sufficient to activate a yellow warning light if there is a failure in the braking system. Tests have indicated that drivers even get used to emergency operation quickly in nearly every type of vehicle.

RELEVANCE FOR PEDESTRIAN SAFETY

A test during the development of the system involved equipping a vehicle with the new electro-hydraulic braking system in order to compare it to an identical model with a standard braking system. The test car required 18 m before coming to a halt from 66 km/h. The car equipped with standard brakes was still going 38 km/h at the 18 m mark and required 5 m more to come to a halt. Even if this is an isolated result, and therefore not representative, it does indicate a possible advantage. The highly dynamic nature of the electro-hydraulic braking system presents new opportunities, for example, for triggering highly dynamic autonomous braking in conjunction with an advanced driver assistance function if the vehicle's sensors detect an imminent collision with a pedestrian, ❻.

SUMMARY AND OUTLOOK

The MK C1 integrated braking system from Continental offers functional advantages compared to existing solutions. The advantages include greater braking dynamics compared to conventional systems. The pedal feel is adjustable. There is optimum support for recuperation strategies that require not only an uncoupling of the pedal, but also quiet and highly dynamic control of braking force. Added to this is the fact that this modulation works quietly, even in the dynamic range of regulation.

What is more, the new brake-by-wire system weighs up to 4 kg less than a conventional braking system, depending on the basis of comparison. Greater space for deformation is available in a crash, thanks to the shorter design. Since the MK C1 is generally more compact than hydraulic solutions and is installed in the same place, it will be suitable for deployment in platforms in which hybrid versions of the same model will be offered. Special attention was paid to the transmission of unlimited force modulation to each individual wheel with regard to anti-slip functions.

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HAZARD DETECTION FASTER THAN THE HUMAN

6D Vision is able to reproduce human three-dimensional spatial and temporal perception and the detection of potential hazards in small, on-board, high-performance series-production-capable hardware for the very first time. Analogously to the human two-eye model, 6D Vision uses a stereo camera, from whose images the situation in front of the vehicle is analysed in real time with the aid of algorithms developed at Daimler.

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LEARNING FROM ACCIDENTS

In the development of pioneering driver assistance and safety systems, Daimler pursues what it calls its Real Life Safety Philosophy. Since 1969, the company has investigated accidents on German roads and streets. The findings resulting from this work provide important impulses for the development of new safety systems. Accident researchers from the passenger car sector today investigate around one hundred accidents a year. Based on photos, sketches, accident reports and sensor data, Daimler researchers create computer simulations that permit detailed conclusions to be drawn concerning accident cause, sequence of events in the accident, and accident consequences. This enables researchers and engineers at Daimler to develop technologies and systems that act to counter accident causes in a targeted manner and lessen the accident consequences.

A glance at accident statistics shows that there are three main causes for accidents with personal injuries: in first place, veering off the roadway, in second place, rear-end collisions, and in third place, collisions with road users crossing the vehicle's path.

Daimler researchers are working to consistently mitigate these major accident problem areas. Thus, the danger of veering off the road was counteracted by the development and standard use of the Electronic Stability Programme (ESP), which has demonstrably led to a significant reduction in accident figures.

For the second most common cause of accidents, which is rear-end collisions with the vehicle travelling in front, Daimler researchers have also developed solutions. Thanks to proximity control and braking assistance systems, many rear-end collisions can be either prevented entirely or their consequences can be at least noticeably mitigated.

6D Vision now concentrates on the third major accident cause. State-of-the-art stereoscopic camera technology and innovative algorithms make it possible, for example, to recognise children running onto the road or vehicles crossing the car's path as hazards even before they enter the vehicle's driving corridor, thus enabling the on-board electronics to brake or take evasive action before a collision occurs.

SPATIAL IMAGE PROCESSING

6D Vision is an image processing technology that brings together spatial stereoscopic vision and temporal motion estima-

❶ Two cameras generate three-dimensional measuring points

❷ A crossing pedestrian is detected before he arrives the driving lane

❸ Special image features are identified and pursued

tion, in other words, the optical flow. The system consists of two cameras and a high-performance chip on which the algorithms developed by Daimler run.

With the two cameras, 3D measuring points are generated, ❶. In the same manner as the human eye, the cameras can observe any given point from two different points of view. From these two visual impressions, the human brain generates an image with depth effect that makes it possible to distinguish between what is near and what is far.

This stereoscopic vision principle can now be generated electronically. For the engineers involved, it was a great challenge to implement stereoscopic vision efficiently in a vehicle-compatible control module, because existing systems such as Semi-Global Matching in their original form could not deliver meaningful results under unfavourable visibility and weather conditions.

The challenge was to develop a precise algorithm that enables the processing of the measuring points to be performed in a control module, although the camera system has a base of only 20 cm and a resolution of 20 pixels/degree. It makes it possible to generate a 3D image in real time with a range of up to 50 m, ❷.

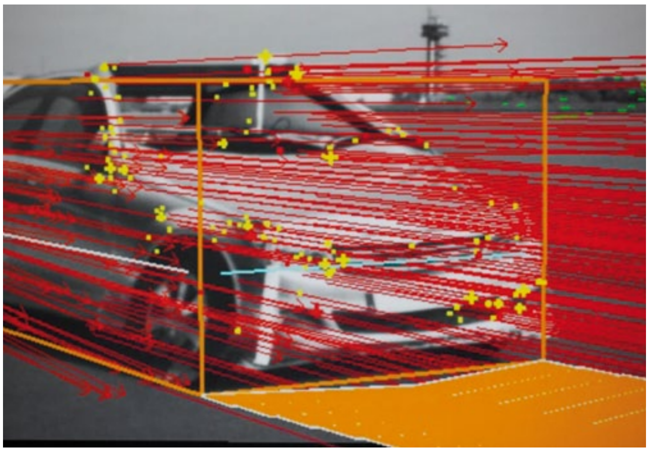
Temporal evaluation of the movement is carried out with the aid of the so-called optical flow. First of all image features adequate for further processing are identified in the pair of images retrieved by the cameras. These features are followed over time by the tracker, ❸. The shift of the image points detected is fused with the distance data obtained from the stereoscopic analysis by means of a Kalman filter to ensure a simultaneous determination of position (three dimensions) and movement of the relevant image points (three further dimensions). The six components of the state vector, the three position dimensions and the three speed dimensions, give the system its name: 6D Vision.

Through the recursive estimation process of the Kalman filter, every image point is – mathematically elegantly – modelled as a body with a mass and moving in space, momentarily on a straight trajectory and at a constant velocity, ❹. The state of a dynamic model under the application of appropriate measurements is then corrected in such a manner that the variance of the estimation error is minimised. In the Kalman filter, the image shifts of the optical flow and the corresponding stereoscopic disparity are used as measurements. Since the search sector for this can be drastically limited, the complexity of the calculation of optical flow and stereoscopic detection is significantly reduced.

Since the measurements are made relative to the vehicle, a determination of its own movement is also necessary. This can be achieved by means of the inertial sensors in the car or also from the image data. In each case, this is pos-

❹ The image points are modelled as bodies with a mass

❺ A determination of the vehicle's own movement is also possible



❻ The pixel-based analysis is supplemented by an intermediate representation

sible without any further image processing steps, ❺.

The decisive difference with respect to the conventional process is the possibility to measure shifts of any desired magnitude in constant computing time, even at high speeds or in bends. Conventional processes are not able to measure such large image shifts. In order to determine the optical flow in real time, Daimler developed a new process for the perception of movement: the so-called Power Flow. It delivers reliable results even for high vehicle speeds and in changing lighting conditions.

For this computing-time-critical application, pixel-based analysis is optimised by being supplemented by an efficient intermediate representation. Analogous to the pixel, which represents a single picture element, the so-called stixel represents a stick in real life. This model enables static road scenes to be described with only a fraction of the data quantity otherwise required. Thus, it provides information not only referred to the object height, but also about the free space for driving.

Unlike other differential systems, the 6D Vision concept leads to an integrative measurement, taking account of the image history. This is a fundamental requirement for its use in the automotive sector. By fusing spatial and temporal perception components, it is now for the first time possible to discriminate between stationary and moving objects from a vehicle in motion.

One great advantage is that the 6D Vision system is a "track before detect" concept. This means that motion is first detected on the pixel level, before the object itself is detected through the appropriate grouping with position and motion data. This has proven itself under unfavourable visibility conditions and for hidden objects, which in consequence enables moving objects to be reliably distinguished from static objects, even if the former are hidden by obstacles or other vehicles. Innovative aspects of the concept lie in the certain, rapid determination of position and velocity. Furthermore, the course of other road users can be predicted, thus preventing collisions with road users crossing the vehicle's path. This is possible even if they are partially concealed by another object. The vehicle system takes just 0.2 s to react to a pedestrian concealed by an object. By way of comparison, an alert driver would need around 0.5 s in order to perceive hazards that appear suddenly. Consequently, it can be said that, due to 6D Vision, the car "understands" and "reacts" faster than the driver. The effectiveness of 6D Vision supports the driver in precisely those situations that are particularly accident-prone because of the complexity of the traffic situation, for instance at street crossings and in roadworks areas.

REVOLUTION IN COMPUTER VISION

6D Vision is a basic technology that opens up new possibilities for future driver assistance systems in order to make Mercedes-Benz vehicles even safer in future, ❻. Conceivable systems could be, for example, Brake Assist for the event of road users crossing one's path, turning-off, crossing or left-turn assist and also evasive-action assist systems. Apart from safety-relevant driver assistance systems, 6D Vision can also help to reduce the strain on the driver and significantly increase ride comfort, for example with a Traffic Jam Vehicle Follow assist system or a roadworks site assist.

Since 6D Vision prevents accidents with more vulnerable road users, such as children running onto the road, Daimler will make this technology available to other automotive manufacturers.

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PEER REVIEW

PEER REVIEW PROCESS FOR RESEARCH ARTICLES IN ATZ, MTZ AND ATZ ELEKTRONIK

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.

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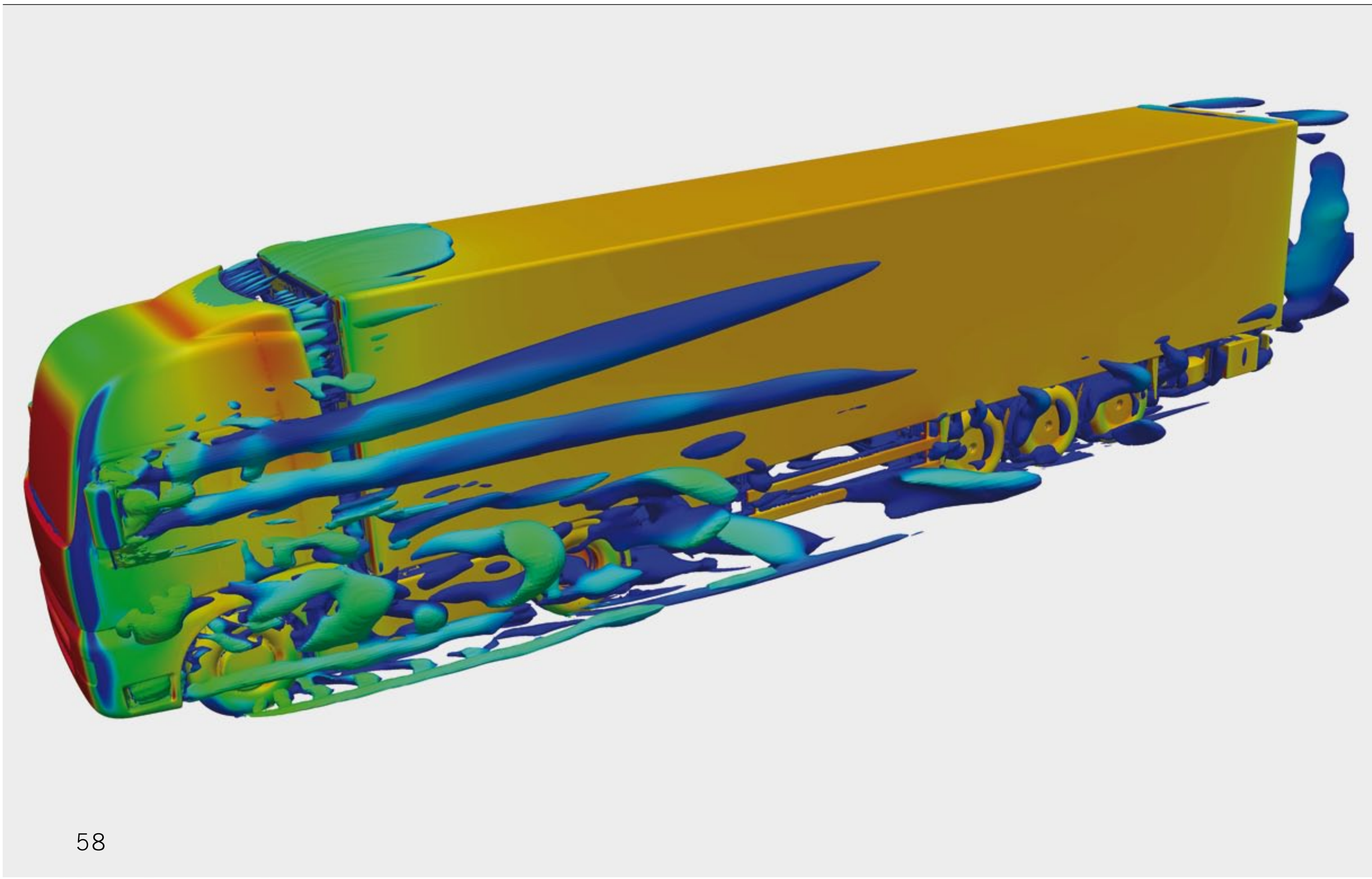
CONSUMPTION REDUCTION OF COMMERCIAL VEHICLE COMBINATIONS BY USING AERODYNAMIC PRINCIPLES

In terms of aerodynamics of commercial vehicles, there is tremendous hitherto untapped potential for optimisation that still remains to be seized in the future. In the FAT research project "Energy-efficient Tractor-trailer: Consumption Reduction at Commercial Vehicle Combinations by Using Aerodynamic Principles" FluiDyna GmbH pinpoints some of these opportunities on the basis of numerical and experimental investigations. However, fully exploiting the potential would require adjustment of some current European directives on commercial vehicle design.



1 SCOPE OF WORK

Increasingly scarce oil resources and growing transport volumes of commercial vehicles have an impact on the development of new generations of commercial vehicles. Tomorrow's trucks need to become more fuel-efficient, environmentally friendly and economic. While it is true that aerodynamics continuously improved in recent decades, there are still a lot of opportunities that remain untapped at present. One of the main reasons is that the European Union Directives 96/53/EG and 97/27/EG specify all dimensions of a commercial vehicle; when designing a truck, these dimensions are not to be exceeded. According to Directive 96/53/EG, for instance, the overall length of a truck shall not surpass 16.5 m. Directive 97/27/EG, however, allows some exceptions. As an example, the regulations on a truck's length do not take into account number plates, wiping and washer equipment or illuminating devices to name just a few. As this article will demonstrate, allowing even more exemptions which are relevant for the aerodynamic optimisation of trucks offers great potential in terms of fuel efficiency, environmental friendliness and economic effectiveness.

Up to now, most of a truck's existing space is being optimised with a focus on transport functions and drivability rather than aerodynamics – loading capacity is being made as large as possible and the driver's cab is being designed comfort in mind. Nevertheless, even a little slack in the current regulations would have a positive impact on aerodynamics and could therefore provide the industry with greater freedom for various fuel-saving measures.

Six major players in Europe's commercial vehicle industry joined forces and dedicated themselves to this challenge during about one year. The German Association of the Automotive Industry e.V. (VDA) provided financial support for this project. The collaborating partners were: Daimler, Iveco und MAN (product: tractor) and Kögel, Krone and Schmitz Cargobull (product: trailer). FluiDyna GmbH conducted all numerical and experimental investigations. Furthermore, FluiDyna was responsible for the development and assembly of a wind tunnel model and carrying out all of required wind tunnel tests.

The research project was based on the key consideration to which extent additional lengths, widths and heights (through aerodynamically optimised designs or aerodynamic devices) would contribute to a reduction of air resistance and thus fuel consumption. In real life, a commercial vehicle's height and width cannot easily be adapted due to the existing infrastructure (bridges, street width, etc.). This is why these parameters remained unchanged. Instead, the fundamental question was raised as to how selective length modifications provide room for optimisation and how large the potential improvements might be.

2 TRUCKS AERODYNAMICS: STATE OF THE ART

The forces F acting on the truck surfaces through friction F_r and pressure F_p are not only depending on the significant projected area A of the truck, but also road and weather conditions as well as geometric and functional parameters play a major role (Eq. 1). For this reason, the definition of the air drag coefficient c_d is widely used as a representative characteristic of the vehicle aerodynamics:

EQ. 1
$$c_d = \frac{F_p + F_r}{\frac{1}{2}\rho U_\infty^2 A}$$

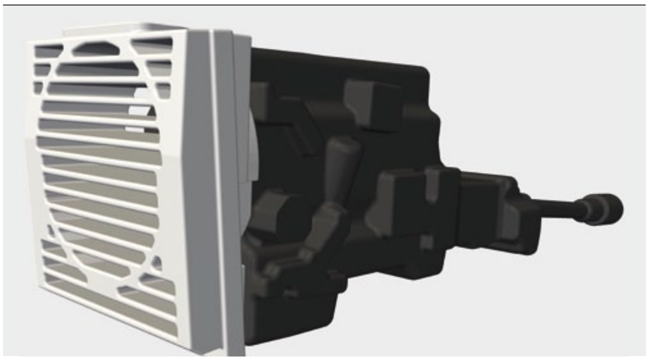
Present trucks air drag coefficients fall between a range of 0.6 and 0.8. As a comparison, classical c_d of present cars lie between 0.25 and 0.45.

Among past research on aerodynamics of commercial vehicles several measures were identified to be promising, focusing on the practicability and potential of drag reduction. The state-of-the-art literature built in this research project was a gathering of passive techniques found to influence the flow around trucks, according to a categorisation into front, length and rear design [1]. Active techniques were neglected because of their additional costs, weight or electricity consumption.

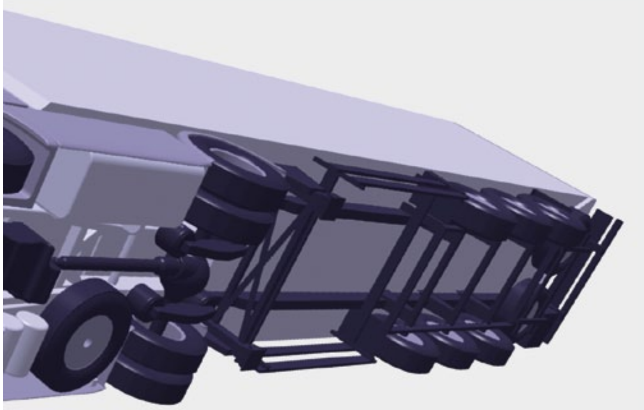
2.1 FRONT DESIGN

The flow around the tractor shall lose as little kinetic energy as possible and produce a tangential inflow for the long surfaces of the trailer parallel to the flow. A low-loss flow topology is achieved when the number and extent of detachment regions remain as small as possible. For this reason the design of the front radii is of primary

❶ Amber-like visualisation of the generic truck-tractor



❷ Generic engine with simplified cooling system



❸ CAD view of the trailer undercarriage

importance. Hence, those shall not overshoot a critical value r_{min} given by Eq. 2, so that the flow can remain attached [2]:

EQ. 2	$r_{\min} = 1.3 \times 10^5 \frac{v}{U_\infty}$

This applies to: v: kinematic viscosity and U_∞: inflow velocity. For example, at a representative speed of at least 60 km/h, r_{min} reaches a critical value of 117.5 mm.

2.2 LENGTH DESIGN

Key point is the most low-loss flow of the undercarriage. Not only the drag of the components of the undercarriage plays here a major role, but the turbulence generated there increases the energy losses of the flow very near the vehicle, hence diminishing the level of velocity around the body. Consequently, the pressure at the back end is lowered. In order to avoid these phenomena, several fairing systems were developed as well as so called teardrop-like trailers [3].

2.3 REAR END DESIGN

A fluctuating vortex system forms in the wake of a truck, followed by a time averaged stable recirculation region. There are two main possibilities to enhance the pressure on the back end. First, the flow can be controlled and redistributed to the back surface. Or the formation of the back vortices can be spatially delayed, so that the low-pressure region induced by these vortices remains away from the rear end surface.

3 GENERIC TRUCK FOR TRUCK RESEARCH AND INDUSTRY

A particular feature of the research project was the fact that it revolved around a generic – thereby manufacturer-independent – truck model which was specifically created for this purpose. This model assisted in conducting the investigations to quantify the aerodynamic opportunities adequately. Using Computer Aided Design (CAD) software, a representative commercial vehicle was designed. It contained geometric features that had been provided by the project partners. A model manufacturer constructed the model body on a 1:2.5 scale in order to be able to run the experimental measurements. Both numerically and experimentally, this model represented the basic geometric shape. All newly designed combinations – implementing aerodynamically-effective measures – were compared with the model and opportunities for drag reduction were deduced from it.

3.1 TRUCK-TRACTOR

For the external surface of the semi-trailer, the mean average of surfaces of the three manufacturers' geometries was taken locally and subsequently combined. Thus, a representative body shell was created without being able to recognise particular features of the truck companies involved in the research project, ❶. The roof spoiler of the generic base model was designed in a way that its angle of attack ensured a tangential transition to the upper edge of the semi-trailer. To simplify the generic base model, sun visors, vanes, a third mirror, horns and other manufacturer-related elements had been deliberately abandoned. However, some selected chassis components like spare tyre, drive components and fuel tank were taken into consideration because these parts have a particular impact on their surrounding flow due to their shapes and sizes.

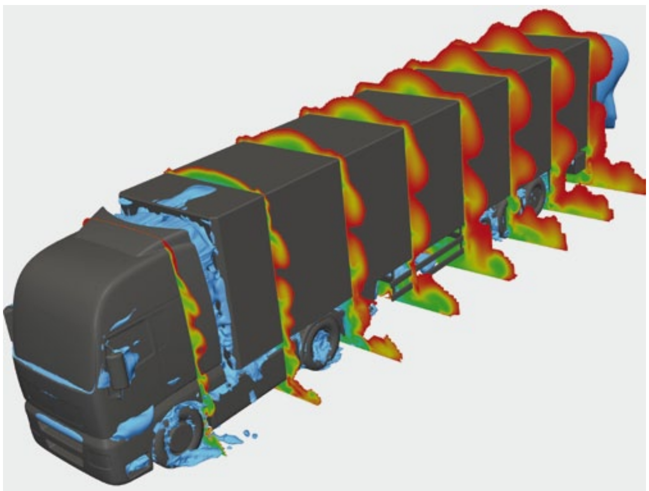
3.2 COOLING SYSTEM

The generic vehicle was equipped with a cooling air circuit for the engine, since it is known to significantly influence the flow around the driver cabin and the undercarriage. However, the modelling of a sophisticated engine compartment was avoided. The engine itself (made available from MAN) was simplified and integrated as a "black box", ❷.

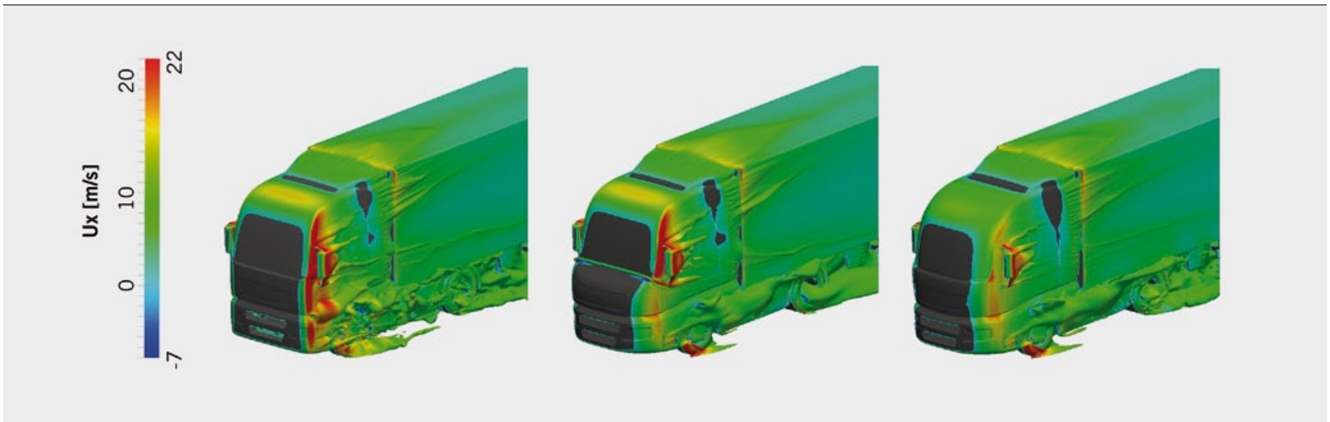
The usage of porous media should be avoided – both numerically and experimentally. Therefore the cooling system was designed as a prism and has slots to create a life-like decrease in pressure. The cooling system was placed 20 mm upright in front of the engine.

3.3 TRAILER

Concerning the trailer, the focus was laid on the design of the undercarriage because the load space remains almost the same for all manufacturers with a 2.55 m wide geometry (no refrigerated trucks were considered). The trailer undercarriage contents mostly the main chassis beam and the cross beams as well as two spare wheels at the rear of the trailer, ❸. All sidings were excluded, but a simplified pallet compartment on one side was incorporated, but no cladding (sides, undercarriage, etc.) were used.



❹ Boundary layer visualisation on the generic truck, at different cut-off; blue surfaces enclose regions of back flow



❺ Regions of loss of kinetic energy at the generic truck (left), a variant with extension of the engine compartment (middle) and a variant of complete extension of the front (right)

The axle positions and support elements were averaged from the three available geometries. The front of the trailer was designed with chamfer of 45° on the sides to produce the most representative flow around it. The top side edges possess a rounding of a radius of 25 mm.

4 AERODYNAMICAL INVESTIGATIONS

For the numerical simulations in this project the open-source CFD software suite OpenFoam was used. This software contains many standard solvers that calculate the solution of Navier-Stokes equations on a structured or unstructured grid for incompressible or compressible laminar or turbulent flows in or around complex geometries. In this research project, incompressible steady simulations were undertaken. The applied turbulence model was the SST variation of the k-ω model of Menter which already proved its efficiency in the automotive industry [4].

The computational grids for the numerical simulations in this research project were produced with the hexahedra dominant mesh generator Spider [5] which is an octree-based meshing method that produces boundary fitted, locally refined, conformal meshes with optional boundary layer cell rows in surface normal direction. The produced grids for this research project included at least 45 million cells, in order to obtain a satisfactory resolution of the grid in the vicinity of the truck surfaces.

All experimental investigations were carried out in the Daimler AG's wind tunnel, in Stuttgart, Germany. A six-component balance under the floor, where the truck model was fixed on, was used to measure the drag, hence requiring no strut correction. Several local and global flow pattern investigations were undertaken with the use of smoke lances. All measurements took place without extraction of the laminar boundary layer. The blockage remained fairly low (5 %), so that blockage corrections were not required neither. Reproduction measurements showed very small deviations (Δc_d = ±0.001).

4.1 RESULTS ON THE REFERENCE TRUCK

The general configuration was investigated numerically and experimentally. The aerodynamic drag coefficient obtained in the simulation was c_d = 0.442, against 0.424 obtained in the wind tunnel. This deviation could be explained by the length of the model which was for this wind tunnel slightly over-dimensioned. Nevertheless the results were in satisfactory agreement.

The air drag of the research project truck was, as expected, found to be lower than of conventional trucks, since the design was simplified and the level of detail quite reduced. ❹ shows that the tractor generated only few detachments and back flow regions, corresponding to an aerodynamically good flow, with minimal loss of kinetic energy.

The pressure distribution showed that a massive region of stagnation pressure developed at the front, but the pressure at the back end remained quite neutral, explaining the high overall pressure drag of the vehicle. Also in the gap between cabin and trailer front an almost constant pressure dominated the flow, creating on both sides reciprocal thrust and drag effects.

The boundary layer grew significantly in the vicinity of the symmetry plane of the truck, under the influence of longitudinal vortices on the roof of the trailer. Also the flow around the exterior mirrors induced strong and long vortices that generated major irregularities in the boundary layer thickness. Both effects combined created a very inconstant boundary layer profile close to the rear end of the truck, as shown in ④.

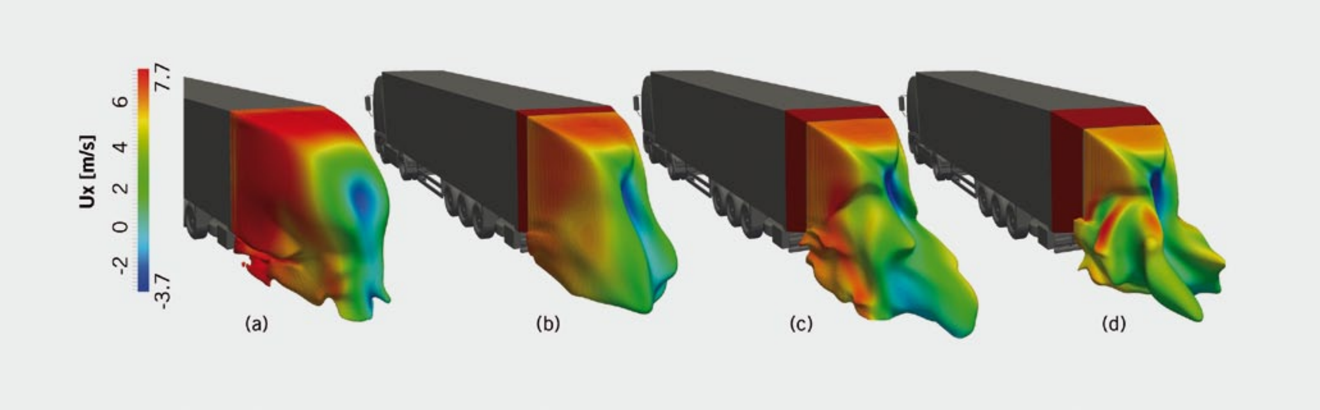
4.2 INVESTIGATIONS ON THE FRONT DESIGN

The front radii of the generic truck model were estimated in a range between 20 to 150 mm. However, Eq. 2 recommends, that they should not fall below a critical value (r_{min}) to avoid detachments. At a driving velocity of 80 km/h, where the simulations and experiment were undertaken, this critical radius can be calculated at 88 mm.

The front radii of the generic geometry were adjusted to the critical value by extending the front part of the tractor of about 500 mm forward, and enhancing the front roundings, by means of Exa PowerClay (a morphing simulation tool). As a result two geometries were created, shown in ❺: in the first one, the complete front part was

EXTENSION OF THE WHOLE FRONT	EXTENSION OF THE ENGINE COMPARTMENT
Simulation: Δc_d = -2.8 %	Simulation: Δc_d = -1.5 %
Wind tunnel: Δc_d = -4.0 %	Wind tunnel: Δc_d = -0.7 %

❻ Air drag differences for front design, in comparison to the reference



❼ Wake topology for the tested four-flap systems: generic truck (a), boat tail with 400 mm (b), boat tail with 800 mm (c), boat tail with 1200 mm (d)

extended about 500 mm, in the second one, only the area close to the engine compartment was extended, in the fashion of the front opening hood of US-American truck tractors. After those changes, illustrated in ⑤, the front radii were estimated in the desired range between approximately 85 and 800 mm.

⑤ shows as well that the major detachments of the lower area of the front (mostly at the junction between cabin and bumper) were reduced or totally removed in both variants. The velocity colour map of ⑤ displays the acceleration processes at the front edges of the tractor and highlights the fact that flow around the two elongated configurations did not accelerate as much as around the reference case, which is advantageous for the surrounding of the tractor and the inflow of the trailer. Also the region of stagnation pressure at the front decreased in size, as well as the intensity of the low-pressure zones on the sides of the cabin, and sank the pressure air drag.

Globally the air drag through those two extended designs was reduced. The numerical and experimental results agreed quite well for the prediction of the drag differences, ❻.

In the case of the complete extension of the front, the exterior mirrors were in the flow, whereas they were positioned in the generic configuration in a low-pressure zone. Therefore, they played a major role and contributed to about 10 % of the whole air drag, meaning that the use of camera systems instead of classical mirrors could drastically further sink the trucks air drag. However, those systems are until now prohibited in the European Union.

4.3 INVESTIGATIONS ON THE REAR END DESIGN

In the past research on truck aerodynamics, it has been proved that optimally designed flaps (fashioned as truncated Boat-tails) or blades at the rear end could be very promising for the reduction of air drag, since they can locally improve the flow topology and enhance the surface pressure at the rear end. In order to quantify the aerodynamic potentials of such devices, three rear end four-flap systems, shown in ❼, were designed with a constant angle of incidence of the flaps of 13° and varied lengths: 400, 800 and 1200 mm.

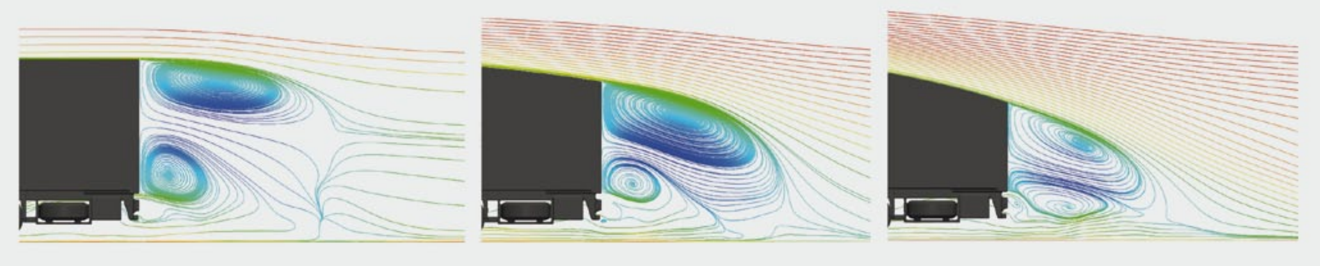
Numerical simulations resulted in a maximum drag reduction of almost 10 %, slightly overestimating the experimental results. Nevertheless, the agreement between both methods was satisfactory. Most of all, both experiment and simulation surprisingly provided the highest drag reduction for the design with the shortest flaps, ❽.

In all three cases, the improvement of the aerodynamic features of the truck was reached by decreasing the size of the wake and strength-

BOAT TAIL WITH 400 MM	BOAT TAIL WITH 800 MM	BOAT TAIL WITH 1200 MM
Simulation: Δc_d = -9.4 %	Simulation: Δc_d = -7.7 %	Simulation: Δc_d = -8.3 %
Wind tunnel: Δc_d = -7.7 %	Wind tunnel: Δc_d = -6.8 %	Wind tunnel: Δc_d = -6.5 %

❽ Air drag differences for rear end design, in comparison to the reference

❾ Three-flap system (400 mm) built at the rear end of the vehicle



❿ Streamlines at the rear end in the symmetry plane of the truck: generic geometry (left), tear-drop-like geometry with 3.5 m height (middle), tear-drop-like geometry with 3.0 m height (right)

ening the vortical structures at the upper part of the trailer back end. ⑦ attests how the flow topology drastically changed near the rear end of the truck, compared to the generic truck without aerodynamic devices. The upper vortices diminished in size but gained in intensity, so that more air could be brought to the rear end surface, increasing the pressure and generating additional thrust on it.

In the lower part of the wake, the topology changes remained secondary. That was an opportunity to test the role of the lower flap in the investigated four-flap systems. Removing the lower flap (❾ shows one of several three-flap systems, developed for wind tunnel purposes) resulted in a worsening of the aerodynamic features, compared to the four-flap system with the same length, of about 0.8 % (Δc_d = -6.9 % instead -7.7 % drag reduction compared to the reference geometry). This was an interesting result because rear end flaps in the lower part of the truck inhibit a bigger risk in the case of an accident with a passenger car.

4.4 INVESTIGATIONS ON THE ROOF DESIGN

Inspired from the so-called teardrop trucks, two variants with a rounding of the trailer roof were investigated in this research project via numeric simulations. The modification of the roof started at the position of the first trailer axle and smoothly rounded the roof from a 4.0 m height until the rear end at a height of respectively 3.5 and 3.0 m.

A comparison of the wake pattern between the reference truck and the two developed teardrop-like geometries could be undertaken with ❿. The significant reduction of the wake led to an increase of the pressure on the rear end surface and an attenuation of the kinetic energy losses. The two tested designs let the air drag of about 6.8 % (height: 3.5 m) and 10.0 % (height: 3.0 m) down. However, their use would diminish the maximum freight quantity and could only be compensated by an extension of the trailer.

5 CONCLUSIONS AND OUTLOOK

The air drag reduction Δc_d is often transformed into an estimation of fuel consumption reduction ΔDL/100 km. This coarse estimation is mostly used when there is no possibility to perform real driving tests, as in this research project. It is based on following Eq. 3:

EQ. 3

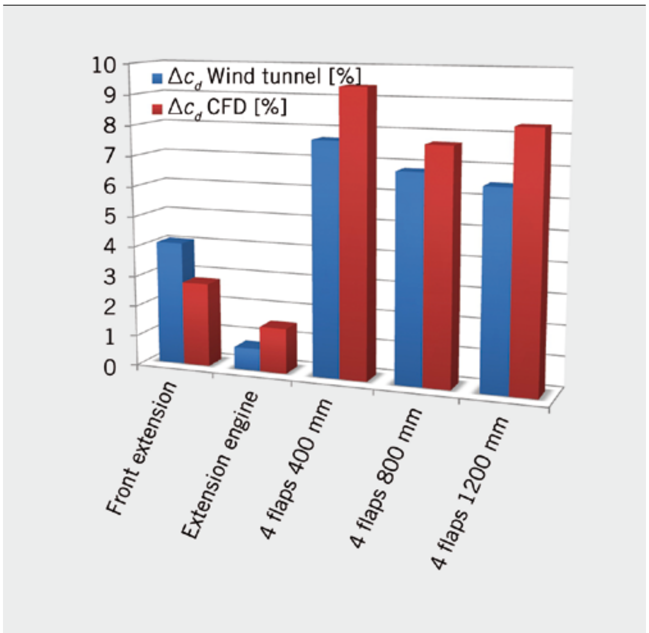
$$\Delta c_d = M \times \Delta DL/100\,\text{km}$$

The multiplication factor M is an attempt to take into account real traffic, load and weather conditions. Its value was adjusted to $M = 3.5$, in agreement with the OEMs involved in this research project.

The outcomes of this FAT research project show that, merely by optimising the truck's front design (increasing front radii), aerodynamic improvements may lead to a potential reduction of air resistance of up to 4.5 %, which corresponds to 1.3 % in fuel reduction according to Eq. 3. Compared with current truck geometries, this value represents a significant improvement as fuel consumption is reduced. However, these measures require considerable technical efforts and are therefore expensive to put into practice.

With respect to the rear design, all measures that were tested enable a significant quantitative advantage indeed. The most efficient configuration – with a 13 ° angle of attack – enabled reducing fuel-consumption levels by up to 2.7 %. Only an extension by 400 mm would be necessary with this configuration (variants that were even longer either had the same or less impact). If the EU Directives 96/53/EG (Entire Length) and 97/27/EG (Aerodynamics) were to be adjusted, allowing longer trucks than presently allowed, this would have positive economic and environmentally friendly impacts on truck transport.

This research project compared traditional methods of aerodynamic design. As ⓫ illustrates, numerical and experimental inves-



⓫ Direct comparisons between numerical and experimental estimations of air drag changes tigations tended to result in rather similar air resistance differences even though numerical approaches used to overestimate most air resistance changes.

FluiDyna will address the challenge of so-called European swap-bodies (18.75 m long) and EuroCombis (25.25 m long) using the same method. In 2011, EuroCombis were authorised for initial driving tests in Germany. Over the next few decades, they should become a more environmental-friendly and more efficient transport option.

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