Prospects of Holistic Purpose Design by the Example of the Electric Vehicle Concept “SpeedE”

Dipl.-Ing. Sven **Faßbender**, Univ.-Prof. Dr.-Ing. Lutz **Eckstein**,
Dipl.-Ing. MBA Björn **Hören**, Dipl.-Ing. Johannes **Stein**, Dipl.-Ing. Lars **Hesse**
Institut für Kraftfahrzeuge, RWTH Aachen University, Aachen, Germany

Dr.-Ing. Peter **Urban**
Forschungsgesellschaft Kraftfahrwesen mbH Aachen, Aachen, Germany

Summary

The “SpeedE” vehicle concept focuses on the innovation potential of electrically powered vehicles. It offers a research and development platform for partners from industry and science enabling joint development and dissemination of innovative technologies for future vehicles. This paper presents some of the technologies currently being analysed and developed in the project “SpeedE” and explains how they can support in enhancing the acceptance of electric vehicles.

1 Introduction

In the last years the automotive industry has made considerable progress in the area of battery electric vehicles (BEVs). Today, different companies, from small and medium-sized enterprises to large OEMs, offer state-of-the-art BEVs in various segments. However, the market penetration of purely electrically powered cars is still far behind the expectations or hopes of both society and government. For example only 1,419 of the 296,722 new passenger car registrations in Germany in June 2012 were BEVs [1]. In order to achieve the target of the German government namely having 1,000,000 BEVs on the roads in 2020, these figures have to improve significantly.

Analysing customers expectations related to BEVs can help in understanding the reasons for their hesitant emergence. Different market studies indicate that in general, customers are open-minded about BEVs. However, the expectations of most of the respondents in particular regarding costs and range are clearly not met by BEVs on the market today [2] [3] [4]. It is likely that BEVs will achieve mass popularity only if offering added value to the customer. Greener individual mobility itself can be a key added value if the gap in performance and cost between BEVs and conventionally powered vehicles will be reduced by technical advances. Consequently, research in this area is essential to facilitate the success of BEVs in the long term. However, in the present paper a complementary approach to enhancing customer acceptance of BEVs will be presented. The basic idea behind that approach is to gain added value by establishing innovative functions enabled or at least improved by inherent benefits of electric propulsion. Excellent controllability of electric motors is only one simple example of these inherent benefits that can be used to fully exploit the prospects of purpose design and provide functions and features that serve as competitive differentiators and selling propositions of BEVs.

2 Approach

Concerning several vehicle properties, current BEVs still do not achieve the level of comparable conventionally powered vehicles. Mostly this affects so called performance properties like range. According to Kano [5] the customer is aware of these performance criteria. There is a steady and proportional correlation between improvement or decline in performance criteria and customer satisfaction. This means depending on the level of fulfilling a performance criterion by according invest in development and production the customer will be satisfied or dissatisfied. In contrast to this, the customer does not expect attractive properties. Consequently, the absence or decline of attractive properties will not cause dissatisfaction. However, as soon as a product or more specifically a vehicle offers attractive features enthusiasm and satisfaction are provoked. In addition, the customer satisfaction rises progressively with the improvement of attractive properties. In total this means that for attractive properties even small fulfilment or invest can significantly improve the customer´s attitude towards the product.

When comparing a current BEV and a similar conventionally powered vehicle, the decline in some performance criteria like range for example is likely to be significant enough to cause dissatisfaction of certain customers, as illustrated in Fig. 1. In the same figure two options to regain satisfaction are indicated.

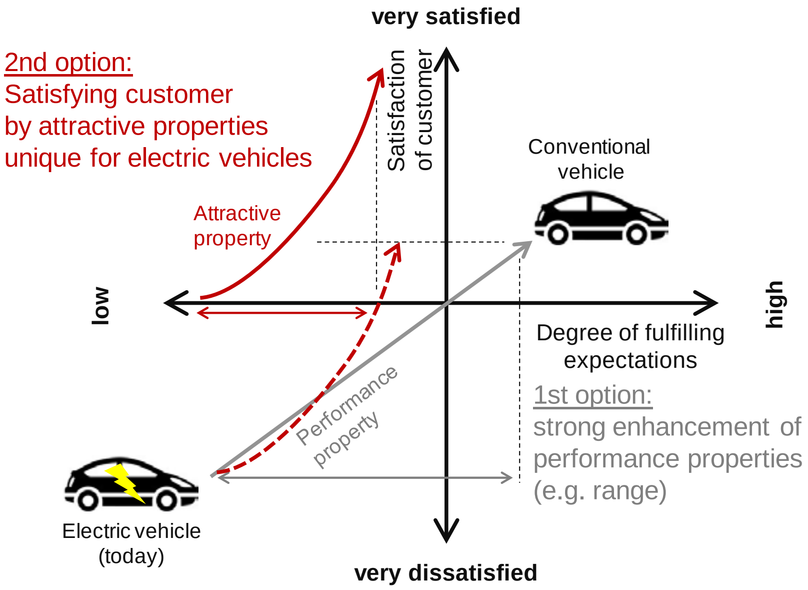

Fig. 1: Options to achieve customer satisfaction based on the Kano model [5]

The first option is to improve the performance property of the electric vehicle and bring it to the level of the conventional vehicle. This will demand significant invest in development and/or production. The second option is to accept the decline in the performance property but add an attractive property to the BEV that is ideally based on an inherent benefit of electric propulsion like for example a unique package or a vehicle dynamic function. This feature will serve as a competitive differentiator with regard to the conventionally powered car. As an attractive property it may immediately enthuse certain customers. Thus, with manageable invest a level of customer satisfaction comparable to the conventionally powered vehicle can be achieved.

The approach to enhance customer acceptance of BEVs presented in this paper will focus on the second option. The idea is not to emulate conventionally powered vehicles but to design unique BEVs that are attractive to the customer exactly because of their uniqueness. This will result in benefits and drawbacks compared to conventionally powered vehicles but should form a balanced compromise between customer values and invest. Certainly, the unique, differentiating features will be specific to the vehicle type or segment, and certain vehicle types will be more suitable for this approach than others. In this paper, an electric sports car will be regarded as an example.

In an initial step, unique features suitable for the concept have to be determined. Some of the concept features selected for the “SpeedE” electric sports car concept are shown in Fig. 2.

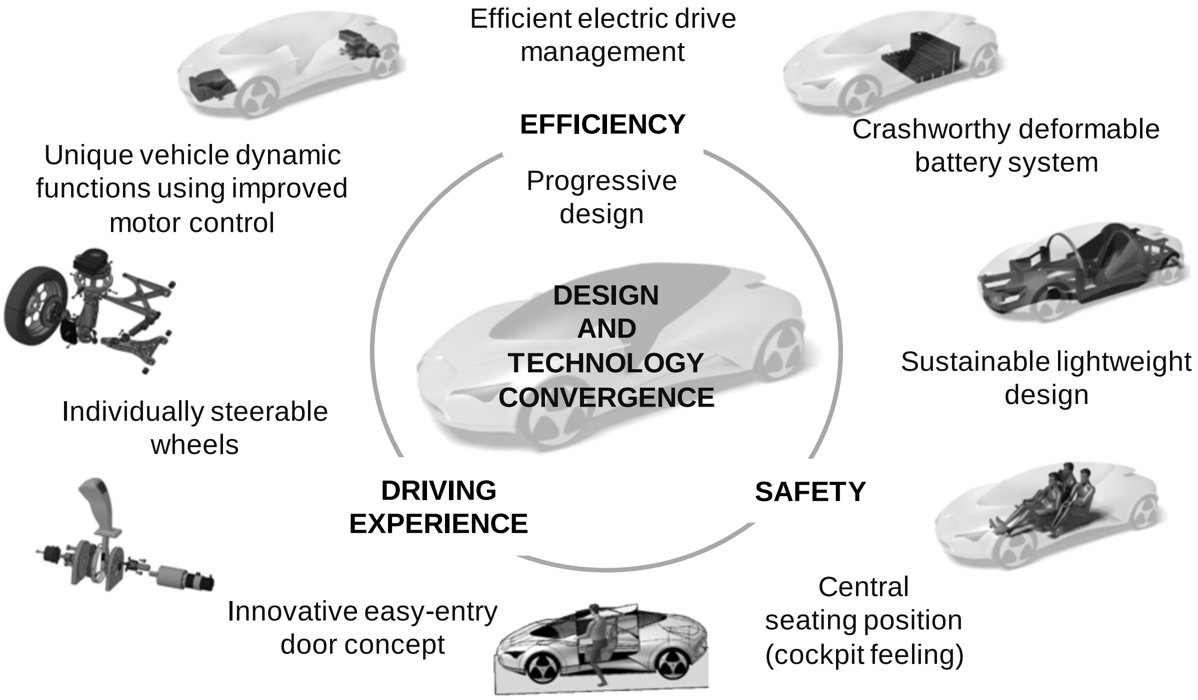

Fig. 2: Abstract of unique features of the “SpeedE” vehicle concept

Not all of these features are based on inherent benefits of electric propulsion. The idea is rather to have consistent features that in total generate a unique experience of the vehicle and prevent comparison with the expectations related to conventionally powered vehicles resulting from habit. The vehicle shall be regarded as unique from the very first moment. Starting from the exterior appearance (progressive design) via ingress (vertically rotating sliding doors and “step-in entry”), driver seating position (central) and control of the vehicle (sidesticks) to driving functions (e.g. turning on the spot) experiencing the “SpeedE” concept will be completely different from conventional vehicles.

3 Concept Features

As a demonstration and development platform the “SpeedE” vehicle concept and in particular its innovative features will be developed in several internal, bilateral and collaborative sub-projects. For some of these projects the state of development is presented in the following sub-chapters.

3.1 Progressive Design

The progressive exterior design of the “SpeedE” vehicle concept distinguished the car from conventional super sport cars at the first glace. A huge challenge with innovative and advanced vehicle design is to achieve a car that appears really new to the user’s eye but at the same time fulfils formal design rules as well as technical and legislative requirements. This requires good cooperation and communication between designers and engineers during the design and technology convergence process. In order to improve this process, ika and the faculty of Transportation Design of the university of Pforzheim, one of the world´s leading schools in automotive design, have started a cooperation in research and education. The “SpeedE” vehicle concept is the first joint project in this partnership. Some impressions of the initial strategy in design development and refinement are shown in Fig. 3.

The design themes for the “SpeedE” vehicle concept have been developed in Pforzheim. Two groups of designers were challenged to design the exterior and the interior respectively for an advanced electric sports car. In this initial phase the boundary conditions were limited to the approximate main dimensions, the number of passengers and the space requirements for the main package components. In addition the designers should consider that the vehicle will be controlled via sidesticks instead of a steering wheel and think about an appropriate ingress strategy. From the final proposals of the designers, an exterior design and an interior design have been selected for further development. A characteristic element of the chosen exterior design is the rotationally symmetric greenhouse. In this example “form follows function” in order to enable rotatory sliding doors.

The first step in the design and technology convergence process was to match the exterior design proposal and the rough package. This was done in Aachen in cooperation between the exterior designer and the vehicle engineers in iterative steps using 2-d package drawings and full-scale tape renderings.

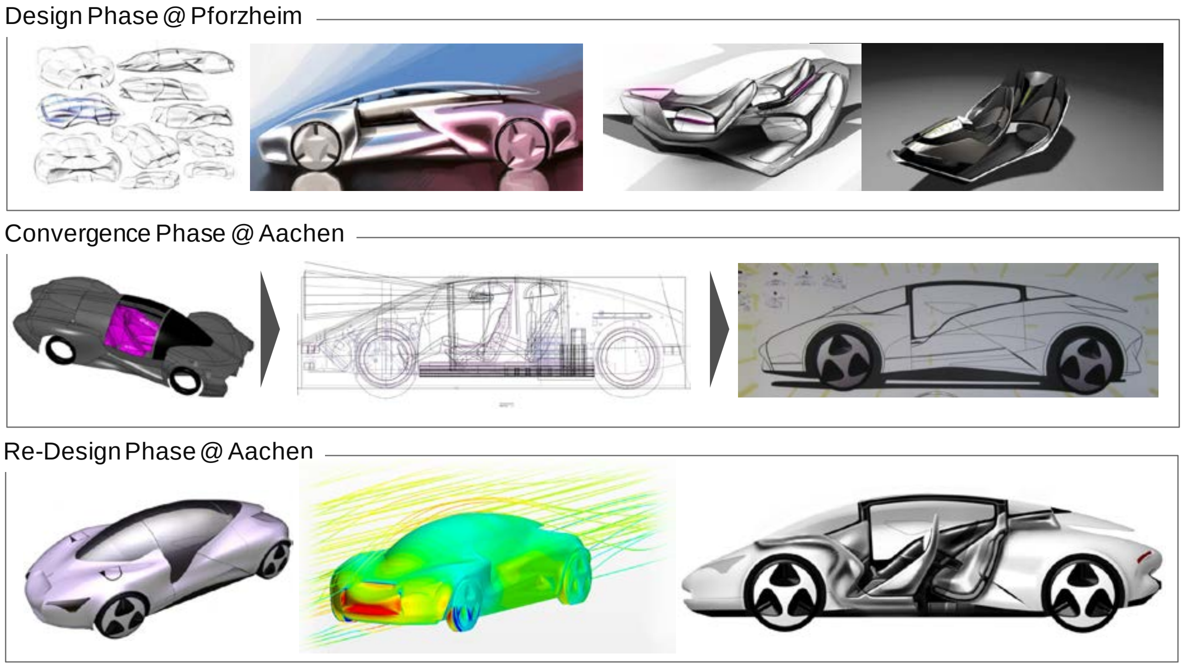

Fig. 3: Initial design and technology convergence process

After achieving both a coherent exterior design and compliance with the main technological and legislative boundary conditions, hard-points were agreed and frozen. Based on these hard-points the 3-d models of the package and the exterior were re-designed simultaneously. The final design was analysed in terms of principal aerodynamic behaviour and checked for technical and legislative demands that require a 3-d representation. It was also made sure that the interior design proposal matches the exterior design and the package. The design and technology convergence for the interior will be carried out at a later stage of the project since further information, e.g. about the body structure, is required.

The successful and fruitful cooperation between the faculty of Transportation Design of Pforzheim University and ika in the “SpeedE” project has lately led to the foundation of the German Design Studio Aachen (GDSA). The GDSA offers studio and office space as well as design equipment at the facilities of ika and fka in Aachen in order to intensify the cooperation beyond the project “SpeedE”.

3.2 Driver Centred Occupant Package

The central seating position of the driver is one of the elements of the “SpeedE” vehicle concept supporting the unique driving experience. Certainly, the idea of positioning the driver in the centre of a vehicle itself is not new. Few production cars, e.g. the McLaren F1, and many concept cars follow that package approach since it offers several benefits like:

- Improved side crash protection (considering statistical occupancy rates)
- Free choice of side for ingress/egress
- Possibility to reduce cross sectional area (aerodynamic drag reduction)
- Omission of left-hand / right-hand driving derivates

However, there are disadvantages associated with that layout as well. Reduction of comfort is a major drawback. Ingress comfort is reduced since the driver has to overcome a longer distance from the sill to the seat. Especially for flat sport cars this can be difficult. If, in addition to the driver, two passengers have to be accommodated they are usually positioned slightly behind the driver and next to each other. In order to optimise the cross-sectional area of the greenhouse and the head clearance of the rear occupants the seating orientation of the occupants may be moderately angular as shown on the right side of Fig. 4. This is in order to minimize width and length of the vehicle. However, it results in less seating comfort of the passengers compared to the comfort of the front passenger in a traditional 2-seater layout as shown on the left side of Fig. 4.

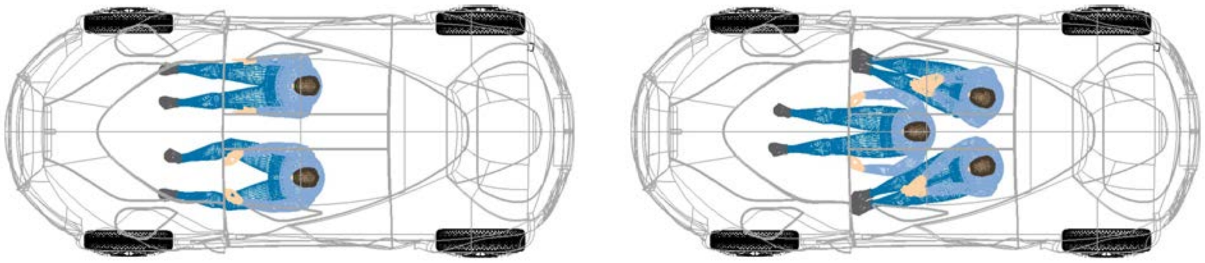

Fig. 4: Comparison of 2-seater and driver centred 3-seater layout

For the “SpeedE” vehicle concept, comfort is improved by a unique easy entry strategy and an increase of the passenger cell in length by 350 mm compared to a 2-seater reference sports car in conventional mid-engine design. Using a compact electric twin-motor transversally installed at the rear axle instead of a longitudinally installed combustion engine enables to increase the passenger cell in length without changing the overall vehicle length.

Ingress of the driver becomes more comfortable compared to traditional 3-seater sport cars like the McLaren F1 by using a rotatory sliding door. This door system enables to provide a large door opening in direction of the vehicle centreline. The CAD-model of the “SpeedE” vehicle concept with the left rotatory sliding door opened is shown on the left side of Fig. 5.

The key idea of the ingress strategy is to allow the driver and passenger to step into the vehicle before taking the seat. In order to determine the minimum door opening size or maximum roof strut width respectively required to enable that strategy and in order to evaluate the actual ingress comfort a seating buck study has been carried out. For that purpose a seating buck with variable interior dimensions, like roof strut width, sill height etc., has been designed based on the exterior design model (Fig. 5 left) and build up (Fig. 5 right).

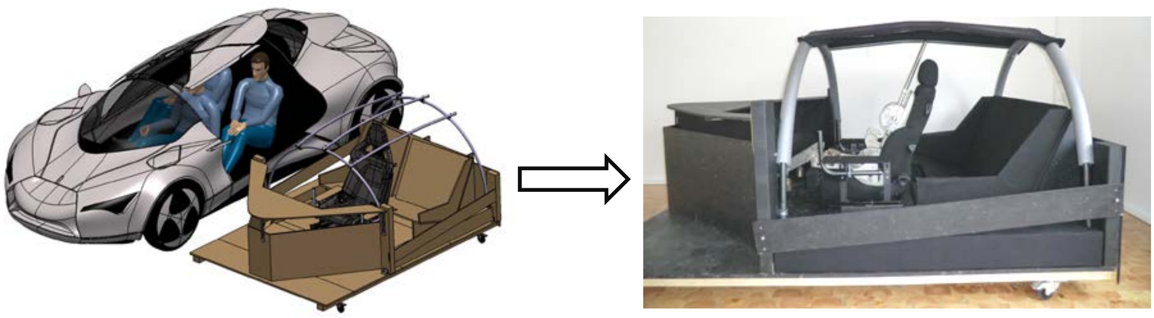

Fig. 5: CAD development and build-up of seating buck

The seating buck study involved 46 test persons from 21 to 63 years of age. The study has shown that a lateral door opening width of 310 mm (edge of opened door to interior sill trim) is sufficient to enable the step-in ingress strategy. All of the test persons used the step-in strategy but chose different strategies to take their seats afterwards. The strategies mainly depend on the size of the test persons. The ingress strategy used by most of the test persons is shown in Fig. 6. Due to the low vehicle height, the feeling of ingress comfort depends strongly on the age of the test person. While most of the test persons younger than 45 years of age evaluate the ingress comfort indifferently on a scale ranging from 1 to 5 the test persons over 45 years of age evaluate the ingress less comfortable. However, the study proved that persons up to 2000 mm of height are able to get into the driver seat without major difficulties.

Fig. 6: Most common ingress strategy chosen by test persons

Within the seating buck study several ergonomic parameters of the interior layout have been analysed and defined. This includes for example the position of the sidesticks (armrest 370 mm above the floor and vertical stick axis 240 mm ahead of the H-point) or the accepted sill height (upper edge in step-in area 400 mm above ground).For the rear passengers the major comfort constraint is the limited head clearance. Different seating strategies have been analysed in order to improve the head clearance of the rear passengers. However, the study has shown that the preferences regarding the seat arrangement in the second row are individual to the test person. In the study a commonly preferred design has not been identified. Thus, the rear seating row of the “SpeedE” vehicle concept will be designed to allow a tandem seating arrangement and a triangular seating arrangement the later as shown on the right side in Fig. 4. The backrest angle will be adjustable around the vertical axis allowing occupants to choose the angle of their seating orientation.

3.3 Vehicle Dynamics Control

A unique vehicle control and innovative driving dynamics functions along with the resulting driving experience clearly distinguishes the “SpeedE” vehicle concept from conventional cars. The innovative vehicle dynamics control system is one of the unique concept features focussing on the benefits of the electric drivetrain. It is enabled by establishing a system of control loops including the active sidesticks, individual steering actuators for both front wheels, individual electric drives for both rear wheels and the control input of the driver as well as the feedback of the total vehicle. The simplified communication scheme of the vehicle control system is shown in Fig. 7.

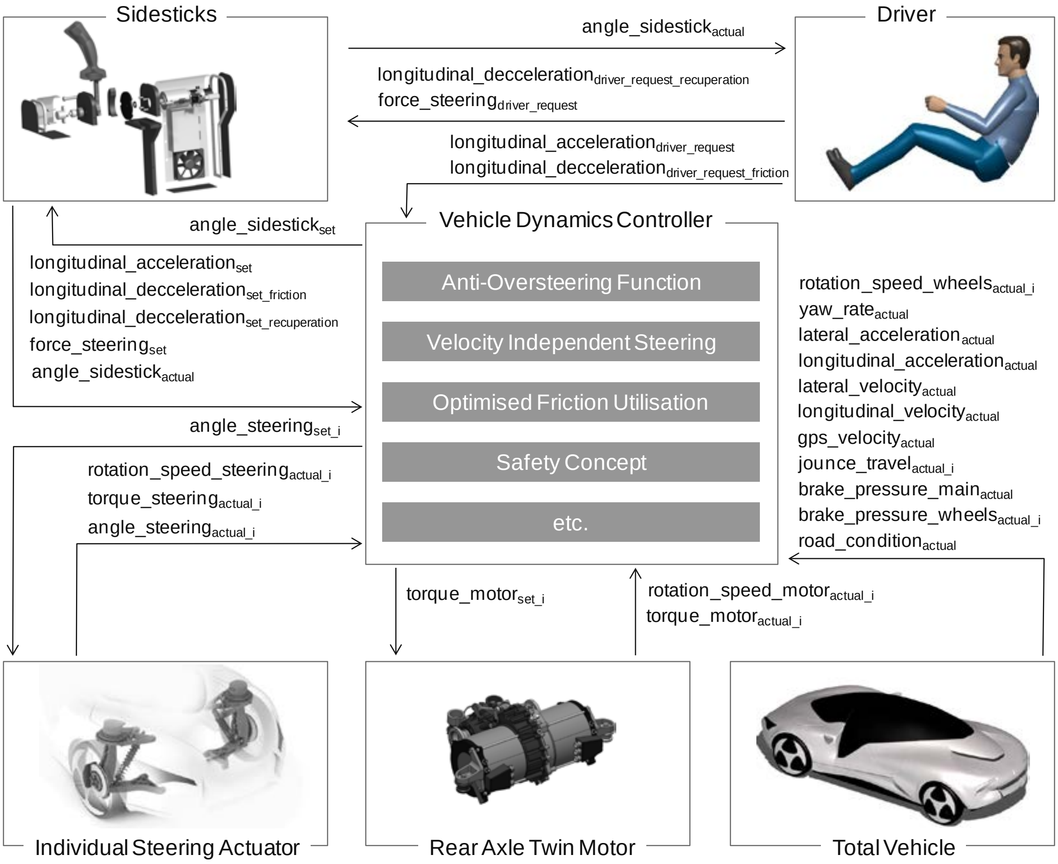

Fig. 7: Simplified vehicle dynamics control scheme

In terms of longitudinal dynamics the main control input is set by the driver conventionally via an accelerator pedal and a brake pedal. However, there is an additional proportional button to control recuperation. This button is part of the sidesticks that are used for defining the driver´s input regarding lateral dynamics. The driver controls lateral dynamics normally with both hands via two force-coupled sidesticks. Accordingly, the added total force input represents the driver´s steering request. Based on that, the steering inclination for each wheel is calculated using a single-track-model. The driver gets feedback on the actual radius of curvature of the vehicle trajectory via the angular position of the active sidesticks continuously set by electric motors integrated in the sidesticks. Controlling the radius of curvature of the trajectory is intuitive to the driver and offers the advantage of decoupling turning radius and turning speed. For further information on the sidestick control please refer to [6].

To enable innovative vehicle dynamics functions, central control interventions can be superposed to the input for both steering actuators, both rear axle motors and all friction brakes. Total vehicle sensor information is used to determine required interventions. In particular, the joint control of individual single-wheel steering in the front and individual single-wheel drive in the rear enables unique functions. Amongst others the vehicle will be able to turn on the spot, adapt toe-in based on friction requirement and reduce the risk of oversteering.

Since the vehicle control concept is based on a full steer-by-wire system the safety concept is essential. Previous proposals to realize steer-by-wire systems deploy redundancies of components and network architectures resulting in disadvantages such as increase of weight and package space or high costs.

An alternative approach is the utilization of degraded operating states, which presently are used in vehicle subsystems, such as drive train emergency programs, only. For the safety concept development of the “SpeedE” concept vehicle, this approach is adopted across subsystem boundaries reducing the number of necessary redundancies. For the example of a steering angle error on one of the steered wheels, other actuators of the vehicle are able to compensate this failure and the intended driving trajectory is maintained within reasonable limits. Further information on the safety concept can be found in [7].

3.4 Integrative Vehicle Architecture

The influence of electric propulsion on the vehicle architecture has been controversially discussed ever since the latest revival of the interest in electric vehicles. In fact, the distinctive differences in drivetrain package compared to conventionally powered vehicles justify the analysis of benefits resulting from vehicle architectures optimised for the package of BEVs. However, conversion design approaches for the vehicle structure appear most efficient due to economics of scale and ease of complexity management as long as e-mobility is regarded as an additional drivetrain option for conventional models only. If though a vehicle shall holistically be tailored to the benefits of electric propulsion, following a purpose design approach for the structure is reasonable. This is because differences to conventional vehicle architectures and body structures arising from the full exploitation of new package alternatives or implementation of different components may disable integration in conventional platform families. In case of the "SpeedE" vehicle concept several unique concept features have influences on the architecture and the structure:

- Optimized battery integration (package freedom and crash safety)
- Maximisation of interior space due to compact electric motor
- Joint arrangement of high voltage drivetrain components
- Increased wheelhousings for 90° steering inclination
- Large door openings for easy entry of centrally positioned driver
- Omission of steering wheel

Certainly, not all of these features represent direct consequences from the exploitation of the benefits of electric propulsion. As indicated earlier, some features are to support the unique driving experience. The basic layout of the "SpeedE" concept car is shown in Fig. 8.

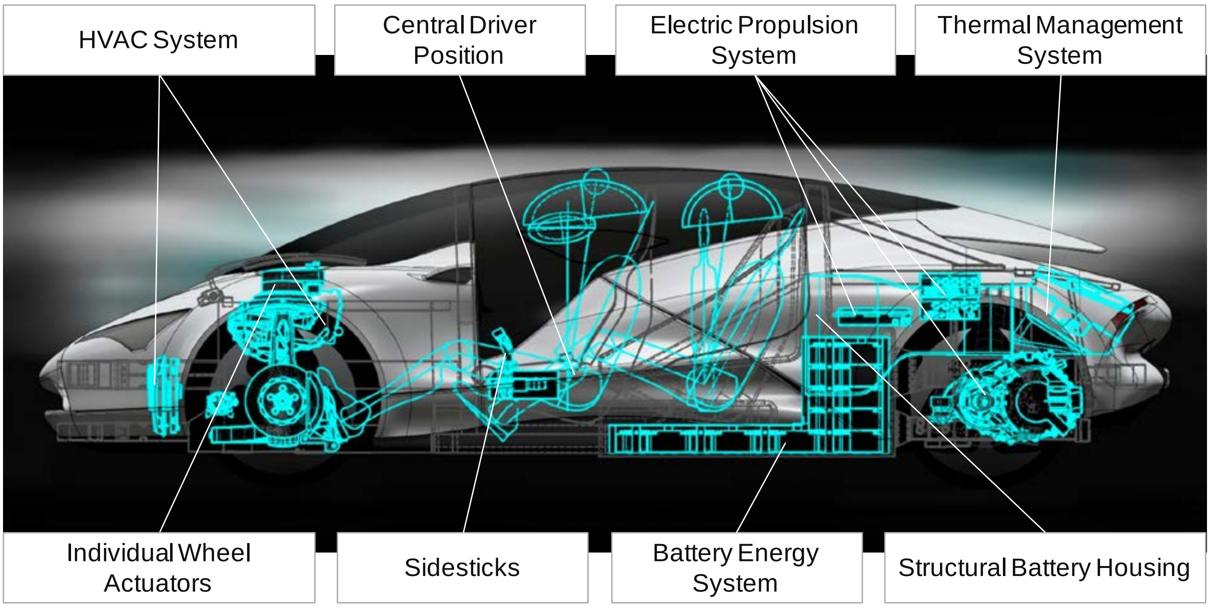

Fig. 8: Main package components

The central element of the architecture is the battery system. The battery modules are located behind the backrest and under the seats of the rear passengers. The battery housing made from CFRP itself forms a structural element of the car body. All of the electric drivetrain components are located together close to the battery in the rear in order to minimize high voltage wiring harness.

For reducing complexity the thermal management system has been packaged close to the electrical drivetrain components. A separate HVAC system is installed in the front. Replacing the steering wheel with sidesticks offers free space in the cockpit. This can be used to improve downward visibility and enables to evaluate alternative restraint strategies.

The body structure is a key element of the vehicle architecture. It has to support the unique package components, form a stiff and durable frame and manage energy and deformation in the event of a crash. For the “SpeedE” vehicle concept these tasks shall be fulfilled while focussing on simple design and efficient as well as flexible battery integration. Targeting for low volume production the body structure will be in multi-material spaceframe design featuring a multi-functional central tub made from CFRP with the battery housing structurally integrated. In addition to the so-called battery monocoque the body consists of the sub-assemblies front section, rear section and greenhouse as principally indicated in the centre of Fig. 9. The structure is covered by body panels.

While the completed body is in multi-material design, the single sub-assemblies are made of a unique material in order to simplify design, manufacturing and recycling. The weight target for the body structure is < 250 kg.

Crash management in BEVs is a specific challenge since, unlike the fuel tank in conventionally powered vehicles, a large volume of highly deformation sensitive battery cells has to be packaged in a way that the single cells are not inadmissibly compressed in the event of a crash. For this reason battery packs are often positioned far away from the deformation zones of the structure. This strongly confines the freedom in package design. In order to improve the safety of battery systems and allow packaging batteries in areas that are potentially exposed to moderate deformation in a crash, ika has developed a deformable battery system together with partners from university and industry in the project “e performance” fonded by BMBF [8]. Certainly, the battery cells of this system themselves are still sensitive to deformation. However, as indicated in Fig. 9, the standard “18650” consumer cells used are pressure resistantly bonded in so-called “macro cell” modules. Due to their trapezoid shape these “macro cells” are able to slide aside if pressure is applied to the battery housing during a crash. The space required for sliding is generated by deforming thin-walled tubes of the liquid cooling system as indicated in the lower right side of Fig. 9.

In the “SpeedE” vehicle concept the deformable battery system is used for side crash management. The aim is to ensure crash safety of the battery system while maximising the tolerable lateral dimension of the battery pack. The lateral dimension of battery packs is strongly confined by the side crash intrusion area in particular for the pole crash.

In contrast, the free deformation zones in the front and in the rear of the “SpeedE” vehicle concept are long enough to absorb the energy of typical accidents and prevent deformation of the battery pack. This is shown by the example of the 80 km/h rear crash according to FMVSS 301 in the top of Fig. 9. However, it has to be mentioned that most of the standardized crash test are not sufficient to evaluate battery safety, since they have been design to evaluate occupant safety only. Thus, for dimensioning the complete system of battery and body structure for crash safety, additional and adjusted load cases should to be considered. For example, the pole crash should be analysed not only for an impact in the area of the driver´s head but for several locations along the bodyside. Further research is necessary to come up with more detailed proposals for crash test requirements and protocols for electric vehicles.

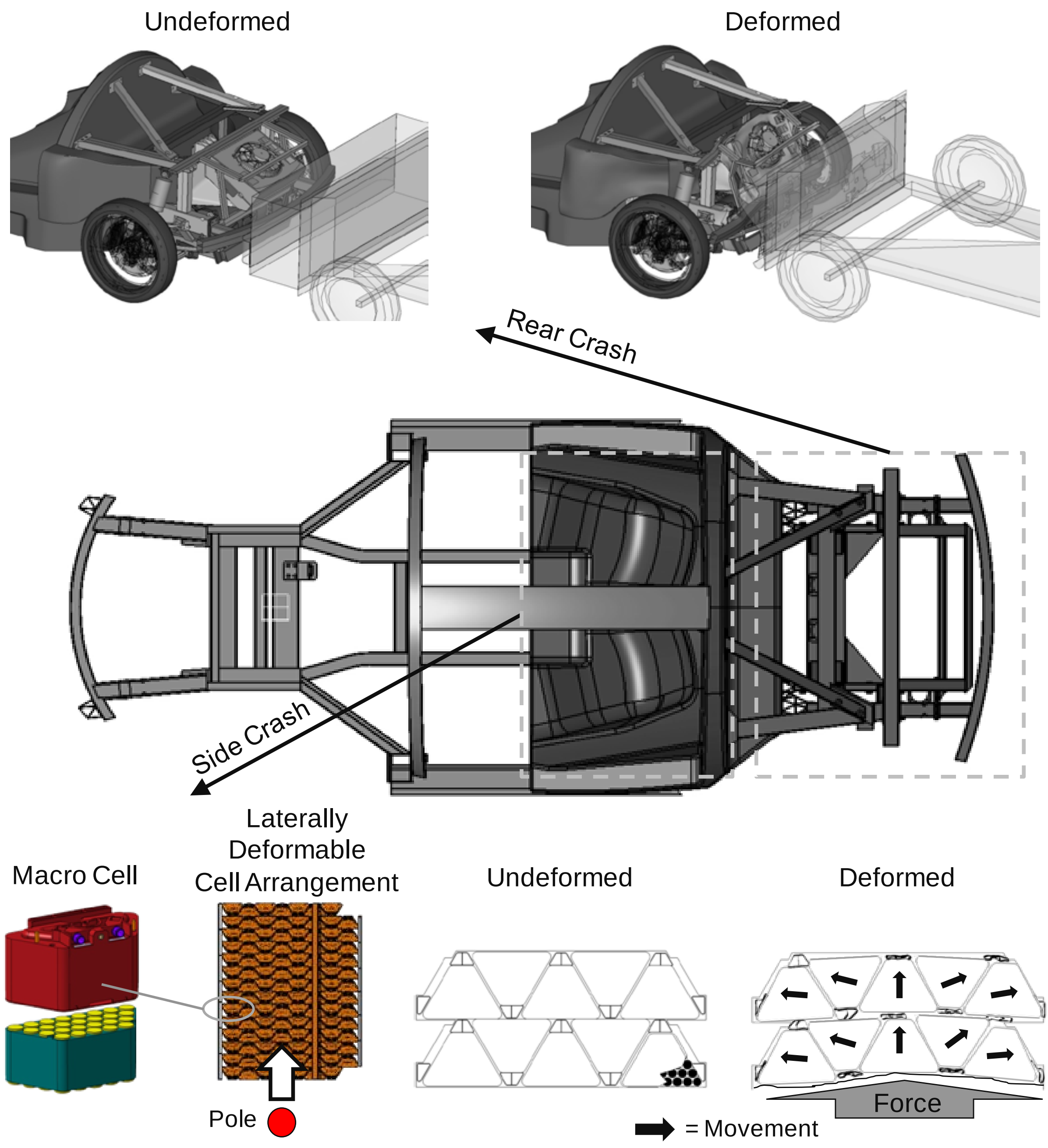

Fig. 9: Crash management concept

4 Outlook

This paper has provided an overview of the “SpeedE” vehicle concept and presented some of the technologies currently being developed based on that research platform. In the course of the associated projects the different technologies and features will be further developed, designed and optimised to a detail that allows prototype assessment. By including further innovations, technologies and research topics, the “SpeedE” vehicle concept may result in a full vehicle prototype offering a real experience of the innovations.

However, the progressive “SpeedE” concept car mainly serves as a test environment and a demonstrator for the technologies included. This means its purpose is rather to validate and gain attention for the certain innovations than to form a commercial product. Consequently, the specific technologies are not designed for exclusive use in this concept or in the sports car segment in general. In fact, the technologies themselves are explicitly intended to be applicable for various vehicle types from small urban vehicles to delivery vans. The innovations may come form or result in more detailed individual projects.

5 Definitions, Acronyms, Abbreviations

BEVs	Battery electric vehicles
OEM	Original equipment manufacturer
ika	Institut für Kraftfahrzeuge RWTH Aachen University
fka	Forschungsgesellschaft Kraftfahrwesen mbH Aachen
GDSA	German Design Studio Aachen
H-point	Hip-point; theoretical, relative location of an occupant's hip; approximately the pivot point between the torso and the upper leg of the 95 percentile male in normal seating position
CFRP	Carbon fibre reinforced plastics
HVAC	Heating, ventilation and air conditioning
BMBF	Bundesministerium für Bildung und Forschung

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