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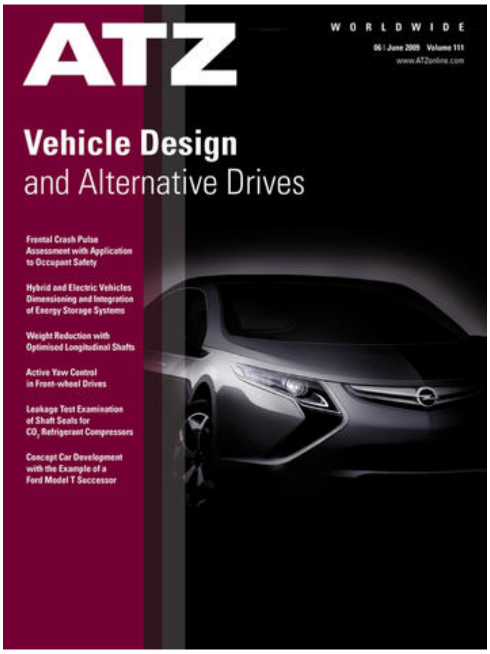

ATZ .worldwide 6/2009, as epaper released on 19.05.2009
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ATZ

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New Energy

Dear Reader,

The Vienna Motor Symposium, which can without exaggeration be described as a Mecca for powertrain developers, has been one of the industry's leading events for 30 years. In their entirety, the presentations that Professor Lenz brings together with his untiring élan serve as a barometer for the very latest development trends.

So which way is the arrow pointing on the scale between the persistent further development of the internal combustion engine and the hype surrounding the technical revolution known as the electric drive system? I believe that both extreme positions remain unchanged, but gradually a new voice of reason is starting to be heard. One that realises that crude oil, or even energy itself, is gradually becoming a scarce resource. Dr. Warnecke, who presented key findings of a Shell study, pointed out that, by 2030, the CO_2 emissions caused by German car drivers will fall by only 23 percent if the focus remains only on the optimisation of existing technology. This is a reduction that seems almost irrelevant when set against the background of higher levels of goods traffic and a global increase in mobility. Only if electric and hybrid drive systems gain a significant market share of 60 percent will it be possible to reduce CO_2 emissions by 38 percent by the year 2030.

For the first time in Vienna, there were no longer discussions on abstract hybrid designs but presentations of real developments that will be on the roads this year. And the view into the future, for example with compact range extender powertrain modules from AVL and FEV, was not 'Powerpoint engineering' but was tangible in the form of functioning prototypes on the companies' stands.

Once again in this issue, we provide you with detailed information on the very latest approaches – not only in the design cover story but also about lightweight design on page 24.

Johannes Winterhagen
Vienna, 8 May 2009

Johannes Winterhagen
Editor-in-Chief

ATZ WORLDWIDE
06|2009

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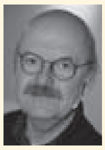
Vehicle Design and Alternative Drive Concepts

The Author



Professor
Wolfgang Kraus
is Professor for Vehicle Concepts and Design at the Department of Vehicle and Aircraft Engineering at Hamburg University of Applied Sciences, the institution succeeding the well-known "Wagenbauschule" (Germany).

Ever since the invention of the car, there has always been a conflict between technical possibilities and design. Electrification is now offering new degrees of freedom for vehicle design – but also new restrictions. Professor Wolfgang Kraus from the Hamburg University of Applied Sciences provides ATZ with a view into the future.

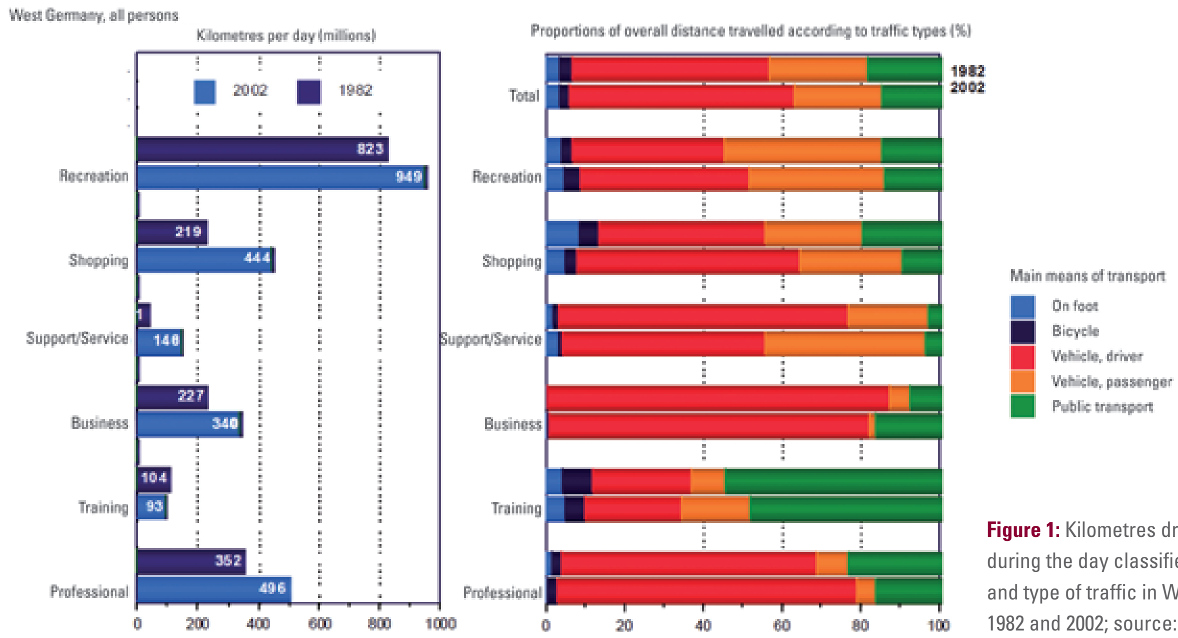


Figure 1: Kilometres driven per person during the day classified by purpose and type of traffic in West Germany, 1982 and 2002; source: [1]

1 Introduction

There is no doubt about the necessity to provide sufficient mobility in an advanced society. It is an undisputed fact that the car has been making a key contribution towards economic growth for more than 100 years. It not only allows people to reach their destination quickly, safely and with little effort. The enjoyment of mobility and the pleasure of ownership are also other reasons for buying a car.

Today therefore, cars are both an expression of our wishes and our necessities at the same time. Will people's mobile behaviour essentially change due to current developments? The answer is probably "yes and no". Basically speaking, new technologies have always resulted in changes in our social behaviour and therefore have influenced our product world. And vice versa. Such conflicts are the driving force behind the constant process of development and the design of our environment. At the same time, changes in the development of vehicles take place step-by-step and tend to be evolutionary.

The importance of road traffic is clearly shown in a study carried out by the German Federal Ministry of Transport [1]. It clearly shows that the number of kilometres travelled per person is increasing for all types of use, **Figure 1**. Cars are becoming more important especially for leisure use. For business travel, cars have even lost relative market shares. Therefore, in future it is not a question of whether we need individual car transport but of how we design it. In addition to the more objective and rational reasons for driving a car, people will always take pleasure in movement. This has always inspired designers and coachbuilders to build cars that express driving pleasure through their design.

Today, we need to ask the question to what extent new technical concepts will have an influence on vehicle design. Or will the new technical possibilities even initiate changes in our mobile behaviour? It is clearly impossible to describe in detail at this point what future cars will really look like. But show cars and prototypes have already revealed certain trends that will influence future automotive designs in their shapes and proportions.

Design is an integral component of the overall development of a car and will be influenced not only by engineers but will also inspire designers towards creative solutions. The final shape is therefore not the result of an individual person but, in effect, the result of all people involved in the process and their interactions. Therefore, every new car is the expression of this unique process that cannot be copied.

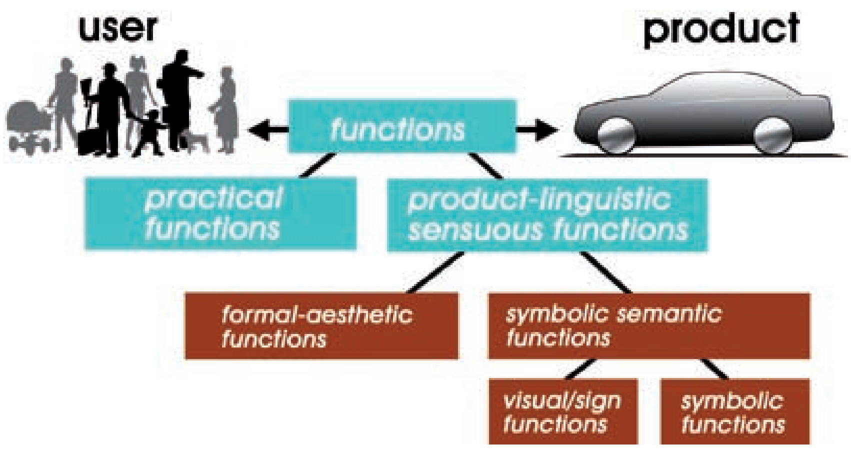


Figure 2: The tasks of design, design of product-language functions

2 Parameters for Design

The design of cars is a complex process in the conflicting area of functional economic, ergonomic and aesthetic criteria. The most important task of designers in future will be to design a car body according to the following requirements:

- presentation of a brand-typical design or corporate design for a company
- design according to the requirements for product-language, sensuous contents, **Figure 2**. In the ideal case, the form and the contents are combined in symbiosis. A sports car must also be clearly recognisable as such.

But we must be careful. Aesthetic model concepts are subject to constant change. Technical changes have always found their expression in the design of a vehicle. I would call this area the stylistics of cars. Stylistics can certainly follow fashion trends that are subject to what tend to be short-term changes. Long-term influences can be expected from the area of new technologies. In this respect, the current development towards alternative drive concepts is a more exciting development for designers than has been seen for a long time.

Fundamentally, cars are and will remain dynamic objects. This dynamism in particular must ultimately be visible in the design, regardless of the type of drive system that powers the vehicle.

3 The Influence of the Drive System on Body Design

The vehicle concept can be subdivided into three basic areas: the drive concept, the chassis and the body. Of these three areas, it is the body that is the determining component which, in its design, is most strongly influenced by the user's requirements. Our behaviour, our wishes and our objectives with regard to mobility determine body shapes. For example, families prefer vans, gardeners might choose a pickup, while fun-seeking drivers will buy a convertible. The engine power might vary considerably within a user spectrum.

Our mobile behaviour and therefore the user spectrum are not expected to change fundamentally. Derived from the package that determines how our vehicle is used, most vehicle shapes can be represented with just a few design elements, **Figure 3**. However, the conditions and solutions resulting from new technical possibilities may change. For users, the design of the drive system is ultimately of secondary importance provided that their desire for mobility is fulfilled and the car remains affordable.

3.1 The Package

The proportions of vehicle bodies are determined in particular by the arrangement and position of the technical components in the vehicles. The sensible arrangement of all components related to the overall vehicle concept is called the vehicle package. Basically, this is a driveable vehicle that does not yet have its exterior and interior design — in other words, the body.

In the package process, all the technical and design-relevant arrangements of the units and subassemblies are fixed in their dimensions at an early phase long before the actual design process. The package is designed in joint coordination between the development engineers and the design team. Beginning in the early phase of vehicle development, the package process is a constant process of coordination right through to the so-called 'design freeze'. An excellent vehicle concept must not necessarily lead to a good design concept and, conversely, an attractive design concept might result in a poor result from a technical or economic point of view. Finding the right balance requires that both sides make acceptable compromises.

In the package process, all dimensions are derived from the product strategy to form a dimensional concept according to the module or platform strategy. The following aspects are considered:

- the main dimensions of the sub-assembly modules for the drive system and chassis
- all important interior components, ergonomic specifications and the legally and functionally important exterior body contours
- comparisons with the contours and dimensions of direct competitors and the company's own models
- a list of innovations and competitive advantages
- verification of compliance with legal requirements related to the target markets

For designers, the main task after the definition of the package, **Figure 4**, is the formulation of the exterior and interior design within defined dimensional limits. Their job here is to use their design skills to convert the dimensional specifications from the package process into an attractive shape in an optimum manner.

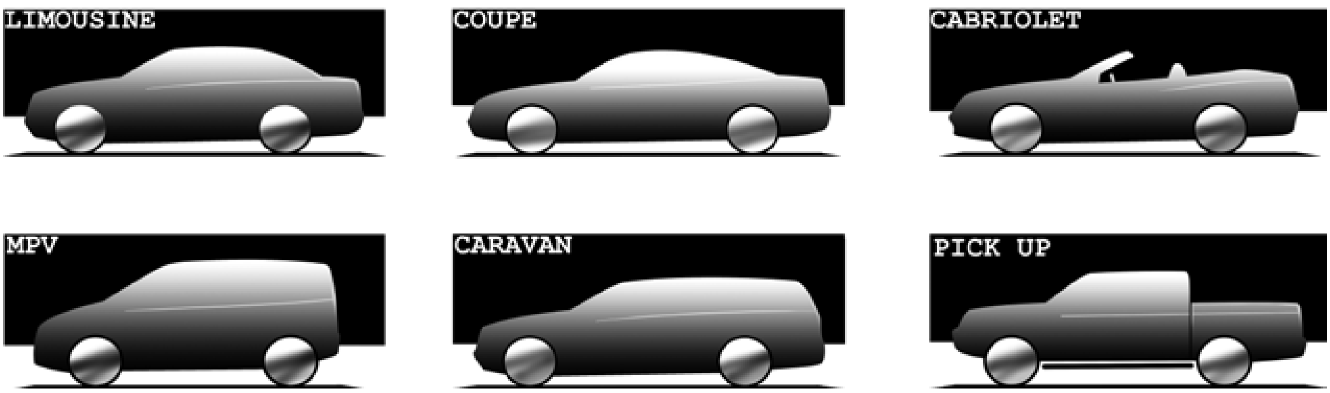


Figure 3: Basic body design

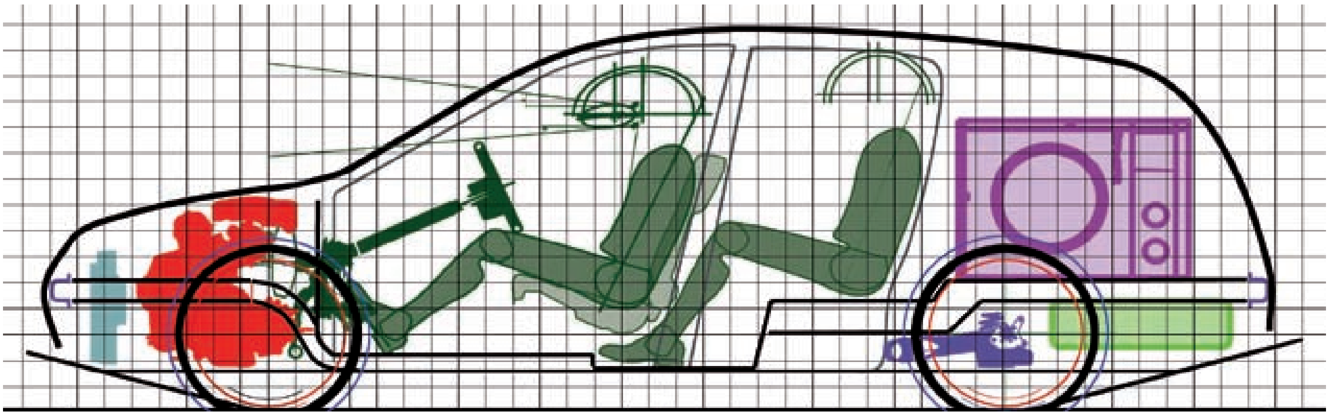


Figure 4: Concept package

One example of many other coordination problems is the way in which the proportions are influenced by the design concept of front-wheel-drive and rear-wheel-drive vehicles. In front-wheel-drive vehicles with longitudinally installed inline six-cylinder or eight-cylinder engines, the front overhang ahead of the front axle must be increased due to the length of the engine and the arrangement of the transmission and steering. The distance to the bulkhead and the root of the windscreen is shorter. This also has influences on the arrangement of the doors and how easy it is to get into or out of the car.

In rear-wheel-drive vehicles, the engine can be moved further towards the occupant space. As a result, the proportions are improved in favour of smaller vehicle overhangs. In this way, they correspond to the wishes of most vehicle designers.

In vehicles with a large front overhang, the large overhangs are concealed by strong tapers or sweeps in the frontal view and large transition radii from the front to the side. For the design, axle positions close to the vehicle ends are beneficial, **Figure 5**. This design appears more stable and emphasises the centre of gravity between the axles. Small vehicle overhangs also seem much more dynamic.

For the transition scenario towards hybrid vehicles, no fundamental changes to today's vehicle proportions are to be expected. As can be seen in current vehicle concepts, the main problem is that of installation space for additional components. The basic package structures usually remain unchanged. As a general tendency, vehicles with a large volume or underfloor concepts are particularly well suited for this drive system. A sandwich floor can be particularly easily installed in MPVs and vans.

Installation space management is also important for fuel cell and electric vehicles, but from a completely different perspective. The challenge here lies in creating the necessary installation space for the energy storage systems (the batteries) and the fuel cell stacks. For the design and proportions of these vehicles, greater degrees of freedom are available with regard to the wheelbase and the overhangs. When one considers the studies published and the small-series vehicles produced so far, it is clear that underfloor solutions are preferred. Related to this are higher seating positions (H-point positions) and greater roof height. As far as the axle positions and vehicle overhangs are concerned, designers can implement their wishes more easily. Examples are the concept vehicles from Mercedes-Benz and General Motors. Whereas Daimler implements a sandwich floor concept in its A-Class and B-Class vehicles, GM showed a

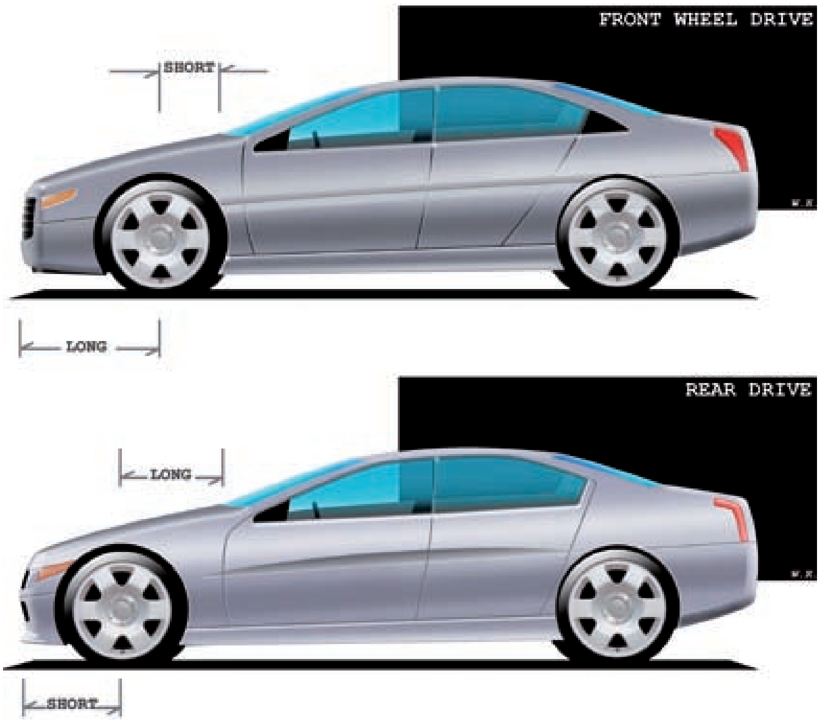


Figure 5: Proportion study, front vehicle overhang

Figure 6: GM Skateboard and Mercedes-Benz A-Class

completely new approach as long ago as 2003, which was described by the company as a 'skateboard', **Figure 6**.

Another challenge for design is presented in particular by sports cars, in which a customer expects a flat and low silhouette. In the course of the further development of energy storage systems, improvements are to be expected in particular for the package design and the proportions of the body.

For fuel cell and electric vehicles however, completely new package concepts will also be possible. These drive concepts offer a series of possibilities for repositioning the subassemblies within the body. This offers the designer new degrees of freedom in design. If all subassemblies are distributed in the floor or installed cleverly beneath the seats, new seating arrangements and storage space concepts are conceivable. This also applies to new door arrangements and interesting concepts for getting into and out of the vehicle. Storage spaces can be completely redefined.

Or will these new concepts also bring about a change in our understanding of the silhouettes of sports cars? It is not yet possible to make any clear statements on this. The vehicle concepts presented so far do not have any uniform package definitions.

In studies carried out with students at the HAW Hamburg, a change in the understanding of future vehicle shapes can certainly be recognised. Even though the sporty character of vehicle designs is emphasised by young designers, initial approaches to new proportions are becoming apparent, **Figure 7** and **Figure 8**.

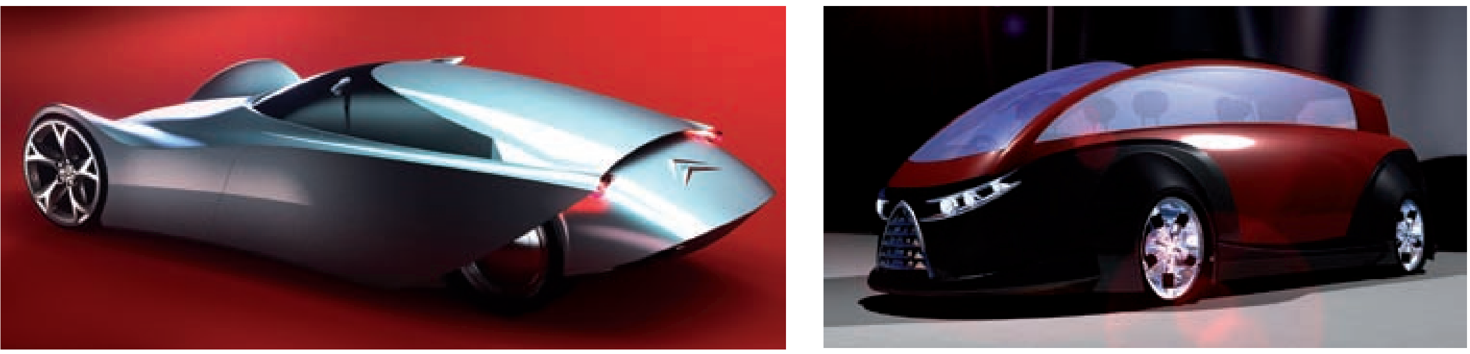


Figure 7: Vehicle studies at HAW Hamburg (sources: Voigts, Bussmann)

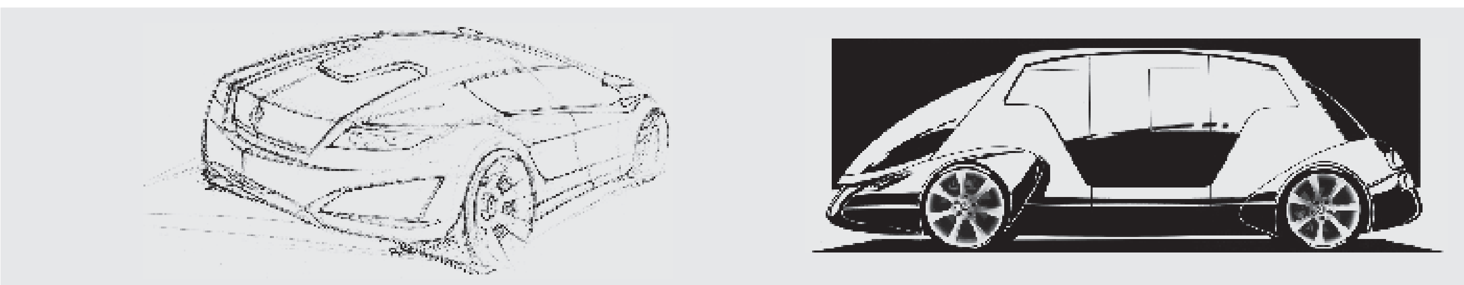


Figure 8: Vehicle studies at HAW Hamburg (sources: Cai, Bast)

Figure 9: Vehicle studies at the IAA 2007

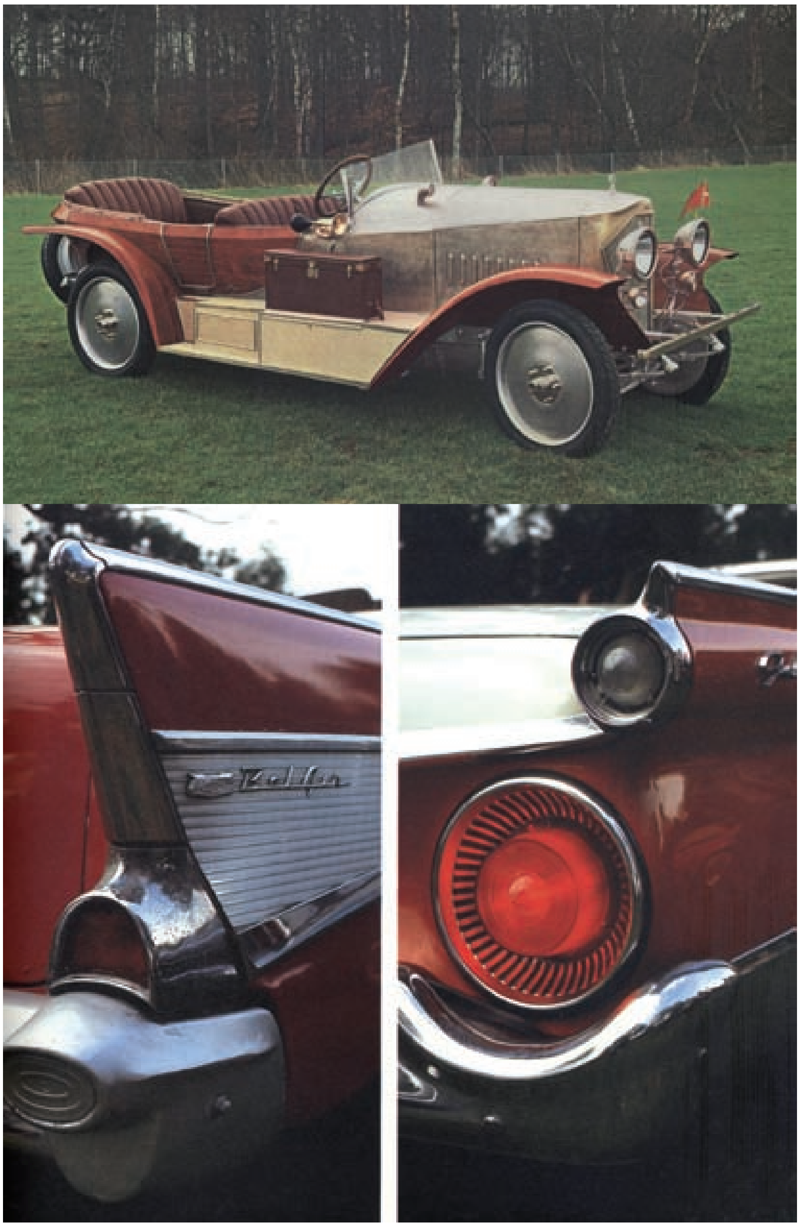


Figure 10: Boat design, jet design and aircraft spoilers in automotive design (source: Archiv Eckermann)

For the exterior designer, the structure and proportions of the front face can be redefined by the new drive concepts. As conventional components such as the classic radiator are no longer required, front face graphics with completely new faces are possible. Vehicles without a classic radiator design have already been presented as studies, **Figure 9**.

3.2 Stylistics

The influences on stylistics are always dependent on the time in which the design of the product is developed. There is always a mutual relationship between all genres involved in cultural progress. These are art, architecture, engineering, product design and social developments of thought. All these have had a mutual influence on each other and have developed style forming objects. Clearly, the aim is to find a design in addition to corporate design that can be typical of new drive concepts. In the ideal case, this design will visualise the new technology.

In the early years of automotive development, designs often followed the technical guiding concepts of the respective age, **Figure 10**. Examples are the boat style in the 1920s, which was replaced by the aerodynamic design of the 1930s, which was modelled on the Zeppelins and aircraft engineering. The rear fins of the 1950s can be interpreted as a stylised jet engine. In the 1960s and 1970s, there followed an era that was strongly influenced by concepts of functionalism. Designs were characterised by function, with the application of principles of order and an architectural design language.

Figure 11: Proportion study (source: GM, Collage Kraus)

Since the 1970s and 1980s, the development of car design has been emancipated and has found its own inherent styles. The development was considerably influenced by the aspect of the semantics of designs, so-called product semantics. This resulted in designs with increasingly high emotional and symbolic design contents.

The stylistics of future vehicles must visually symbolise the high technical performance of a car in the sense of a semantic expression and, due to short-term influences, it can only be vaguely predicted. It will be interesting to see how designers apply their design language to the new technologies of alternative drive concepts.

Future vehicles will be fundamentally influenced by new materials (lightweight, translucent, soft touch, changing colour, etc.). New lighting systems will have the greatest influence on the car's face, as is already common practice today. The use of LED lighting systems allows new designs with high degrees of freedom. However, these aspects work independently of new drive systems.

Completely new tasks for designers will result from the low noise produced by the new drive systems. Acoustic designers must create a sound for the quieter vehicles. Sound modules with individual or historic acoustic properties are conceivable (for example, artificially generating the acoustics of a boxer engine).

The design and operating strategy of the many new electronic systems in the interior must also be determined. Autonomous or semi-autonomous driving will have effects on the arrangement and design of the vehicle interiors.

Another possibility is plastic bodies that change colour according to the occasion.

But what will remain, as has been the case throughout the history of automotive design, is a demand for a mobile, dynamic design. Vehicles have always been designed with surface elements such as edges and beads to provide interesting light changes and reflections to express motion as part of the design. Designers have always used long body lines to support dynamic shapes. In the end, it does not matter which technology is used to power the vehicle.

Based on an assessment of current concepts, the following trends can be recognised for the design of vehicles with alternative drive concepts:

- a change in proportions towards higher vehicles
- high H-point positions and therefore high entry and exit
- Shorter vehicle overhangs
- new design of air guidance components/front face
- LED lighting technology
- interesting material combinations
- new package concepts with effects on interior design, door arrangements, position and concepts of usable space and storage space.

Figure 11 shows possible basic changes in the overall proportions of a future vehicle concept.

4 Outlook

The complex developments mentioned above can only be mastered with a high level of technical intelligence. There will not be any home-made bodies. Future developments will certainly not be restricted only to the aspect of alternative drive concepts, even if this is the prevailing issue at the moment.

In future, vehicle development will still require a high level of passive and active safety. Ecological and economic aspects and further requirements will have to be addressed in addition to the development of alternative drive concepts.

And what about the traditionalists? For such customers, sound designers will generate the gentle growling sound of a large-displacement eight-cylinder engine, while perfume makers might work on reinventing the scent of 99-octane fuel.

New possibilities for vehicle design that point to interesting solutions are now opening up. Today, we are only at the beginning of vehicle development with new technologies and therefore a wide range of possibilities for body design.

Without doubt, design will always be exciting!

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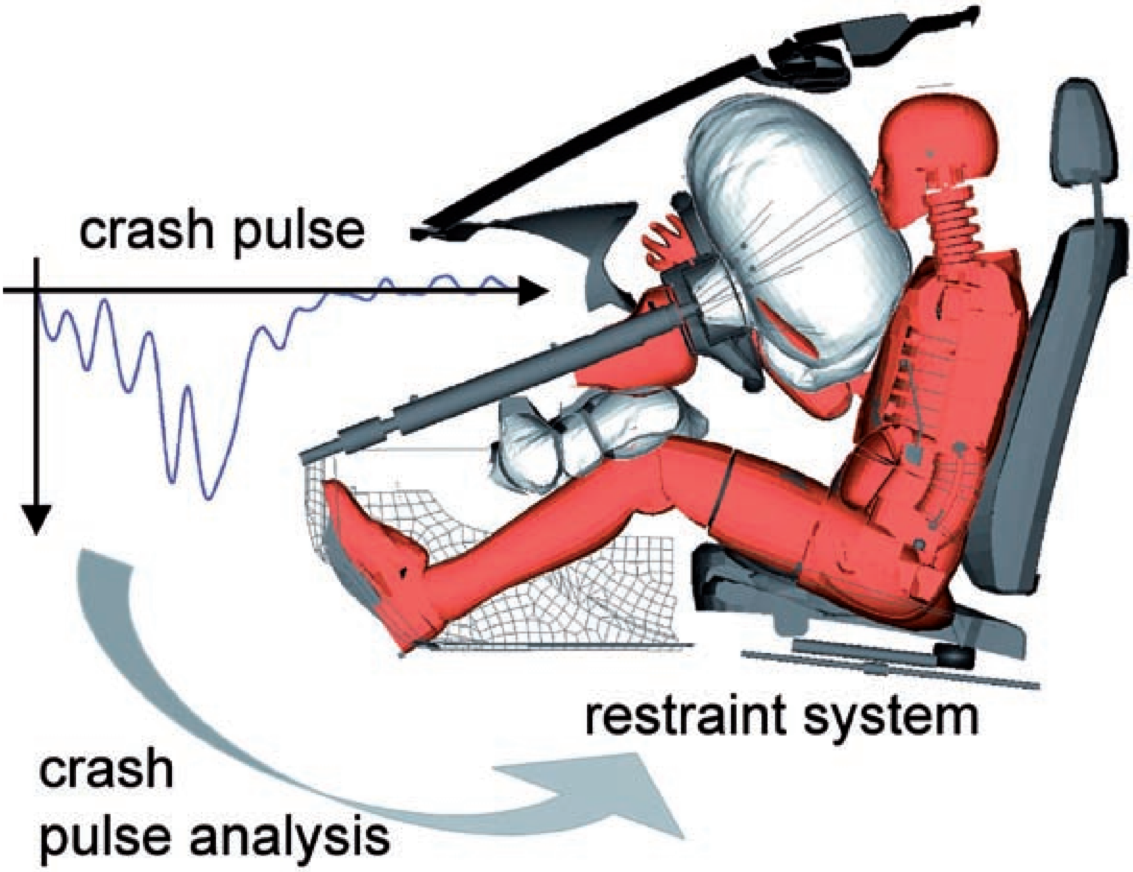
Frontal Crash Pulse Assessment with Application to Occupant Safety



Well tuned restraint systems are essential for occupant safety. A key parameter in this context is the crash pulse. TRW Automotive has examined suitable criteria for the characterization of crash pulses and proposed an extended pulse criterion. Furthermore, based on this extended criterion an approach has been investigated to give vehicle manufacturers and safety suppliers an early indication for the potentially recommended safety equipment.

1 Introduction

Occupant restraint systems are essential parts of today's vehicles to reduce occupant injuries during collisions. In order to evaluate the restraint performance, computer simulations, sled tests and vehicle crash tests are conducted for several frontal collision types. A substantial parameter in this context is the acceleration field effective on occupants during a crash test – the so-called crash pulse.

Crash pulses strongly influence the development of restraint systems because their variations have significant influence on the overall system responses. This paper deals with the development of a crash pulse criterion that allows a robust assessment of crash pulse "severity" and also gives an indication on restraint component selection. It is focused on the specific load-cases of US market and on passenger side.

2 Crash Pulse Criteria

In literature many crash pulse criteria are known and some of the most important are explained in the following. A detailed description is given in [1]. Several of the proposed criteria are derived directly from the pulses by means of simple mathematical operations, e.g. maximum acceleration, point in time when the vehicle velocity is zero $T_{v=0}$, velocity difference, average acceleration, or sliding mean SM_x, where x defines the window size for averaging. Other criteria exist, that are calculated on the basis of simplified mechanical models, e.g. occupant load criterion (OLC) or frontal crash criterion (FCC) based on [2].

OLC takes into account the principal physical behavior of restraint forces applied to the occupant chest. At the beginning of a frontal crash the restraint forces are very low – therefore in the OLC model set to zero. The occupant remains at its initial velocity (v_a) until the relative distance of 65 mm between occupant and vehicle is reached (area A1 between vehicle and occupant velocity curve, **Figure 1**). After this free flight phase it is assumed that the occupant is ideally restrained, which causes a constant deceleration until additional 235 mm relative displacement between occupant and vehicle is reached (A2). The constant deceleration of the occupant defines the OLC value.

FCC is based on a similar approach to OLC. A two-mass model is applied. The crash pulse is imposed on mass m1 which represents the vehicle. Vehicle and occupant (mass m_2) are connected by a spring element. The spring represents the restraint system elasticity in a standard vehicle environment. Analogous to OLC, free flight is taken into account by a relative distance between vehicle and occupant in which no forces are exchanged. After this slack phase the spring is activated. The spring rate defines a linear force versus displacement characteristic. The maximum acceleration of m_2 is calculated which determines the FCC criterion value.

3 Analysis of Correlation

To investigate the quality of pulse criteria, the correlation between injury parameters and pulse criteria is considered.

3.1 Approach

Injury parameters depend on load case, vehicle structure, vehicle interior, restraint system, occupant and its position. In this study the restraint system is configured by standard passenger and driver airbags, constant load limiter and retractor pretensioner. The specific vehicle interior is a middle class vehicle. A large number of US NCAP crash pulses of various vehicle classes and manufacturers are imposed on a system model. The model is set up in Madymo [3] including 50th perc. Hybrid-III Ellipsoid Dummy. In parallel, all crash pulse criteria are evaluated for each crash pulse imposed.

Finally, injury parameters generated by the system model are displayed versus corresponding crash pulse criteria, **Figure 2**. A regression curve is built for each criterion and injury parameter combination according to all pairs of crash pulse and corresponding injury parameter values. The regression is built by polynomial (2nd order) least squares regression. For the assessment of correlation quality, the root mean square (RMS) is taken into account which is a measure of the mean distance of all sample points to the regression curve.

3.2 Evaluation of Results – Selection of Suitable Criteria

The results of the correlation analysis are visualized exemplarily for injury pa-

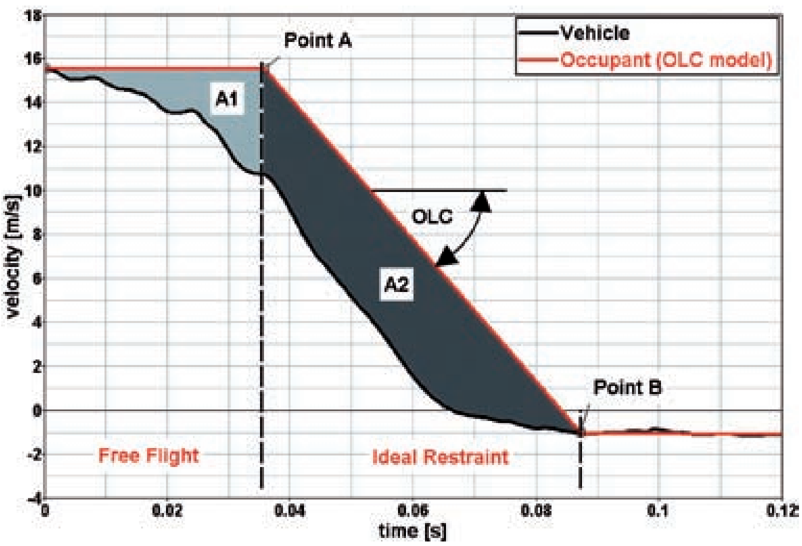


Figure 1: Occupant Load Criterion

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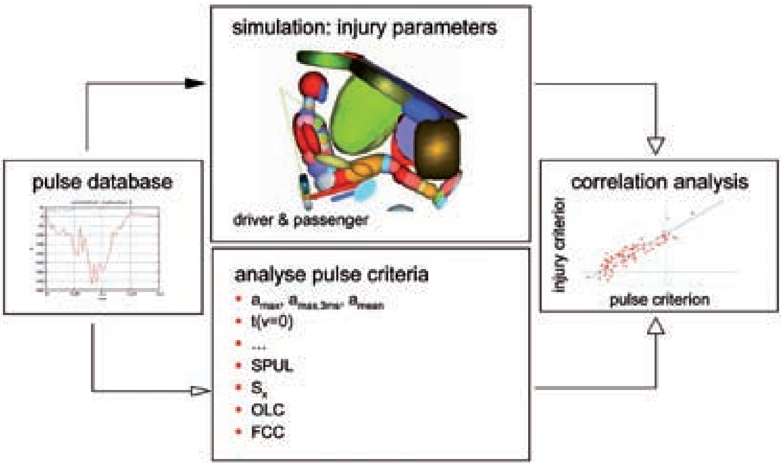

Figure 2: Approach correlation analysis

rameters HIC_{36}, $Chest_{3ms}$ versus OLC. The correlations are arranged separately for passenger and driver occupant, **Figure 3** and **Figure 4**. All crash pulse criteria described in Chapter 2 are investigated. A summary of RMS-correlation values of the most promising crash pulse criteria is given in **Table 1** (green). As possible candidates for pulse assessment with low RMS values OLC, FCC, $T_{v=0}$ and SM_{36} are identified. All other examined criteria show significantly worse correlations, e.g. the 3 ms value of the maximum acceleration, Table 1 (red), and are therefore not further considered.

4 Development of a Robust Criterion

For all criteria found in Chapter 3, pulses can be identified where the criterion value indicates higher injuries, while lower injury values are observed. This is investigated in more detail by conducting a robustness analysis utilizing a generic US NCAP pulse field that covers a wide range of possible crash pulse shapes. In a subsequent step an optimization is carried out to develop a new criterion with improved correlation and robustness for the US NCAP load-case.

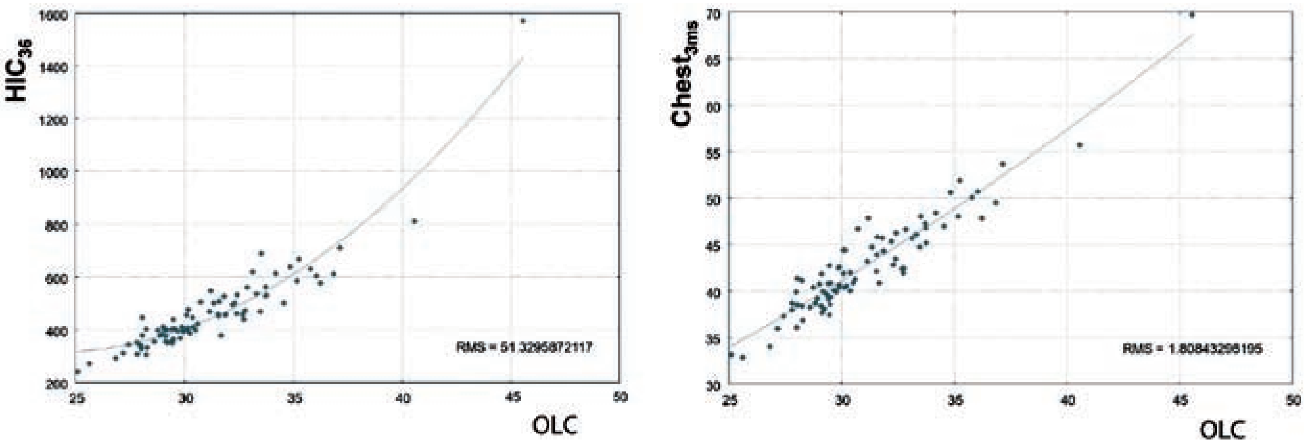

Figure 3: Passenger correlation (HIC_{36}, $Chest_{3ms}$) vs. OLC

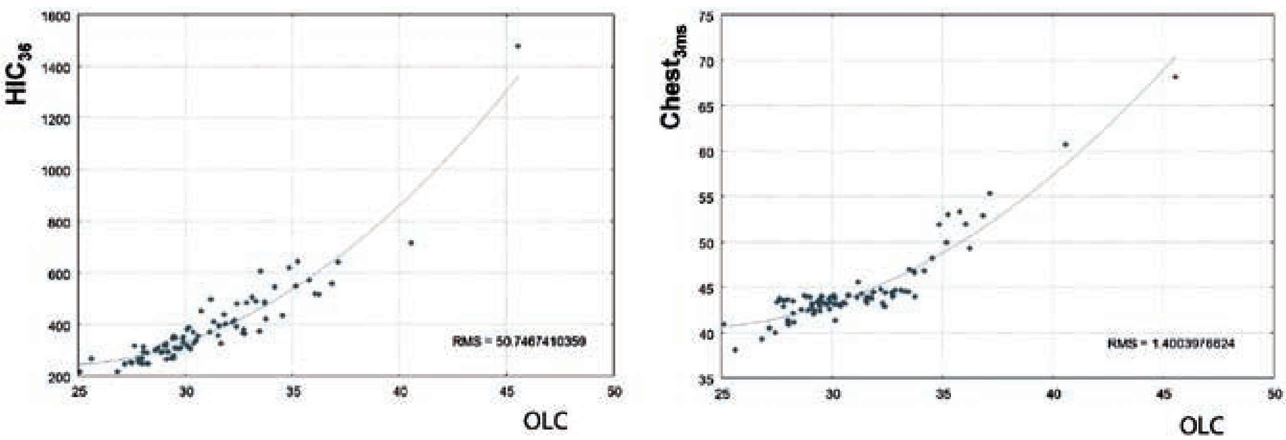

Figure 4: Driver Correlation (HIC_{36}, $Chest_{3ms}$) vs. OLC

Table 1: Summary of correlation – RMS. Left: passenger; right: driver

Pulse Criterion	RMS	
	HIC_{36}	$Chest_{3ms}$
OLC	51.33	1.81
FCC	53.21	1.81
$T_{v=0}$	44.15	1.58
SM_{36}	63.00	1.99
$a_{max,3ms}$	133.42	4.05
	...	...

Pulse Criterion	RMS	
	HIC_{36}	$Chest_{3ms}$
OLC	50.75	1.40
FCC	51.41	1.41
$T_{v=0}$	43.75	2.08
SM_{36}	54.02	1.28
$a_{max,3ms}$	139.36	3.19
	...	...

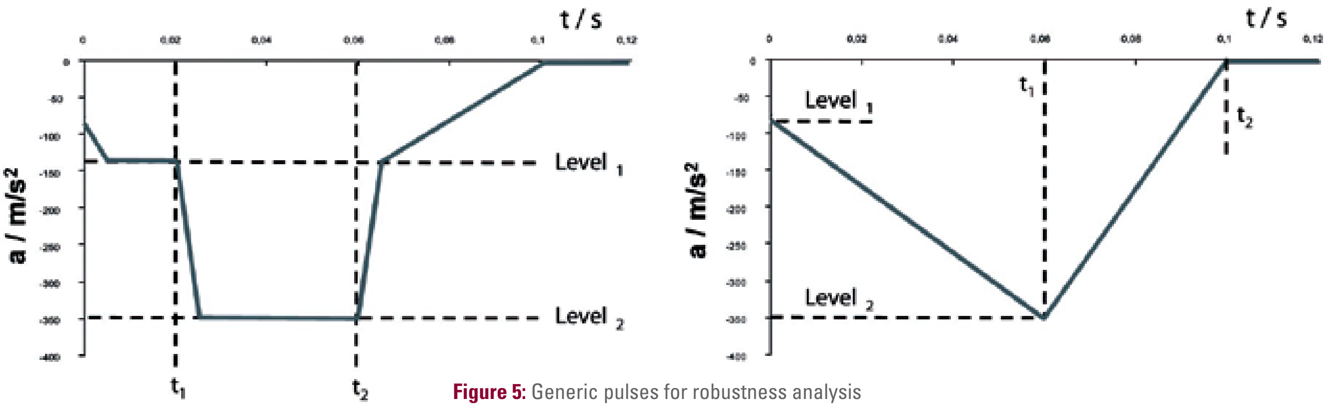

Figure 5: Generic pulses for robustness analysis

4.1 Robustness Analysis

In order to evaluate robustness of the relevant pulse criteria to various pulse shapes, generic pulses are defined. Two-stage pulses and triangular pulses are utilized, **Figure 5**. For both generic pulse types $level_1$, $level_2$, t_1 and t_2 are varied respectively. According to Chapter 3 a correlation analysis is carried out. The results show that for all criteria, injury parameter values can be identified with a substantial lack of correlation.

As an example, in **Figure 6** HIC_{36} is given over OLC. With increasing OLC a strong divergence of HIC_{36} values is observed. Consequently an extended criterion with improved correlation properties is developed.

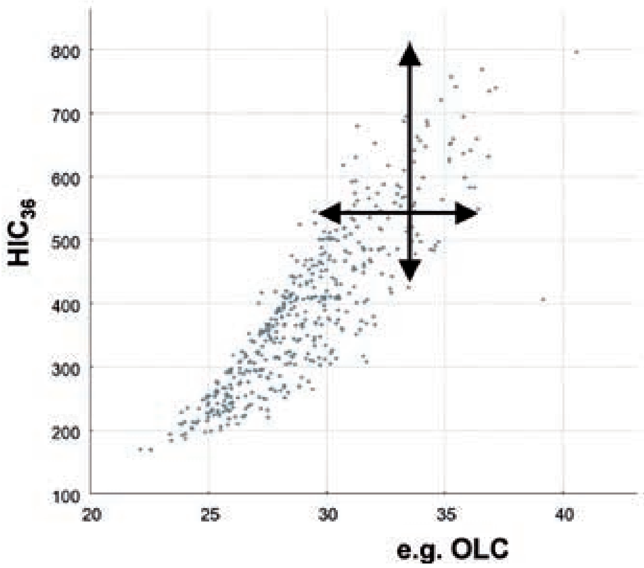

Figure 6: Correlation of OLC to HIC_{36} for the generic pulse field

4.2 Optimization of the Pulse Criterion

The robustness investigation in the previous section indicates the need of an optimized criterion that shows better correlation and robustness to the US NCAP load-case. Possible additional terms for the criterion and the combination of all terms is realized utilizing the numerical optimization tool optiSLang [4].

4.2.1 Definition of a New Criterion

In order to define a pulse criterion with better correlation and robustness properties, potential additional terms are identified by analysis of pulses with the same criteria values but with substantial difference in injury values and vice versa – as indicated by arrows in Figure 6. It is found that all criteria identified in Section 2 are beneficial for some of the pulses. Hence, the idea is to combine OLC, $T_{v=0}$ and $SM_{\Delta t}$ in one criterion and adjust the coefficients a, b, c and the sliding mean window size Δt, Eq. (1)

$$OLC^{++} = a \cdot \frac{OLC}{41} + b \cdot \frac{v_a}{297 \cdot T_{v=0}} - c \cdot \frac{SM_{\Delta t}}{381} \quad \text{Eq. (1)}$$

4.2.2 Optimization of OLC++ Coefficients for US NCAP Load-Case

The objective for the optimization of a, b, c and Δt is to maximize the correlation of OLC++ to the US NCAP load-case. This is achieved by minimizing the RMS values for HIC_{36} and $Chest_{3ms}$ for the field of generic and real vehicle pulses. The multi-criteria optimization algorithm SPEA in optiSLang [4] is applied. In **Figure 7** the result of the optimization is given with the Edgeworth-Pareto (EP) optimal front as continuous line. All solutions on the EP-front have to be considered as optimal, because it is not possible to improve one criterion without worsening the other. Any solution can therefore be chosen from the set of EP-optimal solutions. The previous investigation indicated that all terms in Eq. (1) are beneficial for specific pulse shapes. Thus it was decided to use that design on the EP-front where the term with the overall lowest weights (c, SM) has its largest coefficient max(c). It follows the OLC++ function for US NCAP, Eq. (2), where the sliding mean window size is chosen to 25 ms.

$$OLC^{++} = 0.2454 \cdot OLC + 0.6810 \cdot \frac{v_a}{T_{v=0} \cdot 9.81} - 0.0735 \cdot \frac{SM_{25}}{9.81} \quad \text{Eq. (2)}$$

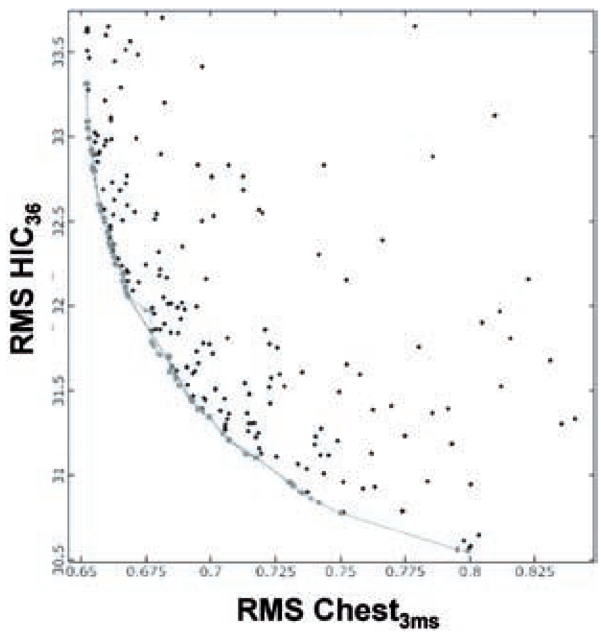

Figure 7: Multi-criteria optimization of OLC++, EP-optimal front

4.3 Comparison of OLC++ to other Criteria

An interesting question is then how the new OLC++ correlates to the existing pulse field with real vehicle pulses (as used in Chapter 3) in comparison to the original criteria. In **Table 2** the corresponding RMS values are shown. It can be seen that the OLC++ criterion leads to a substantial improvement for chest acceleration and HIC with respect to all other criteria.

5 Pre-selection of Restraint Components on the Basis of OLC++

With an improved criterion another question arises: Is it possible to identify areas of pulse severity based on the new criterion that allow for a pre-selection of restraint components for a specific vehicle on the basis of its crash pulse? This question is examined utilizing the simulation models from the previous correlation analysis. The following focuses on one vehicle type (executive), the US market and passenger side. Several combinations of restraint components are examined – each for a variety of crash pulses. A crucial point for such an investigation is that in contrast to the previous correlation analyses, absolute values of injury measures, legal requirements and consumer ratings have to be taken into account. All setups are therefore tuned by numerical optimization with respect to each specific pulse and the actual restraint components. Criterion bounds are identified subsequently.

5.1 Examined Restraint Systems

The baseline model is equipped with a seatbelt system with retractor pretensioner and constant load-limiter and a standard passenger airbag. Following types of load-limiters and airbag features have been combined and investigated

- constant load-limiter (CLL)
- degressive load-limiter (DLL)
- switchable load-limiter (SLL)
- adaptive load-limiter (ALL)
- regular airbag with constant vent
- airbag with additional active bag vent (ABV).

For all adaptive components (SLL, ALL, ABV), the possibility of an occupant detection (IE), that distinguishes between the 5th perc. female and the 50th perc. male dummies, is assumed.

5.2 Optimization Criteria and Approach

To optimize each restraint system to the US market, the regular bag vent is first adjusted to the unbelted load-cases FMVSS 208, except 30° oblique. Then a numerical optimization is carried out with the minimization of the $P_{combined}$ value (US NCAP, model year lower than 2011) as optimization goal. As inequality constraints all injury measures for 5th perc. and 50th perc. from the FMVSS 208 belted load-cases (both 56 kph) are taken with 20 % undershoot, e.g. HIC<700*0.8. Further, a safety distance

Table 2: RMS values, passenger side, real vehicle pulses without generic pulses

Pulse Criterion	RMS	
	HIC_{36}	$Chest_{3ms}$
OLC	51.3	1.81
SM_{36}	63.0	1.99
$T_{v=0}$	44.1	2.08
OLC++	**31.6**	**1.03**

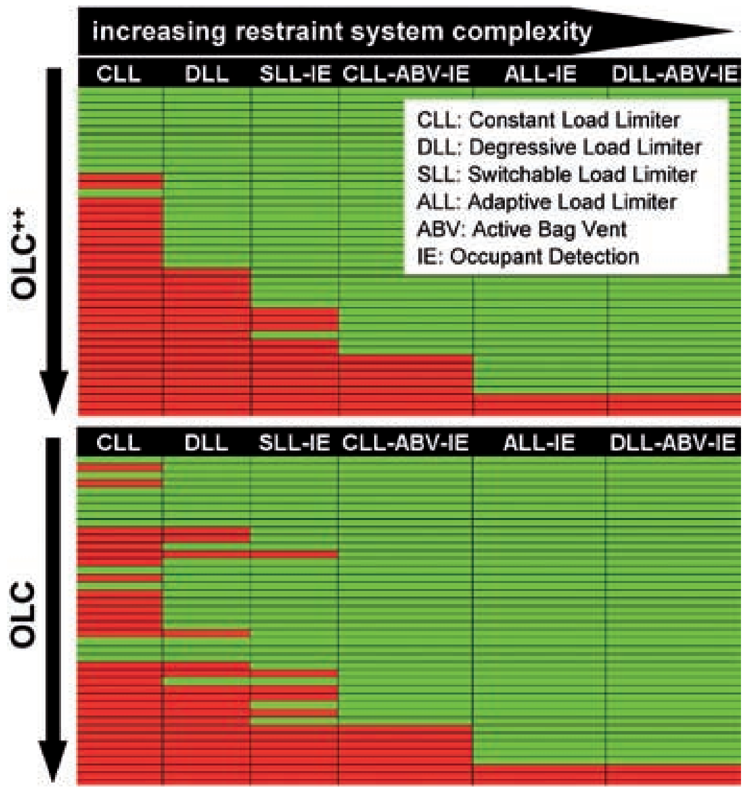

Figure 8: Pre-selection of restraint-components using pulse criteria OLC++ vs. OLC, passenger model

of dummy head to interior parts is ensured. An adaptive response surface method is applied, compare [4] or [5].

5.3 Results

The results of the investigation are given in **Figure 8**. Each line represents an US NCAP crash pulse from a specific vehicle with downwards increasing criterion values OLC++. The columns define different restraint system combinations as discussed in Section 5.1. Every field in this matrix represents a restraint system tuned to the actual pulse and restraint component combination. Green indicates that it is possible to reach 5 stars in the US NCAP rating with 20 % undershoot of FMVSS 208. Red indicates that this is not possible with the specific restraint system for that pulse severity.

In the upper diagram in Figure 8 the pulses are sorted by OLC++. Almost unique bounds of the criterion values can be identified which distinguish between pulses that allow five stars, and such that do not for the given restraint system. It can also be seen that for increasing restraint system complexity, these threshold values increase as expected. This gives further confidence in the robust correlation of OLC++ to the injury values and it indicates the general possibility to identify criterion bounds for restraint component combination.

In comparison to the OLC++ results, in the lower diagram in Figure 8 the pulses are sorted by OLC which leads to a substantial divergence of criterion values for the first three restraint systems. In this fuzzy region it would not be possible to identify unique threshold values. Again, this is an indication for lower robustness of OLC in comparison to OLC++. Analogous behavior is observed for all criteria identified in Chapter 3.

The question remains how the identified criterion bounds fit to existing vehicles. The presented approach is based on several assumptions and approximations e.g. it is based on mathematical simulation in one vehicle environment where only pulses are exchanged. A first crosscheck with existing vehicles indicates that the bounds fit relatively well for vehicles of similar vehicle classes. For strongly different vehicle types like super-minis, SUVs and sports cars the criterion still gives a good indication. However, the bounds for required restraint systems seem to be shifted.

6 Conclusions and Outlook

Several crash pulse criteria exist that show the correlation to injury values in different load-cases e.g. OLC, sliding mean, time of velocity zero crossing. A common factor for all, however, is that a better correlation would be preferable for the development of occupant restraint systems. In this investigation on basis of a robustness analysis, existing criteria were extended to a new combined criterion: OLC++.

Further, criterion bounds for the new pulse criterion were identified, that give an indication for a pre-selection of restraint components depending on the specific vehicle pulse. It has been shown that the OLC++ criterion has the potential to define criteria bounds with respect to specific restraint component combination.

The investigation is ongoing and several topics are planned

- Further correlation analysis and indication of required restraint system for the Euro NCAP load-case,
- Investigation for the new US NCAP rating,
- Taking different vehicle types into account e.g. super-minis, SUVs and sports cars,
- Develop an extended, general criterion using relevant geometrical information.

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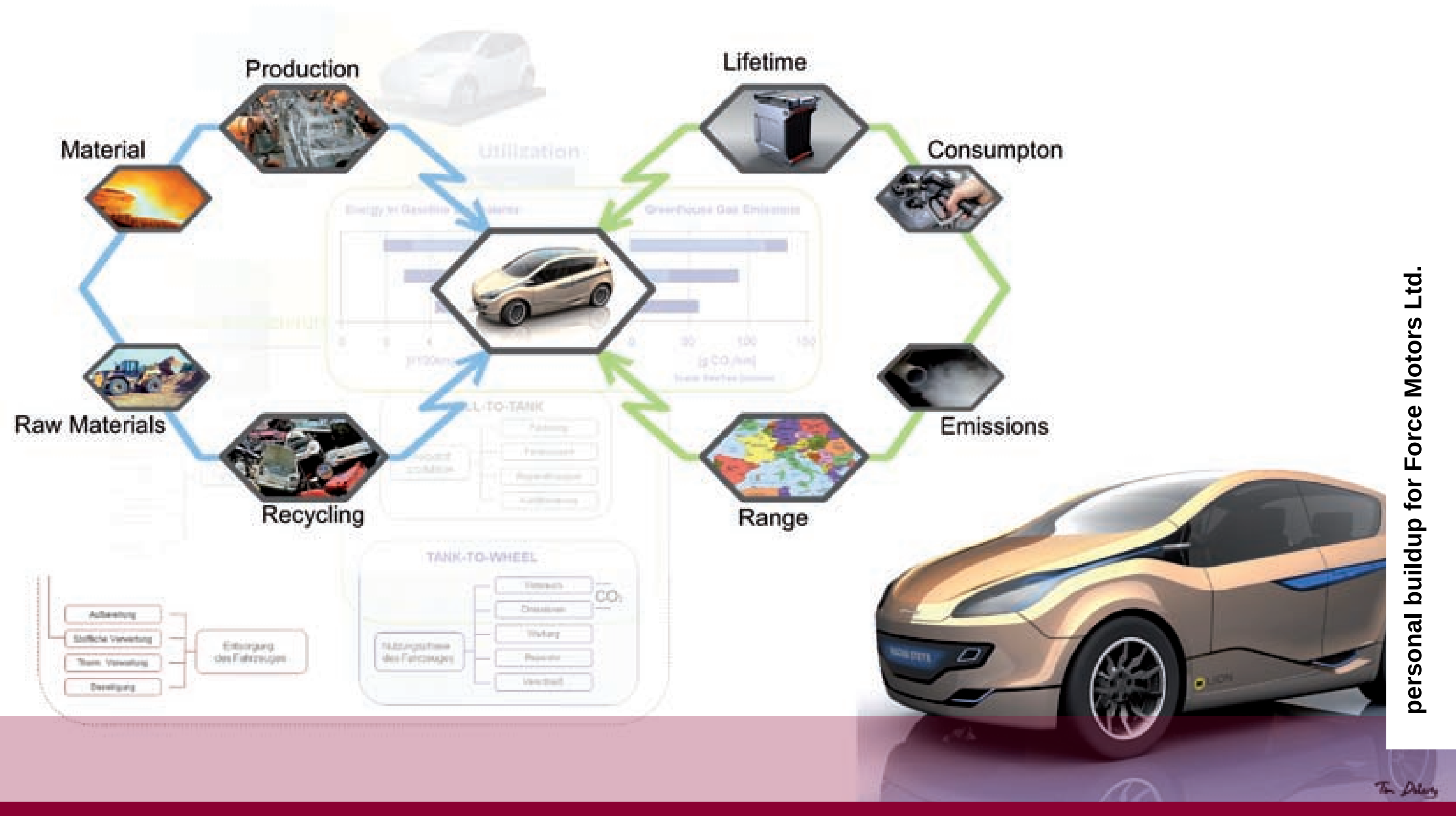

Hybrid and Electric Vehicles

Dimensioning and Integration of Energy Storage Systems

Magna Steyr shows with an argumentation guideline, which dimensioning criteria and target conflicts need to be handled for a future city vehicle. The question, which high voltage energy storage systems are suitable for which car concept and application is answered. The Austrians come up with a modular concept, that is especially characterized by a special energy management and operating strategy approach. Within this the acceptance of potential consumers, cost considerations and over all energy balances of vehicle concepts are taken into account.

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1 Introduction

At the assessment and strategic choice of future vehicle concepts methods like Well-to-Wheel-Considerations are executed – overall cost and energy balances play a decisive role. Therefore the consideration of entire life cycle of a vehicle with the focus on energy needs, all environmental impacts and cost is needed, **Figure 1**. The ecological evaluation method therefore is the so called Life Cycle Assessment (LCA) the Life Cycle Costing (LCC) respectively. Already in a very early phase of product development Magna Steyr places emphasis on the LCA for the systematic consideration and optimization of technical and ecological properties and impacts of the product over the entire life cycle. Using LCA and LCC the meaningful and feasible usage of new technologies within the propulsion system of a vehicle can be evaluated. Magna Steyr discusses in this article state of the art storage technologies and the integration of these within vehicle concepts, **Figure 2**.

2 Core Technology: Electric Storage Systems

Analyzing possibilities of allocation of primary energy within a vehicle, the result are electric, chemical and mechanic storage possibilities. Electric energy storage systems – here the focus of discussion – based on high voltage become more important due to the fact of increasing the energy efficiency within hybrid power train applications in middle and long term, **Figure 3**. For electric hybrid vehicles, electric storage systems are used that show a high power but low energy density. Hence the system is cond, less for pure electric range, more for optimized recuperation and best possible load point shifting, which leads to emission and energy efficient operating points of the internal combustion engine (ICE). For the recuperated and high efficient energy several, dependant on the application, different storage systems are available. The field of applications varies from Formula I over road transportation to special purpose. Two main representatives in the areas Formula 1 and special vehicles are the short term storage systems like Supercaps and the Kinetic Energy Recovery (KIT) system. High power density and cycle stability characterize these systems. Capacitors could be called the electric hydrostatic storage systems. They are already in field testing as an option for replacement of hydraulic systems. A major technical drawback is the high voltage gradient, that might lead to difficulties in the control of the electrical machine – a further rectifier might be necessary.

Because hybrid vehicles use as well a not negligible amount of energy, these systems drop out for the bigger part of hybrid vehicles. Today's hybrid vehicles are equipped with nickel metal hydride batteries – a wide experience in field and the cost benefit up to now are arguments for the use of these systems. Especially in high volume production it seems to be hard to beat this technology. On the long run NiMH systems are going to be replaced by Lithium Ion ones due to their much better system weight, higher energy density and more compact dimensions. The exact time and the degree of substitution will be determined by the market and the progress in the development and production of this new energy storage systems.

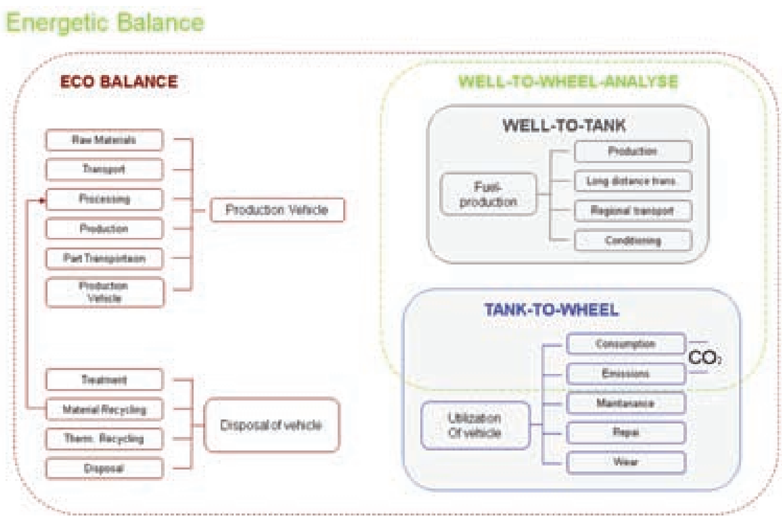


Figure 1: Entire life cycle of a vehicle

Compared with the Kinetic Energy Recovery systems and the Supercaps, both systems have a much higher energy density at still high power density. So these systems are qualified for the use in the entire hybrid segment. The voltage gradient at charging and discharge of the systems is much lower compared to the short term storage systems. A drawback is the lower cycle stability. Anyway the up to now executed life time testing looks promising. From the integration point of view the tempering concepts for this storage systems is a quite high effort. Especially the power output and input capability of this systems at low temperatures (<0 °C) and at high temperatures (>45 °C) needs to be considered. At Lithium Ion chemistry further safety measures need to be addressed due to issues like fire risk, gas evolution (e.g. carbon monoxide) and deposit of hydrofluoric acid. For these risks the used chemistry for anode/cathode/separator/electrolyte has a high impact.

A further variant of an energy storage system is the so called Zebra battery – a high temperature storage system based on sodium nickel chloride. This system is used in civil and military vehicle application. The battery has to be kept on 300 °C by being plugged to the grid and consuming some energy for heating.

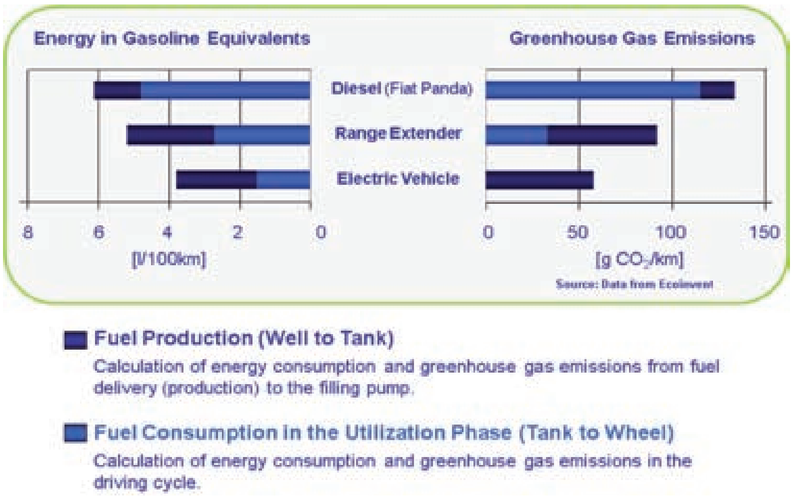


Figure 2: Well to Wheel Analysis of several powertrain concepts

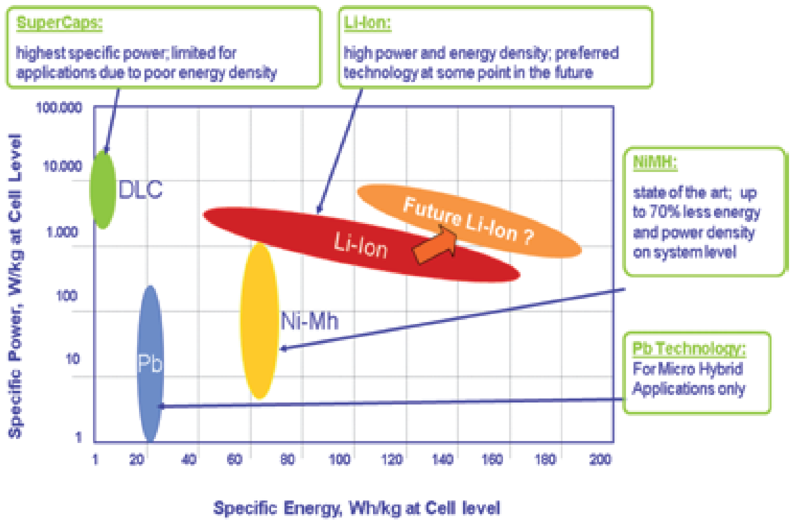


Figure 3: Portfolio of high-voltage energy storages

3 Degree of Hybridization

All up to now mentioned systems are based on the same approach, out of which the ICE is dominating propulsion system. In general hybrid systems of today are more electric assistance systems than real propulsion units, which have mainly the challenge to support and complement the ICE and power train of the vehicle. With the upcoming expansion of the electric dominance in the power train of hybrid vehicles, **Figure 4** – Plug in hybrid electric vehicle (PHEV) and range extender – the ICE will take over the supporting and complementing role.

Variants of Plug-in hybrid electric vehicles:

- ICE dominated plug-in vehicle
- ICE for higher power and increased range
- coupled operation possible (parallel hybrid)
- electric driving in near field (Green Zones)
- electric dominated plug-in vehicle (range extender)
- ICE for increased range
- mainly serial hybrid
- electric driving.

Energy storage systems like batteries need to be designed for these requirements – a migration out of the power storage systems (cells with 5 to 7 Ah) to an energy storage (cells with 20 to 60 Ah) will take place. Energy storage systems (contrary to power oriented storage systems) are necessary for the final stage, the pure electric vehicle (EV).

One main discrepance that needs to be considered: By increasing the energy density of the battery system, the power density is reduced. A promising approach for solving this point could be the combination with Supercaps –an interesting and very often discussed solution statement. The resulting additional costs and weight need to be evaluated. Equally the advantages of increased life time due to better filtering effects of current ripple and short time spikes need to be evaluated.

Another disadvantage is the temperature behavior analogue to the power oriented storage systems, whereas these systems have a higher thermal capacity. For the tempering system (heat/cool), also air cooled systems are imaginable, although if there is still the lack of experienced data for today's chemistry.

A very important factor for the evaluation of storage systems, that allow more electric range, is the ratio between "energy/power density and overall weight". Why is this value that important? The electric energy storage system is a challenging the current fuel storage systems. To keep the system weight and the range approximately constant, the energy density of gasoline or diesel fuel of approximately 10 kWh/kg needs to be the target dimension. Today's electric storage systems are around 100–150 kWh/kg. So for being able to answer the question of the best power train system under consideration of CO_2 emissions for a certain application, several parameters of the vehicle/system and the utilization need to be defined.

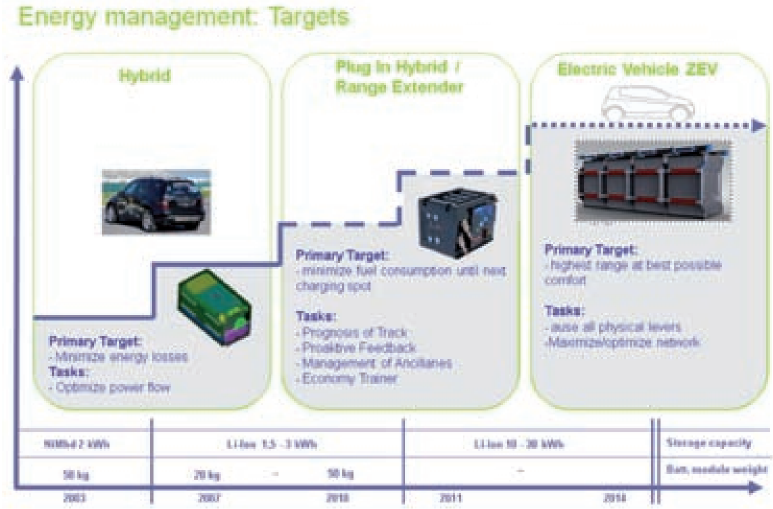


Figure 4: Electric storage dimensioning: motivation and tasks

4 Electric Storage Dimensioning

The target data in **Figure 5** illustrates the challenges for an EV, starting from target costs over to system weight and comfort/range requirements. For example the range of today's vehicles with one tank content is more than 600 km in average. The average daily mileage within high density areas is around 50 km and more than 75 % of the earth population is living within this areas. Prognosis show that this percentage is going to rise to 85 % until 2020. So a vehicle with about 100 km of range per day would cover most required mobility within this areas. In general the consumer is currently still requesting the same mileage like conventional cars have, even though statistically this mileage is not used. A different situation could be found if you analyze the segment of second cars, but here the purchase price and the maintenance cost, or better to say cost of ownership are very important attributes.

Analyzing the segment of second vehicles, the small to lower middle class vehicles are the main representatives. So the target values of such a vehicle, shown in the target value table, result in a limited corridor for comfort and respectively for the vehicle dynamics. For the EV weight a reduced target value needs to be considered and the range requirements are at this point kept constant. All this requirements need to be more detailed and split down for singular components.

As Figure 5 and **Figure 6** show, the reduced requirement of electric range and the linked weight reduction, result as well into better circumstances for the rest of the vehicle like in the area body structure/materials, and crash safety. For market placement of this vehicle with reduced range, the price and surplus values are very important. Taking a look at current second vehicles, a price corridor of 14,000 to 25,000 Euro seems currently to be a meaningful segment for such a EV. Taking the current energy storage system price out of Figure 5, the system price would be between 10,500 Euro to 18,000 Euro, due to this the lower segment of the target corridor seems currently to be out of range for a pure EV application, so the class of compact vehicles remains as target group.

Today's compact vehicles have a price range between 15,000 and 25,000 Euro on the consumer market. Hence this, only a small number of vehicles remains within the target group and still for this group the cost target seems to be possible but hard to reach nowadays. For making the EV in future compatible to conventional vehicles, on the one hand the cost for the energy storage systems needs to be dramatically reduced and on the other hand the market for this vehicles needs to be more attractive. Today plug-in hybrids seem to be an attractive combination between electric mobility, range and costs.

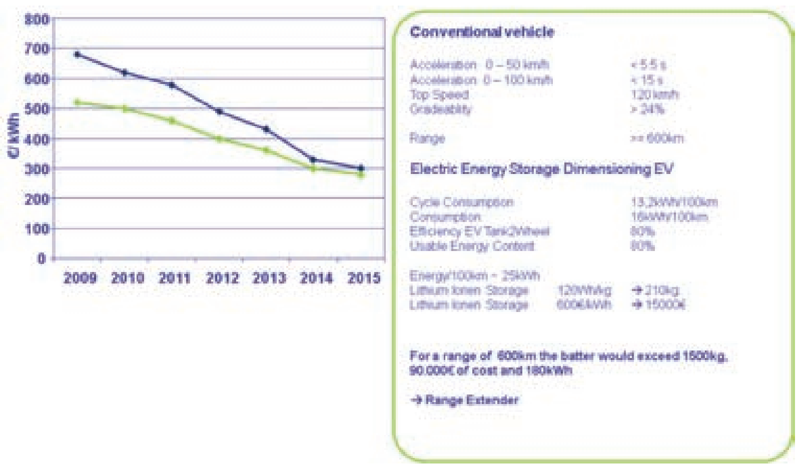


Figure 5: Vehicle requirements, Storage Dimensioning and Costs

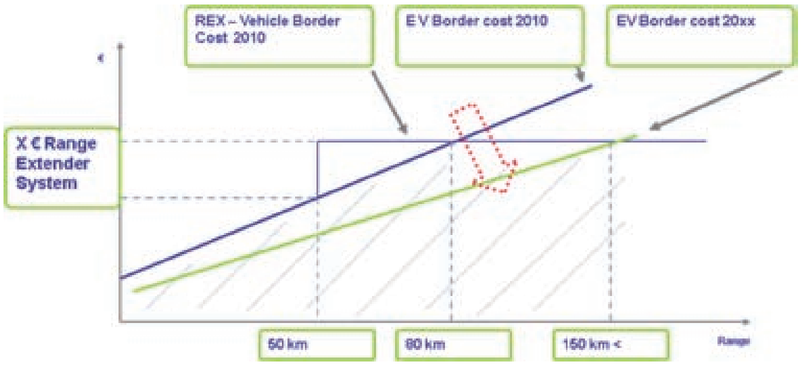


Figure 6: Balancing of costs and performance of range extender and EV-concepts

5 Modular Energy Storage Concepts

The discourse in the former chapter illustrates, that EVs are one of several solutions for the mobility of tomorrow. Even if there are still open points, this technology should be introduced into the market for gathering the information for future improvements. One still remaining main challenges is the storage of electric energy, even if essential steps have already been made. The question to be answered is, how could this process be speeded-up for gathering the necessary information for optimization? For reaching this one big step is the bridging between plug-in hybrids and the EV.

A first step is to make the entire vehicle concept and the energy storage modular, so you could use the same platform for both, the EV and the PHEV. Due to this reusability approach, costs could be reduced. One of the main weaknesses of this concept is the lack of standards for the entire system properties like voltage and current levels and cooling systems. Because of this situation, also on the module level changes are required and so the entire modular approach is put again into challenge. For this there are already ambitious efforts going on, but a speed-up of this would be very supporting and desirable.

A second approach that would make bridging become more easy would be the standardized system integration on vehicle level, functional and mechanical. A further step in integration depth of singular systems like DC/DC converter, DC/AC inverter and charger into one central system shows several potentials, even if the question for exchangeability of this systems is still open.

For all these appendage exists one key technology on the vehicle level, that mainly influences the bridging and marketability. Exactly this technologies are under focus of the development work done at Magna Steyr in Graz. Next to the key technology energy storage system that is developed in an separate department, the focus is set to the central themes integration and energy management and respectively operating strategy, without which no holistic approach would be possible.

6 Key Technology – Integration and Operating Strategy

Previous of a vehicle development there is the need for evaluating the propulsion technology that is the most efficient solution related to the entire target values. Considering all possible propulsion topologies including the energy storage systems and the available energy distribution network, the "pure" EV currently addresses a niche market. The already discussed combination of propulsion systems (PHEV) increases the market potential. Expanding this approach with the modular concept for the energy storage system and completes the system with the modular power train concept, discussed before, the opportunity to address both markets is given.

What is the impact on the integration and the operating strategy for such a vehicle – especially on the energy storage, the propulsion system and the requirements for the aspects of comfort and dynamics? The core of a vehicle with a high degree of electrification is the energy storage.

At this system, the factor chemistry weight to overall system weight, that has been introduced before, needs to be taken into account. The overall weight could be optimized and reduced by means of light weight design and integration of the battery into the vehicle structure. Due to this high level of integration, new interfaces with the supplier come up, because the battery isn't a box anymore. So this new interfaces require a much deeper cooperation of the integrator and the supplier. The before discussed standardization would lead to lower costs in this case, because the basic platform would already be specified for this purpose. Further challenges are coming up at system testing – for example at electromagnetic compliance, thermal and crash safety testing. One main difficulty is the definition of the system borders and responsibilities. For illustration – if the supplier of the energy storage system delivers "only" the modules, than the integrator needs to take care of all integration work done and takes over all the responsibility for the entire system. But if this interface and responsibilities are solved in a proper way, further cost saving potential arises.

Magna Steyr come up with its modular concept, **Figure 7**. With the modular concept and its components it was possible to realized, due to close cooperation of the energy storage supplier and the integrator, the optimal energetic material at optimal cost – currently steel is used. Because the energy storage system was integrated in a modular design – the modular concept and its components also the energy content, the cost and weight are easily scalable, so as well the propulsion system need to be designed in a similar modular way for reaching the markets mentioned before. By combination of a Range Extender – electric machine with 25 kW continuous power and a two-cylinder ICE with 25 kW – and an pure electric propulsion unit, the vehicle can be driven pure electrical, in a serial and in a parallel hybrid mode. Using this propulsion system, the vehicle can be built as a pure electric or electric dominant plug in hybrid electric vehicle. If the vehicle is built as a PHEV the energy content of the battery

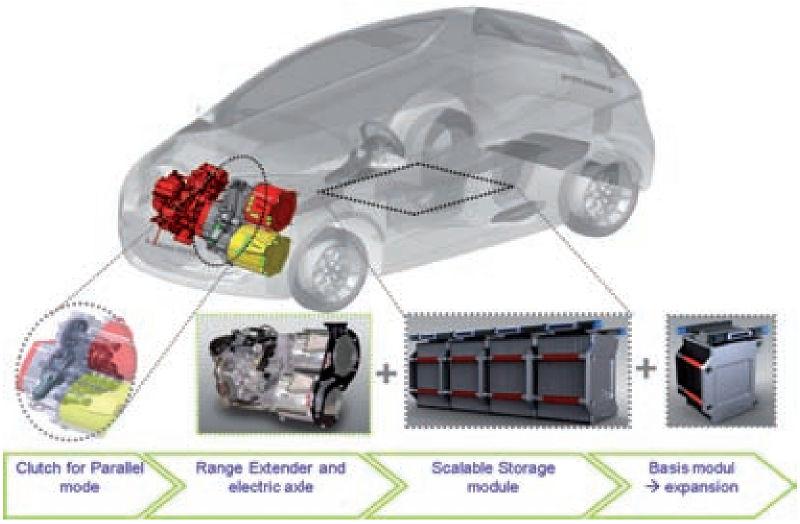


Figure 7: The modular concept (IMC) shown by Magna Steyr

system can be reduced. Despite the additional combustion engine including all periphery the vehicle can be realized weight and cost neutral compared to the pure EV. In the shown example the power of the range extender is comparable high. For a further increase of efficiency the possibility of direct coupling of the ICE to the wheels has been introduced. This PHEV combines an increased range with the possibility of low cost electric mobility in the near field.

A central exercise is handled by the energy management while the utilization phase of the vehicle. The so-called operating strategy is in charge to solve the stress field of dynamic and comfort in an optimal way. Further measures reduce cost and weight: thanks to new strategies of preconditioning of the entire vehicle, for instance heating and cooling at parking condition and integration of navigation and driver data the storage system could be reduced by 5–10 % (for example never again ICE scarping or entering a too hot vehicle).

7 Simulation

For reaching all targets, the necessity of modeling the entire vehicle and its subsystems within a simulation is given. From the beginning on the operating strategy and the dimensioning of the subsystems need to be harmonized. For the development of the modular concept in Graz several simulation tools have been used and merged (VeDyna, KULI, Matlab/Simulink). At the beginning the singular systems are modeled and analyzed. In case of conclusiveness the systems are merged.

From this time on basic operating points can be investigated. Out of this analyzes the characteristics and properties of systems and singular components can be derived. For example the necessary tempering methods and insulation values have been calculated and derived by this tool chain. Based on the results out of the simulation and the existing and patented generic solution for the power train management of full hybrid demonstrator "HySUV", the operating strategy was enlarged for the requirements of an electric dominant PHEV, Figure 3 – targets of energy management (Chart Operating strategy) The existing rudiment was expanded by new functionalities in the area driver assistance (Track information/Driver information), energy management of ancillaries (climate/cooling) and charging. These new functionalities enable an optimized strategy not only while driving, but as well while charging and parking condition. In the area of ancillaries the further possibility of demand controlled systems has been implemented, still taking the cost-benefit ratio into account. The entire operating strategy, developed in Matlab/Simulink Stateflow, is integrated in this platform. It can be simulated and tested within this tool chain and be validated with measurement data of the vehicle. These new functionalities enable the system to reduce the necessary energy within the electrical system for comfort components from 5 up to 15 % and to stabilize the load on the electric system. This continuous virtual approach of development increases the degree of maturity of a concept in the early phase and conducts the reduction of development time and physical slopes with cost intensive prototypes.

8 Conclusion

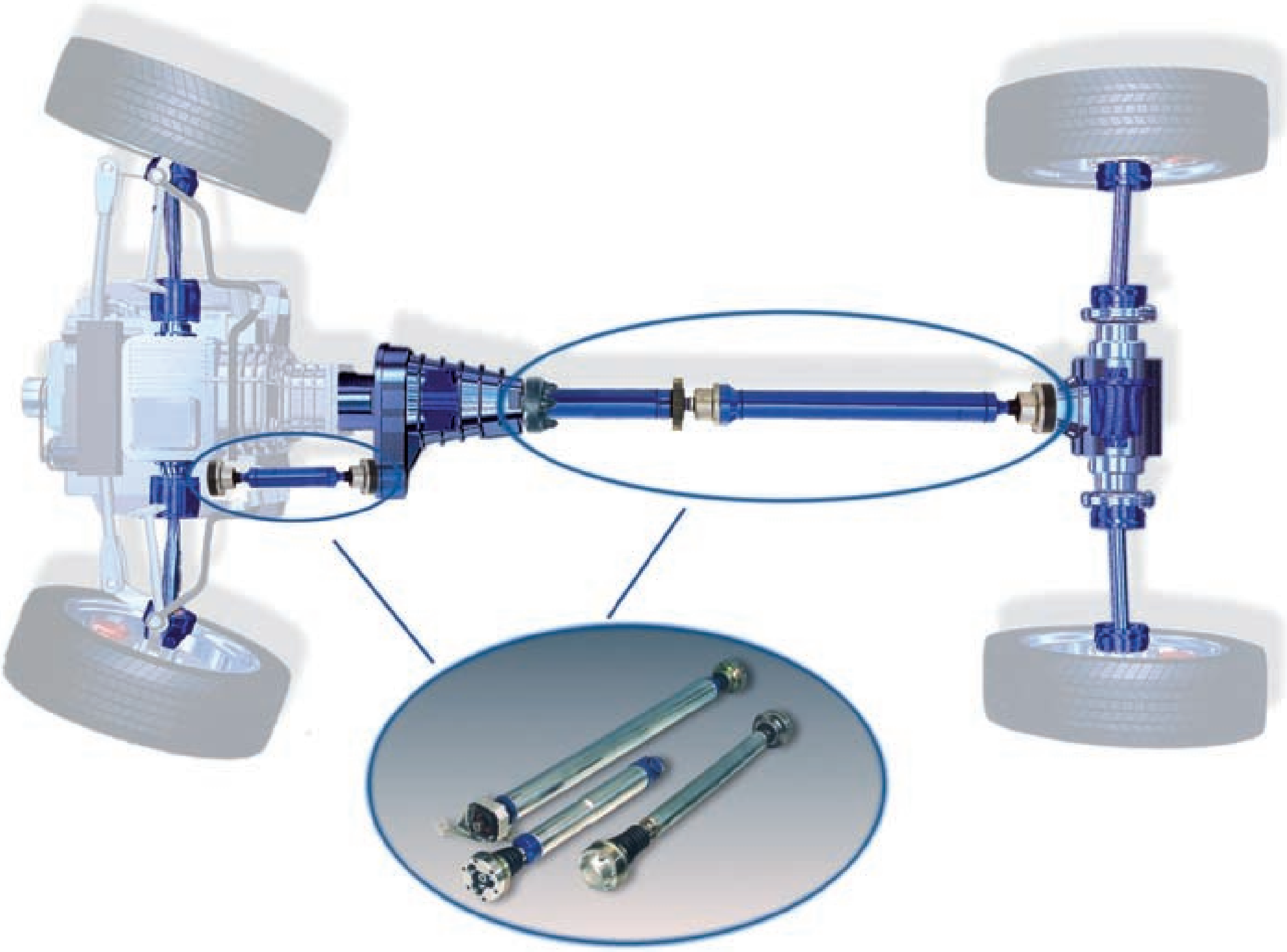
Magna Steyr shows with the continuous illustrated module concept and the innovative energy management and the realized operating strategy a possible solution for the mobility of tomorrow. Central focus is set on the themes standardization and respectively shared platform solutions and conducted with this the cost reduction with consideration of energetic optimal life cycle.

Are all problems solved? For sure not. There are still a lot of issues and questions open and many of them are not even known up to now. Furthermore the necessary infrastructure for a wide spread energy supply needs to be introduced.

When are the hybrid vehicles substituted by the electric vehicle within cities? The answer to this is given by the core technology, the energy storage itself and especially by the cost/kWh and the energy/power density. If the currently planned targets, like 200 Euro/kWh, are reached, the change to electric mobility can be reached within the middle term. ■

Weight Reduction with Optimised Longitudinal Shafts

The engine/transmission unit shall be connected robustly, uniformly and without vibration with the differential. This was done in former times by "cardan shafts" and cardan joints with certain disadvantages. Nowadays GKN uses longitudinal shafts with constant velocity (CV) joints. One solution is called Direct Torque Flow (DTF) utilizes modern CV joints and fulfils the competing targets weight reduction and cost savings by eliminating the bolted connection.



1 Introduction

Longitudinal shafts (propshafts) link the engine/transmission unit with the axle differential, thus transmitting torque and rotational speed to the driven axle. Cardan joints were often used in the past, and as a result the term "cardan shaft" is still often heard. Except in the case of purely front-wheel drive vehicles, any vehicle needs at least one longitudinal shaft, apart from those with electrically driven axles. Nowadays, modern NVH-optimised vehicles often use constant velocity (CV) joints. These allow torque to be transmitted uniformly and without vibration, and also decouple movements of both the engine/transmission unit and the differential.

2 Current State of the Art

Current longitudinal shafts with constant velocity joints at the gearbox or the differential are designed as flange or disk joints. Such joints are generally bolted onto the counter flange with six bolts. This bolted connection must provide both sealing and torque transmission. Even today, as a consequence of the development of higher torques and the limited space available for installing these connections, they are already being subjected to extremely high stresses and therefore the torque can no longer be transmitted by friction alone, so the connection is subjected to additional shearing forces. As a result of this, in assembly plants considerable importance must be attached to the tightening accuracy of the bolts.

Another disadvantage of this connection is the frequent diameter changes in torque transmission and the large number of components, this solution requires. For example, there is a jump from the small diameter of the gearbox pivot/differential pinion to the large diameter of the bolted connection. This is followed by a reduction to the small diameter of the stubshaft, followed in turn by another jump to the large diameter of the tube. The disadvantages described form the point of departure for a new way of connecting longitudinal shafts.

3 Direct Torque Flow

The "Direct Torque Flow" (DTF) principle by GKN simply turns the CV joint round: the longitudinal shaft is welded directly to the large external diameter of the joint, while the output shaft from the gearbox or the differential is inserted directly in the inner part of the CV joint. This has several advantages:

1. Flange, bolts, washers and one stubshaft are eliminated
2. Vehicle assembly involves less work
3. reduced weight
4. improved unbalance as a consequence of reduced weight.

DTF solutions can be designed for fixed or plunging joints with various types of axial retention. The text that follows describes two application examples that have been selected.

3.1 Plunging Joints

The solution for plunging joints involves connecting the cardan shaft to the vehicle (front axle gearbox, distributor gearing and rear axle gearbox) with the aid of a slotted sleeve. This sleeve solution is specially designed for a plunging joint, because in this case it achieves a compact design with integration of the boot. Instead of the conventional flanged connection, **Figure 1**, with bolted connections and an angled torque flow, the new DTF constant velocity plunging joint, **Figure 2**, is fitted directly to the gearbox shaft and has a smoothed torque flow. The torque is transmitted through the output shaft splines.

The DTF connection makes the cardan shaft's stubshaft redundant, and depending on the design this can make it up to 800 g lighter. Eliminating the bolted connection and the vehicle flange allows up to 1.8 kg mass to be saved if the DTF connection is used on one side of the vehicle. In addition, eliminating the flange/gearbox shaft interface has a positive effect on residual unbalance and the space required by the system.

This DTF solution offers OEMs clear process advantages when assembling the longitudinal shaft: Manually fitted onto the pinion shaft or transmission output shaft, it is centred by means of a clearance spline to spline. The clearance in the spline results in a radial clearance and backlash which, as a consequence of the self-centring of the splines does not result in higher unbalance within the drive train. Unbalance tests show that the values obtained are in line with the state of the art.

No increase in backlash was found in dynamic resistance tests, which went well beyond the service life of the longitudinal shaft. For NVH-critical vehicles a major diameter fit spline is available that eliminates the radial clearance of the joining parts as far as possible.

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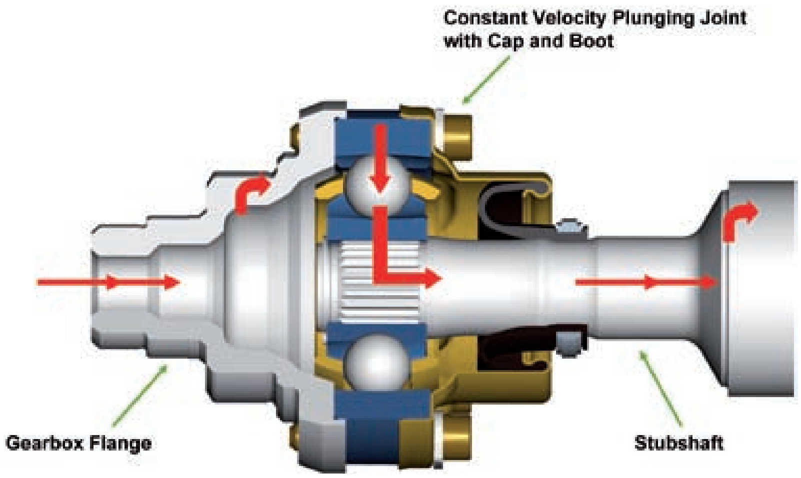

Figure 1: Parts and torque flow (red arrows) through a conventional connection

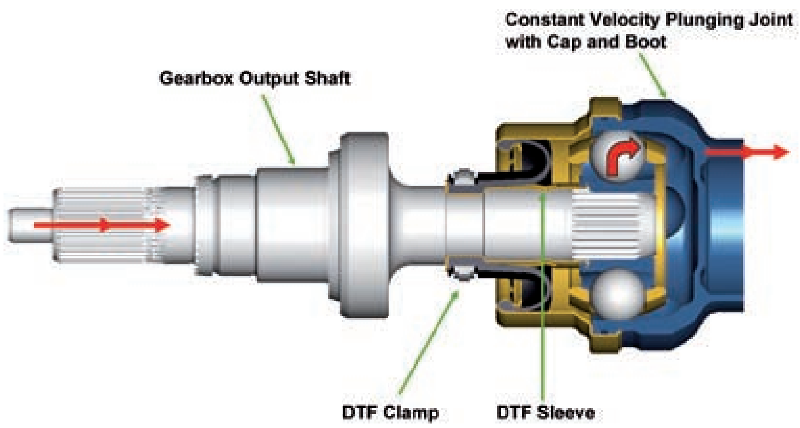

Figure 2: Torque flow through the new DTF solution

Axial retention up to an axial load of 5 kN is provided by closing a clamp. As this can only be done via the gearbox shaft's groove, process control for the assembly procedure is assured. There is no further need for time-consuming bolted connections.

3.2 Fixed Joints

Another DTF design is particularly suitable for fixed joints. Here, the inner part of the joint is fitted onto the gearbox pivot or differential pivot and bolted by means of a union nut. This permits an extremely compact and weight-saving design, which in turn has a positive impact on the residual unbalance that can be achieved. As a consequence of using a fixed joint, the design of the protective boot is extremely compact. This allows the amount of grease required to be reduced.

The slightly greater workload involved in mounting the longitudinal shaft in the vehicle by tightening the nut is compensated for by the possibility of additionally centring the joint via a cone. In the case of the combination with fixed joints, further cost-effective solutions are currently being developed in order to secure the longitudinal shaft axially with the aid of a circlip.

4 Summary

DTF solutions from GKN have allowed the two normally conflicting aims of reducing weight and cost to be achieved. Eliminating the bolted connection allows OEMs to obtain cost advantages in assembly. At the same time, the reduced weight also reduces the residual unbalances that can be achieved in the shaft/gearbox system. ■

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Active Yaw Control in Front-wheel Drives

As a manufacturer of manual and axle transmission systems, Getrag has developed solutions for 'Active Yaw' (AYC) systems in all drivetrains. Two different approaches for a front-wheel drive, torque-led and speed-led, are presented below. The customer benefits gained from FWD understeering are also noticeable to a normal driver. Getrag has therefore taken a step towards practical implementation, demonstrating that Active Yaw produces astonishingly positive drive dynamics when used in front-wheel drive systems.

1 Introduction

When the standard rear-wheel drive (RWD) and front-wheel drive (FWD) systems are evaluated, the RWD offers distinct benefits in terms of longitudinal and lateral dynamics. This is due mainly to the fact that in RWD systems the steering and drive functions are distributed over front and rear axles, whereas in the FWD the front axle must handle both functions.

The vehicle's self-steering behavior is more heavily influenced by the drive torque in FWD systems than in RWD systems. This becomes more noticeable as the engine torque increases or when the tire-road adhesion coefficient (coefficient of friction) is low. A helpful simplified model is "Kamm's circle", **Figure 1**. The maximum drive power that the wheel can transfer is the power resulting from the longitudinal and transverse forces.

In acceleration on a skidpad with a constant radius, it can be seen that the greater the induced drive torque, the greater the steering angle requirement (tire slip angle / understeering increases). Further acceleration is prevented when the lateral acceleration limit is reached. The open differential "torque scale" function limits the transmittable torque of the entire front axle due to the unloaded wheel on the inside of the curve.

What is advantageous here is that a vehicle with FWD remains stable, as the power engages in front of the vehicle's center of gravity.

In the case of RWD vehicles, the self-steering behavior is not so dependent on the drive torque. In addition, the rear axle's dynamic axle load shift means that the wheel on the inside of the curve is more loaded, which allows the RWD vehicle to achieve a higher lateral acceleration.

However, the RWD vehicle shows a tendency to oversteer in the limit range as the power engages behind the vehicle's center of gravity.

The effects that different drive torques will have on the steering torque militate against the use of AYC systems on the front axle. Unwanted steering problems, e.g. steering torque, can occur as soon as a torque difference builds up on the front axle. In this case the manual torque will drop on one side and in extreme cases the steering wheel will even turn in one direction by itself.

The sensitivity of the steering system to such torque differences depends on various factors, e.g. axle kinematics, toe-in flexibility and scrub radius. The design and the type of steering system also play an important role here. Experience gained during the development of the Twinster four-wheel drive concept and the active limited slip differential on FWD application was particularly helpful.

2 Requirements

Two different AYC concepts were chosen for testing and the requirements were defined in terms of the driving dynamic.

2.1 Schnellster (speed-led system)

Superimposed gearset parallel to the open differential

Requirements:

- 10 % speed offset
- 1200 Nm torque difference
- response time <100 ms.

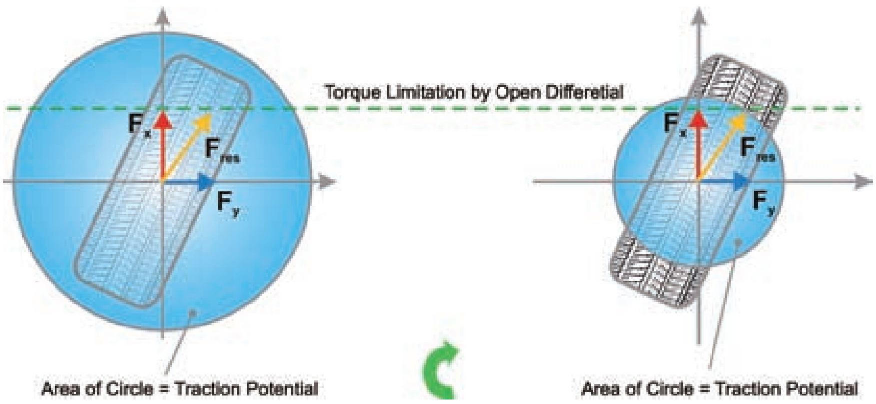
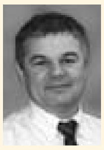


Figure 1: „Kamm Circle", open Differential: acceleration on constant corner radius

The Authors



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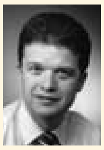

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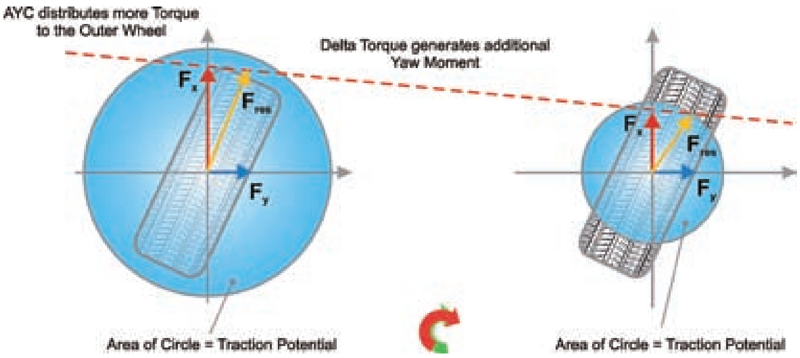

Figure 2: „Kamm Circle", AYC system: acceleration on constant corner radius

2.2 Twinster+ (Torque-led System)

Two separately controlled wet multiple-plate clutches, no open differential
Requirement:

- Maximum wheel torque must be reached (1800 Nm per clutch)
- Response time <100 ms
- μ-split acceleration must be acceptable

2.3 Schnellster

The system does not depend on the engine drive torque. To generate a torque difference between the wheels, the required speed offset is supported on the road surface, **Figure 2**.

A torque difference can be delivered at any time if there is sufficient tire-road adhesion potential at the front axle.

Turning radii at which speed differences that are greater than the offset of the superimposed gearset are geometrically induced will require the system to drop out. Otherwise the yaw support can be lifted or the transmission can run in self-blocking mode.

2.4 Twinster+

The system is designed as a two-clutch system. The drive torques are transmitted to the relevant wheel according to demand by the separate clutch control system. The open differential drops out and the system must therefore be driven with a higher complexity of control compared with the Schnellster.

The basic thinking behind torque-led systems is that the vehicle is in a "drive-torque free" state when it drives along the ideal line. Understeering that has been initiated by induced drive torque can be reduced by a torque difference that is adjustable at the front axle. It must be noted that only the driveline torque can be varied. In throttle off mode relatively little engine drag torque is delivered at the wheel, depending on the gear, but wheel selective braking to boost yaw on demand is feasible. Single-side braking will not then be felt as interference by the driver, as he will want to slow the vehicle down in any case.

The system must have very good adjustment accuracy and fast adjustment speed so that, for example, the torque for the wheel with the lowest friction coefficient can be applied for both wheels when accelerating to μ-split (different left / right friction coefficients). Otherwise a high yaw moment will build up and this will affect driving stability.

The clutches' torque capacity will lie above the maximum wheel torque. The clutches have a fail-safe design (open without power applied).

3 Control Concept

The control concept has a modular structure and it is essentially identical for both systems. It includes the following modules

- traction
- agility (for pre-controlling)
- yaw support and yaw damping
- smart actuator
- valve control
- clutch thermo-management
- torque interface to other control systems
- differential (Twinster+ only)
- starting clutch (Twinster+ only).

The Twinster+ controller is a wheel-slip based controller and therefore needs an additional speed sensor fitted at the clutch input.

4 Test Vehicle

A Mini Cooper S/R53 was chosen as the test vehicle. This model had already been used in previous four-wheel drive and clutch development projects, which means that 9 different driveline systems have now been investigated in this vehicle.

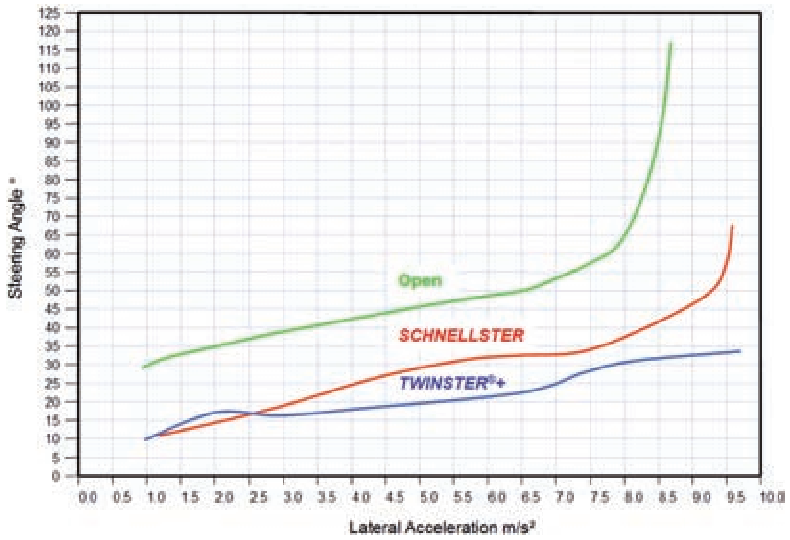

Figure 3: Moderate acceleration on constant corner radius (80m), dry asphalt steering angle versus lateral acceleration

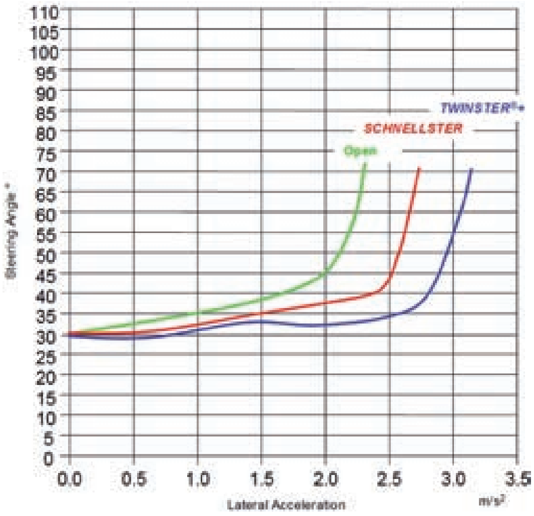

Figure 4: Moderate acceleration on constant corner radius (115 m), packed snow, steering angle versus lateral acceleration

5 Driving Dynamics Results

5.1 Slow Acceleration on the Skidpad (Asphalt and Snow)

The vehicle was accelerated slowly up to vmax on the skidpad from a low vehicle speed. The driver kept the cornering radius constant by adjusting the steering angle accordingly. The diagram shows the steering angle that was applied during the lateral acceleration for a high friction coefficient, **Figure 3**, and a low friction coefficient, **Figure 4**. The lower steering angle required by the AYC system is clear to see compared with the open differential. The steering angle is less for the Twinster+ than for the Schnellster. The Twinster+ also achieved an approx. 15 % greater lateral acceleration on snow than the Schnellster.

5.2 Acceleration from Steady Cornering on Snow

The vehicle was brought to a steady cornering speed and then accelerated. The steering angle was not changed during the acceleration phase. The vehicle reaction can be followed here in the yaw angle speed gradient, **Figure 5**. The mass-produced model quickly lost yaw speed and slid tangentially over the front axle and off the skidpad. The AYC system ensured that the yaw moment was maintained for considerably longer. Twinster+ also exhibited the best yaw characteristics.

5.3 Steer Step Input from a Straight Line at Full Throttle

The vehicle was driven straight at 50 km/h. It was then accelerated at full throttle and steered at a steering angle of approximate 90°. **Figure 6** shows the essential track curves for the tested versions. Again, the advantages of the AYC system can be seen clearly. A tighter circuit was driven as opposed to the series version and the vehicle with the AYC system slid less over the front axle towards the outside of the curve.

6 Discussion of the Test Drive Results

All the driving maneuvers set out here clearly document the gain that is achievable with AYC systems in front-wheel drives. The fact that the yaw support function can be adjusted over the full lateral acceleration range without restricting the known driving stability of the front-wheel drive system is extremely advantageous. This means that the vehicle reaction always remains transparent until it reaches the limit areas. Any driver, regardless of whether he has a "defensive" or "sporty" driving style, can experience the increase in safety and driving dynamics. Both systems can also be adjusted so that the torque differences have only very minor interaction with the steering torque. The Twinster+ system offers further slight advantages when compared to the Schnellster system. This is because with the Twinster+ system the wheel torque for the wheel on the inside of the curve can be reduced to zero in extreme cases, allowing the remaining tire-road adhesion potential available to this wheel to be used for building up side force capability. This is particularly advantageous when driving at a low friction coefficient and thereby in the lower lateral acceleration range (<5 m/s²). This means that the wheel load change in the lateral direction at the front axle is of secondary importance. The wheel on the outside of a curve can always maintain a yaw moment even at high wheel-spin. On the other hand, the

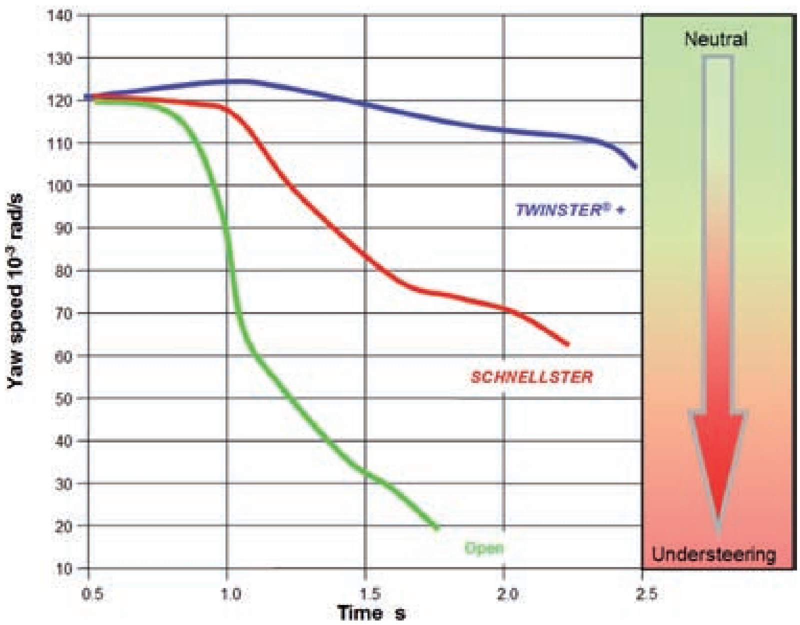

Figure 5: Acceleration from steady state cornering on snow, yaw speed versus time

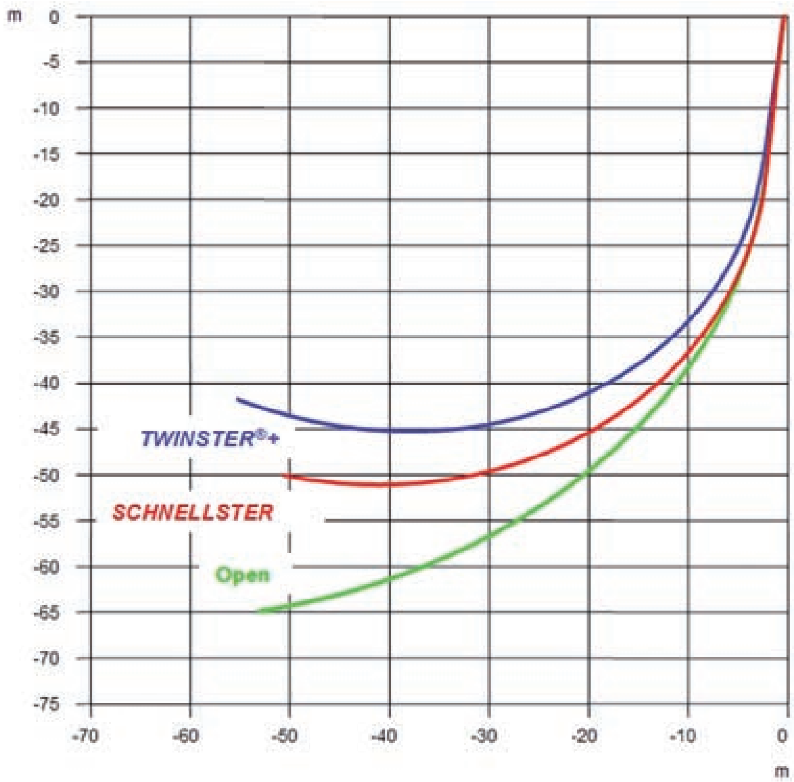

Figure 6: Step steer input during wide open throttle acceleration on dry asphalt, path of vehicle centre of gravity

Schnellster system does also transfer drive torque to the wheel on the inside of the curve. In this case the front axle's side force balance will be less sufficient, especially if the front axle is heavily loaded or even overloaded with drive torque. An improvement can be achieved by limiting the engine torque. In the Schnellster, the torque difference is freely adjustable, which can be advantageous in certain situations.

7 Energy Input

At the start of the project the question as to whether the Twinster+ clutch system could fulfill the vehicle's service life requirements was raised . The control concept has been designed to prevent high torques being paired with high clutch slippage. In the simulation the energy inputs for high clutch torques with the necessary clutch slippage when cornering with full steering lock were calculated. The results showed that the energy inputs did not necessitate any active cooling of the Twinster+ system.

This was confirmed later on during the testing phase by road load data measurements taken on the 'Nordschleife' at the "Nürburgring" race track, as well as on country roads and by city road profile measurements. The highest overall clutch oil-sump temperature recorded was 109 °C on the 'Nordschleife'.

8 Twinster+ Constructive Assembly

The special characteristic of the Twinster+ design, **Figure 7**, is that the transmission transfers the drive power to the wheels without the customary differential. This task is undertaken by two independently working, wet multiple-plate clutches. The Twinster+ clutch unit is flange-mounted on the transmission output. As there is no differential case, the final drive wheel is mounted on a carrier in the transmission and linked to the clutch unit's external plate carrier by means of a socket spline.

The internal plate carrier grips the splines on the left and right side shafts of the front wheels. The two clutches work on a "normally open" basis and are hydraulically operated. The two pressure pistons are vertical pistons and are sealed with low-friction PTFE seals in the Twinster+ casing. The piston force is transferred to the disk assembly by means of a needle bearing. The air gap in the disk assembly is crucial to the drag torque. To ensure that the air gap is always reset after actuation, a corrugated spring between the outer plate carrier and the needle bearing moves the piston into the end position.

To allow the Twinster+ unit to be installed in the confined space of the transmission output, a carbon compound material offering a high power density is used as the friction lining. The Twinster+ unit is sealed to the transmission, so that the clutch can be operated with an ATF that is beneficial for the tribosystem.

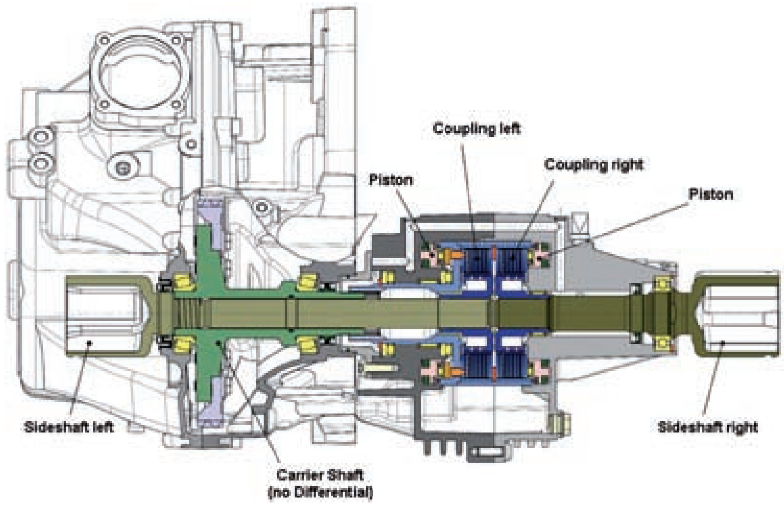

Figure 7: Section view Twinster, mounted to transmission

This also allows the oil level to fall, which ensures less churning.

For economic reasons there is no separate oil pump for oiling the clutch. This task has been taken over by the clutch components themselves in that the rotating external plate carrier collects the oil in the sump and spins it off into a collecting recess in the upper section of the Twinster+ casing. From here the oil flows through holes to the internal plate carrier, at which point centrifugal force presses it through the disk assembly, thereby creating a constant flow of oil.

In summary, it can be concluded that the Twinster+ module can be applied beneficially in today's existing vehicle architecture in that the interface and the installation space of the PTU can be used by four-wheel drive applications.

9 Schnellster Constructive Assembly

The basic construction of the Schnellster system, **Figure 8**, is based on today's transmission architecture. The torque is transferred to the drive wheels by means of an open differential. A superimposed gearset mounted on the transmission output is used to deliver a yaw moment.

The superimposed gearset uses a three-level planetary gear train. The sun of the first level is connected to the transmission differential by means of a socket shaft. The sun of the second level is connected to the right side shaft by a drive-type spline. The third sun is mounted in the Schnellster casing and engages in a friction plate. To achieve an efficient mesh, the step planet's three splines are slotted into place in a single working process.

The planet carrier has a dual function, both holding the step planets and taking over the function of the clutch. This is why friction material has been bonded onto the planet carrier. The planet carrier rotates at the side shaft speed in straight-line driving. The rotating planet carrier must be braked in order to generate a yaw moment.

To do so the ring piston presses down on a steel plate that pushes the axially floating planet carrier against the steel plate located opposite to it inside the casing, clamping it like a brake disk. The step up from the first planetary level to the second causes the right side shaft speed to increase, which for example corresponds to left-hand cornering. The yaw moment is produced in the other direction by the activation pressure in the second piston braking the third sun by means of the steel plate. The step planet's third planetary wheel now rolls away from the fixed sun, producing a step down between the differential case and the right side shaft. This differential effect increases the left side shaft speed.

Although the Schnellster system transfers a torque difference of ±1200 Nm to the right side shaft, only a percentage of the speed offset, i.e. 120 Nm, is required as the braking torque in order to brake the planet carrier or the third sun. As the recorded clutch power is produced without this boosting factor, good heat dissipation into the friction gap must be ensured. The steel plates used here have a thickness of 4 mm and the direct connection to the casing ensures good heat dissipation. As the system has only two friction points, the rotating planet carrier and the third sun's friction plate, the system produces very low drag torques. This is a very important characteristic as the loss becomes very low when driving in a straight line.

The asymmetrical construction of the Schnellster system, in which the yaw moment is produced by increasing or reducing the speed at a side shaft, makes it ideally suited for front lateral transmission installation. If already fitted, it can be applied almost without modification by accessing the four-wheel drive interface at the transmission output.

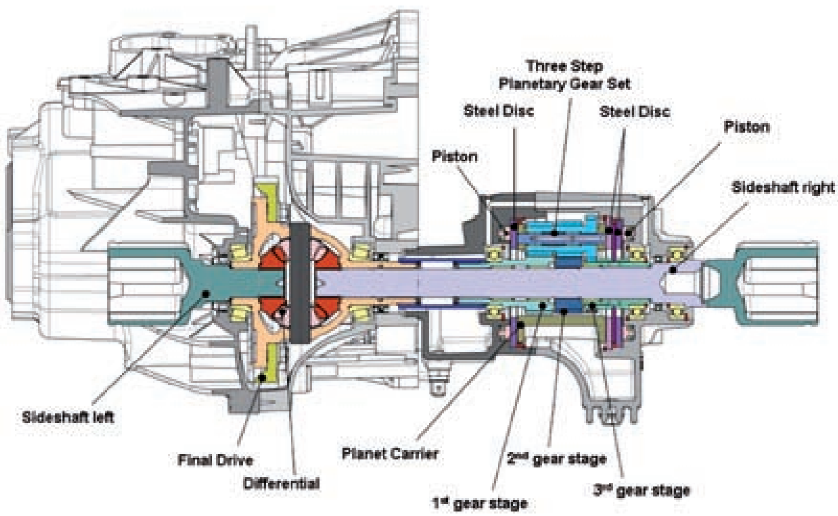

Figure 8: Section view Schnellster, mounted to transmission

10 Actuator

The actuator, **Figure 9**, used in the prototype vehicle is a further development of Getrag's standard clutch actuator. The pressure needed for the clutch does not depend on the driveline. A brushless electric motor (BLDC) drives a hydraulic pump directly, i.e. the clutch pressure is generated as needed. The driving dynamics and the clutch controller are "imported" from the microprocessor that is needed to operate the BLDC motor. No separate ECU is required.

A high proportion of same parts enables cost-effective use in several projects. The reservoir (6) must be optimized for different installation positions. Different plugs are configured using specific "end caps" (9). The two different clutch torques are controlled by pressure control valves and sensors downstream of the pump. These are in the form of external valve blocks in the prototype. Given the required dynamics (0 to 6000 rpm < 50 ms), the motor has been designed as an internal rotor motor, which also ensures good heat dissipation of the stator. The power electronics have been designed as an aluminum substrate in direct contact with the motor casing. The logic board is in the form of a double-sided FR4 board. Microproces-

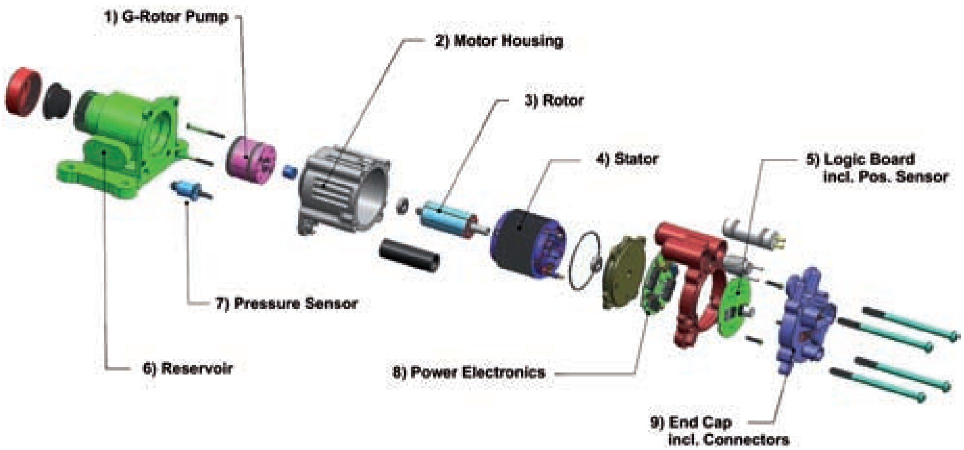

Figure 9: Hydraulic clutch actuator

sors (XC164) and voltage regulators are mounted on the top to enable direct contact with the heat sink. The plug is part of the plastic end cap, as the plugs are molded around the pins in the manufacturing process. The coil and the capacitor are both sealed due to the high mechanical loads generated when fitting transmissions.

Torque control is based on a pressure measurement. In the standard actuator the sensor is mounted in the pump outlet, while in multiple-clutch actuators sensors are fitted in each pressure circuit.

A coupling connects the pump to the rotor. High volumetric efficiency (80 %) and low torque at high speeds were considered during development. The pump consists of a sintered rotor, two aluminum covers, a rotor shaft and a shaft seal. Two of the pump screws also serve to secure it in place. The ring-shaped pressure outlet allows a flexible package.

In the standard actuator the reservoir is sealed by a large cover and ventilated through a diaphragm. Two clutch systems require a larger volume of oil, so the reservoir in the prototype is modified and ventilation is now in labyrinth form.

The standard actuator measures 100 x 85 x 200 mm and weighs approx. 2.5 kg. Less than 10 A is required from the onboard power supply when operating at a maximum pressure of 45 bar. Average power consumption is less than 2A. In the prototype vehicle the actuator and the valve block are mounted in the engine compartment.

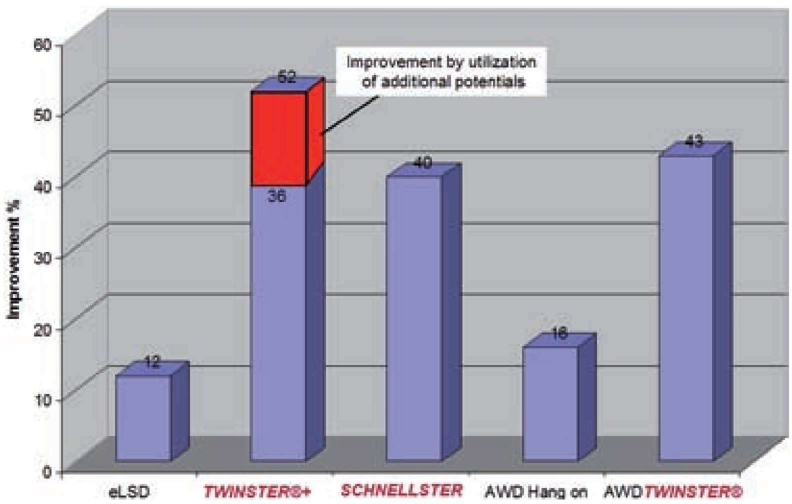

Figure 10: Improvement in comparison to FWD with open differential (eLSD = electronically controlled limited slip differential)

11 Development Potential

The Twinster+ system has been primarily designed as an AYC system. However, there is also potential for the integration of "external" functions. Functions that can be integrated:

- differential: The system can be integrated in the differential installation space
- shift transmission clutch (so clutch is not needed): space can be used for e.g. a hybrid drive; starting clutch function adapted to the road surface friction coefficient (snow/sports mode)
- limited slip differential
- road surface friction coefficient detection
- torque limiter
- decoupling of the transmission and wheels: Free running function in overrun mode (consumption savings through "coasting"); no torque interaction between the wheels with selective wheel braking (ABS/ESP).

12 Overall System Evaluation

Both AYC systems were finally compared and evaluated against other driveline system designs already investigated. Initially only the driving dynamic characteristics were evaluated, characterized by 22 different driving situations. The additional potential that can be gained from functional integration was then included in the evaluation. The improvement potential compared with series models with open differentials is shown in **Figure 10**. The Schnellster appears to be better than the Twinster+ if the functional integration is excluded from consideration. The area marked in red in the Twinster+ column indicates the additional gains from functional integration. The Twinster+ concept is the best solution when all of the requirements such as improved driving safety, increased agility and more driving enjoyment at less cost and lower weight are added together. ■

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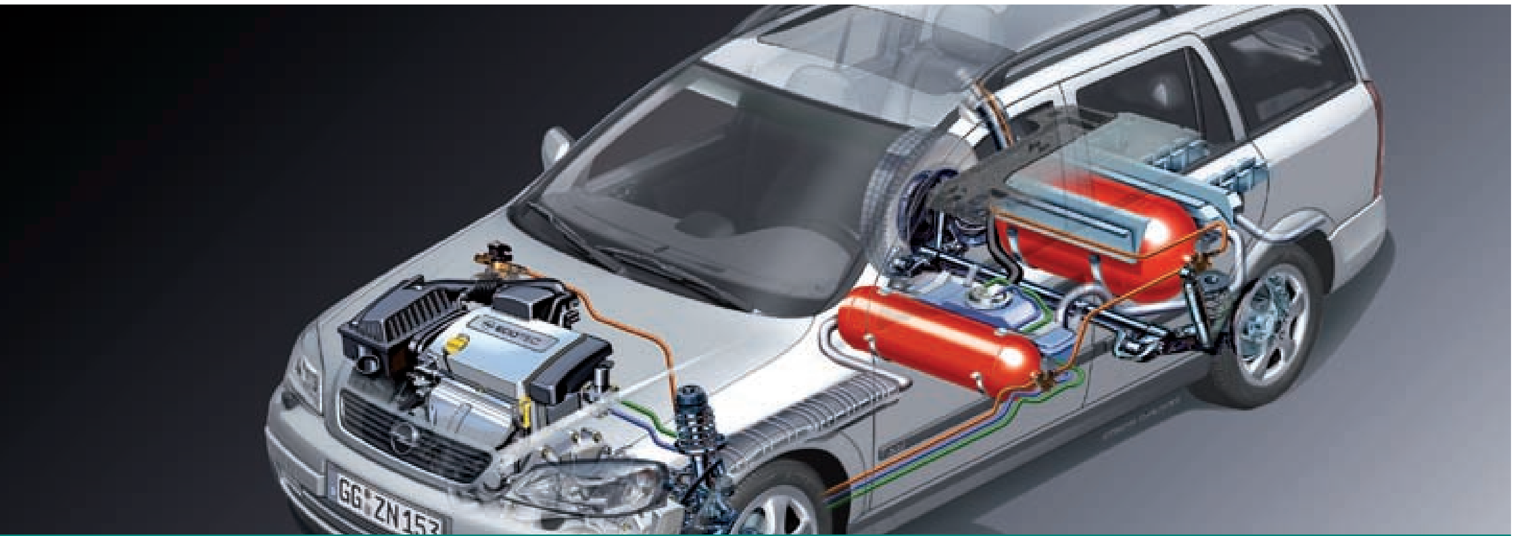

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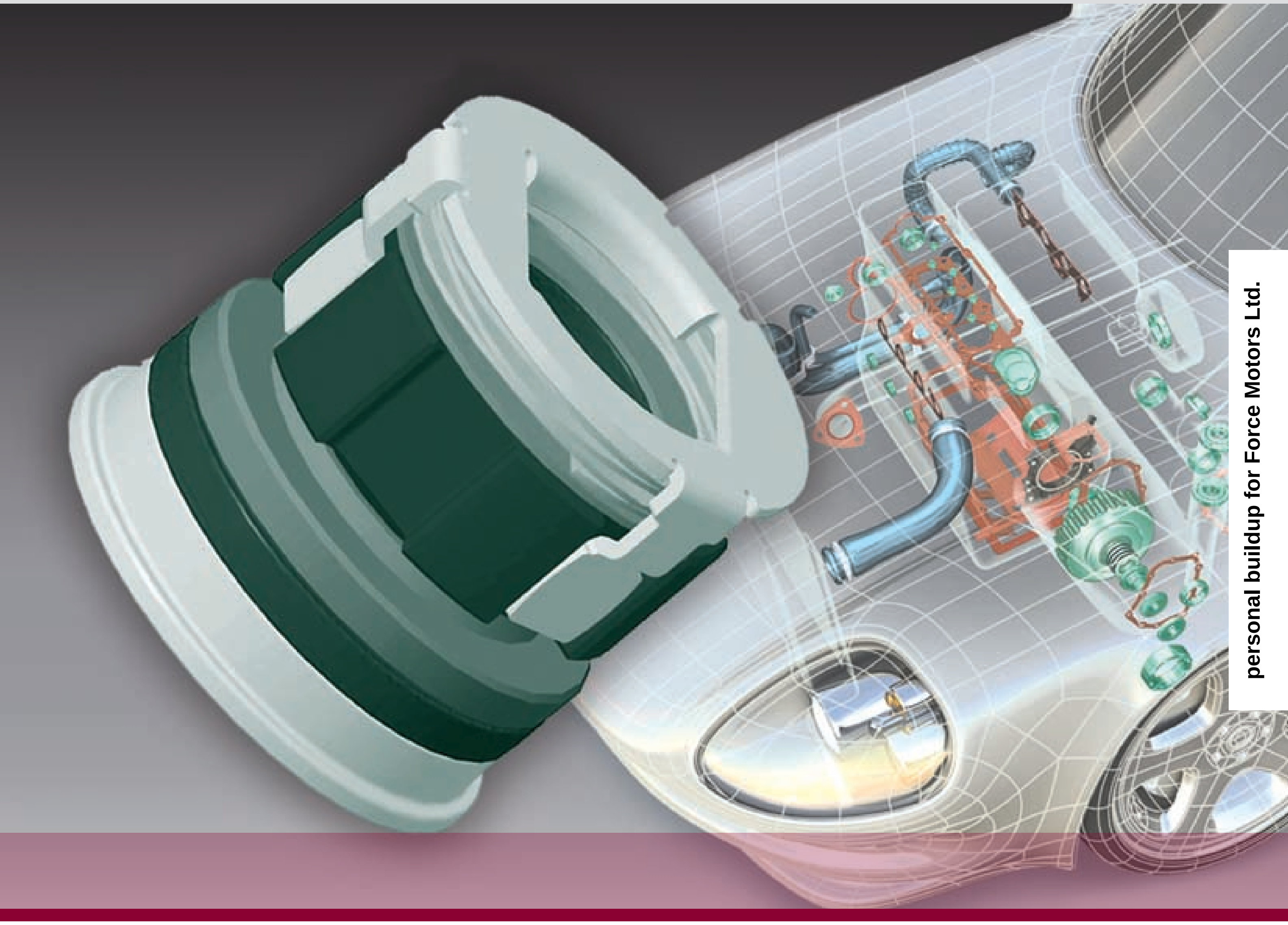

Leakage Test Examination of Shaft Seals for CO_2 Refrigerant Compressors

Axial face seals are well suited for dynamic shaft sealing in CO_2 (R744) refrigerant compressors for air-conditioning units in regard to design. An axial face seal by Kaco Dichtungstechnik GmbH has been released for series production and is currently being run in at nearly all producers of compressors worldwide. In multiple fleet tests the seal has been proven beyond doubt and fulfils all required criteria within its specification. With the presented test results it is proven that shaft sealing for CO_2 refrigerant compressors can be mastered.

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1 Introduction

For decades, Kaco Dichtungstechnik GmbH has been well known as an innovative partner in the automobile and supplier industry in solutions for complex dynamic sealing from the powertrain as well as in auxiliary aggregates. The materials used have been specially developed and optimized over years – in particular with the axial face seals for water pumps used in passenger cars and commercial vehicles; thus having acquired an exceptionally respectable standing in Europe and the global market.

The skill and knowledge in overcoming pre-production development challenges in regards to design, testing methods and the preparation for production have all been put into the development of the dynamic axial shaft seal for the CO_2 refrigerant compressor. Kaco have been working on these sealing problems since 1999, challenges that have been regarded as unsolvable by many. Specific test stands, **Figure 1**, were developed at Kaco in order to proof all necessary specification requirements of the CO_2 axial face seal.

2 Refrigerants – from R12 to CO_2

For the past few decades most automobile producers have been using fluoride compounds like chlorofluorohydrocarbons (CFC) as refrigerants in their mobile air-conditioning units (A/C units). The CFC used in early A/C units, known as R12, quickly became known to damage the ozone layer and to be a large contributor to the green house effect. The media CFC, a harmful refrigerant gas, was globally banned from all markets.

In the 1990s the hydrofluorocarbon (HFC) R134a became the new refrigerant. Initially, HFC was planned as a temporary solution only because it was known to have a high global warming potential (GWP) of 1200: That means that 1 kg of R134a has got the same impact on the green house effect as 1200 kg of CO_2.

Since these times, the automobile and supplier industry worldwide are looking for an environmentally friendly refrigerant, which is to be the ultimate solution with mobile A/C units. The requirements on material used are varied. Flammables and toxics are not an option as the handling of synthetic material holds many risks in regards to liability. Yet without the toxic effect fully known, many US-American and some Asian OEM are preferring the flammable refrigerant R1234yf (also a HFC) as their favourite, a synthetic, partly fluoridised hydrocarbon. The use of environmentally friendly refrigerants with all new automobiles (that means newly developed models) will be a new European law as from 2011. As from 2017 all new vehicles need to be equipped according to these new European guidelines.

Figure 1: Test stands for CO_2 shaft seals

The GWP of a refrigerant must not exceed 150 by law. At this point only two chemical compounds come into question – the R1234yf with a GWP of 4 and CO_2 (R744) [1]. However, there is only insufficient production experience for R1234yf available. The initial production could be launched by the end of 2010.

On the other hand CO_2 is a natural substance, which can be easily reclaimed and has got a GWP of only 1. And as long as the filling of the system has been recovered from the environment, a leakage would have no negative impact on the green house effect. In comparison with other refrigerants CO_2 has got the advantage that due to its thermodynamic characteristics and, that combined with a suitable engineering, a CO_2 A/C unit can also be used as a heat pump. Due to the efficiency of modern combustion engines there is a lack of radiated waste heat that could be used to heat the interior of a passenger cabin. CO_2 can suitably compensate for this. In particular, this applies to hybrid, fuel cell and electric vehicles. Furthermore, development tests show that under most test conditions using a R744 A/C unit is much more fuel efficient than a comparable conventional R134a system.

3 Aims and Objectives

At the IAA 2007 in Frankfurt/Main (Germany) the VDA had announced that as from 2011 onwards CO_2 will be the refrigerant to be used in the future by the automobile industry that was confirmed in October 2008 [2]. Since then all research and development have been intensified by the participant suppliers with the aim to keep to the schedule.

A lot of attention has always been directed to the shaft sealing of compressors. Due to remarkably higher pressure levels compared to R134a the requirements are also of much higher standard. The pressure characteristics of the sealed mixture composed of refrigerant oil and CO_2 under dynamic conditions are between 30 and 70 bar, peaking at 90 bar. Under static conditions (engine standstill) the pressure levels reach as high as 110 bar. The revolution range is measured analogous to the transmission ratio between the crankshaft and the compressor belt disc ranging from 600 to 10.000 rpm running at temperatures up to 180 °C. The requirements for impermeability are developed accordingly in order to function service-free for the entire lifespan of a modern car's A/C unit.

Kaco's latest generation of axial face seals meets all current requirements of shaft tightness. Corresponding results were the outcome from various in-house testing processes in addition to compressor and vehicle tests.

4 Test Equipment

Essentially, three parameters are necessary to define a good shaft seal. These are the following three points:
- life span under known test specification
- leakage behaviour
- The seals' frictional torque.

In order to define the efficiency of a sealing system it is inevitable to have to test the parameters with a suitable technique. Apart from the development of the sealing system it was necessary to develop specific test stands, measuring processes and the corresponding measuring instruments. Due to the systems´ unique nature all processes and equipment needed special research and development as there was and there is no such technology available.

4.1 Test Stands

Specific test stands, Figure 1, were developed at Kaco in order to proof all necessary specification requirements of the seal. The test stands can present all required temperatures and pressure levels throughout the entire revolution range. To ensure realistic conditions the test head had been adapted to the shape of a compressor design. It is highly important to closely monitor the temperatures and pressure levels within the test cell. As standard, the frictional torque of the seal is being measured in every test run. Various long term test stands have been running since 2003. When needed, they can operate at temperatures below zero in an accordingly climatized closed-off unit.

One of the biggest challenges in developing this seal proved to be the measuring of the leakage. The compound of refrigerant oil and CO_2 within the test cell is inevitably leaking to the airside and is constantly measured. In the case of an oil leakage this is easily realized by filtering the leakage flow and measuring it in a gravimetric process. The measuring of the gas leaked is much more complex since there are no suitable processes available for continuously measuring – with adequate accuracy – under atmospheric conditions.

4.2 Measuring Processes

Gas-chromatographs or mass spectrometers were used in the usual measuring processes for high precision analysis of gas leaks. These instruments and their components are complex in their engineering, little flexible and were not easily applied to this unique situation. For

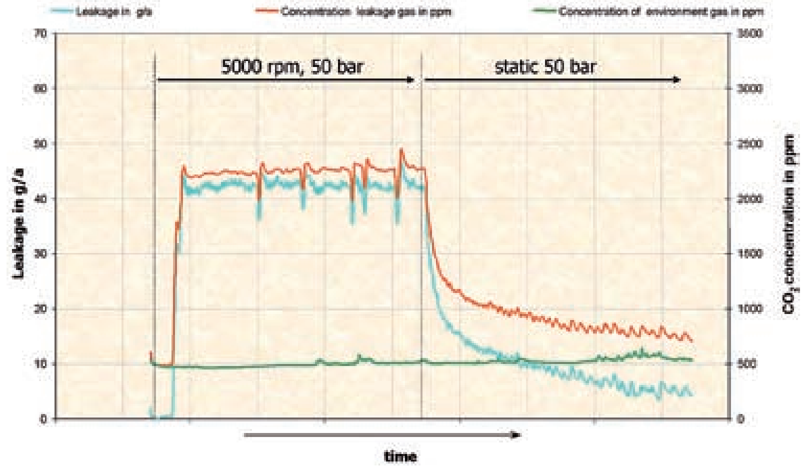

Figure 2: First ever measurements with the CO_2 leakage measuring device

an indirect measuring of the leak other measuring processes use Helium or other test gas endowed with Helium. However, processes using Helium as a device could falsify the measuring results.

In particular due to the specific characteristics of CO_2 in regards to permeation. Therefore Kaco developed their own measuring processes in order to exactly determine the leakage of their shaft seal at stand still as well as in operating conditions.

4.3 Measuring Instruments

In 2005, after a research period of three years, the first measurements with the leakage measuring device were done, **Figure 2**. Two specifically arranged CO_2 sensors within the measuring device are continuously comparing the concentration of ambient air with the concentration of ambient air accumulated with the leakage gas.

Here it is highly important that a constant flow of gas at a constant temperature is flowing through the CO_2 sensor. The leakage of the seal is monitored under all required operating conditions, static as well as dynamic, by means of monitoring temperatures, measuring the flow and by a continuously comparison of the two concentrations.

To date, four of these measuring devices have been put into operation. Comparing measurements of the leakage have already been carried out at the test head and have led to corresponding results. A declaration of exactness of the CO_2 leakage can be given at ±1 g per year. As a standard leakage results are analysed in all tests.

5 Test Conditions

All test conditions have been carried out analogous to the VDA performance specification for CO_2 refrigerant compressors. The performance specification includes all relevant revolutions ranging from 600 to 10,000 rpm, temperatures and pressures. In order to simplify the test procedure with variable pressures always the highest pressure level was used. The specification also stipulates the determination of the total leakage according to varying climatic conditions as well as individually, at stand still and in operation.

The individual stages of operation are valued differently depending on the frequency of occurrence. Naturally, the static operation at environment temperature is of great importance. In developing the seal the main emphasis was put on the achievement of as little leakage as possible in static mode. In operating mode a collective of rotational speed are run at varying temperatures in order to operate in the corresponding conditions of vehicles worldwide.

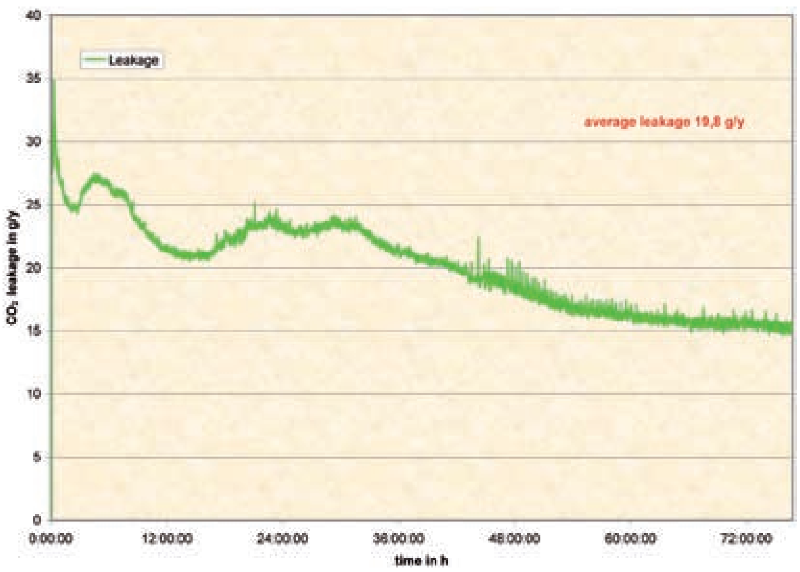

Figure 3: Static leakage in novel shape – obsolete design of the seal

6 Test Results

In the following, the measurement results for static and dynamic leakage with the new and the obsolete design of the axial face seal shall be presented and compared.

6.1 Static Leakage in Novel Shape with Obsolete and New Design

The leakage under stand still condition of the seal in novel shape is most important. The sealing surface of the used axial face seal is treated in a specific process in regards to its roughness and flatness of the sliding surface. Yet, as with all other face seals, a pre-operational running period is needed for the seal to work properly. An optimal leakage (nearly no leakage) is achieved only after a particular running time.

Under realistic conditions at the assembly line the seal is fitted inside the compressor which only then is filled with oil. Next, the finished compressor is fitted within in the A/C unit and that again inside the vehicle. Only here the A/C unit is filled with the refrigerant, and thus can eventually be tested in regards to its tightness. It can take up to several weeks or months from the sale of the vehicle to the first ´real-life-taking-into-operation` of the A/C unit. High leakage in the in-between time is unacceptable. Therefore additional measures have to be taken in order to absolutely minimize this initial leak. **Figure 3** displays the initial leakage of the obsolete design. The level is already reasonably low due to optimal matching and tuning of the sliding surfaces. However, the achievable results of an average of 19.8 g per year are too high in order to match the specification. For economical reasons a wearing process in period of the new seal at fitting stage is not an option. With the newly developed design, **Figure 4**, very low test results are obtained from the very start. They are barely measurable at 1.1 g/a.

6.2 Static Leakage in Run-in Condition with Obsolete and New Design

As mentioned before, there is special meaning put on the percentage of the static leakage in comparison to the real operation of the compressor. Excellent results have already been obtained with the obsolete seal design after it had been

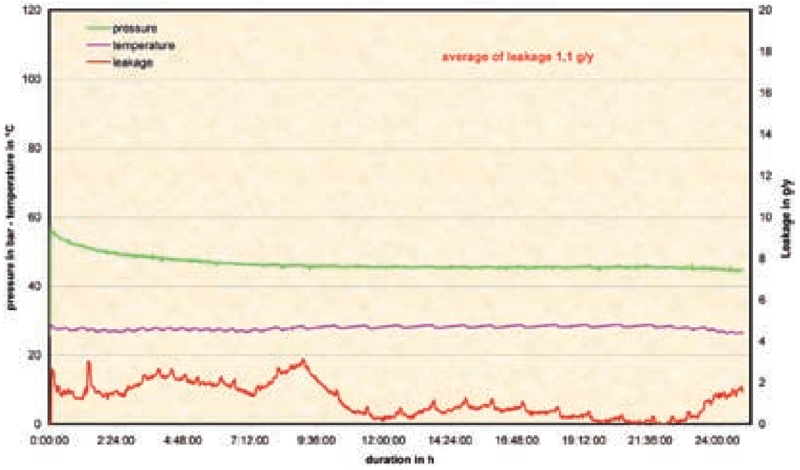

Figure 4: Static leakage in novel shape – new design of the seal (28 °C oil temperature and 46 bar pressure)

ditions. All entered figures have been determined with the newly developed seal design and tested on Kaco's test stands.

In order to display a general and realistic impression, only the figures that have been determined under static leakage conditions and under run-in conditions have been entered. Values measured with seals in novel shape are even lower, as shown in Figure 4. Yet, we believe those figures could be unsuitable for a realistic impression. A total leakage of 7.2 g/a calculated at all operating points is a very good result and is clearly much better than any currently known specification.

run-in – even after long periods of complete stand still up to 700 h, as displayed in **Figure 5**.

With the research for a new seal design the aim was to maintain these values. **Figure 6** and **Figure 7** display the results of the newly developed seal design. With measurements as excellent as ranging around 5.5 g/a CO_2 the brilliant level of the predecessor is being maintained and continued. Even during very long periods of stand still (700 h) the leakage values are stable and absolutely of no concern at 4 g/a.

6.3 Dynamic Leakage with New Design

The measuring process of the leakage under dynamic conditions, that means with the compressor shaft rotating, has been performed in exact accordance with VDA performance specifications. These specifications require a collective of revolutions at varied pressure and temperature conditions, which needs to be run through in several cycles. Despite a relatively high environment temperature of about 150 °C the results displayed in **Figure 8** show low measurements of CO_2 leakage at about 45.8 g/a.

6.4 Determination of Total Leakage

The determination of the total leakage according to the VDA performance specifications follows a pattern mentioned before and displayed in the **Table**. Here, the great importance of the leakage at stand still is also emphasised in comparison to the leakage under dynamic con-

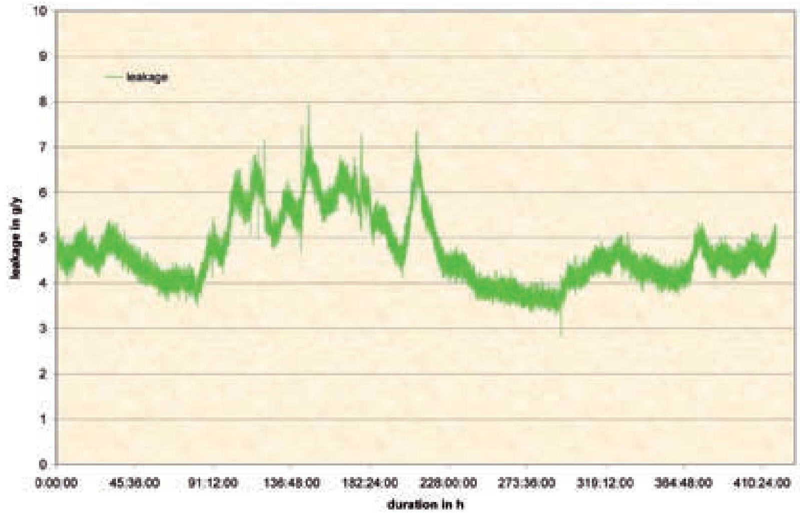

Figure 5: Static leakage under run-in condition – obsolete design of the seal

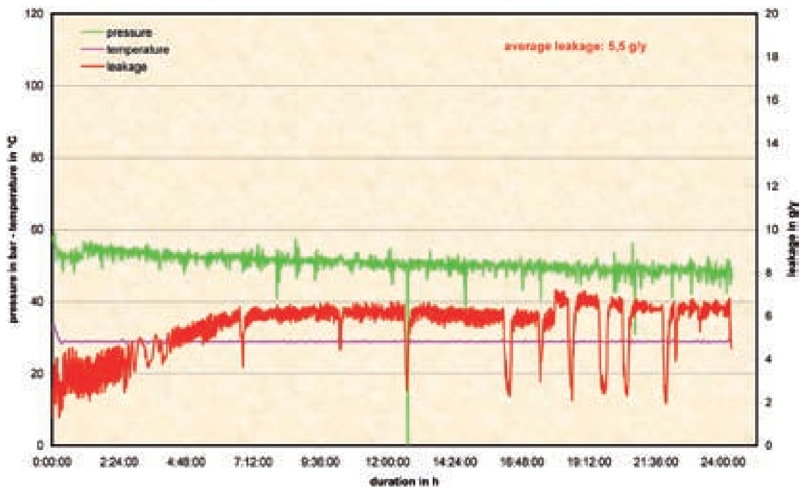

Figure 6: Static leakage under run-in condition – new design of the seal (20 °C oil temperature and 54 bar pressure after 144 h operation time)

7 Conclusion

The sealing manufacturer Kaco has developed a new axial face seal for CO_2 air-conditioning units, which was proofed on test stands extensively. To master the challenge of this sealing location has without doubt been proven to be manageable. It is important to point out that all results have been obtained by using prototypes. The prototype seals have been created under as close to possible realistic production line conditions. The results in the present case display that the newly developed seal design of the shaft seal for the R744 refrigerant compressor meets all leakage requirements at all operating conditions. These are in detail as follows very low levels of

– static leakage in novel shape of a seal
– static leakage in novel shape during long stand still periods
– static leakage at run-in condition – even after long stand still periods
– dynamic leakage at all relevant operating conditions.

All currently known leakage requirements for these sealing systems were fulfilled. Furthermore, multitudinous life time tests on test stands have been performed on both, the compressor and the vehicle during the developing period. All test results were positive. Also the extremely low power loss of friction of this particular sealing built is to be emphasized. Kaco now are preparing the production line of these seals. The first application of this seal is estimated for 2011, based on the decision of the VDA. Hopefully, other OEMs on a global level will take similar decisions in order to obtain an environmentally friendly and lasting effect.

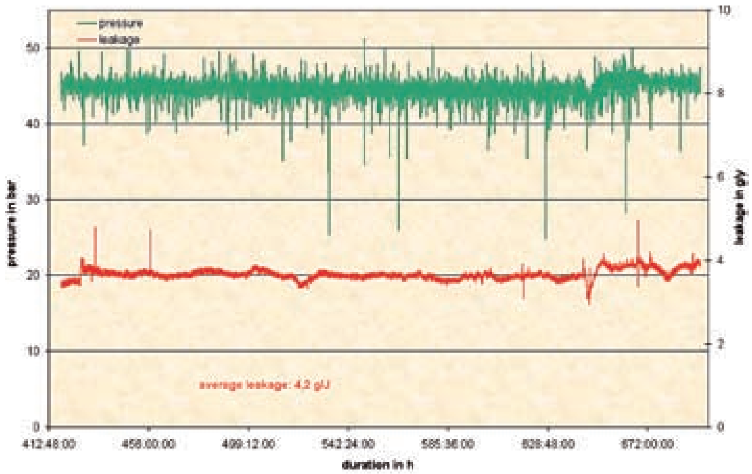

Figure 7: Static leakage during a very long period of stand still under run-in condition – new design of the seal (150 °C oil temperature and 45 bar pressure, 700 h in VDA test)

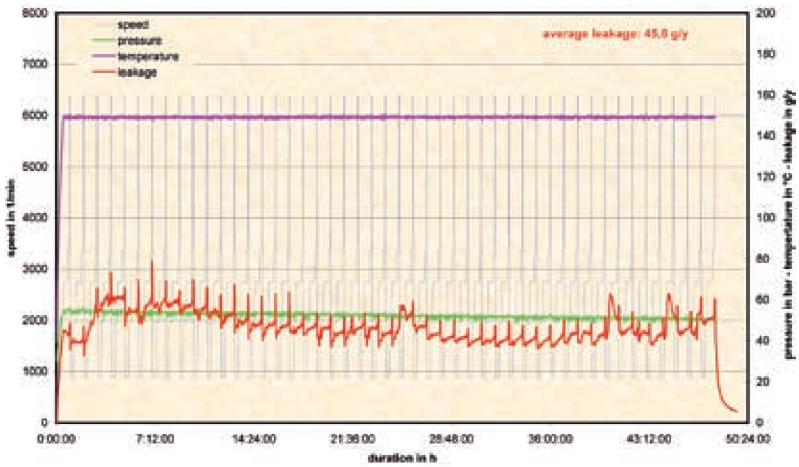

Figure 8: Dynamic leakage – new design of the seal (150 °C oil temperature and 45 bar pressure)

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Leakage test			
Operation time: 8760 h / year			
stand still conditions	duration 8146 h		
pressure / temperature	leakage [g/y]	weighting	leakage - weighting [g/y]
90 bar / 54°C	11.6	0.069	0.8
55 bar / 20°C	5.5	0.616	3.39
35 bar / 0°C	1.5	0.206	0.31
7 bar / -30°C	1.4	0.041	0.06
result stand still		0.932	4.55
operation conditions	duration 596 h		
crankcase pressure / temperature	leakage [g/y]	weighting	leakage - weighting [g/y]
45 bar / 150°C	45.8	0.041	1.88
45 bar / 120°C	27.8	0.017	0.47
45 bar / 90°C	29.2	0.01	0.29
result operation		0.068	2.64
result stand still + operation		1.0	7.2

Table: Calculation of total leakage

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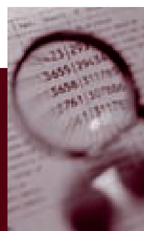

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personal buildup for Force Motors Ltd.

Concept Car Development with the Example of a Ford Model T Successor

Only three months were needed by a team of the Institut für Kraftfahrzeuge (IKA) of RWTH Aachen University in order to develop an innovative vehicle concept which is capable of carrying conventional as well as alternative drivetrain modules thanks to its scalable design – a modern "Tin Lizzy" for the year 2015 with a basic sales price of less than 7000 US dollar.

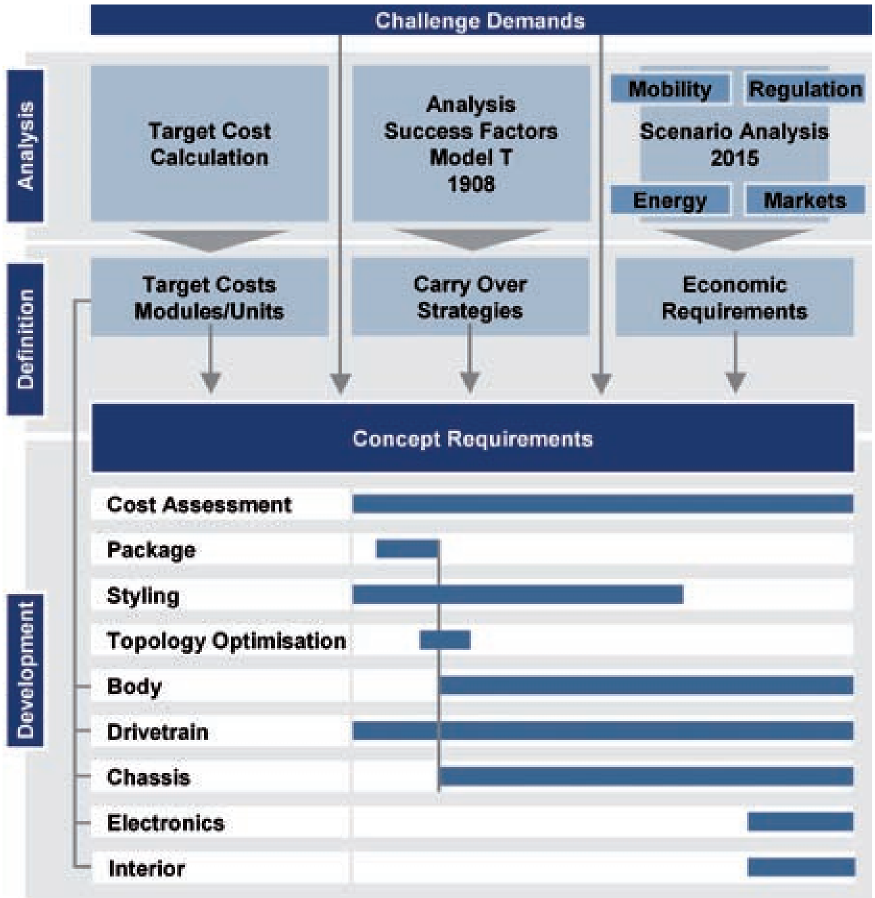

Figure 1: Flow chart of the concept development

1 Introduction

The legendary Ford Model T is still one of the most successful and sold models of vehicle history. Over a hard to imagine production duration of 19 years, about 15 million units have been sold which were used for very different applications. This variability was one of the aspects that had to be regarded in the Ford Model T Challenge 2008. The Ford Motor Company has launched this competition under five universities worldwide to celebrate the 100th anniversary of the Tin Lizzy.

The demand was to develop a modern Model T in only three months time while being simple, robust, light and compelling. In addition hard facts like space for at least two passengers, a range of 200 km as well as a maximum basic sales price of 7000 US dollar were required with the latter surely being the hardest challenge.

2 Approach

A scientific approach, though inspired by the industrial development process, was chosen for the development of the concept vehicle, **Figure 1**. Based on the demands that were given for the challenge, the requirements for the vehicle have been analysed. This included a detailed examination of the success factors of the predecessor, the historic Model T, as well as an investigation if and how these could be transferred to a modern car. The scenario analysis revealed further boundary conditions and economic requirements of the relevant markets. The main

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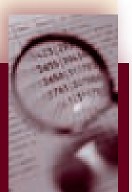

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Received .... February 4, 2009
Reviewed............ February 25, 2009
Accepted .... March 16, 2009

driver was the very ambitious basic sales price from which target costs for every module had to be derived using a target cost calculation.

The requirements which had been depicted in the analysis phase were then collected as concept specifications for the definition phase. Based on these, the actual concept development started which was characterised by highly parallel processes and a permanent cost controlling. In order to generate not only concept ideas but technical-feasible solutions in the very limited time given, strategies for efficiency increase had to be applied. It was mainly the parallelisation of component development and styling, traditionally an up-front process, which significantly saved time. The rough styling was decided based on hand sketches while the detailed surface construction was done in parallel to the body structure. This again could be increased using topology optimisation.

3 The Success Factors of the Historic Model T

Only five years after the foundation of the Ford Motor Company in 1903, the production of the Model T started. Its success was gained by fulfilling the market demands of those days to a very high level. Besides a classic passenger car, it was also used as a truck, tractor or even tank. In addition, the main success factors were the low sales price of 650 US dollar and its robustness for the poor and unsurfaced roads of the era.

Furthermore, the simple construction allowed easily repairing or adopting the car for other applications. Today's trend towards multi-material design was also consequently utilised those days. Hence, a modern concept has to combine the success factors of the historic model with the dominant requirements of a car to be launched in 2015.

4 Scenario Analysis

With the aim to meet the major demands that a world car has to accommodate in the 21st century, a scenario analysis for the target year 2015 was carried out. Social, economic and technologic trend studies, for example [1, 2], have been regarded and were amended by own findings. The major influencing factors are given by the mobility demand, legal regulations, the availability of energy and the market situations. The focus was placed on the markets of the Triad as well as of emerging and developing countries.

The need for mobility is increasing worldwide. Individual mobility will stay the basic need of mankind. With public transport being able to fulfil these needs only to a limited amount, the vehicle market will grow especially in the emerging countries. Besides the trend to mega cities, the majority of the population will still live in rural areas. Regional differences in availability and development of transport systems, infrastructure and routes have to be regarded for the target scenario. The new Ford Model T as a world car has to meet not only the requirements and customer demands of accessed markets but also increase the brand awareness and attractiveness in export markets to be accessed. In parallel to individual mobility, customers also ask for automobile individuality. Open source approaches with defined interfaces can be adapted to vehicles and offer one potential solution for conflicts in relation with the individualisation of a mass product.

Furthermore, the age structure of clients is of importance. The age pyramid is showing an aging population. This aspect is to be met by the concept amongst others by optimised ergonomics offering a high and up-right seat position. One central feature of the scenario analysis was the question which energy sources are available and accordingly which drivetrain options are best-suiting for the year 2015. The results show that the internal combustion engine will keep its dominant role besides all on-going efforts towards hybrid and electric vehicles, **Figure 2**.

Main factors are the energy infrastructure as well as lasting high costs for electric energy storages. Alternative propulsion concepts will gain importance in some markets though due to legal requirements (city limitations and CO_2 taxation) as well as demands by customers with ecological awareness.

5 Model T Concept for 2015

The low sales price was a key challenge during the development of the concept.

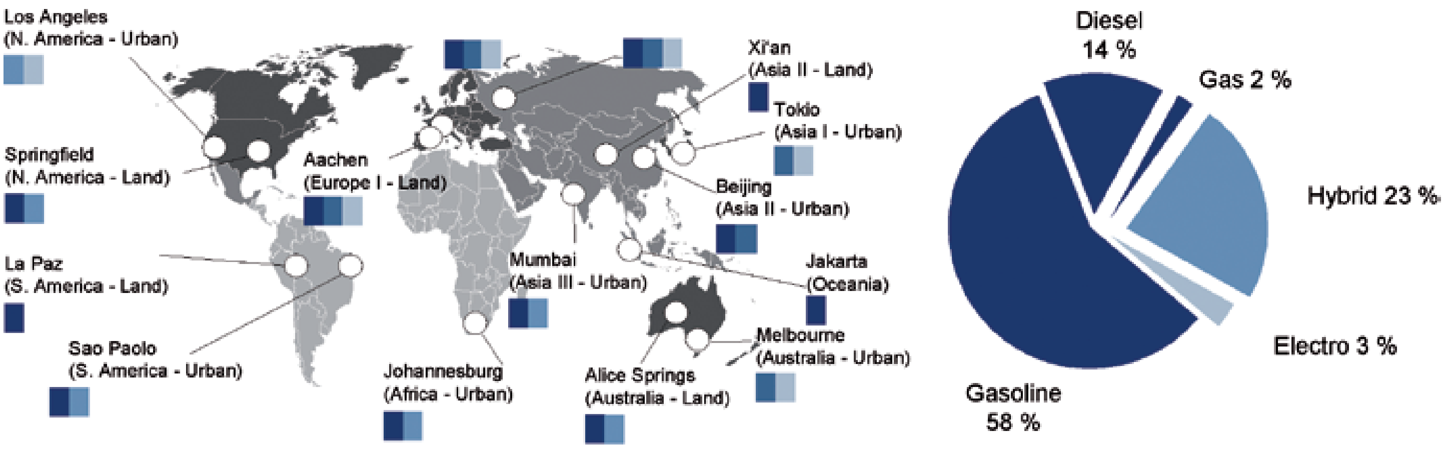

Figure 2: Distribution of propulsion systems and markets in 2015

Different studies have shown that low-cost cars can be offered profitably at a sales price of 7,000 $ or even below [3, 8, 9, 10, 11]. Consistently, changes in production, sales and distribution but also design are claimed to be necessary in order to succeed. This includes low-investment for on-site assembly of smaller volumes in lean production with increased manual processes. Standardised low-cost components, which are used by different brands and produced in low- cost countries, so-called "industry modules", enhance the economy of scale. The global vehicle structure has to be designed for basic functionality with low complexity of parts. A modular design of the vehicle enables further economy of scale and re-use of particular parts. At the same time, this carry-over reduces R&D costs that can be further optimised by extensive implementation of simulation tools. For automotive low-cost strategies, the part of logistics and sales is important. A reduced centralised dealer network is essential. Even sale via internet is an option. Finally, marge and costs for marketing have to be reduced.

The aspects motioned above were considered in the early concept phase when setting the target costs for the Model T. The subsequent concept development was attended by target costing. Therefore, target costs for the main components body, chassis, interior and electronics had to be established first, **Table 1**.

Accordingly, the maximum allowable cost of each component had to be established, assuring not to exceed the basic sales price of 7000 US-$. The percental distribution is based on a typical C-class vehicle (class of compact vehicles) [3]. The different cost items were derived from this percental distribution while the concept specification was determined from the scenario analysis, following market economy principles, as well as the major success factors of the historic Model T and the cost target.

Table 1: Target cost definition in US dollar

Basis sales price 7000 $			
Production costs 4970 $		**Additional costs** 2030 $	
Assembly	890 $	Logistic	420 $
Body	980 $	Marketing	560 $
Chassis	800 $	Overhead	420 $
Drivetrain	880 $	Guarantee	250 $
Interior	750 $	Marge	420 $
Electronics	630 $		

Therefore, the main dimensions were defined at first, influencing not only the outer appearance but also some essential technical properties. The trend towards smaller cars is apparent. One reason among others is the fact that the average number of passengers per ride is as low as 1.4 [4]. Accordingly, the team agreed very early that a modern Model T shall be positioned in the C-class (compact or sub-compact class). At the same time, there is an increasing demand for interior space and luggage by the emerging markets in which the new Model T shall be the first vehicle. The compromise of compact appearance and offered space was finally found in a short but wide vehicle with relatively high ground clearance and an up-right seat position for the passengers, **Figure 3**.

The width of the car allows sufficient space for three passengers in one row. The driver is centrally positioned and slightly ahead of the two passengers. This avoids different models for left and right hand steering. The concept is characterised by modularity, scalability and individuality, going from derivates, **Figure 4**, that are based on the scalable basic structure via changeable outer plastic panels to the drivetrain concept.

Package, vehicle architecture as well as structure of the modern Model T are easily adoptable for usage as a hybrid drive, a plug-in hybrid drive or pure electric drive. The base model is driven by a gasoline engine as internal combustion engine (ICE). Its position in the rear of the car, together with the semi-trailing arm axle, is supporting an efficient package, can easily be accessed and thereby allows the modularisation of the drivetrain.

In the front section there is a high freedom of package. This offers space for a maximum of passive safety.

Besides technical concept specifications, styling requirements for the new Model T had to be defined. A complete retro-styling approach as often used for remakes of automotive icons did not seem feasible from a technological, economic and design zeitgeist point of view for the 100 years old Model T. The idea was rather to transfer distinctive elements of the historic styling such as the massive cooler frame or the characteristic wheel house arc and to combine them with current styling characteristics. A

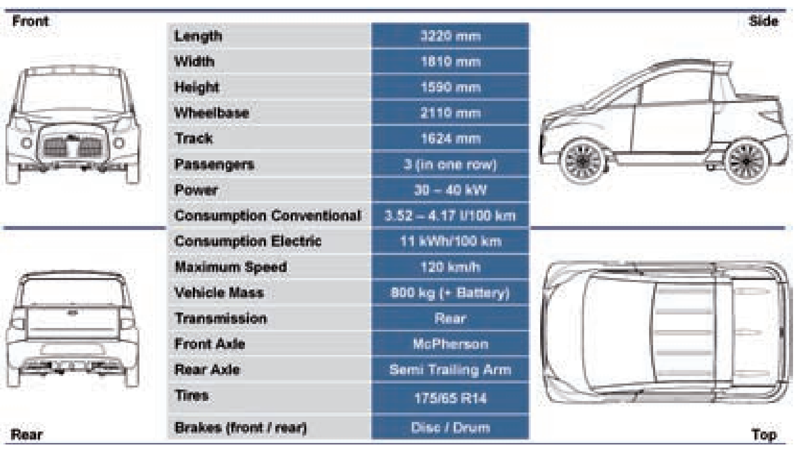

Figure 3: Technical specifications of the new Model T

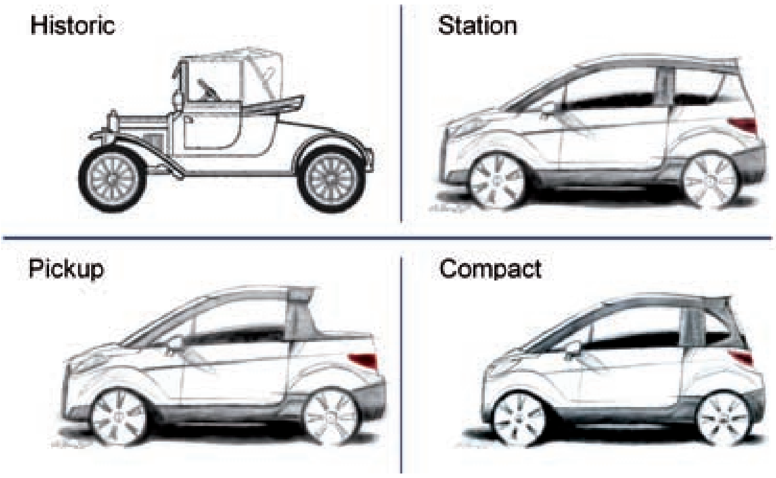

Figure 4: Styling of the derivate vehicles

worldwide commonly used design concept is believed to foster the brand identity, an aspect that is gaining importance for success in the market due to an increasing technical unification. Following the definition of the concept specifications, the development of the different main vehicle components started in parallel. Body and drivetrain development are described in detail in the following chapters. At the end of the project, a cost assessment of the complete concept was carried out. **Table 2** shows the overview of the total costs for the different drivetrain options of the pickup variant model.

The efforts for cost models increase more than proportional with the degree of detail respectively accuracy. Hence, an efficient cost prognosis must be based on analogies. Starting with comparable components with known cost structures, the costs of the new Model T components have been scaled using values such as dimensions, weight, power, energy content etc. [3, 5, 6]. While current market prices have been used for standard components, the electric drivetrain had to be calculated using price prognoses for future price development under mass production assumptions [7].

Besides the economic and production-wise cost reduction strategies mentioned above further conceptual cost reduction methods enabled the low basic sales price. In addition to the avoidance of a left and right hand steering model, some comfort functions have not been implemented but are technically compensated to a certain extent. Furthermore, only standard tools are required for production, the passenger seats are not adjustable and planar glazing as well as module and common part strategies are used, altogether having a positive cost effect. According to the historic Model T, long production duration is planned. The changeable outer panels, the lighting parts and the interior allow an easy re-styling and technology updates, thereby keeping the

Table 2: Cost overview in US dollar of the pickup variant model for different drivetrain options

	ICE	Hybrid drive	Plug-in hybrid drive		Electric drive	
			15 km	56 km	75 km	140 km
Production costs	**4930 $**	**5340 $**	**6890 $**	**8190 $**	**7410 $**	**11.790 $**
Assembly	890 $	890 $	890 $	890 $	890 $	890 $
Body	960 $	960 $	960 $	960 $	960 $	960 $
Chassis	742 $	742 $	742 $	742 $	742 $	742 $
Drivetrain	780 $	1280 $	2830 $	4130 $	3350 $	7730 $
Interior	750 $	750 $	750 $	750 $	750 $	750 $
Electronics	588 $	718 $	718 $	718 $	718 $	718 $
Additional costs	**2070 $**	**2100 $**	**2160 $**	**2210 $**	**2180 $**	**2360 $**
Logistic	420 $	420 $	420 $	420 $	420 $	420 $
Marketing	560 $	560 $	560 $	560 $	560 $	560 $
Overhead	420 $	420 $	420 $	420 $	420 $	420 $
Guarantee	250 $	280 $	340 $	390 $	360 $	540 $
Marge	420 $	420 $	420 $	420 $	420 $	420 $
Total	**6780 $**	**7440 $**	**9050 $**	**10.400 $**	**9590 $**	**14.150 $**

Model T modern and appealing over a long time.

6 Body

For the body development the trade-off between low-cost and lightweight had to be put in focus, since both requirements were formal objectives of the challenge. The team added the additional target to design a body type compromising the special demands of conventional and electrified drivetrains in a common platform. This is to enhance the market relevance of alternative drivetrains by cost reduction due to economies of scale. In addition, to enable various derivates the body should be designed scalable in length and should be made of simple parts manufactured using standard tools.

Comparing different types of body design showed that these requirements in total can be met best using a hybrid design of steel deep-drawing parts and profiles together with plastic outer panels. On the one hand the team applied structural lightweight design techniques for the cost efficient steel basic structure. On the other hand for the body panels the lightweight potential of the material was used. The principle of structural lightweight design is to select the topology of the structure based on the loads acting on it. This means material shall be applied at the actual load paths only. In order to determine these load paths, the team used the method of FEM-based topology optimisation.

The starting point for this was the available design space for the body. This describes the volume that remains when substracting the wheel envelopes, the interior space and all package components from the volume enclosed by the outer contours of the vehicle. The design space was meshed and the load cases such as static torsion and bending as well as quasi-static dummy loads for front, side and rear crash were applied. After calculating and masking the finite elements that are less relevant for the load cases in terms of stiffness, the abstract load paths could be analysed. This topology had to be interpreted and transferred to producible and joinable parts using CAD tools, **Figure 5**.

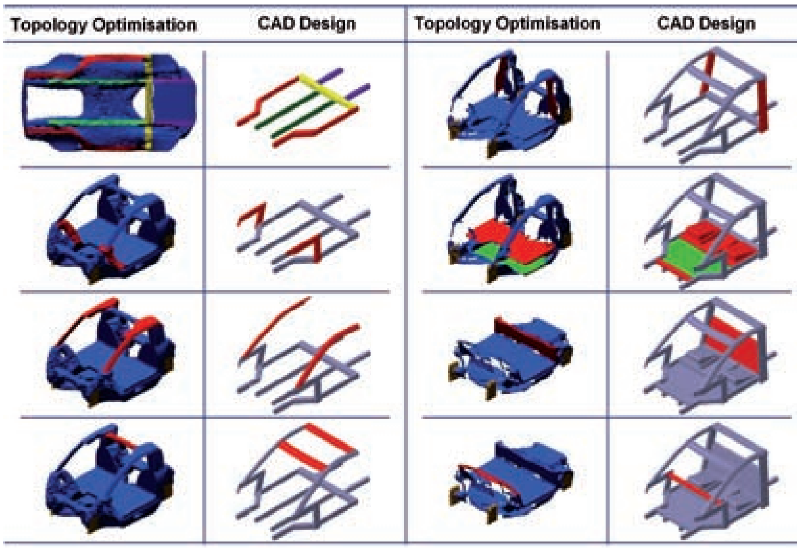

Figure 5: Topology optimisation and CAD design

Following the results of the topology optimisation the CAD model includes a main longitudinal member that merges the sill, a very stiff rear crossmember designed as an integral part with the passenger backrest, a sandwich floor structure and two longitudinal floor members. Each part is characterised by a stretched shape. In addition, all parts in the area close to the rear crossmember are parallel and exactly straight-line. This way, the body can be scaled in length at this area as well as at the front and rear overhangs, **Figure 6**. For the doors and lids that show a profile-intensive design, the hinges are integrated in the support structure.

7 Drivetrain

The background for the drivetrain concept was defined by the results of the scenario analysis. The demands of future drivetrain systems with regard to efficiency and emissions will become stronger due to rising energy prices and stricter legal requirements. Considering these, potential drivetrain concepts for the modern Model T were analysed and compared regarding re-powering infrastructure, qualification for vehicle integration, total efficiency and production costs, **Table 3**.

In addition to conventional drivetrains based on combustion engines, un-

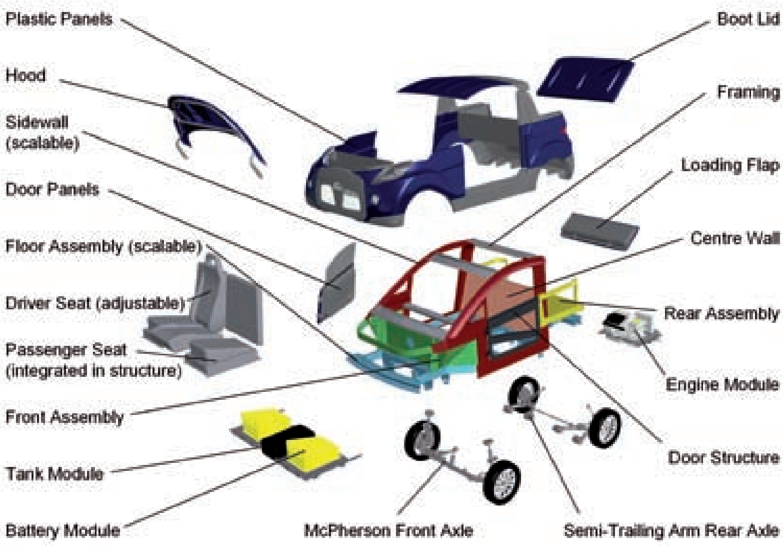

Figure 6: Vehicle components

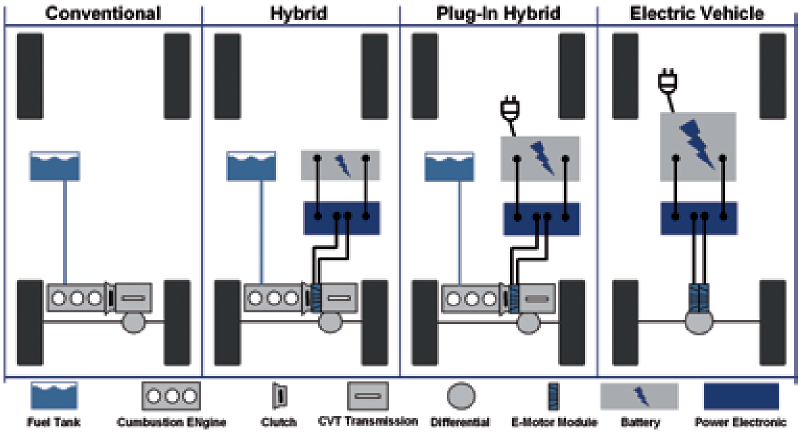

Figure 7: Drivetrain construction kit

conventional systems were taken into account. However, the comparison of the different systems revealed that for 2015 the internal combustion engine will still offer the best compromise. Reduced fuel consumption can be achieved by combining efficient, downsized engines with lightweight compact-class vehicles.

However, electrified drivetrains should not be neglected in order to serve the growing demand for these vehicles in the establihed markets. Consequently, the modern Model T offers different drivetrain options on the same platform. The systems are going from the conventional gasoline drivetrain via hybrid and plug-in hybrid to the battery electric vehicle. Both battery electric vehicle and plug-in hybrid are able to run fully in electric mode. A modular drivetrain construction kit was developed for this in order to maximise the number of common components, **Figure 7**.

Since the daily range has significant influence on the operating costs for the plug-in hybrid drive option, the emissions and the efficiency of the vehicle, the battery system is designed in a modular way. This means, the customer can select the energy content of the battery based on his personal demands, for example the distance from home to office. In the next step, the components of the different drivetrain options were dimensioned and selected considering the outer vehicle dimensions, the vehicle mass, the top speed, an assumed aerodynamic drag coefficient of 0.3 and different driving cycles.

For dimensioning and further evaluation of power requirement and energy consumption, a model library for simulation of longitudinal dynamics in Matlab/Simulink was used. Depending on the particular driving cycle and the drivetrain system, a peak power requirement from 17 to 28 kW was determined. Consequently, a 30 kW ICE or a 40 kW hybrid drive were selected. With the level of drivetrain electrification, the costs increase, Table 3. However, operating costs and emissions can be reduced. For instance CO_2 emissions vary between 54 g/km and 100 g/km for the different drives while a specific CO_2 emission of 500 g/kWh for electric power generation is assumed.

8 Summary

Only three months were needed by a team of the Institut für Kraftfahrzeuge (IKA) of RWTH Aachen University in order to develop an innovative vehicle concept which is capable of carrying conventional as well as alternative drivetrain modules thanks to its scalable design – a modern Tin Lizzy for the year 2015 with a basic sales price of less than 7000 US dollar.

An efficient approach and an effective realisation of requirements allowed the concept to be simple, light and compelling – following the spirit of its predecessor. A focus was therefore placed on a simple production and a robust design of chassis and body as well as possibilities for an individual styling by using changeable outer panels. The modular drivetrain allows to offer alternatives to the at

Table 3: Qualification matrix for drivetrain systems (ICE = internal combustion engine)

	Re-powering infrastructure	Qualification for vehicle integration	Total energy efficiency	Production costs
Compressed air	–	– –	– –	++
Gasoline engine	++	++	0	++
Diesel engine	+	++	0	+
Electric/ICE hybrid drive	0	+	++	0
Hydrostatic/ICE hybrid drive	0	– –	++	– –
Fuel cell	– –	– –	+	– –
Battery electric motor	0	0	++	– –
Hydrogen ICE	– –	0	0	0
Natural gas ICE	–	+	0	0

least in the medium-term still dominant internal combustion engine such as hybrid or battery-electric traction.

The IKA developed a completely new vehicle concept which fulfils all given requirements. These were depicted both from the challenge by the Ford Motor Company as well as a detailed analysis of the aimed markets in 2015. The biggest challenge was given by the basic sales price which was not to be exceeded. In the end, real costs were estimated to be slightly below the target with only 6780 US dollar. A new interpretation of historic constructions based on modern technologies allows interesting solutions for low cost vehicles in very short time. Finally, the team of IKA thanks the Ford Motor Company for being part of the Ford Model T Challenge 2008 which was inspiring and fostered the creativity of students as well as researchers. It was an outstanding example which both stimulated and supported the personal advancement of young academics.

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ATZ WORLDWIDE

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06|2009 · June 2009 · Volume 111
Springer Automotive Media | GWV Fachverlage GmbH
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