CRASH ADAPTIVE VEHICLE STRUCTURES AND COMPONENTS

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INTRODUCTION

Daimler firstly introduced PRE-SAFE® applications in the S-Class, 2002. Up to now sensor information is used to bring front seats in a crash optimized position, to close windows and sunroofs, to eliminate the risk of penetrating objects, to pre-stress restraint systems and to activate braking systems in advance of a physical impact.

Future PRE-SAFE® applications are under investigation at the Research and Development Lab of Daimler. In cooperation with suppliers and Research Institutes crash structures have been developed which can be adapted to the individual impact scenario.
In general the strengthening of vehicle BIW-structures can be introduced for frontal impact scenarios as well as for side impact scenarios.

The benefits of pressurized front and side members and door components have been evaluated. In general pressurizing is done by gas generators. These components are comparable to state of the art gas generators which are used for airbag applications. Within a few milliseconds the pressure increases up to 20bar. Depending on the initial shape of the structure, pressurizing can force an increase of the cross section and moment of inertia.

Various door beam designs have been investigated. Pressure increased the initial cross section by about 200%. Component and vehicle tests were conducted to assess the repeatability of beam deformation, to emphasis benefits and to set up validated simulation tools.

Using simulation tools active BIW-structures have been assessed for frontal and side impact scenarios.

Having pre-crash triggered crash structures available, an impact on vehicle crash performance, passenger protection and weight reduction is expected.

STATE-OF-THE-ART

Individual mobility and road transports have a fundamental impact on the economical situation and development of the country community. With a vehicle density of about 550 vehicles/1000 inhabitants, Germany is of a comparable order as the US with 470 passenger cars/1000 inhabitants. For China there is a rate published of about 15, for India of 7-8 vehicles/persons; - knowing that traffic distribution can vary quite drastically within the different areas within the countries.
For the year 2008 there was an overall market of about 55Mio vehicles at Germany, 240Mio passenger cars at US and about 27.3 Mio (non military used vehicles) at China (2004) and about 6-7 Mio vehicles at India. In total there is an estimated worldwide market of about 942Mio vehicles (passenger cars, commercial vehicles). Compared to the 942Mios vehicles the number of worldwide newly manufactured vehicles (passenger cars, trucks, busses) is less than 10% and was 73,1Mio vehicles (2007), with a German achievement (6.2Mio) of less than 10%.

The vehicles move on an established road infrastructure of about 32 Mio km (2007) worldwide. 32Mio km runs in the magnitude of 800 times the circumferences of the earth or more than 80 times the distance between moon and earth.

Within Europe there is a number of about 226Mio vehicles in the road with a total amount of 9800km/person/year and about 4444Billion Pkm.

With about 1.25Mio accidents and 41000 fatalities (EU25, 2005) the European Community has to deal with two main aspects:

- environmental impacts and
- safety issues.

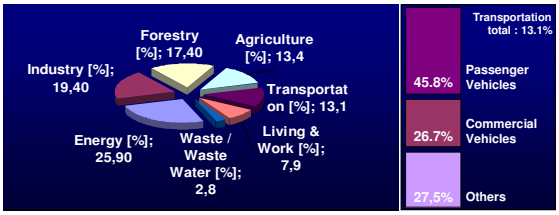
ENVIRONMENTAL ASPECTS

The actual discussions are mainly focused on the reduction of fine dust pollution and greenhouse gas concentration (carbon dioxide, methane, nitrous oxide, sulfur hexafluoride). The European Commission ratified the United Nations Kyoto Protocol, which was initially presented 1997 in Kyoto and entered 2005 in force. The industrialized countries agreed a greenhouse gas reduction of 5.2% (8% for the European Union). For Germany the agreed overall greenhouse gas reduction is about 21% compared to the 1990's level, achievable until 2012.

Germany started in 1990 with an amount of 1014to Co2-äquivalents/year. Until 2002 a reduction of 15.4% was achieved. With a worldwide Co2-equivalent of about 30892Mio to/year the German

share is about 2.78% (Co2 Germany 2007: 861to), which amounts to about 10to/person/year.
For Germany it is established that less than 20% of the Co2-emission is related to transportation (s. Fig. 1).

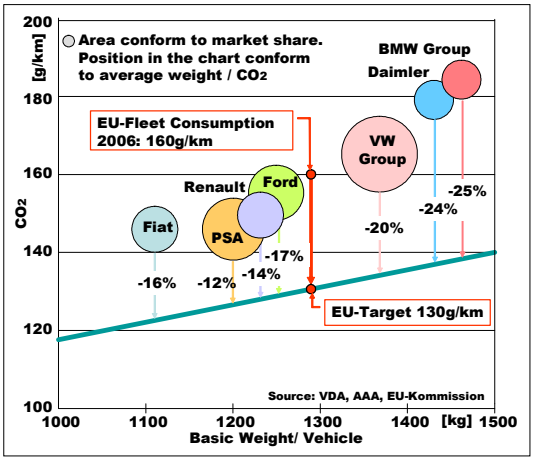
Fig. 1: Co2 share representing German market.



On a more detailed look, only about 50% of the transportation share is related to passenger cars.

To force the reduction of the passenger cars Co2-emission, the European Commission agreed on a directive, targeting maximum Co2-limits to 130g/km as an average-equivalent for new vehicles, sold in the European community starting 2012, with a minimum percentage of 65% volume and climbs up to 100% latest 2015. Penalties for non-compliance will follow.
It is expected that the new US-government might set up comparable targets in the next future.

Figure 2: CO2-levels and European market share [3].

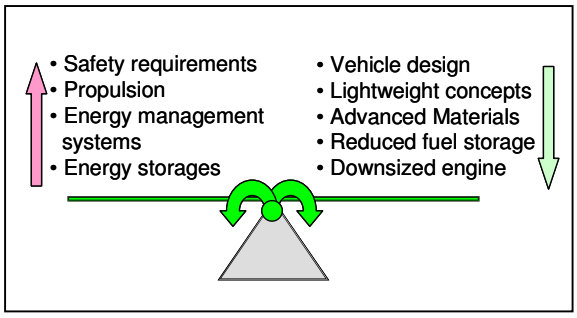


Comparing various car manufacturers, fuel consumption is obviously widely spread and so are market shares for the individual car makers (s. Fig. 2). The average Co2-equivalent for all new cars, sold in Germany in 2007 was about 170g/km (Europe (2007: 158g/km)). Daimler's 2007 Co2-average was 176g/km.

To achieve the EU-committed fuel efficiency there is a strong need to strengthen all main impact aspects which provide a higher level of fuel efficiency. Next to premium, luxury and super sports cars with a higher level of fuel consumption, Daimler offers with the SMART CDI a vehicle, which fulfills already today future requests (fuel consumption 3.3l, 88gr Co2/km). The new E-Class introduced 2009 cuts fuel consumption by 13% to 24%.

For our today's vehicles various counter measures are actually introduced or will be introduced in the next future. Under discussion are optimized and new propulsion systems and gear boxes, energy management countermeasures, rolling resistance tires, aerodynamic counter measures as well as adapted vehicle designs. Lightweight is another major key function for all vehicle components due to the fact that various counter measures will initially add weight (s. Fig. 3).

Fig. 3: Weight balancing aspects.



From theoretical investigations it is known that a weight reduction of 100kg can reduce fuel consumption by 0.2-0.5l for standard propulsion systems, depending on the utilization scenario.
To reach a minimum vehicle weight, advanced vehicle-, material-, joining- and manufacturing concepts are an absolute necessity.

Daimler has presented at Detroit 2009 a visionary contribution to sustainable mobility. 3 propulsion lines are presented: Blue ZERO E-Cell, Blue ZERO F-Cell, and Blue ZERO E-Cell Plus (s. Fig. 4).

Fig. 4: Blue ZERO vehicle lines.

The indicated traveling ranges ran from 200 (Blue ZERO E-Cell) to 600km (Blue ZERO E-Cell plus). To store energy, lithium-ion batteries with a weight of about 200-250kg are needed. 700bar hydrogen storages (Blue ZERO F-Cell) add additional masses of approximately 100-150kg. The entire propulsion systems could increase vehicles weight in order of about 150kg to 300kg compared to standard powered vehicles. To reduce vehicle weight, for all kinds of propulsions, intensive weight saving counter measures has to be applied.
There is a fundamental premise at Mercedes-Benz that there is no compromise or back stepping regarding safety, comfort or handling attitudes - standards for all Mercedes-Benz cars.

SAFETY CHALLENGE

It seems that road safety will be one major challenge for the future. Looking at German traffic fatalities one can see a reduction in total numbers from 21332 (1970) to today's level of 4467 (2008).

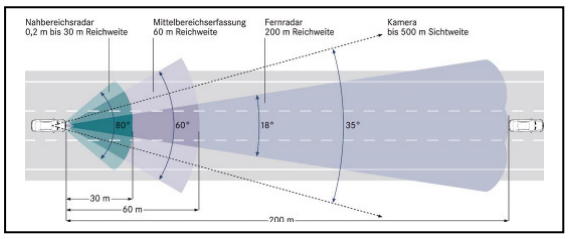
Nevertheless starting 2001 with about 40000 fatalities within EU 15 the WHO predicted that about 1.2 Mio people are fatally injured each year, worldwide. The number of severely injured people will run between 20 and 50Mio persons/year.

The European Community enforced the goal to reduce the European fatalities from 40000 (EU 15) in the year 2001 to 25000 (EU 25) in 2010, which is equivalent to a 50% reduction in fatality. The fatality rate for Germany came down from 6977 (2001) by almost 30% (2007). Up to now it is not obvious, if the 2010's safety-goal can be reached for Europe in time.

Taking a look into the future the grade of mobility could increase from today's 9600km/person to about 10300km/person (Europe, 2020). In addition it has to be expected that the vehicle/1000 persons-quote will increase quite quickly in countries like India and China.
Minor increases are expected for Western Europe, USA and Japan (less 10%).
Nevertheless we have to face ourselves with the expectation that with the increasing markets the number of fatalities could raise up to 2,1Mio/year between 2030/2050.

Sensors and software tools which are able to detect, predict and announce critical driving situations can help to break out of this vicious circle.
Using pre-crash sensors it is possible to establish PRE-SAFE® applications like introduced in Mercedes-Benz S-Class, 2002, and established at the 2009's E-Class (s. Fig. 5).

Fig. 5: Sensors incorporated at the new E-Class.



Pre-crash applications are triggered using 3 radar sensors (2 short range 24 GHz radar, 1 long range 77 GHz radar) installed in the bumper area. Various standard acceleration sensors are used for trigger confirmation.

Overall, for typical frontal impact scenarios, such as cross-over collision or running up to preceding trucks, it can be assumed that sensor information can indicate critical situations up to 100-200m in advance of an impact. Side /lateral sensing is still under development, but sensing will be limited to a few 100 millimeters.

For Germany/Europe studies have been shown that about 49% of severe accidents are frontal impacts and about 35% are side impacts (s. Fig. 6a, 6b).

Fig. 6a: Real world passenger car impact distribution.

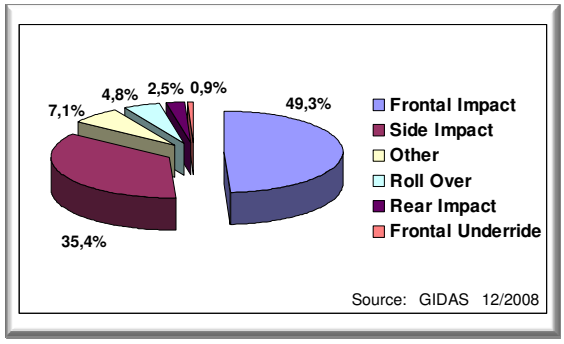
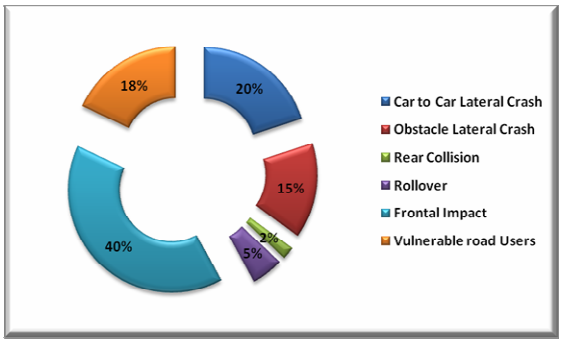


Fig. 6b: Fatality rate (cars involved, Europe) [4].



Using pre-crash information it is possible to adapt vehicle structures as well as restraint systems. Using a 77GHz radar sensor, obstacle detection can be done in a rage of about 200m with two 24GHz sensors up to 30m. Therefore there are about 3s available for triggering an action (closing velocity 200km/h). For side impact applications reaction time comes down to 0,14s (50km/h, 2m). Time which can be used to reduced the speed of the vehicle, change seating from a comfort optimized position to the safest position and to strengthen BIW-components and restraint systems.

Crash adaptive safety applications are introduced at passenger cars up to now mainly for interior, restraint and seat applications.
The optimization and pre-activation of the restraint systems in advance of a physical impact leads to various benefits such as lower speed deployment of the driver and passenger airbags as well as improved belt action do to pre-strengthening. Having sensor information available one has the ability to reduce the vehicle's velocity before crash. By reducing the impact speed passenger loadings are reduced in general.

Preparing vehicle structures in advance of an impact there is the possibility to

- increase deformation length/deformation space
  - (active motor hood (pedestrian protection s. Fig. 7)),
  - movable front-end (improved frontal impact, s. Fig. 8, Fig. 9))
- increase/decrease crash load levels (s. Fig. 10).

Fig. 7: Crash active motor hood (E-class).

Fig. 8: Movable front-end with improved crash length (research study).

Fig. 9: Pressurized crash box with improved crash length (research study).

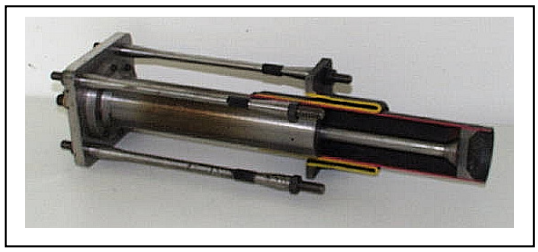
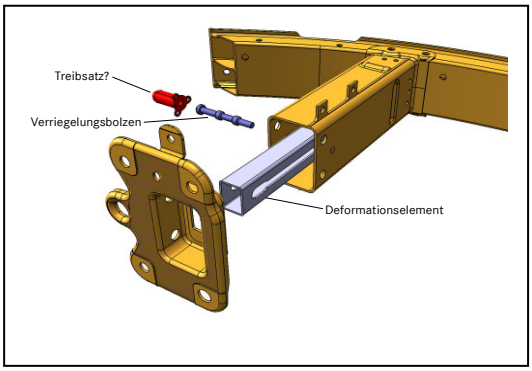


Fig. 10: Crash active crashbox.



All solutions shown in Fig. 7 to 10 were investigated at the Daimler Research and Development Lab, in a strong cooperation with the Safety-Department. Safety benefits were confirmed for standard test procedures. Real life safety benefits can be expected.
Nevertheless all of these technical solutions have in common that the vehicle weight increases and the technology is proven up to now to a feasibility level.

Only the crash active motor hood, was introduced to fulfill pedestrian protection requirements.

Having crash performance, weight restrictions and packaging aspects and multi propulsion vehicle solutions in mind, one technical solution seem to be a very attractive approach to create overall benefits: ”Pressurized structures”.

PRESSURIZED VEHICLE COMPONENTS (P-VCs)

Together with the company AUTOLIV GmbH basic research and development has been conducted. Autoliv is technology experienced as a main supplier of standard airbags and “metallic airbags”, as are used in the LEXUS LS600H and Renault Laguna, acting as seat anti sub-marining devices (front and rear seat applications). Basic investigations for structural applications have been announced [1], [2]. For passenger cars BIW-applications are not established up to now.

The research project, which runs at Mercedes-Benz over 2 years, incorporating various departments, was directed mainly to BIW- and door components.

Investigations were performed to apply the technology to structural components which are especially loaded during front and side impacts.

During the design process various simulation tools, finite element codes like ABACUS and LSDYNA, have been used to analyze moments of inertia and to assess crash performance under quasi-static and dynamic load conditions.

In general two principals have been investigated:

- For the first principal the initial structural shape of the components stay in the same way they were before being pressurized (s. Fig. 11a). Therefore pressure has to be adjusted carefully.

- The second principal is described in a way that the structure expands from a small cross-section to a bigger one when being pressurized. This effect can provide great benefits, such as packaging benefits (s. Fig. 11b) or extending the crash length.

Fig. 11a: Pressure loaded front member. No significant geometry change.

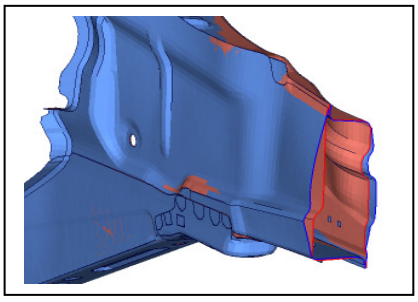
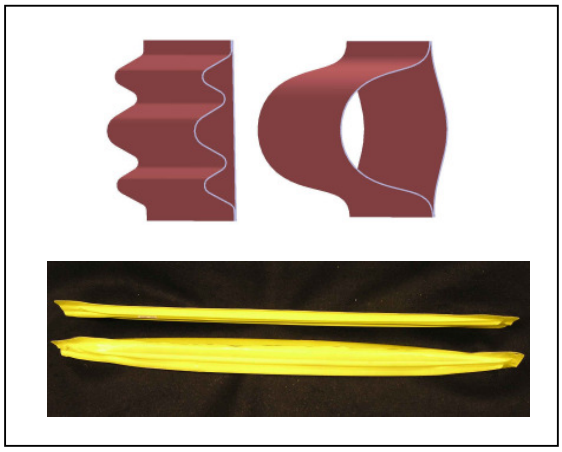


Fig. 11b: Pressure loaded side impact protection beam. Significant geometry increase.



In addition two ways of action can generally be applied:

- Adding a gas generator which keeps a defined, almost constant pressure level over a period of time. This firing time should fit with the ongoing deformation of the involved structures and run for the various applications between 10ms and 20ms.

- Having a gas generator which is able to deform a component from an initial structural shape to a final one, without generating pressure longer than needed for deployment.

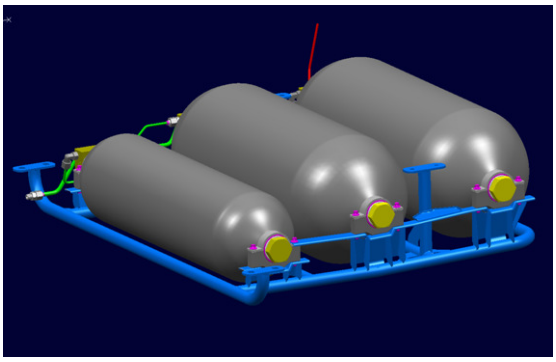
Modified standard gas-generators, like used for airbag applications, are suitable to fulfill the tasks. Other applications like explosive cords are a cost-effective and lightweight options. Up to now there are various technical and handling questions open, which contradict a short range product application.

In general there is an almost sealed component design necessary to work without an additional sealing bag. If that is not possible, due to cataphoretic treatment or other aspects, an additional bag has to be applied to the structure.

Various components such as front members (P-FMC), side members (P-SMC), e. g. door beams, rockers and seat lower cross members have been assessed theoretically.

In addition, there seems to be a good change to achieve safety and/or packaging benefits for non-structural applications (s. Fig. 12), such as mounting and assembly frames for hydrogen storages.

Fig. 12: Sub-frame for gas storages.



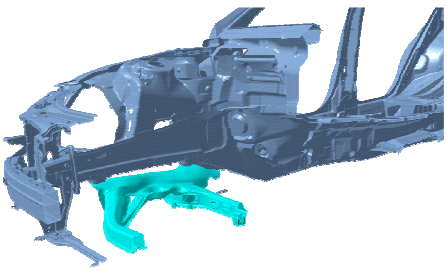
Detailed investigations have been conducted for front side members and door side impact members, knowing that lateral pre-crash sensing is not solved finally yet.

FRONT MEMBER APPLICATION (P-FMC)

Basic investigation, using the explicit finite element code LS-DYNA, proved the possibility to increase crash load levels and energy absorption for regular front members.

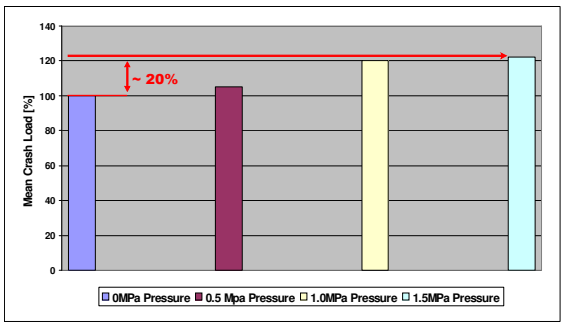
For assessment purposes a S-Class structure has been chosen. The side member is made from steel (ZstE 340), with about 110mm*75mm (heights/ width) and 1,75mm in thickness. Two facial sheets are glued and spot-welded together. The members are structurally quite inhomogeneous due to local reinforcements and weaknesses (holes) and mountings such as a highly stiff sub-frame (s. Fig. 13).

Fig. 13: Front structure of the Mercedes-Benz S-Class.



Simulations have been performed with a modified front structure (no engine, with and without sub-frame). For pressure levels of up to 15bar the mean crash load increased by more than 20% (s. Fig. 14).

Fig. 14: Mean crash-load versus pressure level (reduced front structure incorporating sub-frame).



For the simulation model it was assumed that there is a constant pressure level over the whole deformation process. In total the mean crash load increased by about 30kN, deformation was reduced by 100mm. These results open crash-wise the opportunity to reduce the wall thickness in theory by 20 to 30% or to shorten the required crash-length.

In general there is an overall assessment required. A higher load level has to consider also front bulkhead intrusions, thickness reductions NVH-constrains and shortening the member length will have an impact on crash pulse, packaging and design.

The crash model of the pressurized structure was set up using fully integrated shell elements (type 16). A distributed load was applied representing the internal pressure. The pressure load is adapted over time, corresponding to pressure measurements from tests.

In particular, the interaction of pressure and structure has been considered, which only works in one direction, i.e. the pressure load causes deformation of the structure, but the deformation of the structure doesn't cause a change of the pressure load. Jointing was considered in a non-failure model (spot-welds, adhesive) during the pre-assessment stage. With the ongoing project the impact of the joints was getting obvious and therefore failure criteria were considered.

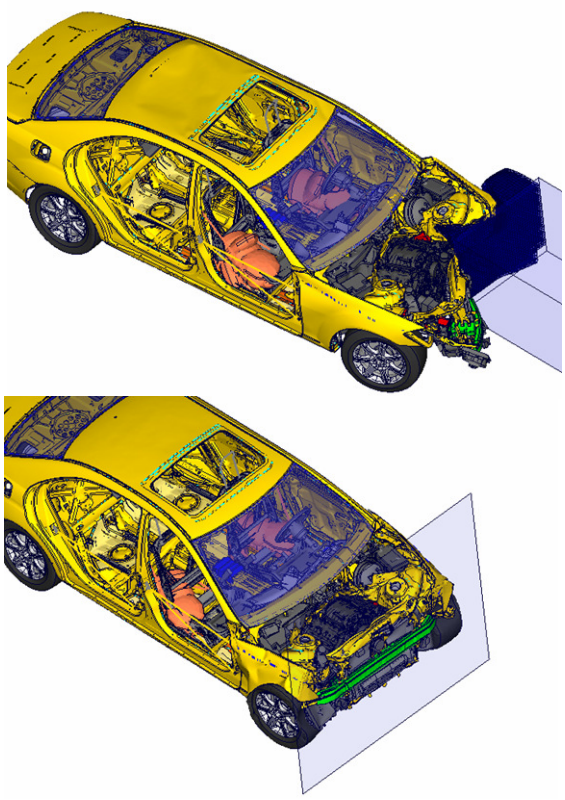
Further investigations have been directed towards the consideration of P-FMC for different car specifications, such as

- the size of the car (large vs. small),
- mass of car (heavy vs. light) and
- the propulsion (large versus small engine and multi propulsion BIW approaches).

In addition P-FMCs seems to be suitable to combine national specific crash rating requirements with reduced weight.

For the initial development step the crash boxes were kept non-pressurized. Pressure was added to one or to both front members. That allows to fulfill low impact crash and easy to repair requirements. Nevertheless the system could be optimized, by pressurizing the side member as well as crash boxes for high speed crashes.
If the crash boxes are not pressurized the system can be triggered by contact sensors. With an overall time request of about 20ms, frontal impacts can be addressed up to 50km/h with a S-Class vehicle concept. For higher impact speeds, or more sophisticated actor responses, pre-crash sensors, which provide 12ms to 16ms (100km/h, 200km/h closing velocity) additional time, are requested.
Two frontal impact scenarios (Euro-NCAP, US-NCAP) have been investigated (s. Fig. 15).

Fig. 15: Crash simulation Euro-NCAP, full frontal US-NCAP.



Simulations provided benefits regarding the mean crash loads between 29 to 39kN (s. Tab. 1) and energy absorption (unmodified reference structure).

For Euro-NCAP the deformation seems to be reduced by more than 100mm. For the full frontal US-NCAP set-up the improvement came down to 10mm.

Tab. 1: Simulation results for Euro- and US-NCAP.

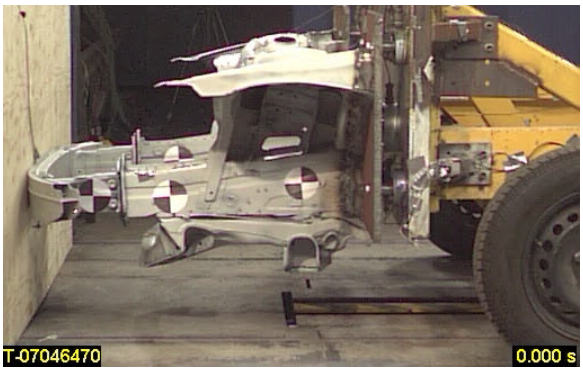
	Intrusion (abs.), [mm]	Intrusion (delta), [mm]	Mean Crash Load (abs.), [kN]	Mean Crash Load (delta), [kN]
Test Set-Up (reference)	540		129	
Test Set-Up (pressure)	440	100	158	29
EURO-NCAP (reference)	1241		278	
EURO-NCAP (pressure/one side)	1127	114	309	31
EURO-NCAP (pressure/both sides)	1135	106	317	39
US-NCAP (reference)	624		455	
US-NCAP (pressure)	614	10	487	32

All simulations have been conducted with a simulation model comparable to the standard test configuration.

Further simulations and tests have to prove, if front structures might be shortened (EURO-NCAP) by using pressurized members, fulfilling all other requirements.

For validation tests have been conducted with a special test set-up. To correlate the structural deformation with US-NCAP, test mass and test velocity have been adjusted and set to v: 40km/h, impactor mass: 1190kg, equal 70kJ, pressure: 15bar (s. Fig. 16).

Fig. 16: Test set-up for dynamic component testing.



Results showed a good correlation between tests and simulations. Nevertheless it was getting obvious that jointing should be redesigned to achieve more repeatable results. In addition high speed videos proved a need to come up with a modified test set-up (mounting rupture).

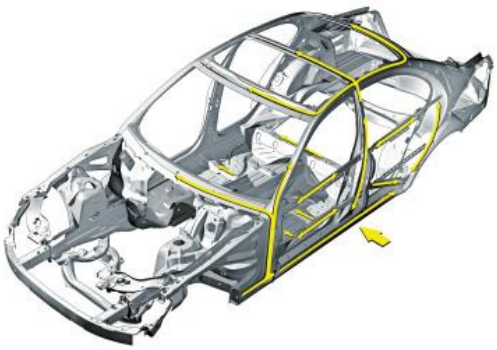
With increased mean crash loads, P-FMCs could be introduced to cover small and large sized engines

without BIW- modifications. In addition it seems to be possible to introduce new propulsion concepts, which can incorporate higher component weights (batteries, hydrogen storages), without major structural modifications.
With a weight optimized design of P-FMCs it seems to be possible to safe 1.5 to 3kg/vehicle in weight.

Next to a crash assessment all technical functions have to be addressed.

SIDE MEMBER APPLICATION (P-SMA)
There are various load carrying components involved during a side impact (s. Fig. 17).

Fig. 17: Load carrying structures for side impact.



To assess achievable benefits pressurized rockers, seat lower cross beams and other components were assessed.

In the first step a side impact intrusion bar was investigated in detail.

Standard side protection door beams are made from steel or aluminum. The door/door beam-stiffness performance has to be assessed quasistatically (FMVSS214, door component test) and dynamically (IIHS and others, full vehicle side impact test).

Various beams have been designed and analyzed via simulation to fulfill FMVSS214 without gas generator ignition.

The main design parameters were:

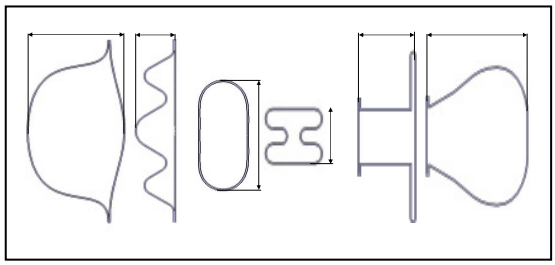
- sealed double sheet design
- material: steel, aluminum, FRP or hybrid material
- ability to increase the cross-section more than 100%
- comparable moments of inertia without being pressurized

- weight reduction compared to serial product
- improvements for dynamic impact performance with and without pre-crash sensing
- jointing technology
- component/door assembly

The door beam of the actual C-Class is made from steel, grade: MSW 1200. It has a length of about 1030mm, a maximum depth of 26mm, which results in 1900gr weight. With an additional weight of 200gr to 400gr for the gas generator there was a real challenge to establish a design which provides weight reduction as well as safety performance benefits.

Instead of having an open shaped profile various crash active designs have been investigated (s. Fig. 18):

Fig. 18: Cross-section door beam study.



Design 1: Main deployment direction: ⇦ **Design 2:** Main deployment direction: ⇧ **Design 3:** Main deployment direction: ⇨

The extension rate, which describes the rate between deformed and undeformed cross-section shape came out to approximately 250%, 100%, 300%.

With materials of 1.0 mm for the front sheet and about 0.5mm for the rear sheet (design 3) weight was reduced to 1,2kg, without recognizing the gas generator's weight.

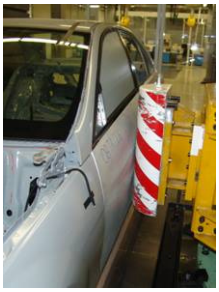
The SPS itself was seamwelded and almost sealed. The front door beam was directed within the door frame, comparable to the C-Class side protection beam. This fact allowed, for assessment purposes, to use the original door structure and mountings. Nevertheless simulations showed an important impact of the jointing area design. For the initial assessment the gas generator was mounted at the left end of the P-SMA.

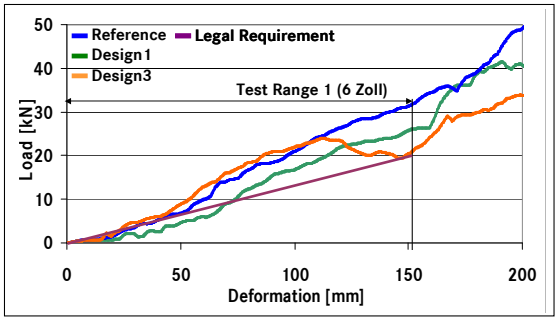
In addition to the prototype set up other component designs have been established and assessed. Weight came down below 1kg (without considering gas generator weight) incorporating aluminum and aluminum/FRP designs. Especially CFRP, with a very high stiffness directed along the fiber direction and a quite low strength perpendicular to the fibers, constrains almost the application of an aluminum/ unidirectional CFRP reinforced P-SMA.

Depending on the initial design the main deployment direction is directed outward the car, to the driver/passenger, or up-/downward within the door.
From safety aspects there was a strong demand to have the main deployment directed outwards or within the door. During the assessment process up-/ downward directed deployments do not prove major benefits. Therefore there was a development focus on design 1.

All designs fulfilled undeployed FMVSS214 static requirements (s. Fig. 19).

Fig. 19: FMVSS214 static pole test.





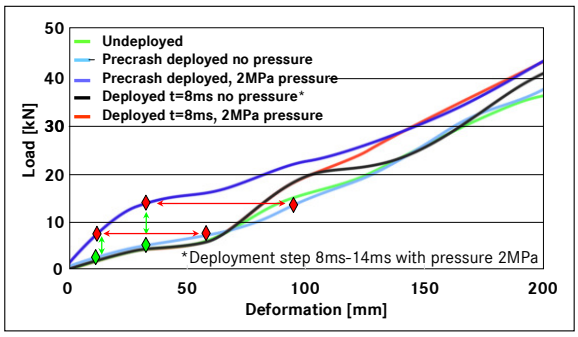
In the first design step the door beam has been designed, along with stiffness requirements, to fulfill FMVSS214 standard without being pressurized.

Analyzing the failure mode it was obvious that failure occurred mainly in the mid range of the beam. Therefore the position of the gas generator has been changed from one end of the SPS to the middle. Having the gas generator tube as a load carrying component introduced, the load level increased by 4.5kN

Additional benefits could be achieved by adding a flexible bridge, which could be realized by a

modified gas generator. This structure should be able to bridge the gab between the front and rear sheet of the SPS after deployment.
Having in addition a pre-crash trigger (20ms before impact) of the P-SMC, which seems to be not excluded by the static standard test procedure, the mean crash load would increase in addition.

Fig. 20: Performance various impact scenarios (design 1; sub-component test, sensing, pressure).



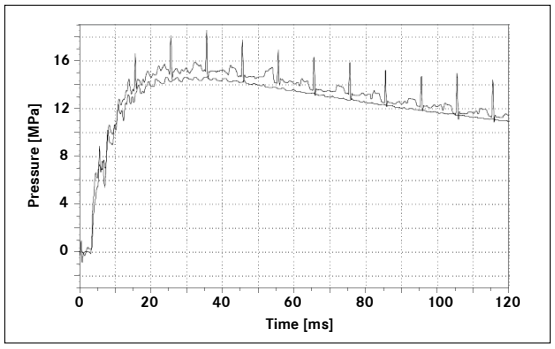
For pre-triggered, pressurized beams it was shown in door sub-component tests that the crash load stays on a high level right from the beginning. For in-crash deployed and pressurized beams, it took about 8ms, after applying pressure, to achieve the load level of the pre-triggered component.

Various door sub-component tests proved a load increase by deployment and applying pressure. Pre-triggering can course a change of the shape of the load-deflection-curve.

To deform the beam in the described manner an interior pressure of about 2 to 3MPa has to be applied. Pressurizing and deploying the beam takes about 20-27ms in total. With a seal component

pressure was kept nearly constant over 100 to 120ms, which corresponds with the ongoing deformation (s. Fig. 21).

Fig. 21: Pressure line versus time.



For IIHS configuration (s. Fig. 22), it was proven via crash simulation that deployment can be initiated during impact and will provide component strength.

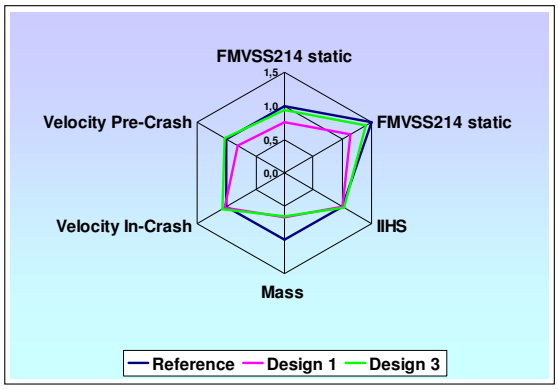
Fig. 22: Test set-up for IIHS validation.

Tests and simulations proved comparable maximum intrusions for the design 1 and 3 to the reference car, with lower component weight (s. Fig. 23).

Reviewing the results, it has to be remembered, that the door was not specially designed and adapted to incorporate inflatable beams.

In a second assessment step the focus of the investigation was directed towards door trim behavior and occupant protection.
It was very exciting to see that the predicted intrusion velocity came down by more than 15% for the design 1 (pelvis area). Design 3 velocities were comparable to the reference.

Fig. 23: Assessment for 2 door-beam designs.



FMVSS 214 pole tests have been assessed for design 3 via simulation for the 5% and 50% pole position.
For both test configurations the maximum intrusions have been quite similar to the reference values.

CONCLUSION

As a long-term goal, emphasized safety assistance systems, as well as internet and car-to-car communication will lead to accident free driving. Nevertheless it is expected that infrastructural countermeasures have to be introduced to support the safety goals.
It is expected that the world automotive market could rise from about 800Mio vehicles today to 2Mrd vehicles before 2050.
Having no significant safety innovations, which can be applied worldwide, especially to the rapidly growing markets, we have to realize that road driving fatalities will exceed the 2Mio limit between 2020 and 2030. In addition we find a multiplier of about 80 between fatal and injured road users (Germany, 2007).

New propulsion and modified vehicle concepts are necessary to achieve confirmed fine dust pollution and greenhouse gas concentration levels.
For all vehicle concepts and propulsion systems there is a strong demand to optimize and reduce weight, not only for the BIW, but also for all other disciplines like power train, chassis, and interior.

Pressurized structural components seem to be a technology which can help to apply safety improvements and establish packaging and design freedoms without adding weight.

To transfer the technology to commercial applications a few challenges have to be solved. Knowing, that the maximum benefits will be achieved for pre-crash applications, front and lateral sensing has to be established, which allows to introduce pre-triggered, pyrotechnical based safety devices, without additional in-crash signal confirmation.

In addition optimized jointing, handling and assembly concepts have to be developed and established.

From the suppliers there is a strong need to come up with cost and weight reductions for gas generators or other deployment devices.

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