ABSTRACT

A great opportunity for increasing range and decreasing the production costs of battery-powered vehicles is to lower vehicle weight as far as possible. To this end, designers not only can incorporate lightweight materials, but also reduce the size of the vehicle and limit the equipment installed as excellent weight-saving strategies. Since this strategy could lead to crash incompatibility, ultra-compact electric cars are subjected to enormous loads in the event of a collision with a heavier vehicle. The high structural rigidity and limited deformation paths produce a high crash pulse, with higher forces acting on occupants than are experienced in conventional vehicles. The objective of the safety task force within the Visio.M project funded by the German government was to draft, implement, and test a concept that resolves these conflicting interests and provides sufficient protection for ultra-compact vehicles. Using an analysis of the potential accident scenario involving ultra-compact electric vehicles as a starting point, specific safety requirements were derived for these vehicles. To meet these requirements, a strategy for an integrated safety design was developed to reduce the occupant loads. The integrated safety concept incorporates pre-crash systems, occupant protection systems, and a CFRP monocoque, among other features, and was developed using numeric simulations. Verifiable proof of the operative function and benefit of the safety concept was provided by leveraging numerical simulation techniques, carrying out comprehensive component tests, and conducting a series of full-scale crash tests using a Visio.M prototype. In the end, the integrated safety strategy is the key to realizing a sufficient level of protection for sub-compact vehicles.

INTRODUCTION

According to targets set by the German federal government, one million vehicles powered by alternative technologies should be running on German roads by 2020. By 2030, this figure is expected to grow to 6 million. Efficient, electrically powered small motorized vehicles have the potential of driving the expansion of electromobility forward. Yet most previous concepts have either been too heavy or too expensive, or do not reach the safety level expected by the market. Traffic experts have expressed concern that the current safety level for vehicles of the L7E homologation category (quadricycle category) is insufficient for mass traffic. Tests by Euro NCAP partially revealed serious deficiencies in vehicles of the L7E homologation category. Currently, safety requirements in the quadricycle category are low, but safety experts are demanding effective occupant protection if the number of ultra-compact vehicles circulating on roads should increase. The Visio.M Consortium has taken on
this challenge and is developing concepts for electric vehicles that are not only efficient and cost-effective to manufacture but are also considered to be safe. In particular, the Safety workgroup led by Daimler AG was working with its partners Autoliv, IAV and the Technical University of Munich on developing and implementing an integrated safety concept (See Figure 1) and verifying its worthiness.

![Figure 1. The integrated safety concept of the ultra-compact vehicle Visio.M.](image)

**BOUNDARY CONDITIONS**

**Ultra-compact vehicles and safety**

Discussions concerning the appeal and acceptance of battery-powered vehicles center on their limited range. A major opportunity for increasing their range while decreasing production costs is to lower vehicle weight as far as possible. Weight-saving strategies with considerable potential that are being employed by designers are the incorporation of lightweight materials, the reduction in vehicle size and limiting the equipment installed in the vehicle. This opens up new possibilities in terms of vehicle homologation. Vehicles with a curb weight of up to 400 kg (450 kg beginning in 2016) without an energy storage unit and a maximum continuous output of 15 kW are not considered to be conventional passenger cars of the M1 vehicle class, but can be homologated as category L7E vehicles. The limited requirements that apply to vehicles of this category, which are similar to today's passenger cars both in terms of their characteristics and usage, result in the risk that important yet non-regulated safety standards will be disregarded. Ultra-compact vehicles that circulate on public roads are particularly vulnerable to the high forces which occur during a collision with heavier vehicles since their reduced weight and the resulting large differences in mass to conventional vehicles on the market today lead to crash incompatibility. The necessarily high structural stiffness as well as the smaller deformation zones inherent to ultra-compact vehicles lead to a high crash pulse and, compared to conventional vehicles, to considerably higher forces that act on the occupants. In conjunction with reduced safety features, this crash incompatibility results in a greater risk to the occupants. However, to avoid negatively impacting the broad acceptance of electric vehicles and to ensure occupant safety, there should be no discrepancies to conventional vehicles regarding the level of occupant protection in actual accident situations. Against this background, the approach used in the Visio.M project, which is to align the vehicle target weight with the weight limit of the L7E approval category, presents a major challenge to the design of the occupant protection systems. Despite the limited requirements for this category, the vehicle should reach an adequate safety level that is in accordance with the specific requirements dictated by how the vehicle is used and the expectations of
customers and society. An analysis of the actual accident situation is the basis for defining the requirements placed on the safety concept of the Visio.M. The goal is to evaluate the potential risks of this vehicle type under the boundary conditions related to its specific usage in general traffic situations.

**Analysis of potential accident situations of ultra-compact vehicles**

In cooperation with the traffic accident research department at the Technical University of Dresden, one aspect of the Visio.M project was to analyze the potential accident situations of ultra-compact vehicles in comparison with current general accident situations. The analysis is based on the GIDAS (German In-Depth Accident Study) database, in which around 2000 accidents from the greater Dresden and Hannover areas have been documented and reconstructed since 1999. Based on accident data from all accident passenger cars of model year 1995 or later, which were used as the control group, general statements were first made on the overall accident situation in Germany. In contrast, however, there are almost no accident data on ultra-compact vehicles because of their limited presence on the market at this time. The potential accident situation of these vehicles was therefore analyzed using the GIDAS data for passenger cars most closely related to ultra-compact vehicles because of their small size, usage characteristics and use conditions. The analysis concentrates on making a prognosis of the accident situation that can be expected to develop in the next several years for electric ultra-compact vehicles. The evaluation of the accident data shows a significant shift of the accident type toward urban scenarios for ultra-compact vehicles compared to other groups (See Figure 2). Thus, compared to accidents in general, ultra-compact vehicles can be expected to be considerably less involved in front/rear collisions yet will be more subject to lateral collisions due to the growth of intersection accidents. The analysis of the impact distribution shows that the great majority of front/rear collisions are frontal impacts in which a considerable overlap occurred. Side pole collisions, which frequently lead to serious injury in accidents in general, played a subordinate role in accidents involving ultra-compact vehicles in urban use. While the share of collisions with bicyclists increased for ultra-compact vehicles in urban use, no difference could be determined between the two groups regarding the frequency of pedestrian collisions, rollovers and tipping. The shift of accident situations toward urban accident scenarios means that only approx. two in three urban accidents result in an endangerment of occupants.

![Distribution of accident types for conventional passenger cars and ultra-compact vehicles.](image-url)
The analysis also showed that because accident situations involving ultra-compact vehicles are concentrated in urban traffic regions, collision speeds are considerably lower. In conjunction with the low mass of ultra-compact vehicles, this results in a general reduction in the overall collision energy. However, in a collision with a heavy accident counterpart, these smaller and lighter vehicles can only partially benefit from this advantage since they must absorb a large share of the collision energy. The accident severities resulting for an ultra-compact vehicle with a curb weight of approx. 450 kg in frontal and side collisions were predicted by the accident analysis based on energy-equivalent computations. To evaluate the accident severity of frontal collisions, the respective energy equivalent speed (EES) was computed. The distribution functions of the respective EES values show that ultra-compact vehicles are subjected to an EES of more than 30 km/h in 40% of all frontal collisions, while this is the case in only 20% of all frontal collisions of accidents in general. The majority of frontal accidents expected for ultra-compact vehicles have an EES of up to 55 km/h. To estimate the accident severity of side collisions, the energy-equivalent value was calculated for the collision speeds observed for the group of ultra-compact vehicles relative to the mass of the side impact barrier used by Euro NCAP. A comparison with the distribution of the equivalent collision speeds of the impact vehicles in the current accident situation in general shows that similar accident severities can be expected on average for both groups.

Requirements placed on the safety of the Visio.M vehicle

The evaluation and assessment of accident data show that special safety requirements exist for electric ultra-compact vehicles compared to conventional passenger cars due to the urban nature of the accident situations, crash compatibility and the associated changes in the collision speeds. The test scenarios used to verify the crash safety of electric ultra-compact vehicles in frontal and side impacts under the current traffic and infrastructure conditions are orientated on the predicted energy-equivalent values, taking into account the expected impact constellations. The performance of the vehicle structure should be in accordance with today's established safety standards: It must ensure a stable passenger compartment and prevent battery intrusions while providing deformation areas specifically designed for energy absorption. These considerations along with assessments of the potential risk for the group of ultra-compact vehicles give rise to the demand for equipping these vehicles with comprehensive integrated safety systems that prevent accidents or reduce their severity. In addition, the vehicle structure and occupant protection systems should be designed for the following load cases:

- Frontal impact: 40% offset, ODB, 64 km/h; Euro-NCAP
- Side impact: MDB, 50 km/h, ECE R95
- Criteria:
  - Stable passenger cell, no battery intrusion
  - Occupant load values fulfill legal requirements, ideally Euro NCAP 5 stars

For both load cases, the design is confirmed in full scale crash tests with a prototype. In addition, further load cases such as rear crashes as per ECE R32, pole side impacts as per Euro NCAP configuration and a roof depression test were examined and verified by simulation with respect to the vehicle structure. Based on these requirements, an overall safety concept was drafted initially and the individual elements were then designed and worked out in detail.

Safety concept

The requirement for a stable passenger compartment results in a very stiff design of the vehicle structure in small and very light vehicles. In conjunction with the great speed changes that ultra-compact vehicles experience due to the differences in mass of the collision partners, this high stiffness leads to a hard crash pulse and thus to high occupant loads. This must be taken into account by the occupant protection concept. In addition to these requirements, steps should be taken to reduce the accident severity or ideally to prevent
accidents altogether. This results in an integrated safety concept consisting of a vehicle assistance system, pre-collision and in-crash measures and a hybrid vehicle structure. A comprehensive system consisting of radar and camera sensors provides 360° detection of the vehicle environment and thus forms the basis of accident prevention and collision mitigation systems such as autonomous emergency braking and lane departure warning systems. To counteract the increase in turning/intersection accidents, an intersection assistance system is considered to have great potential. In addition, to prevent impending rear collisions, various strategies are being examined that enable vehicle evasion toward the front. In this connection, the electrical drive and the low weight of ultra-compact vehicles are proving to be highly advantageous. During an accident, the vehicle structure plays a key role. In the defined load cases, it must provide for a stiff passenger compartment to secure the occupant survival space on the one hand, while also providing a sufficient deformation range for absorbing collision energy on the other. The lightweight structure concept of the Visio.M vehicle is therefore based on an aluminum and carbon fiber reinforced plastic (CFRP) hybrid design. The closed passenger cell is built using an innovative, multi-part monocoque of CFRP and is characterized by a particularly high degree of stiffness. The structure of the front and rear sections of the vehicle consists of aluminum profiles to achieve the highest possible defined energy absorption with sufficient strength and stiffness. However, because of the small dimensions of ultra-compact vehicles, the deformation path made available by the crash structures in the front and rear sections of the vehicle are limited. The innovative safety concept being developed therefore focuses on a needs-oriented extension of the effective deformation zones in the front and side areas of the vehicle in the form of pyrotechnically deployed structure-airbags. To ensure that the deformation zones required to absorb the impact energy are available at the time of the collision, these crash-active systems must be triggered in the pre-crash phase, in the last few milliseconds before an accident that has been assessed as being unavoidable occurs. The crash pulse resulting from frontal impacts in ultra-compact vehicles, which exerts a larger influence on occupants than in conventional vehicle designs, is counteracted by means of an innovative seat belt system consisting of a three-point seat belt and an additional two-point seat belt. Because there is a high risk of serious injury to occupants on the impact side of the vehicle due to the close distance between the door and the occupant in ultra-compact vehicles e.g. caused by vehicle elements intruding into the passenger compartment, an active lateral displacement of the occupant on the impact side of the vehicle toward the middle of the vehicle is provided in the final milliseconds prior to a side collision. As a result of this pre-acceleration, the crash pulse acting on the occupant can be further reduced. The integral protection strategy can be summarized as follows, subdivided into the particular load cases:

- **Frontal impact:** Pre-crash sensing / initiation of automatic emergency braking / active extension of the crash length through deployment of a structure-airbag / positioning and optimal restraint of the occupants with high performance belt tensioners and a 3+2-point seat belt system / energy absorption through the crash structure / prevention of intrusions through sturdy CFRP monocoque / controllable force limitation/deployment of airbags to prevent collision with hard interior structures
- **Side collisions:** Pre-crash sensing / intersection assistant activation / optimal restraint of occupants with high performance belt tensioners and a 3+2-point seat belt system and activation of a lateral occupant displacement / active increase of the side stiffness of the vehicle through deployment of a structure-airbag / prevention of intrusions through sturdy CFRP monocoque / deployment of airbags for early restraint and prevention of contact with hard interior structures, penetrating structures / deployment of airbags to prevent crash-related interactions between vehicle occupants
- **Rear impact:** Pre-crash sensing / activation of automatic evasion toward the front / positioning and optimal restraint of passengers with high performance belt tensioners and a 3+2-point seat belt system / energy absorption through crash structure / prevention of intrusions into the passenger compartment through sturdy CFRP monocoque
An additional requirement in electric ultra-compact vehicles is that the high-voltage system must be electrically disconnected from the battery as soon as a heavy impact is detected to prevent electric shock and the risk of fire. A detailed description of the components and functions and their design is provided in the following chapters.

SAFETY COMPONENTS AND SYSTEMS

Assistance systems/environment sensing electronics

A complex sensor and control system was designed for the Visio.M vehicle with respect to the needs-oriented control of restraint components. A combination of radar and camera sensors creates a "virtual 360° safety cocoon" around the vehicle. The principle of sensor redundancy was applied for the planned pre-crash deployments. The sensors are designed for a comprehensive vehicle assistance package (e.g. Euro NCAP 2020). They help to prevent critical driving situations as well as accidents and were used to trigger pre-crash systems. The evaluation of the integral functions of the individual components was conducted in a simulation using selected urban intersection scenarios.

Restraint systems

The core element of the restraint system is a highly adaptive belt system consisting of a three-point seat belt with an additional two-point seat belt. This 3+2 seat belt design (See Figure 3, left) provides for optimal occupant restraint and largely prevents uncontrolled occupant movement during frontal and side impacts and rollovers. The forces on the occupants during a crash are controlled by optimally coordinated actions of electrically controlled, adaptive belt tensioner and force limiter systems. The electrically controlled high performance belt tensioner achieves a restraint force of up to 900 N. In connection with the pre-crash sensing of frontal and rear collisions, this makes it possible to keep occupants in their optimal seating position, or even to pull them back from an unfavorable position, even in the case of an autonomous full brake application. Airbag systems in passenger compartments are consistently only used where an impact with a hard vehicle structure or an interaction between the passengers must be prevented. A conventional driver airbag module is used in the steering wheel. Adaptive components such as multistage deployment or active venting can be added if required. Lateral protection is afforded by the combination of a head airbag mounted on the roof frame and a thorax-pelvis airbag attached to the body shell. Because of the specific seating design of the Visio.M vehicle in which there is no seat adjustment along the vehicle longitudinal axis (fixed-eye-point design), it is impossible for a belted front passenger to make contact with the dashboard. For this reason, standard installations of a front passenger airbag and knee airbag are not required. The fixed-eye-point design additionally makes it possible to precisely define the area in which protection must be provided and helps in designing compact modules. A special feature is the protection system against interaction between the driver and front passenger. In the event of a crash, an airbag is deployed between the shoulders and heads of the vehicle occupants to prevent them from being thrown against each other. The airbag is mounted at shoulder height on the driver's seat in the vehicle interior.

Active lateral occupant displacement

Another innovation is the active lateral displacement of the vehicle occupant (See Figure 3, left) on the impact side in the event of side collisions. Investigations have shown that it is possible to displace the seat and the occupant by approx. 100 mm toward the center of the vehicle through a pre-crash triggering that occurs approx. 150 ms before a collision. Simulations demonstrate that the load reduction averages 22.3 %. In addition, the boundary conditions for designing the side airbags are improved. The occupant displacement mechanism is implemented using a pyrotechnical actuator in the seat. The seat also houses the unlocking mechanism, the shock absorption at the end of the movement and the seat fixation after displacement. Use of
this function requires the space in the center of the vehicle, which exists in the Visio.M (missing center console/tunnel), and an interaction protection mechanism between the occupants.

![Figure 3. Active lateral occupant displacement, 3+2 seat belt design and sidebag (early design phase) and Frontal structure-airbag.](image)

**Structure-airbags**

Another innovative feature is the structure-airbag concept (See Figure 3, right) for actively influencing the crash pulse during frontal and side collisions. Triggered before a collision, a hose fabric is filled with gas (approx. 16 bar) and supports the composite structure of the vehicle as a load-absorbing element. For frontal protection, this structure airbag is mounted on the cross member behind the bumper covering. When activated, the covering is pushed forward by approx. 12 cm directly prior to the crash (approx. 50 ms) and the structure-airbag behind it contributes to an effective extension of the useable crumble zone. To fill the structure airbag, a gas generator technology is used which largely operates without pyrotechnics and whose performance is therefore minimally dependent on temperature and which is especially aging resistant. Operating pressures up to 30 bar achieve support forces of up to 300 N/cm². Burst membranes are used to specifically release pressure in the structure airbag by means of controlled venting of the stored energy. The same technology is used to provide protection during side collisions. Integrated in the door module, this structure-airbag pushes the lower area of the door outward immediately prior to a collision, establishes a stiffening connection between the A and B-pillars and counteracts overriding of the door sill. The design of the structure airbag and the occupant protection components is closely coordinated with the performance of the vehicle structure.

**VEHICLE STRUCTURE**

**Structure concept**

The structure concept of the Visio.M vehicle is based on the requirement for lightweight design on the one hand, and on the safety requirements for ultra-compact vehicles on the other. The hybrid structure (See Figure 4) enables a stiff vehicle passenger compartment for securing the survival space in the presence of a sufficient deformation path for specific energy dissipation through the use of different materials in different areas of the vehicle. To secure the survival space, the passenger compartment is built with an extremely stiff, multi-part monocoque in a shell design. The low seating position in the vehicle permits an almost complete protection of the occupants while material use through the monocoque is kept to a minimum. The monocoque consists of CFRP materials. With the "tub-like" shape of the monocoque, the lightweight construction material – which is still expensive at this time – is used to preserve the passenger compartment in the event of a crash. All other crash-related areas in the structure are made of the less-expensive standard aluminum profiles to achieve the greatest possible energy absorption levels with sufficient strength and stiffness.
Monocoque

The structural design of the monocoque consists of 11 single parts which were manufactured from CFRP using prepreg as semi-finished material with CFRP tools. The low number of components made it necessary to develop single parts in such a manner that their package, design and structure are multi-functional and optimally designed in terms of production and joining. In light of the possibility of a small series production, CFRP tools were selected because they achieve a considerably higher number of pieces while reaching smaller production tolerances than epoxy tools. The prepreg semi-finished products used were both woven and unidirectional mats, which were used in various areas of the monocoque depending on the load and design. By means of the local use of lightweight cores, such as Rohacell and aluminum honeycombs, the single parts were joined in a device with structure adhesive and then hardened using the autoclave process to form the component. By designing the adhesive flanges according to the applied load, it was possible to eliminate the need for other joining methods. After completion of the monocoque, all joints were analyzed for uniform thickness distribution and voids using ultrasound technology to rule out the possibility of errors in the joining process. To ensure the integrity of the structure, multiple quasi-static pressure tests were conducted. The monocoque was clamped into a device and forces derived from the crash simulation were applied to the points of load application in the front, rear and side wall areas. To perform an acoustic analysis, measurement heads were attached to the surface of the monocoque. The evaluation and analysis of the acoustic signals are used to detect and localize situations critical to the fiber composite. By steadily increasing the load, the load limit of the component is slowly approached without destroying the component, and in this way the computational design of the component can be validated. In addition, the ultrasound test and noise emission test are used for component analysis after the conduction of the crash tests to identify inside or outside damage to the fiber matrix composite and joints that may not be visible.

Doors

The multi-part door design consisting of an inner and outer part with an integrated shaft reinforcement and side collision brackets is also made of CFRP and closes off the passenger compartment on the side. The small installation space between the driver and the outer part make a very stiff door structure necessary. Because of the broad overlap with the door, the monocoque also contributes to the safety of the occupants with its especially high sill in the transition area to the B-pillar. With a total of only 4 structure-related components, the doors contribute to a reduction in the production costs thanks to the integration of functions as well. In addition to the usual components such as the door lock, window lift, loudspeaker, sensors and electrics, the door also incorporates the structure-airbag (see above).
Crash structure

The crash structure in the front section of the vehicle, roof frame and rear section of the vehicle consists of a wide variety of conventional standard aluminum profiles and sheets. Aluminum alloys of the 6000 series were used, which were produced specifically for prototypes using WIG manual welding on a welding device and which then obtained their final strength through T6 heat treatment.

LAYOUT AND VALIDATION

The following paragraphs will give some examples of the different methods which were used during the development phase of the integrated safety concept of the Visio.M vehicle.

Simulations of the integrated safety concept

Many of the components of the integrated safety concept are activated before an accident occurs. The data required for deployment are provided by the environment sensors. Because deployment of irreversible safety components such as the structure-airbag or the active lateral occupant displacement must be absolutely reliable, their validation is closely linked to that of the sensor system. In addition, the safety components only develop their full potential if they are activated in a defined time period prior to the accident. Typical sensor characteristics such as the latency periods, as well as the run times of the associated algorithms, can have a considerable impact on the performance of the safety components (See Figure5). Consequently, the expense of validating these system is high, but can be moderated through the use of simulations. Another advantage is the fact that it is possible to begin with the simulation-based validation very early in the development process since it does not rely on the availability of the components. The simulation of traffic scenarios has the big advantage that they are reproducible, unlike tests on the vehicle testing site. Thus it is possible to focus on a range of different aspects of the safety concept, since the input data are always the same. Based on the use characteristics of the Visio.M vehicle, an entire catalog of urban scenarios was developed and the interplay of the integrated safety concept was designed accordingly. In this way, it was possible to specify the safety concept at a very early stage of development without a prototype. The definition of an accident situation and non-accident situation for these scenarios makes it possible to easily and fully classify the simulation space. Moreover, the following tests and validations of the synthetic sensor system can be performed based on this material. Thus, a procedure was used that can specify, test and validate the sensor and safety features being used for a large number of specific traffic scenarios.

Figure 5. Comparison of an ideal sensor and a sensor considering latency period and noise.
Based on this, the installation position, angle of view and range of the environment sensors were defined so that especially critical intersection scenarios can be detected almost as early as necessary. A variety of sensor technologies were used for the integrated safety concept to ensure redundant coverage of critical areas around the vehicle and to make use of the advantages of the different technologies in an optimal fashion. Based on a synthetic sensor concept, the environment sensor system is simulated independently of the technology. For the individual sensors, specific properties such as the cycle rates, ranges, detection probabilities, occlusion probabilities and overlap signals are modeled. Using this principle, the safety concept can be initially validated for a 100% sensor to identify limitations early on and to counter these effectively. In the next step, the influences of the sensors on the performance of the safety concept were examined to determine if the individual components can be triggered reliably. In particular, the simulation of the cycle rates, the latency periods during sensing and the estimates of the run times of the underlying algorithms are coordinated so that the components can develop their full potential in protecting passengers.

**Simulations and tests regarding the vehicle structure**

The monocoque, doors and aluminum structure packages were subjected to multiple optimization loops overall. To develop a lightweight structure that is appropriate for the load path, one of the techniques applied was the topology optimization method. This optimization method is used to identify load paths within the available installation space. Based on structural mechanical requirements, a static load spectrum was derived for the finite element model, which contained chassis loads, stiffnesses and impact loads. The identified optimal load paths were used in the course of the project as a basis for developing the body shell. To be able to perform design calculations for the specific materials, precise material models are required. The aluminum alloys EN AW-6060 T6 and EN AW-6082 T6 are used in the front and rear sections of the vehicle and in the roof frame. Because the characteristic material parameters vary with heat treatment, for example, the samples of the materials used were characterized. The characteristic material parameters are critical for simulating the impact behavior because they have a highly sensitive response to the material modeling. Based on various tests, these materials were characterized and the corresponding material models were derived from the findings. Although the material EN AW-6082 T6 has a higher yield point than EN AW-6060 T6 (230 MPa compared to 200 MPa), the elongation after fracture is considerably lower (approx. 12% compared to approx. 17%). The material EN AW-6082 T6 is more suitable for structural areas with static loads. However, if high energy absorptions are required that are associated with high plastic deformations, material EN AW-6060 T6 is used. Furthermore, the calculation was validated using component tests (quasistatic pressure tests) with the longitudinal members from the aluminum front section structure. The goal was to determine the deformation behavior and the force level of the longitudinal members using the previously established characteristic material parameters and to compare these results with the calculation results. The findings from the component test and simulations were used to adapt the aluminum crash structure to the design load cases. The design began with a “0° rigid wall” test with full-width impacts. The overlap of the structural deformation values obtained from the calculation and from the test showed very good agreement and confirmed the calculated design of the aluminum structure. For the design of the CFRP monocoque as the central component of the structural concept, a "zero intrusion cell" for frontal and rear impacts was defined as a requirement on account of the small size of the passenger compartment. It was based on static and dynamic calculations. The dynamic calculations involved implementation of the characteristic material parameters of the various CFRP materials into the calculation model. For this purpose, component tests were performed to establish the corresponding damage parameters for the constitutive laws in use. The material models determined in this way were used to identify areas in the monocoque that are subject to high loads.
RESULTS OF FULL SCALE CRASH TESTS

According to the load cases which were defined as requirements on the integrated safety concept of the Visio.M vehicle at the beginning of the development phase three full scale crash tests using a Visio.M prototype were conducted to prove the efficiency of the concept:

1. Frontal impact: 40% offset, ODB, 64 km/h; Euro-NCAP, without deployment of structure-airbag
2. Frontal impact: 40% offset, ODB, 64 km/h; Euro-NCAP, with deployment of structure-airbag
3. Side impact: MDB, 50 km/h, ECE R95

The two frontal impact tests differed in the deployment of the structure-airbag with the objective of figuring out its benefit.

Frontal and side impact

The tests were conducted with a total mass of the Visio.M prototype (See Figure 6, left) including measurement instrumentation, Dummies etc. of 700 kg. The vehicle structure and the occupant restraint systems were acting in accordance with their design. The monocoque kept stable and avoided the intrusion of components into the passenger compartment. The analysis of the occupant load values according to the Euro-NCAP ¹ test protocol for the adult occupant protection box and the offset frontal impact show a result with 15,74 (driver) and 16 (passenger) of 16 possible points. The side impact (See Figure 6, right) was conducted with just one dummy located on the driver’s seat. Its load has also a respectable value of 13,704 of 16 possible points.

Figure 6. Frontal impact: 40% offset, ODB, 64 km/h, Euro-NCAP and Side impact: MDB, 50 km/h, ECE R95.

CONCLUSION

The work and the results of the Safety workgroup of the Visio.M project indicate that, by the use of innovative safety systems and methods, it seems to be possible to reach an acceptable level of occupant safety for ultra-compact vehicles which is comparable to those of compact cars. Even if most of the specified systems and components have just reached a prototype status, the integrated safety concept of the Visio.M vehicle could be beneficial to push the acceptance and thus the market penetration of electrically powered small motorized vehicles in recent years. On the other hand it is questioned if the safety requirements of the L7E vehicle class are sufficient for ultra-compact

¹ Just one test scenario of the Euro-NCAP test protocol was part of the Visio.M load cases – Thus, prediction of a star rating and is not feasible and even was not goal of the working group
vehicles with the character of the Visio.M or a separate homologation class for such vehicles is reasonable. However, this paper shows that higher levels of safety are achievable.

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