Executive Summary

This report documents all findings from earlier stages of the project with relevance for the body design of fully-electric vehicles. The aim is to provide vehicle designers a solid foundation on which to base their concept development activities. Therefore EV (electrical vehicles) specific design practices, rules freedoms and constraints are derived from previous development and assessment work to support the development of future electric urban vehicles.

In practical terms, IKA with the support of IDIADA and SAFER has converted the outcomes of the previous development and assessment work into accessible guidelines for electric vehicles bodies. The guidelines are derived by simulation results and assessment of the VW, Renault and CRF concept.

Conclusions and Guidelines have been derived for ergonomics and interior dimensions of electric vehicles as well as for battery packaging and material selection for each concept. Especially the short front overhang has been analysed with regard to wheelbase, interior dimensions, and battery package. Safety guidelines have also been taken into account while the short front overhang has been analysed regarding pedestrian safety, occupant safety and crash compatibility with respect to the Occupant Load Criterion.
Accessible guidelines for EVs have been derived based on the simulation results of the three ELVA concepts. The three concepts have been placed into different classes; the Renault concept has been placed into Micro class, the CRF concept into A-class and the VW concept into B-class. Guidelines have been derived for the exterior and interior dimension of EVs in each class. The concepts have been compared to combustion vehicles while the main difference has been the short front overhang of each EV concept compared to a conventional vehicle of the same class. The short front overhang has been designed due to the compact electric drivetrain unit. A result of this compact package has been an enlarged wheelbase and larger interior dimensions. A disadvantage for each EV concept has been the vehicle load capacity, which is reduced due to energy efficiency and vehicle range.

The battery package in EVs has also shown an influence for the interior and ergonomics. Due to the battery package under the front and rear seats, most EVs have been designed with a higher seating position compared to conventional vehicles. So the ergonomics have been improved by a good downwards vision as well as a good entry comfort. The simulation tool for ergonomics has been the human builder for analysing the inner vision and to derive parameters for the entry comfort.

Crash safety has been the most important parameter for the battery integration in EVs. The guidelines have been analysed, that battery packages should be built modular by standardised battery modules and should be structurally integrated to the floor structure.

The body of the EV concepts has also been designed for lightweight. The lightweight approach has been to achieve the same weight and structural performance of a conventional vehicle. To reach these targets, the EV concepts have been developed by a multi material body structure. The lightweight design for EVs is essential for optimising range and handling. Furthermore there should be no compromise on safety for the passengers and the battery technology.

Regarding crashworthiness and safety of EVs, guidelines have been derived for structural analysis, crash compatibility, occupant safety and pedestrian safety. Therefore the passive safety load criteria have been fulfilled by the three EVs. Occupant safety has also been taken into account. As a result of the simulations, crash pulses have been calculated for occupant safety. It has been analysed that a certain deformation length is required to guarantee occupant safety. As a result the occupant load criteria should be considered in every loop of the development of the vehicle structure. The derived guideline has been to perform occupant safety in parallel to the optimisation of the vehicle structure in earlier project phases.

The pedestrian safety analysis has considered different front designs, compared to conventional vehicles. There has been a larger risk of impacts with a windscreen and this means that a special design of windscreens should be designed to protect pedestrian head from windscreen impact, especially for windscreen frame.
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Authors
The following participants contributed to this deliverable:

<table>
<thead>
<tr>
<th>Name</th>
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<th>Chapters</th>
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<tbody>
<tr>
<td>Arturo Dávila</td>
<td>IDIADA</td>
<td>all</td>
</tr>
<tr>
<td>Ernő Dux</td>
<td>IKA</td>
<td>2.2</td>
</tr>
<tr>
<td>Johannes Stein</td>
<td>IKA</td>
<td>2.1</td>
</tr>
<tr>
<td>Linus Wågström,</td>
<td>SAFER</td>
<td>2.2</td>
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<tr>
<td>Jikuang Yang</td>
<td></td>
<td></td>
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<tr>
<td>Boris Steeger</td>
<td>CONTI</td>
<td>2.2</td>
</tr>
<tr>
<td>Micha Lesemann</td>
<td>ika</td>
<td>all</td>
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Coordinator
Dipl.-Ing. Micha Lesemann
RWTH Aachen University – Institut für Kraftfahrzeuge
Steinbachstraße 7 – 52074 Aachen – Germany
Phone +49 241 80 27535
Fax   +49 241 80 22147
E-mail lesemann@ika.rwth-aachen.de

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1 Introduction

In the ELVA project three EVs have been developed for urban mobility with the target to reduce energy costs and CO$_2$ emissions. The three EV concepts in the ELVA project have been designed for the Micro class, A-class and B-class. For each EV class future electric powertrain configurations have been designed and new vehicle structures and packages have been derived.

The main objective of this deliverable has been the Electric Vehicle specific design practices, rules and freedoms for the development of EV bodies, derived from the concepts developed in previous development and assessment phases. The conclusions of these previous activities have been extrapolated into general design decision-making rules to support the development of future electric urban vehicles. This deliverable includes the continuous documentation of all previous work with relevance for the body design of EVs.

The information of previous deliverables has been derived into accessible guidelines related to the body of EVs. Design guidelines for the body of EVs have been derived regarding vehicle dimensions, ergonomics, battery integration and material selection. The influences of a longer wheelbase and a short front overhang of EVs have been compared to conventional vehicles of the same class and resulting guidelines for interior dimensions and ergonomics have been derived.

Crashworthiness and safety of EVs has also been taken into account. Specific focus of the crashworthiness and safety guidelines has been on structural design, crash compatibility, pedestrian safety and occupant safety. The structural design has been analysed by previous defined load cases in deliverable D4.2/D4.3/D4.4 Concept Assessment [12]. The influence of the short front overhang has been considered regarding pedestrian safety and occupant safety. Therefore accessible guidelines have been documented to improve the EV safety.
2 Design Guidelines for Electric Vehicle Concepts

In this chapter concept design guidelines for EVs are described, based on the development and simulations of three EVs placed in different classes for urban mobility. Design practices, rules, freedoms and constraints for EV concepts, based on the simulation results of the deliverables D3.2/D3.3/D3.4 Design, Integration and Engineering of the Body, Chassis and Powertrain of the Concepts under Development [11] and D4.2/D4.3/D4.4 Concept Assessment [12] for electric vehicle bodies have been derived. Design guidelines are derived for the body as well as the crashworthiness and safety of electric vehicle concepts. These two chapters include the lessons learned and design guidelines for exterior/interior dimensions, ergonomics, battery integration and material selections as well as passive safety, occupant safety and pedestrian safety.

2.1 Body of Electric Vehicle Concepts

The bodies of the three EV concepts have been analysed regarding the exterior and interior dimensions, ergonomics, battery integration and material selection of each EV concept. Based on these analyses, design guidelines of each criterion and the influence on EV body design are derived. The vehicle dimensions as well as the battery package are taken into account regarding ergonomics. Also guidelines for multi-material mix of each EV concept are documented.

2.1.1 Exterior/Interior Dimensions

Based on the concept comparison of the three EV concepts to conventional vehicles of each class, the lessons learned and guidelines for exterior and interior dimensions are derived. While comparing the EV concepts to combustion vehicles, the main difference concerning exterior dimensions is the short front overhang due to the compact electric drivetrain unit. This results for the VW and CRF concept in a larger wheelbase, which influences the interior dimensions.

The interior of the VW concept provides a larger leg- and headroom for the driver and the second row passengers due to the raised wheelbase and the higher seating position compared to e.g. the VW Polo. For the CRF concept the wheelbase has, due to the battery package under the front and rear seats, also been enlarged to 2,390 mm to provide the same interior dimensions as e.g. in the Fiat Panda. The Renault concept has been compared to e.g. a Renault Twingo 2. Therefore the Renault concept reaches good interior dimensions despite of the smaller floor area.

For the interior and exterior dimensions, the following design guidelines are derived:

- The compact EV powertrain unit enables the construction of a short front overhang.
- A short front overhang results in a larger wheelbase which influences the interior dimension.
• A larger wheelbase enables, with regard to the battery package, the same interior dimension as in conventional vehicles.

• Due to the battery package in electric vehicles, the seating position for driver and second row passengers raise compared to conventional vehicles.

• The vehicle load capacity is reduced due to energy efficiency and range compared to conventional vehicles.

The influence of the short front overhang to the crashworthiness and safety criteria, especially to occupant safety and the derived guidelines, are documented in chapter 2.2.

### 2.1.2 Ergonomics

The three EV concepts were analysed in an ergonomic study concerning inner vision and vehicle entry comfort. With regard to the different vehicle architectures from a Micro up to a B-class vehicle, the assessment from the ergonomics study is derived into guidelines for electric vehicles.

Due to the battery package, the VW and the CRF concept have a higher seating position, compared to combustion vehicles of the same class. This enables good downwards vision with a low hood and a short overhang at the front. The Renault concept seating height is lower compared to combustion vehicles due to the under-body battery package. Thanks to the small front overhang also the Renault concept reaches a good downward vision. Another parameter for the front view is the restriction by the A-pillar. Based on the interior vision assessment, design guidelines are derived as follows:

• A high front seating position and a short front overhang improve the front vision.

• A long and low A-pillar restricts the front vision.

• The side vision is also restricted by the A-pillar, but could be optimised by triangle windows included in the A-pillar.

Besides the inner vision assessment, a vehicle entry analysis was analysed for the three EVs. A three-dimensional human model simulates the entry process. The entry strategy has been simulated for all vehicles in the same way. The simulation shows for each concept how comfortable the entry process is. In the entry simulation specific parameters were analysed as shown in Fig. 2.1. The parameters E1 to E3 have the main influence for the entry comfort. Based on the simulation the following design guidelines could be derived:

• A small distance between the standing H-point and the Seating Reference Point (SgRP) improves the entry comfort due to lower hip and back angles.

• A high distance between the SgRP and the roof rails flange improves the entry comfort thanks to a smaller back angle.
• A large distance between SgRP and lower A-pillar improves the entry comfort because of smaller knee and hip angles.

Due to the higher seating position in the VW and CRF concept, both vehicles achieve good result for the entry comfort. Also the Renault concept, which is the smallest of the three vehicles, achieves a satisfying entry comfort because of the high body and a large distance between the SgRP and the roof rails flange.

Fig. 2-1: Vehicle entry parameters

2.1.3 Battery Integration

As a part of the ELVA project, a modular battery system has been developed for three EV concepts of different classes. The only solution to archive market success for EVs is to offer cost efficient mass products, which will only be able by standardization. One important result of the ELVA project was the development of standardized battery modules for the three EV concepts to satisfy the requirements of each vehicle concept.

The battery module integration has been described in deliverable D3.2/D3.3/D3.4 Design, Integration and Engineering of the Body, Chassis and Powertrain of the Concepts under Development [11] and the results of this deliverable are summarized to derive design rules for the battery integration for EVs. The EV concepts present different battery integrations, shown in Fig. 2-2.

Due to battery safety, the battery integration of the VW concept is based on five battery modules in the tunnel and three battery modules under the rear seats. This T-form packaging enables good variations of seating height for driver and front passenger. The battery package is built of two parts, a ground plate with cooling channels and battery modules as well as the battery housing which is structurally integrated into the vehicles body. The battery package builds a closed unit after the mounting process.
Regarding the CRF concept, the battery package is modular built of one up to three battery housings, each with three battery modules. This modular housing architecture was chosen to reduce the battery itself to save cost, the main obstacle for commercial feasibility of electric vehicles. The battery energy could be chosen individually by the users’ actual needs.

The Renault battery package is built of one central aluminium pack which is completely leak tight and could carry up to eight battery modules. It is mounted on the under-body and could be removed e.g. for checks or maintenance operation.

Comparing the three concepts, the under-body mounting of all concepts enables good maintenance. The most important parameter of the battery integration is the crash safety for all concepts. Therefore the side crash is the most critical crash configuration for the battery because of the small vehicle width. The assessment of battery safety assures for each EV concept good load paths over the respective floor unit. Therefore the following design guidelines were derived:

- Battery packages should be built modularly by standardized battery modules to enable the exchange and maintenance of the standardized modules for different vehicle classes.

- The battery package has to be structurally integrated to the floor structure for good energy absorption and force distribution capacities.
• In case of interior dimensions and passengers ergonomics, battery packages for each vehicle should be integrated to the tunnel, under front and rear seats or as an under floor construction.

2.1.4 Material Selection

Within the ELVA project the material selection has been analysed for three EV concepts. The aim of each concept was to design an EV with the same weight and structural performance of a comparable conventional powered vehicle. In order to account for the weight, range and cost targets, each EV concept developed a multi-material body structure. To reduce cost and weight, the multi-material approach is limited to sub-assemblies. Therefore an example of the VW concept is shown in Fig. 2-3.

The multi-material approach of the VW concept shows an under-body frame built of aluminium while the greenhouse is from steel. To reduce weight, the floor module is made from fibre-reinforced composites and the roof module is a plastic sandwich structure to reduce the centre of gravity. The floor pan module is a composite in multi-fibre design (CNFRP). The advanced approach of the floor pan module is a mix of carbon fibre and natural fibre due to Life-Cycle Analysis (LCA) considerations. The challenge of EVs for 2020 is if the use of reinforced plastic will become possible extensively and in a sustainable way. Today’s challenges are:

• The functional requirements of compliance, including stiffness, strength, e-coating resistance and thermal expansion
• Cost of the process and materials
• In terms of LCA, the possibility to implement a long-term sustainable usage of the materials (eg. continuous recycling as is used for steel, aluminium and certain plastics)
To manage these challenges natural fibres received greater attention in recent years. Especially the carbon neutrality of natural fibres is of particular importance to reduce greenhouse gas emissions. An advantage of natural fibres is the low cost per unit weight as well as good acoustics and damping properties. Concerning life-cycle analysis, natural fibres are biodegradable and can be easily recycled.

The CRF concept is built on a multi-material approach with respect to torsional stiffness and lightweight design. Therefore a polymer/steel sandwich solution was evaluated for the body design, shown in Fig. 2-4. The polymer/steel sandwich solution provides a feasible lightweight solution while achieving the objectives of torsional stiffness. An additional lightweight approach in the CRF concept is a rear plastic floor build of glass and Dynema fibre-reinforced Nylon. Advantages of the rear plastic floor are:

- Saving 8 kg weight compared to a metal sub-frame
- Reducing costs thanks to the integration of the motor support directly on the plastic part
- Improving rear crash performance thanks to the “alveolar” ribs reinforcement designed to support the electronics

Fig. 2-3: Multi-material approach of VW concept
The CRF lightweight approach is completed by an aluminium front structure, shown in Fig. 2-5.

The Renault approach is only using steel and high performance steel instead of composites materials for the BIW design (see Fig. 2-6). The weight has been reduced compared to the Renault Twingo 2 from 290 kg to 201 kg. Therefore an aluminium roof and paint has been taken into account. Also guidelines for small A0 class vehicles are derived:

- Lightweight design is essential for optimising range and handling of electric vehicles.
- Lightweight design should be built on affordable materials in order to reduce the energy consumption.

- There is no compromise on safety, for the passengers and the battery technology.

- Door panels can be done in plastic material, with a longitudinal member in aluminium (see Fig. 2-7).

Fig. 2-6: Steel body with aluminium roof

Fig. 2-7: Door with plastic panel and longitudinal aluminium member
2.2 Crashworthiness and Safety of Electric Vehicle Concepts

The chapter crashworthiness and safety of EV concepts describes the lessons learned as well as the derived guidelines for passive safety, pedestrian safety and occupant safety. The passive safety chapter includes the lessons learned of structural design, analysed load cases and crash compatibility of each EV concept.

2.2.1 Passive Safety

Structural Design

To optimise the energy absorption behaviour and the force distribution in all tested frontal crash load cases, structural design should consider up to three vertically distinct load paths (for a realization example using three load paths see Fig. 2-8 a). Vehicle deceleration issues arising due to the generally shorter deformation length of the front of electric vehicles should also be taken into account during the design process. These issues require a good balancing with the structural integrity imperatives, such as the prevention of upper A-pillar collapse and the limitation of frontal intrusions. For a better load distribution in vertical and horizontal direction in case of car-to-car or car-to-barrier front crashes the longitudinal energy absorbing components require well performing horizontally linking crossbeam connections. In the same way, the vertically distinct load path levels should be linked by strong vertical connecting elements. To better match defined frontal crash compatibility requirements, the positioning of the primary energy absorbing system should respect the vertical dimensions of the so-called part 581 zone. Battery safety against intrusions was not identified as specific issue for electric vehicle front dimensioning during the structural design phase.

Fig. 2-8: Load path for front crash (a) and rear crash (b)
Deliverable D5.6

The rear structure of the body should also consist of several vertical load path levels (Fig. 2-8 b). In this way, the energy absorption and deformation behaviour of the vehicle's rear end can be ideally regulated to prevent any possible intrusion into the battery (and passenger) compartment. Battery safety against intrusion is a possible issue that should be considered in detail already in the design phase of the vehicle's rear end.

Euro NCAP side and side pole crash were selected as only side crash load cases in this study. Therefore, the design focus should be on the stiffness of the rocker and the energy absorption and force distribution capacities of the floor structure. These components have to balance out the requirements for low y-axis acceleration levels on the one hand and low to very low intrusions into the seating space of vehicle passengers and into the battery compartment (for a realization example showing the load path design of an electric vehicle’s side Fig. 2-9). Meanwhile, light weighting and static stiffness priorities can be the dominating aspects for the B-pillar and the roof structure dimensioning.

Fig. 2-9: Load path for side crash

Results of Load Cases

All three vehicle realizations achieve good results concerning the passenger cell intrusion levels. The only acceleration profile target to be achieved concerns the peak value of x-axis acceleration of the vehicle. This target is also reached by all three vehicle models. The single optimisation target is nevertheless not sufficient to assure an adequate occupant protection level against acceleration based injuries. The test of all three models confirms that battery safety against intrusion is no specific issue in case of front crash.

Euro NCAP Side Crash

The rocker area structural components of all three tested concepts show a good alignment with the impacting mobile barrier’s face. This alignment assures a good force distribution into the adjacent structures and therefore low intrusions into the passenger cell. The different
battery pack arrangements of the tested models all proved to be well dimensioned against intrusion, mainly due to good performing load paths over the respective floor unit.

EURO NCAP Side Pole Crash (standard and additional, critical positions)

This load case type demonstrates one major issue concerning the structural design of battery electric vehicles. Low y-axis accelerations, the preservation of survival space on the impacted side of the vehicle and the limitation of possible battery pack intrusion are conflicting structural design targets. Therefore, especially the mechanical modelling of battery systems in the chosen crash simulation environment require further precisions to allow a better performance comparison between different realizations and to prevent over-dimensioning of the respective structures assuring battery safety.

FMVSS 301 Rear Crash

It can be confirmed by the vehicle results that battery safety against intrusion is the dominating imperative concerning the structural dimensioning of the vehicle’s rear end.

Crash Compatibility/Front Crash Pulse

Crash compatibility is a topic that has been discussed extensively in several European research projects such as VC-Compat [1] and FIMCAR [3], along with research activities in Japan and the USA. Despite this, final recommendations on how to solve the problem of incompatible vehicles are yet to be made. Whenever there is mass incompatibility, the lighter vehicle will always be at a disadvantage in car-to-car collisions. It has therefore been agreed that the first step towards improved crash compatibility should be made in terms of structural interaction, i.e. providing frontal structures opportunities to function in their intended manner by placing them in a common interaction zone. Based on a US voluntary agreement [2], this common interaction zone has been established at 16 to 20 inches (406-508 mm) above ground level. This common interaction zone was also regarded by FIMCAR [3] as a good base for evaluation of structural interaction. The ELVA concepts were therefore assessed with respect to their ability to spread loads into this common interaction zone. Focus was placed on vertical load spreading, i.e. how rigid barrier load cell row forces compare to each other, but horizontal load spreading was also regarded. A tool was developed for visualising the loads applied to the barrier from the vehicle front structure.

The crash compatibility assessment of the ELVA concept vehicles showed the importance of load path layout on the initial response of the barrier load cell forces. Later in the crash events, the inertial forces from powertrain and chassis components could be clearly noted in the load cell time histories. Overall, the presence of a lower load path (or secondary energy absorbing structure, SEAS) was important in order to spread the load in a vertically homogenous way over the barrier face. In the CRF concept, a SEAS was not present which made the vehicle force distribution inhomogeneous as illustrated in Fig. 2-10.
A better example of vertical load spreading was the VW concept as illustrated in Fig. 2-11. In this concept, multiple load paths were present, which resulted in load cell forces that were evenly distributed over load cell rows 2, 3 and 4. In this case however, the narrowly positioned frontal longitudinal members were identified as a potential risk of poor structural interaction if loads from another vehicle or object are present outboard of the frontal longitudinal members.

**Recommendations**

A clear distinction whether a vehicle should be labelled as good or poor with respect to crash compatibility cannot be made. It is suggested however that vehicles with multiple load paths should be encouraged. This increases the chances of beneficial structural interaction in car-to-car collisions, decreasing the risk of under riding or over riding.

The frontal crash pulse severity assessment of the ELVA concepts clearly showed how all three concepts have very short stopping distances (i.e. the maximum total longitudinal displacement of the passenger compartment from first point of contact with the rigid barrier). Furthermore, the simplified crash pulse severity metric Occupant Load Criterion (OLC [4]) was higher for all three ELVA concepts compared to a database of 447 vehicles tested in the
US-NCAP crash test programme between 2000 and 2010 at 56 km/h into a full-width rigid wall, as illustrated in Fig. 2-12.

**Occupant Load Criterion**

US-NCAP 56 km/h rigid wall crash, 2000-2010, N=447

![Graph showing OLC vs. total stopping distance for ELVA concepts compared to dataset of vehicles tested in US-NCAP 2000-2010.](image)

Fig. 2-12: OLC vs. total stopping distance of ELVA concepts compared to dataset of vehicles tested in US-NCAP 2000-2010

The OLC is to be interpreted as a crash pulse severity metric and will not give direct information on occupant injury risk levels. Therefore, the OLC shows only the conditions supplied by the vehicle structure for the restraint system to operate in. Higher OLC means poor conditions for restraint systems, i.e. the restraint systems will need to account for a large portion of the occupant kinetic energy. In contrast, when the OLC is low, the vehicle deformation supplies additional ride down distance, which is beneficial for decreasing loads on the occupant. The OLC should therefore be reduced in order to supply beneficial conditions for the restraint system. However, if for a particular restraint system occupant response can be shown to be acceptable in terms of injury risk even with a high OLC, there is no reason for a direct requirement on the OLC.

### 2.2.2 Pedestrian Safety

**Evaluation of design concepts for pedestrian protection**

Pedestrians are among the most vulnerable road users in current traffic. Accident studies have shown that the head and the legs are the most frequently injured body regions in pedestrian accidents. Most injuries and fatalities occur due to impacts with the front of a passenger vehicle. For this reason consumer safety testing (EuroNCAP) and regulatory testing (EC regulations) have focussed on the evaluation of the protection offered by the vehicle front (soft bumpers, hoods etc.). A number of impactor tests on the vehicle front are used to evaluate the injury risk in case of a pedestrian accident. Based on discussion on harmonized future pedestrian safety regulations within the Global Technical Regulations...
(GTR) it can be expected that in 2020 further updates of the test methods and requirements will take place, but that the principle concept of impactor testing will not change. For an overview of pedestrian safety regulations and the expected requirements in 2020 refer to D4.2/D4.3/D4.4 Concept Assessment [12].

Future electric vehicles may have quite different designs than conventional vehicles and the question in ELVA was whether such designs cause an additional risk for pedestrian injuries compared to conventional vehicles and consequently, whether additional measures are needed like more energy absorption or active systems including pedestrian emergency braking systems (that reduce the speed before the impact) and/or systems that become active during a crash with a pedestrian (hood airbags, moving hoods etc.).

Therefore the design concepts of a number of electric vehicle prototypes (EVPs) have been evaluated for their protective performance in view of GTR requirements expected to be implemented in 2020. The evaluation was conducted focusing on global kinematics of a 50th percentile adult pedestrian model developed by Chalmers. A frontal impact of 40 km/h (40 km/h is a reference speed in pedestrian protection regulations) was simulated using the MADYMO multi-body model, where the pedestrian is impacted from the side.

The geometries used were the CRF vehicle developed during the project and three other selected designs from the contest. It was decided to simulate three more extreme potential EV shapes resulting from the ELVA design concepts illustrated in Fig. 2-14. They are referred to as respectively Vehicle A, B and C. Mechanical properties (energy absorbing capabilities) were taken identical to the CRF vehicle. The resulting multi-body model for the pedestrian simulations is illustrated in Fig. 2-13.

![Fig. 2-13: (a) The pedestrian model developed by Chalmers, (b) Configuration for modelling of CRF car to pedestrian impact at 40 km/h.](image-url)
Main dimensions of the CRF vehicle are presented in Table 2-1 in comparison with a range of these dimensions for regular vehicles (D4.2/D4.3/D4.4 Concept Assessment [12]). It can be seen that the CRF vehicle has a very short bumper protruding distance and a rather short hood length. Other dimensions of the CRF vehicle like bumper height and windscreen angle are well located within the range of dimensions for conventional vehicles.

### Table 2-1: Comparison of front geometry design variables and values between the CRF vehicle and regular passenger cars.

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The mechanical properties of the CRF vehicle model were defined based on the available average data from EuroNCAP tested vehicles. The evaluation was conducted in terms of the head acceleration and speed, HIC value, upper leg impact force, tibia acceleration, knee bending angle, and knee shearing displacement.

### Lessons learned

Based on this study a number of conclusions can be drawn. It should be noted that the conclusions are based on simulations with an adult 50th percentile pedestrian only and that
they are not valid for other body sizes and in particular not for impacts with children. Therefore also additional simulations should be conducted in the future with models representing different child sizes.

The simulations show that head impact conditions strongly depend on some of the front geometry design variables. The hood length effects the head impact location: there is a larger risk of impact with the windscreen if the vehicle has a short front end. Therefore energy absorption by the windscreen as well as the windscreen frame is essential for head injury protection. The head impact velocity is in particular influenced by the hood leading edge height and the windscreen angle. A higher hood leading edge results in a lower head impact velocity. A larger windscreen angle results in a lower head impact velocity and a smaller head impact angle.

The height of the bumper influences the leg injury related parameters, such as knee bending angle and shearing displacement. The increase of the bumper height causes an increased knee injury risk. Also a larger bumper protruding distance will increase the knee bending angle and the knee shearing displacement.

The pedestrian kinematics from the simulation of the CRF vehicle in comparison with a conventional vehicle appear to be quite similar, in spite of the differences in bumper protruding distance and hood length between both vehicles. Also the injury related parameters for the CRF vehicle appear to be quite similar to the conventional passenger car. This suggest that for the CRF vehicle it is expected that a similar pedestrian protection can be offered as for conventional vehicles, provided that a similar energy absorbing structures for the vehicle front is included.

The results of the simulations for Vehicle A and Vehicle B, in comparison with the CRF vehicle, show that the impact on the head is less severe and consequently also the risk of head injuries (assuming a similar energy absorbing behaviour of the impacted structure). For the impact with the lower extremities larger loads on the thigh and the tibia were noted for these vehicles. For the knee injury risk the loading was less in vehicle A and slightly larger in vehicle B. The differences in lower extremity injury risk are relevant, but on the other hand it is expected that in the design of the vehicle front structure this can be compensated by an increased energy absorbing capability in the impacted structures and or use of active protective systems. Since the shapes of the two other ELVA concepts do not vary too much from the simulated shapes or from conventional vehicle shapes it is not expected that the two other ELVA concepts would not be able to meet future pedestrian regulations as far as adult pedestrian impacts is concerned.

This cannot be concluded for the concept vehicle-C which has a unique design with the four wheels outside the main body. The configuration in the simulation was set in such a way that the pedestrian is hit by the right front wheel of the vehicle-C. The pedestrian model is thrown to the ground near the right rear wheel with a risk of rollover by the right rear wheel as illustrated in Fig. 2-15 and an increased injury risk due to the impact with the ground (the so-
called secondary impact). So this type of designs may need special attention as far as pedestrian protection is concerned.

Fig. 2-15: The kinematics of the pedestrian model from simulation of Vehicle C right-front wheel impact at 40 km/h.

2.2.3 Occupant Safety

The occupant safety for all concept vehicles developed within this project has been assessed towards the end of the ELVA project, when sufficient data of the vehicle interior and reliable crash pulses from crash simulations have been available. The assessment of occupant safety has been limited to frontal impact scenarios, as this is the most common type of impact, and the degree of detail of the vehicle design was not sufficient enough for a side impact assessment.

The assessment of the occupant safety was carried out based on results of occupant simulations for each concept vehicle. 3D CAD data of the vehicle interior was used to set up the simulation models. Where detailed information about interior components has been missing, known characteristics from an average vehicle have been used. In the first step components of a standard restraint system have been integrated into the simulation models. The standard restraint system consists of:

- Seatbelt with pre-tensioner and load limiter
- Driver airbag
- Passenger airbag
- Energy absorbing steering column

The size of the standard passenger airbag has been adapted to the geometry of the interior of the vehicles, if necessary.

Fig. 2-16 shows the simulation model of the VW concept as an example.
The assessment has been carried out in view of the requirements regarding occupant safety for the year 2020. Therefore the crash scenarios that are part of the Euro NCAP protocol for model year 2015 and later have been taken into account as well as a frontal impact with 56 km/h against a rigid barrier, according to FMVSS 208, which is a requirement for the homologation of a vehicle in the USA and some other countries.

In general, the injury risk for the occupants in the vehicles equipped with the standard restraint system was higher than the injury of an occupant in an average conventional vehicle. Therefore, the characteristics of all components of the restraint system were optimised individually for each vehicle concept. After optimisation of the restraint system including the introduction of adaptive components (where necessary) that can operate on different levels depending on the crash scenario or the size of the occupant etc., the level of occupant safety could be improved, but the injury risk was still high enough that an optimum Euro NCAP rating seems to be impossible and furthermore the risk to fail the homologation test according to FMVSS 208 was still quite high.

Following tendencies could be worked out:

1. The smaller the car, the higher the injury risk and the risk to fail homologation tests.

2. The smaller the car, the higher the risk of missing the airbags and hitting the instrument panel, due to rotation of the vehicle in an offset scenario.

3. The injury risk tends to be higher than the injury risk of a conventional vehicle of the same class.

The next step was to evaluate the reasons for those tendencies.

First of all the crash pulses have been analysed and compared to each other (Fig. 2-17) and to crash pulses of conventional vehicles.

This comparison shows that the crash pulse for the smallest vehicle concept in ELVA (Renault) is much more severe than the one for the largest concept vehicle (Volkswagen). For the largest vehicle it takes approximately 20 % longer to come to a complete stop than
for the smallest vehicle in an impact against a rigid barrier. That results in a 20% higher average deceleration for the smallest vehicle. This explains the higher injury risk for the occupants in the smaller vehicle.

Furthermore, the deformation length of the vehicle frontend is smaller for all vehicles than for nearly all conventional vehicles, and the relevant deceleration of the vehicle expressed by the Occupant Load Criterion (OLC) is higher than for all conventional vehicles. This explains the tendency of the higher injury risk compared to conventional vehicles.

![Crash pulses comparison](image)

**Fig. 2-17:** Comparison of crash pulses (56 km/h against rigid barrier)

**What are the reasons for the higher injury risk compared to conventional vehicles?**

1. The smaller engines and different type of components (electric motors instead of conventional engines, batteries instead of fuel tank etc.) allow a different layout of the drivetrain that requires less space in the front end of the vehicle, and therefore allows shorter front ends.

2. All designers for the different concept vehicles took the opportunity to shorten the front end compared to the underlying conventional vehicle layouts.

3. Important criteria that assess the crash pulses regarding the potential injury risk for the occupant (like zero-crossing of velocity, average deceleration, OLC criterion) have not been taken into account during the assessment of the structural performance of the vehicle.
4. Significant rotations around the vertical axis of the vehicles occur in offset crashes that involve a certain risk of missing the airbag resulting in head impact to the instrument panel. This phenomenon was not studied in detail, but it might be possible that the electric vehicles tend to rotate more than a conventional vehicle due to the shorter front end (higher pulse) and/or a different mass distribution due to the different drivetrain layout.

**What do we learn from this?**

1. Front ends of electrical vehicles should not be much shorter than front ends of conventional vehicles, just because the electrical components require less space, since a certain deformation length is required to guarantee occupant safety.

2. Criteria that assess the crash pulses regarding occupant safety (e.g. OLC) should be used in every loop of the development of the vehicle structure.

3. A criterion for maximum vehicle rotation during an offset crash should be defined and assessed in every stage of vehicle development.

All three points might in the end result in a vehicle architecture for electric vehicles that is different from the architectures developed within the ELVA project, especially for the smaller vehicles.

Furthermore occupant simulations should be performed in parallel to the optimisation of the vehicle structure in earlier project phases, than it has been conducted within ELVA.
3 Conclusion

The report described the design practices, rules, freedoms, and constraints for electric vehicles bodies. Based on the concept development and concept assessment, guidelines have been derived for electric vehicles regarding crashworthiness and safety, crash compatibility, pedestrian and occupant safety as well as for exterior and interior dimensions, ergonomics, battery integration and material selection.

Based on simulation and assessment results of previous reports deliverables D3.2/D3.3/D3.4 Design, Integration and Engineering of the Body, Chassis and Powertrain of the Concepts under Development [11] and D4.2/4.3/4.4 Concept Assessment [12] conclusions of the VW, Renault and CRF concept have been summarized to accessible guidelines. While each EV concept has been compared to a conventional vehicle of the same class, advantages and disadvantages have been presented. The lightweight approach of each EV concept has been achieved by a multi-material design with regard to passive safety and stiffness.

The concept comparison has been shown that the VW and CRF concept have an enlarged wheelbase, due to the short front overhang and interior dimensions. A conclusion of the passive safety simulation, especially occupant safety and crash compatibility has been that a short front overhang of each concept influences safety, since a certain deformation length is required to guarantee occupant safety. Also the occupant load criteria should be considered in every loop of the development of the vehicle structure. Therefore occupant simulations should be performed in parallel to the optimisation of the vehicle structure in earlier project phases.

A general conclusion for future EV’s fronts concerning pedestrian safety has been derived. The EVs front showed significant differences to traditional vehicles. In particular there has been a larger risk of impacts with the windscreen and this means that a special design of windscreens is necessary to protect pedestrian head from windscreen impact, especially for windscreen frame.
## Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIW</td>
<td>Body in White</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>EVP</td>
<td>Electric Vehicle Prototype</td>
</tr>
<tr>
<td>HIC</td>
<td>Head Injury Criterion</td>
</tr>
<tr>
<td>LCA</td>
<td>Life-Cycle Analysis</td>
</tr>
<tr>
<td>OLC</td>
<td>Occupant Load Criterion</td>
</tr>
<tr>
<td>SEAS</td>
<td>Secondary Energy Absorbing Structure</td>
</tr>
<tr>
<td>SgRP</td>
<td>Seating Reference Point</td>
</tr>
<tr>
<td>GTR</td>
<td>Global Technical Regulations</td>
</tr>
</tbody>
</table>
5 Literature


6 Annex

The ELVA project’s objectives have been to make use of the additional freedoms in design that the use of electric powertrains provide for future vehicles. To achieve the objectives, the team within ELVA has developed three different electric vehicle concepts. There have been several design loops, and the results show some of the most appropriate techniques to obtain the best architectures for fully electric vehicles. The solutions are varied, from one motor to various motors, with modular batteries, different suspension systems, smart material combinations and battery packaging. Each concept is placed into one segment.

Table 6-1: Overview of the three concepts

<table>
<thead>
<tr>
<th></th>
<th>VW</th>
<th>CRF</th>
<th>Renault</th>
</tr>
</thead>
<tbody>
<tr>
<td># of seats</td>
<td>4</td>
<td>4</td>
<td>3+1</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>4000</td>
<td>3594</td>
<td>3080</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>1694</td>
<td>1600</td>
<td>1620</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>1554</td>
<td>1548</td>
<td>1533</td>
</tr>
<tr>
<td>Wheelbase [mm]</td>
<td>2600</td>
<td>2390</td>
<td>2060</td>
</tr>
<tr>
<td>Battery capacity [kWh]</td>
<td>14.4</td>
<td>5.3+5.3+5.3</td>
<td>12.4</td>
</tr>
<tr>
<td>Range [km] (NEDC)</td>
<td>170</td>
<td>150</td>
<td>160</td>
</tr>
<tr>
<td>E-motors</td>
<td>Central front / central rear</td>
<td>Central front/ motor axle rear</td>
<td>Central rear</td>
</tr>
<tr>
<td>Maximum power [kW]</td>
<td>50 /50</td>
<td>28 + 25 (2x 12.5)</td>
<td>50</td>
</tr>
<tr>
<td>Maximum torque [Nm]</td>
<td>115 /115</td>
<td>82 + 82 (2 x 41)</td>
<td>115</td>
</tr>
<tr>
<td>Front suspension</td>
<td>Double wishbone</td>
<td>McPherson</td>
<td>McPherson (double pivot)</td>
</tr>
<tr>
<td>Rear suspension</td>
<td>Double wishbone</td>
<td>Twist beam</td>
<td>Semi-trailing arm</td>
</tr>
<tr>
<td>Top speed [km/h]</td>
<td>150</td>
<td>100</td>
<td>110</td>
</tr>
</tbody>
</table>
VW Concept

The VW concept is placed into the B-class and is built by a unique platform strategy enabling an MPV, SUV and roadster configuration. So it enables higher production volume due to the platform strategy with the goal of bringing down the high cost of electric components thanks to economies of scale effects.

Fig. 6-1: VW concept
CRF Concept

The CRF concept focuses on a modular electric powertrain for shorter and longer range. It represents an A-segment car, thus larger than the Renault concept and smaller than the VW concept.

Fig. 6-2: CRF concept
**Renault Concept**

The Renault concept has been placed into Micro class and underlines the focus of an affordable, lightweight and easily manoeuvrable urban car.

![Renault Concept Diagram](image)

**Fig. 6-3:** Renault concept