epsilon - SMALL ELECTRIC PASSENGER VEHICLE WITH MAXIMIZED SAFETY AND INTEGRATING A LIGHTWEIGHT ORIENTED NOVEL BODY ARCHITECTURE

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Summary

The epsilon project aims to conceptualise, develop and prototype a new small electric passenger vehicle for 2020+. It focuses on the development of an innovative electric vehicle concept with maximized safety and high efficiency, specifically designed for the typical transport tasks in urban areas.

This paper presents the development of the epsilon lightweight body architecture and drivetrain based on a scenario and market analysis. The lightweight and safety concept has been analysed by the use of finite element method (FEM). The efficiency has been simulated and validated on a test bench. An outlook on the future testing programme focusing on the core development targets concludes the paper.

1 Motivation and Objective

Funded by the European Commission within the Seventh Framework Programme the epsilon project is focusing on the development of an innovative electric vehicle concept for the typical transport tasks in urban areas. The epsilon vehicle will be considerably lighter, more energy efficient and require less road space than today's sub-compact cars, still offering the same level of safety. Compared to powered two-wheelers, epsilon will provide higher safety, transport capacity and driving comfort under all weather conditions, offering at the same time an appealing driving performance at affordable costs. The epsilon vehicle will address not only the ecological and societal, but also the economic dimension of sustainable mobility. It will close the gap between ultra light L7e vehicles and conventional passenger cars (M1 class) by focusing on safety and lightweight design with a novel body architecture.
2 Scenario and Market Analysis

The scenario and market analysis reviewed global trends which will affect the urban mobility of the future and set the basis for the translation of customer expectations into overall vehicle specifications. The market analysis was based on a questionnaire and took into account a total number of 162 participants including 20 % females and 80 % males. The questionnaire in Fig. 1 was complemented by the analysis of potential competitors and has been the basis for the vehicle characteristics.

Commuting is the main use case for urban individual transport, followed by leisure activities. To address customer needs for these tasks, a rather minimalistic vehicle concept has been derived. Safety still remains to be the most important feature though. Both active and passive safety are prerequisites that must be provided to the customer. The vehicle needs to be safe among the other actors of the city traffic, and the occupants have to feel safe while driving. Practicability is another key characteristic for the customer, focusing on short recharge cycles and sufficient driving range. Also, while road space becoming more and more congested, roominess and comfort remain important. A luggage compartment is requested, but the possibility to accommodate four passengers, even for small trips, is preferred.

Based on first calculations and looking at today's sub-compact vehicles, a full-size, four seat vehicle will not fulfil the stringent efficiency target of 80 Wh/km set for the epsilon vehicle. But a foldable second row of seats, that converts boot space into passenger space could be a viable solution to provide sufficient luggage space at least for everyday shopping. Top speed greater than 110 km/h, in line with the average of competitors and with the possibility to move outside the city, should be realised even if the range could be severely affected at high speed. Agility in the urban context is a non-neglectable objective, and is fulfilled with acceleration from 0-100 km/h in under 10 s. A purely electric range of at least 150 km is provided by using a rather small 16 kWh battery pack – with a positive effect on weight, package space and costs.

![Rating of features](image-url)

Fig. 1: Scenario and market analysis - key features
3 Vehicle Concept

The epsilon vehicle concept shows a methodological package development approach which is the basis for the overall vehicle development. This chapter focuses on the package approach as well as the body, drivetrain and thermal management development with respect to the key features safety and energy efficiency.

3.1 Package

Considering the project scope as well as the scenario and market analysis, the package definition is based on a morphology analysis of 54 possible seating layouts by variation of seating position and orientation of passengers. All seating concepts have been analysed regarding the main criteria of a forward looking position and a transport capacity for at least two 95th percentile males. Thirteen final package concepts have been analysed in detail. Every package concept has fulfilled the main requirements from chapter 2, but varies in exterior dimension, cross section, expected energy consumption and requirements for lightweight design. Thus all final concepts have been compared in an evaluation matrix and rated by an expert jury regarding the criteria transport capacity, weight, footprint, battery integration, driving performance, energy consumption, luggage space etc.

The package concept in Fig. 2 shows a small footprint area, combined with a transport capacity of two 95th percentile males and one 5th percentile female, which has been rated as the optimal package concept for small urban vehicles in this analysis. This package concept has been worked out in detail and is the basis for the body, chassis, drivetrain and design development. It contains vehicle dimensions, passenger positions, field of view, head clearances and package dummies for chassis and drivetrain components.

![Package layout](image)

Fig. 2: Package layout
A wheelbase of 2040 mm combined with short front and rear overhangs leads to a small and agile urban vehicle. Driver and passenger fit into the narrow package due to a longitudinal offset of 150 mm, to provide enough shoulder space. The rear passenger, a 5th percentile female, is placed on a jump seat at the trunk. The higher seating position due to the underfloor battery package improves the entry comfort and overview in urban traffic, also for elderly drivers. This concept setup has been checked by a two dimensional H-Point template, eye ellipses and head clearance measurements as well as 3D human models for an ergonomically optimised interior package.

### 3.2 Body Architecture

The lightweight and target optimised body architecture is a key factor to fulfil the overall vehicle weight of 600 kg including the battery and a maximised safety for this vehicle class. Lightweight vehicles from the L7e class have been investigated by Euro NCAP and evaluated regarding passive safety. The L7e vehicle class is not subjected to strict safety tests like M1 vehicles have to fulfil. The investigation of Euro NCAP for front and side impact resulted in critical structural shortcomings and high risks of fatal or serious injury, even at moderate speeds [1], [2].

The epsilon body features a novel architecture with advanced lightweight design. Structural load paths have been identified using the topology optimisation approach taking into account the load cases for Euro NCAP front, side, pole and rear crash as well as static bending and torsion. To this end, the dynamic Euro NCAP crash load cases have been represented by static load conditions. Based on the material distribution from the topology optimisation, a structural BIW concept has been developed with respect to load paths. The overall BIW development objectives were to minimise the BIW mass and to meet safety requirements for M1 vehicles.

The body architecture has been designed in a hybrid CFRP-Al-Space-Frame-Design, presented in Fig. 3. Usually the production of carbon fibre components is rather expensive. CFRP is mostly used in high-end sports cars, due to low investment costs for tooling and machinery, but time-consuming hand lay-up methods or costly autoclaves.

![CFRP-Al-Space-Frame](image)

**Fig. 3:** CFRP-Al-Space-Frame
The epsilon CFRP beams are designed in multi-cell-structure using a new technology, which could make composite vehicle bodies affordable at small and medium volumes.

The CFRP-Space-Frame is closed by tailored shear panels for specific stiffness and crash safety. The BIW concept is completed by a modular Al-Front-End, rear bumper system and side deformation zone. The exterior skin panels, made of GFRP at the prototype, are adapted to the design and do not add structural performance to the body structure. Injection molding of thermoplastics would replace the GFRP hand lay-up in serial production. The new BIW concept improves the lightweight approach on the one hand and on the other hand the battery safety could be improved with respect to lightweight design.

3.3 Drivetrain

The focus regarding drivetrain components was to achieve the key performance requirements of the epsilon vehicle, which are:

- Vehicle weight < 600 kg
- Acceleration 0-100 km/h < 10 s
- Purely electric range > 150 km
- High energy efficiency < 80 Wh/km

Therefore, several layouts of the drivetrain with off-the-shelf components have been investigated. During these investigations, it turned out soon that the acceleration to 100 km/h in less than 10 s can only be realised with a rear-wheel drive and a motor power of at least 50 kW.

Since the major consumer of energy in the vehicle is the electric drivetrain, an optimised drivetrain is indispensable. Therefore, the investigation aimed not only at the masses of the individual components, but also on the specific energy demand and efficiency.

For epsilon the Bosch SMG 180 (electric motor) in combination with the Bosch INVCON2 (Inverter/Converter-Unit) was chosen. This motor is a water cooled permanent magnet synchronous machine with a maximum power of 80 kW (@ 380 VDC). The maximum torque of 200 Nm cannot fully be transferred to the road due to wheel slip. Therefore the torque is limited within the vehicle control strategy. However, with a weight of 32 kg the motor has a very good power to weight ratio.

The customised HV-battery including the battery management system (BMS) is designed to be placed at the lowest part of the vehicle floor, between the front and the rear axle, enabling a balanced weight distribution. Furthermore the HV-battery integrates a power distribution unit to supply the inverter in the rear and other high-voltage components (AC-charger, heater and refrigerant compressor) in the front of the vehicle, see Fig. 4.
Fig. 4: Layout of the purely electric high voltage drivetrain

Because of the low power demand - caused by the lightweight vehicle architecture - it is possible to use a high voltage Li-Ion battery without liquid cooling. This results in an overall weight of the battery of 110 kg, which is a weight reduction by about 25% compared to liquid cooling at an overall capacity of 16 kWh.

3.4 Thermal Management

The epsilon vehicle will integrate an all-weather in-cabin comfort, which includes an integrated thermal management architecture between the powertrain components and the vehicle cabin. It fulfills the following functions:

- Ventilation of the cabin with fresh air
- Cabin heating, including the functionality of de-icing
- Cabin cooling
- Dehumidifying and/or defogging

The objectives for the thermal management and HVAC system of the epsilon vehicle are based on extremely low energy consumption at affordable costs. Therefore the system uses waste heat of the drivetrain components for conditioning the passenger cabin. This is one of the main requirements for an energy efficient vehicle. The whole thermal system of the epsilon vehicle is designed as shown in Fig. 5.

The specific hydraulic characteristics of a coolant circuit concept have major influence on the consumed electrical energy. The behaviour of the system can be observed by using several temperature measurement points in the cooling circuit. Using this information and knowing the optimum temperature range of each component, the thermal controller unit can actuate the valves and the coolant pump (with variable speed) in a way that all components can operate in the most efficient way. In addition the coolant flow and its temperature level can be influenced by a variable speed control of the front end fan.
4 Simulation and Testing

The simulation and testing chapter describes explicit finite element (FE) simulations to proof vehicle safety as well as the efficiency analysis based on a MATLAB/Simulink® model to determine the energy efficiency and the purely electric range. The complete epsilon drivetrain has additionally been investigated on a test rig.

4.1 Crashworthiness and Safety

For the verification of the passive safety of the epsilon vehicle concept several load cases have been investigated on the virtual level. For this reason a FE model of the full vehicle has been setup for the solver LS-DYNA, which allows simulating highly dynamic load cases. While the components of the drive train, the chassis and other components can be modelled relatively simple by representing the geometry and applying rigid or elastic material characteristics, the modelling of the body structure is decisive for the simulation of the crash load cases.

A FE model of the full structure has been built up taking into account the properties of the applied materials. In order to predict the behaviour of the utilised carbon fibre reinforced polymer (CFRP) and aluminium (AL) components accurately, suitable material models and validated parameter sets have to be applied. The structural CFRP-Al-Space-Frame has been analysed in the full FEM model to fulfil selected crash load cases for M1 vehicles. Fig. 6 shows the corresponding load cases. The structural BIW concept has been optimised based on these simulations. In addition,
bending and torsional stiffness of the BIW have been analysed to achieve typical requirements for M1 vehicles.

![Fig. 6: Crash simulations](image)

### 4.2 Energy Consumption and Driving Range

The requirements of the drivetrain components have been identified by using a longitudinal dynamics simulation model built up in MATLAB/Simulink®. With respect to the air conditioning and cabin heating system as well as with respect to the thermal management of the drivetrain and the battery, the energy demand of the overall vehicle was estimated. In addition, the potential of recuperative braking has been taken into account. Beside the component specification the simulation models are used to determine the energy efficiency and the purely electric range of the epsilon vehicle.

The complete epsilon drivetrain including its cooling system and the HVAC-system as illustrated in Fig. 4 has also been investigated on the powertrain test rig at VIRTUAL VEHICLE Research Centre. Here the driving performance and the behaviour of the drivetrain in the driving cycles NEDC (New European Driving Cycle), FTP 75 (EPA Federal Test Procedure) and the WLTP-C3 (Worldwide harmonized Light vehicles Test Procedure Class 3) has been tested. The WLTP driving cycle for a Class 3 vehicle is divided in four parts for low, medium, high, and extra high speed. Due to

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<th>Crash Test</th>
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<tr>
<td>1</td>
<td>Euro NCAP full width rigid barrier front crash</td>
<td>✓</td>
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<tr>
<td>2</td>
<td>Euro NCAP offset deformable barrier front crash</td>
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<td>3</td>
<td>Euro NCAP movable deformable barrier side crash</td>
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<td>6</td>
<td>FMVSS 301 offset deformable barrier rear crash</td>
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the fact that the top-speed of the epsilon vehicle is 120 km/h, the extra high speed part has been replaced with the low speed part.

The investigations at the test rig have shown a driving range of 156 km at a state-of-charge (SOC) swing of 75 % (90 % SOC to 15 % SOC) for the more challenging WLTP driving cycle. This result has been obtained considering a vehicle mass of 675 kg (including a 75 kg driver). The results of the test rig correlate very well with those of a preceding driving performance simulation showing an energy demand of 76 Wh/km.

![Speed profile (grey) of the WLTP-C3 driving cycle with a total distance of 23262 m and energy consumption (blue) of the epsilon vehicle](image)

**Fig. 7:** Speed profile (grey) of the WLTP-C3 driving cycle with a total distance of 23262 m and energy consumption (blue) of the epsilon vehicle

The complete cooling system has been tested in driving mode with and without cabin heating. During the testing phase special attention has been paid to the thermal controller’s behaviour and to all relevant temperature profiles of the system during different load cases. The heat input into the cooling system by the electric machine and the inverter/converter (InvCon) has been analysed. The thermal system architecture including exemplary measuring points as it was implemented on the test rig is shown in Fig. 5.

5 Conclusions and Outlook

This paper described an innovative electric vehicle concept focusing on lightweight design, energy efficiency and safety. The epsilon concept presents a sustainable mobility solution to urban areas by closing the gap between ultra light vehicles (L7e) and conventional passenger cars (M1) but still offering comparable safety as M1 cars. The concept development has focused on the project objectives and realised an overall vehicle concept with a novel body architecture, an optimised drivetrain, a suitable chassis and a unique package with a new design concept.

Longitudinal dynamics with consumption simulation and measurements at the drivetrain test rig including the complete thermal system have shown that the key performance requirements of epsilon can be fulfilled. With the applied battery system a driving range of more than 150 km can be achieved. This means an energy
consumption of less than 80 Wh/km. The 80 kW motor can accelerate the vehicle to a speed of 100 km/h within 9 s which can be considered as outstanding for such a small and efficient urban car.

Based on the virtual development, a full running prototype will be built and analysed in an extensive testing programme focusing on the core development targets in vehicle safety, energy efficiency and vehicle dynamics. Vehicle safety will be tested by the Euro NCAP full width rigid barrier front crash with a reduced front crash structure and a full crash vehicle structure to validate the simulation results. Also energy efficiency will be measured at the running vehicle. The fine-tuning of the cabin heating and the thermal management of the drivetrain cooling will be done in the complete car. The final efficiency tests will be performed at a roller test bench. Final tests on acceleration behaviour, top-speed and handling will be performed on a test track.

The epsilon concept has been designed for challenging project targets with regard to lightweight design, energy efficiency and safety, which have been fulfilled in the development process. Finally the project results show the potential of a new vehicle class between ultra light L7e and conventional M1 vehicles.

6 Acknowledgement

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7 References

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