13CVI-0281

OPTIBODY: A New Structural Design Focused in Safety

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)
Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

With electric vehicles becoming more and more popular, the classic “general purpose” vehicle concept is changing to a “dedicated vehicle” concept. Light trucks for goods delivery in cities are one of the examples. The European vehicle category L7e fits perfectly in the low power, low weight vehicle requirements for an electric light truck for goods delivery. However, the safety requirements of this vehicle category are very low and their occupants are highly exposed to injuries in the event of a collision. The European Commission co-funded project OPTIBODY (Optimized Structural components and add-ons to improve passive safety in new Electric Light Trucks and Vans) is developing a new structural concept based on a chassis, a cabin a several add-ons. The add-ons will provide improved protection in case of frontal, side and rear impact. Two mains issues also considered in both the chassis and the add-ons design were the crash compatibility and the interaction with the vulnerable road users.

The OPTIBODY project has proposed frontal, side, rear and pedestrian impact tests for improving self and partner protection for this vehicle category. The OPTIBODY vehicle has been designed using this test proposal as targets and the frontal crash test simulations showed an improvement in the cabin integrity and self and partner protection. This vehicle design will provide a new modular architecture for L7e vehicles that will improve self and partner protection and reparability in case of collision.

Introduction

During the last few decades, environmental impact of the petroleum-based transportation infrastructure, along with the peak oil, has led to renewed interest in an electric transportation infrastructure. Electric vehicles differ from fossil fuel-powered vehicles in that the electricity they consume can be generated from a wide range of sources, including fossil fuels, nuclear power, and renewable sources such as tidal power, solar power, and wind power or any combination of those. This kind of vehicles has several advantages over vehicles with internal combustion engines as they are energy efficient (electric vehicles convert about 59–62% of the electrical energy from the grid to power at the wheels while conventional gasoline vehicles only convert about 17–21% of the energy stored in gasoline to power at the wheels) and environmentally friendly (electric vehicles emit no tailpipe pollutants, although the power plant producing the electricity may emit them, furthermore, electricity from nuclear-, hydro-, solar-, or wind-powered plants causes no air pollutants), their performance produces benefits (electric motors provide quiet, smooth operation and stronger acceleration and require less maintenance than internal combustion engines) and they reduce energy dependence (electricity is a domestic energy source).

Last trends show that vehicle manufacturers, instead of the classic general purpose concept, are changing the model, which is becoming more specific, especially for electric vehicles due to their limited driving range. They are manufactured for urban activities as logistics, mobility, etc. To carry out this kind of activities, electric cars need to optimize energy consumption and one of the main parameters to achieve that, is to assure a light weight of the vehicle structure.

That is why the OPTIBODY project was defined and co-funded by the European Commission. It is focused on developing new and safe vehicles as homologated Electric Light Trucks and Vans (ELTVs) as N1 and N2 in Europe and also L7e vehicles (Directive 2002/24CE).

In the early development stages of ELTVs, they were designed using the same vehicle structure and concept as internal combustion engine vehicles, the difference was the electric motor was allocated instead of the classic thermal engine. However, last models of some manufacturers changed the classic concept and introduced new elements which increase the space in the frontal zone of the vehicle. This new configuration allows the engineers, apart from common advantages as weight reduction, to set innovative solutions as removing the entire engine block or focusing the body design on safety of vulnerable road users.

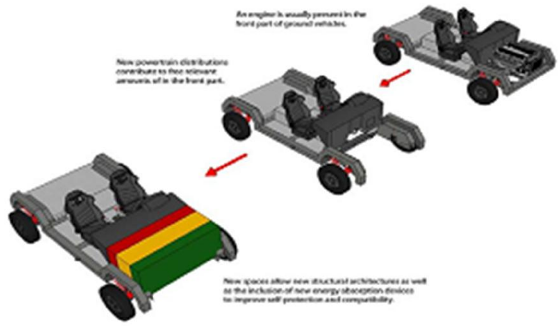


Figure 1. Evolution of vehicle fronts (from classic cars to EVs) and the resulting possibility to use the front of the vehicle to install new safety components.

New possibilities opened by the new electric vehicles configuration, were incorporated in the vehicle of the OPTIBODY project as specific add-ons in order to provide specific self-protection in case of front, rear and side impacts, as well as in case of rollover and partner protection in case of interaction with other vehicles (crash compatibility) or vulnerable users (pedestrian, cyclists and motorcyclists).

The main aim of this project is to improve the passive safety of vehicles under the European category L7e. Several activities were carried out to achieve this goal:

- Enhance vehicle's passive safety
- Enhance crash compatibility
- Optimize the reparability in small crashes
- Optimize ergonomics and space distribution for passengers and main components accessibility
- Improve maintainability
- Modularity with other vehicle categories (N1, N2, M1, M2, etc.)

Vehicles included in the OPTIBODY vehicle category (L7e in Europe and Low Speed Vehicles in the U.S.) have very high fatality ratios when impacting with other vehicle categories due to their typically light design and much less restrictive safety regulations than the existing for passenger cars. To decrease the fatal statistics and to improve the safety concerning to this kind of vehicles, an add-on assembly was designed taking into account the new frontal structure of the vehicle without several elements as the thermal engine and the reparability needs defined in this project.

This paper describes the methodology that is currently been used in the OPTIBODY project and the preliminary results from the analysis of the ELTV regulations in Europe and the United States, the analysis of accidents involving ELTVs and the ongoing work that is been currently carrying out for the chassis, cabin and add-ons design.

Vehicle Definition

The OPTIBODY vehicle is defined as a quadricycle. This kind of vehicle is included in category L7e in Europe (Heavy quadricycles) and is defined by Framework Directive 2002/24/EC as motor vehicle with four wheels, "other than light quadricycles (category L7e). The maximum unladen mass is 550 kg not including the mass of batteries in the case of electric vehicles and the maximum payload mass (payload = maximum technically permissible mass - mass in running order - 75 kg driver) of 1000 kg.

The dimensions of the vehicle must be:

- Length ≤ 4.0 m
- Width ≤ 2.0 m
- Height ≤ 2.5 m

There is not any maximum speed for L7e vehicles and the maximum net engine power must be equal or less than 15 kW.

Regarding passive safety systems, three-point seatbelts must be installed in all the seats but performance of the vehicle in a crash is not established.

Table 1. European Directives for L7e vehicle category.

DIRECTIVE	TOPIC
2002/24*1137/2008	Whole vehicle type
93/14*2006/27/EC	Braking
93/30/EEC	Fitting of audible warning device
93/33*1999/23/EC	Protective devices intended to prevent the unauthorized use of the vehicle
93/93*2004/86/EC	Masses and dimensions
95/1/I*2006/27/EC	Maximum speed
95/1/II*2002/41/EC	Maximum power and torque
97/24/1/III*2006/27/EC	Fitting of tyres
97/24/3*2006/27/EC	External projections
97/24/4*2006/27/EC	Installation of rear-view mirrors
97/24/EC Chapter 8	Electromagnetic compatibility
97/24/10/EC	Coupling devices
97/24/11*2006/27/EC	Safety belts and anchorages
97/24/12*2006/27/EC	Glazing, windscreen wipers, windscreen
2000/7/EC	Speedometer
2009/62/EC (former 93/94*1999/26/EC)	Space for the mounting of the rear registration plate
2009/67/EC (former 93/92*2000/73/EC)	Installation of lighting and light-signalling devices

2009/80/EC (former 93/29*2000/74/EC)	Identification of controls, tell-tales and indicators
2009/139/EC (former 93/34*2006/27/EC)	Statutory markings

In the United States, the equivalent vehicles to the European L7e are the Low Speed Vehicles (LSV), whose features are as follows:

- 4 wheeled vehicles.
- Maximum speed between 32 km/h (20 mph) and 40 km/h (25 mph).
- Gross Vehicle Weight Rating (GVWR) ≤ 1,361 kg (3,000 pounds).

This kind of vehicles corresponds to the safety standard FMVSS 500 Type 1 (lap belt) or Type 2 (lap and harness belt) seat belt assembly conforming to Sec. 571.209, Federal Motor Vehicle Safety Standard No. 209.

Accident Analysis

One of the activities at the beginning of the project was to identify the main accident scenarios in which the vehicles of the OPTIBODY category are involved. For this purpose an analysis of the accident databases from the main geographical areas was carried out [1][2][3][4][8]. One of the main issues during the accident analysis was the lack of vehicle category harmonization when the different existing databases were considered. Depending on the database chosen, the vehicle category where the L7 vehicles are included is defined as “vans and lorries”, “lorries under 3.5 tonnes”, etc. This fact made very complicated the comparison of the results from the different databases.

The results showed that the main issues to focus were self-protection and vulnerable road user (VRU) protection. The OPTIBODY vehicle category is designed to circulate most likely in urban areas, where most of the pedestrian accidents occur. In EU19 the pedestrian fatalities account for 20% of the total number of fatalities and the number grows to 27% when the inside urban areas are considered. Regarding the passenger protection, the percentage of lorries and pedestrian fatalities inside urban areas in EU 19 has grown up in spite of the number of fatalities has decrease in these years. In the “lorries under 3.5 tonnes” the inside urban areas fatalities account for 15% of the total number of fatalities.

The scenarios that accounted for the higher number of fatalities were:

- Frontal crash
- Frontal-side crash
- Collision with obstacle

These three scenarios accounted for more than 75% of the driver fatalities and more than 55% of the passenger fatalities. In terms of injuries they accounted for 57% of the injured drivers and 56% of the injured passengers.

The only detailed study including a category of vehicle (category #21) which refers to quadricycles was performed in OPTIBODY using the “Regione Piemonte database”. The data from 2009 and 2010 showed very small number of fatalities and injuries. In these two years 1 person died in accidents that involved quadricycles and 78 suffered injuries of different severity. In the same period of time, 17 fatalities and 1083 injured people were associated with vehicles included in the trucks category.

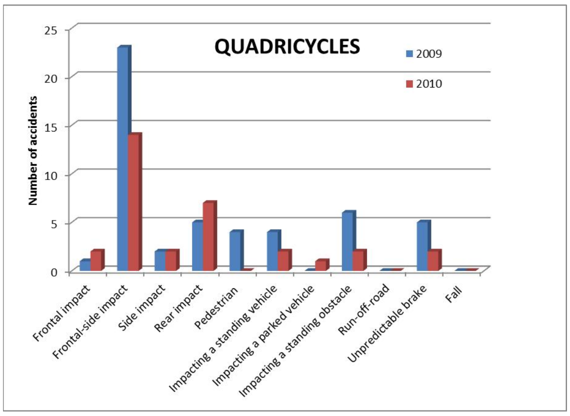


Figure 2. Total number quadricycles accidents per type of crash in the Piamonte region

In the United States, some studies showed that in two-vehicle crashes involving a Passenger Car and a LTV, particularly in head-on collisions, 3.6 times as many passenger car occupants were killed as LTV occupants. When LTVs were struck in the side by a passenger car, 1.6 times as many LTV occupants were killed as passenger car occupants. On the other hand, when passenger cars were struck in the side by LTVs they were killed 18 times more than LTV occupants.

Regarding the injuries sustained by the occupants of the vehicles [5][6][7], the head (25% for cars and 23% for LTVs) and upper extremities (20% and 22%) were the most injured body regions followed by the lower extremity (20% for LTVs and 16% for cars). These three body regions account for 61% of the injuries in cars an 65% in LTVs.

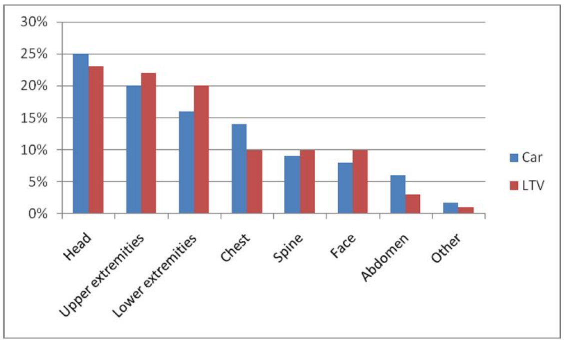


Figure 3. Total number of trucks and quadricycles accidents per type of crash in the Piamonte region

Vehicle Design

In the first part of the project, the identification and selection of the energy storage and the powertrain was done. Two in-wheel motors with a maximum power of 15 kW were considered the best powertrain option and the battery pack was placed on the rear axle, on the vehicle structure behind the cabin.

For the design of the structure and the add-ons some crash tests were used as design targets in which the OPTIBODY vehicle should have a good performance in order to provide of a good safety level for passenger and VRU protection. These crash tests are shown in Table 2 and include different impact directions whole vehicle crash tests as well as impactor tests for pedestrian protection. The crash configurations are similar to the ones considered in both regulatory and consumer tests but the speeds of the crash tests are lower due to the vehicle characteristics.

In this paper, the main chassis structure of the vehicle is explained and special attention is paid to the frontal add-on and the composites crash boxes designed for VRU and frontal impact protection.

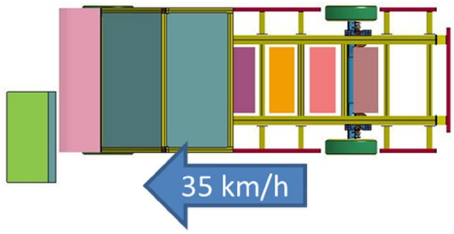
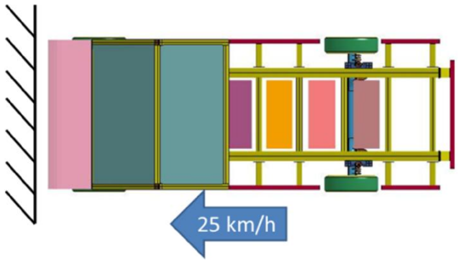
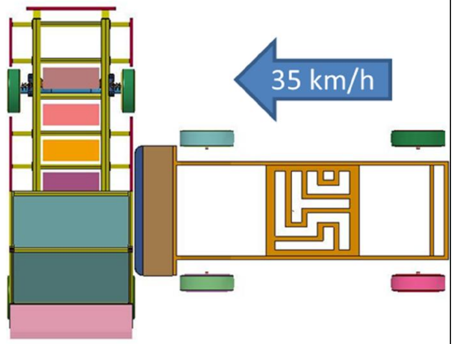
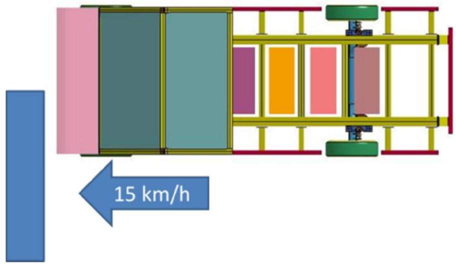
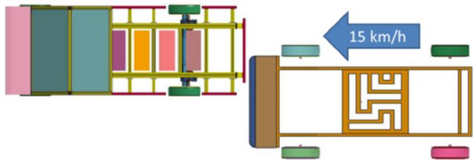
Different structural architectures and material such as high strength steel, aluminum, composites, etc. have been considered. The selection has been made based on classic selection criteria as weight, strength, etc. as was as the Greenhouse Gas (GHG) emissions for production. The frame of the vehicle was made of two aluminum main rails and a series of transverse beams welded to them (Figure 4), also made in aluminum. This solution allows reducing the weight and containing the costs, compared to, respectively, a common steel solution and a normal production aluminum car body.

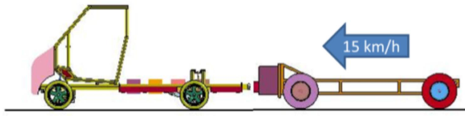
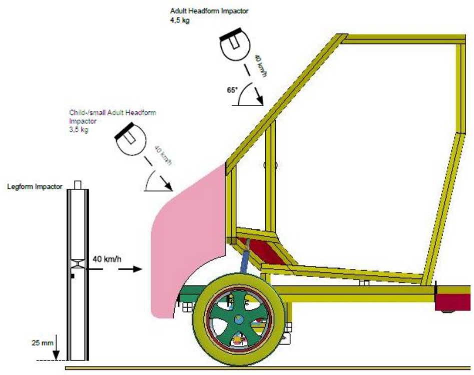
The rear frame is aimed at the transportation of goods and, under the floor, the battery housing. The front part is aimed at carrying the cabin, the powertrain devices and to manage the energy in the case of impact. The two parts are joined together by bolts, improving the modularity of the vehicle, giving the possibility of exchanging the front cabin part with different rear equipment. In the rear part a series of crash boxes and a longitudinal crash beam are fixed to the main rails in order to improve the safety and to protect the batteries in case of side impact. For these two components high strength steels is adopted to improve the energy absorption.

The cabin is a wireframe structure made of aluminum extruded profiles joined by welding. The cabin is welded on the front structure.

The front part of the vehicle is divided in two main portions. The front one, made with a stamped high strength steel crash boxes and crash beam, is aimed to absorb energy at low speed impact (16 km/h). Behind this part, the second portion is a front rail aimed to absorb energy in impact at higher speed (36 km/h). Crash box, front rail and main rail are joined together with bolts in order to improve the reparability. Different solutions in terms of shapes and materials both for the front and side crash boxes and crash beams were taken into considerations. The final solutions are optimized to obtained the best crashworthiness behavior and consequently to maximize the energy absorption. The same approach in terms of materials and structural behavior is being considered for the add-ons.

Table 2. Crash test configurations used as targets for the OPTIBODY chassis and add-ons design

FRONT IMPACT	40% offset Deformable barrier 35 km/h	
	Full frontal Rigid barrier 25 km/h	
SIDE IMPACT	750 kg trolley 35 km/h	
INSURANCECRASH TEST	Full frontal Rigid barrier 15 km/h	
	Full rear Rigid barrier 15 km/h	

REAR IMPACT	Full rear 750 kg Trolley 15 km/h	
PEDESTRIAN CRASH TEST	Head impact test 35 km/h Lower leg impact test 35 km/h	

The cabin is intended to bring an ergonomic and safe space for occupants so, in case of accident, deformations of the structure and intrusion of components must be avoided. Global frontal and side crash tests will bring additional information to understand the behavior of the structure.

Virtual simulations have been performed using a model of the chassis; cabin and add-ons to verify that the vehicle design fulfills the crash test requirements established at the beginning of the project. These simulations included frontal and side crash tests since they are the most common accident scenarios where the OPTIBODY vehicle is involved. In Figure 5 the performance of the OPTIBODY vehicle design in these crash tests is shown. As it can be observed in the picture the deformation of the structure is controlled during the crash and the safety level of the vehicle is really good, being much better than the safety performance of the current L7 vehicles.

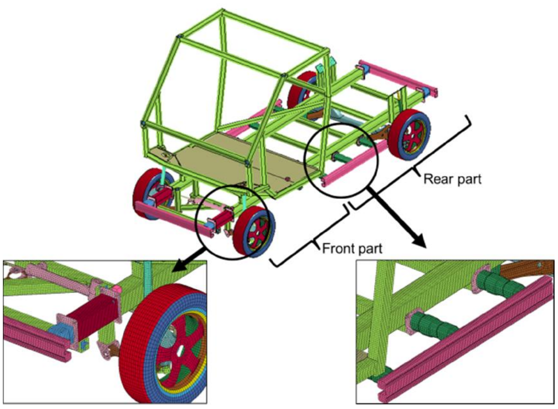


Figure 4. OPTIBODY 3D model chassis. In detail the front and side crash structures.

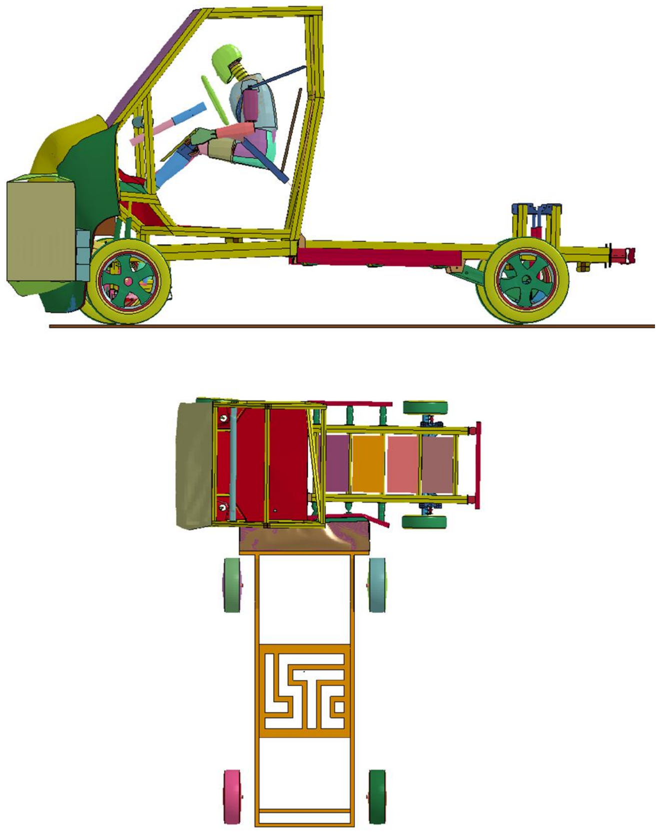


Figure 5. Crash tests simulations of frontal (above) and side impact (below).

The space that the former thermal engine occupied in the front part of the vehicle is now used to accommodate the frontal add-on and other energy absorber devices that will provide of additional protection to the OPTIBODY vehicle occupants as well as to the pedestrians in case of impact. To design the frontal add-on for pedestrian protection, a numerical hybrid III 50th male dummy model is being used in a frontal centered impact simulation. The add-on geometry is being designed to avoid a direct impact of the head against the cabin or the windscreen and it is based on the APROSYS European project considerations concerning the deflection of the pedestrian to one side of the road in case of a run over. Finally, a rounded circular shape was adopted in the contact area with the lower extremity.

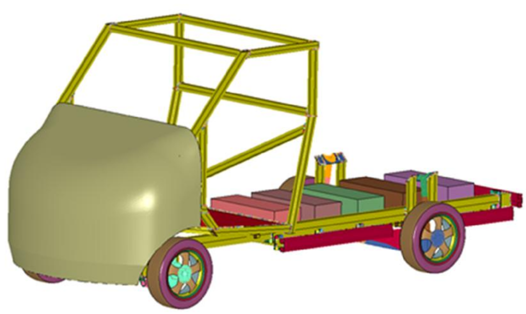


Figure 6. Frontal add-on positioned on the OPTIBODY concept.

Simultaneously, physical impact tests are being performed in order to validate the numerical simulations. These impact tests are carried out by means of simple point impactors that facilitate the analysis of the behavior of the structure during the impact. In this way, data on damaged area, impact speed or energy absorbed are available to be compared to those coming from identical simulated tests.

Figure 7. Impact test simulation for the frontal add-on and real add-on used for the validation of the simulations.

In the current add-on design, a configuration of a glass-fiber skin with internal foam is being used to optimize the energy absorption and the HIC15 values. The total add-on weight has been kept below 30 kg. The virtual add-on has been developed and validated (Figure 8).

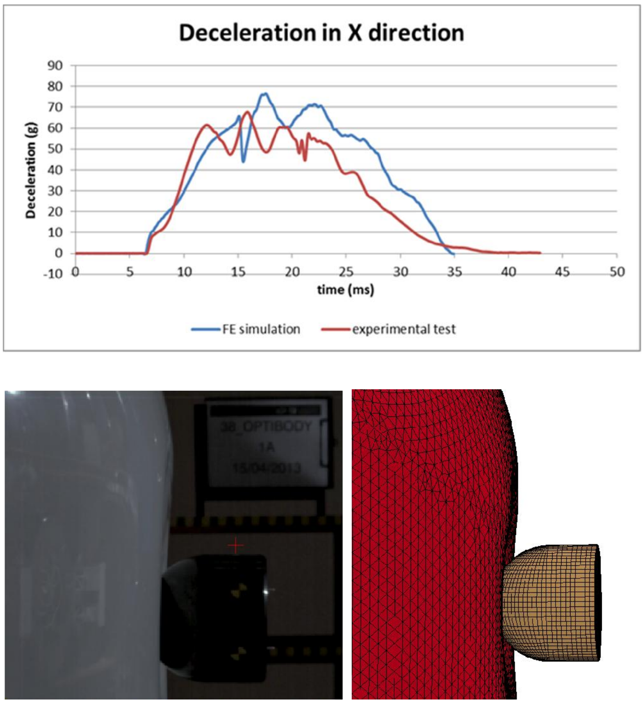


Figure 8. The top image shows the deceleration correlation. The bottom image shows the maximum displacement in the real test and the FE simulation.

Once the FE model was validated, a process for optimizing the properties of the frontal add-on was carried out. This can be made on selection of materials, type and shape of triggering devices, and also on geometry. Sensitivity analysis was carried out to optimize energy absorption and force levels during crash process.

Different configurations of composite materials have been modeled and changes of the foam core thickness have been also checked. The optimum solution found using these simulations has been finally incorporated in the OPTIBODY prototype.

Composite Crash Structure

Design process

The composite crash structure is placed between the steel crash box and the aluminum longitudinal member so it is designed to be more resistant than the crash box but softer than the longitudinal member in case of an impact. Definitions of specifications have been carried out using numerical tools. First peak loads and load carrying capability of the crash box and longitudinal member are calculated numerically in order to determine the boundary conditions for the composite crash structure as can be seen in the Figure 9.

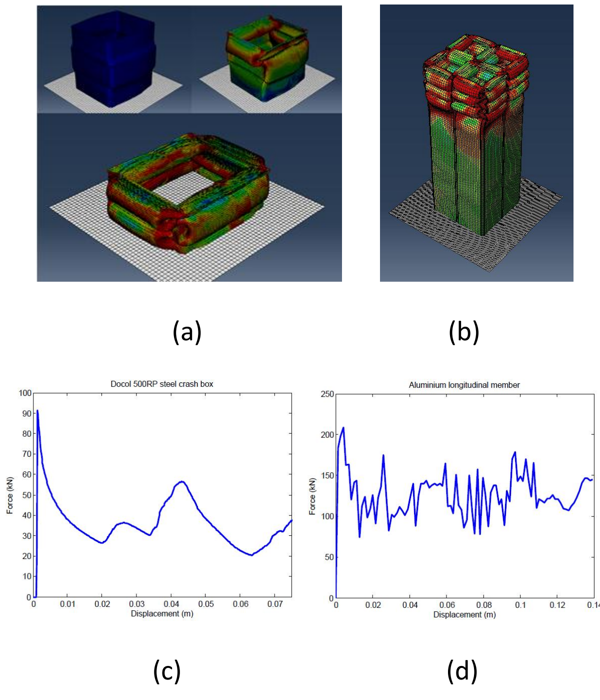
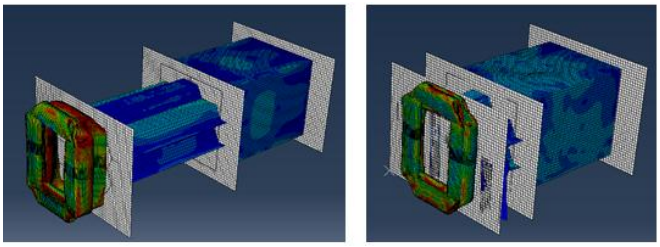


Figure 9. (a) Numerical simulation of steel crash box. (b) Numerical simulation of aluminum longitudinal member. (c) Force-displacement curve for steel crash box. (d) Force-displacement curve for aluminum longitudinal member.

Looking at the results, the first peak load of the composite structure must be between 90 kN – 200 kN so different configurations based on combination of semi-hexagonal profiles are studied to fulfill the specifications.

Finally, the whole structure has been simulated to verify there is a progressive collapse beginning from the steel crash box until the aluminum longitudinal member. As can be seen in the Figure 10, progressive collapse of the different impact structures was obtained.



(a) (b)

Figure 10. (a) Numerical simulation of the crash box collapse. (b) Numerical simulation of the collapse of crash box and composite structure.

Manufacturing and testing at 30 km/h

The manufacturing of semi-hexagonal specimens has been carried out by infusion method in Mondragón Automoción. 8 plies of unidirectional E-glass fibers are placed over a metallic mould and with a vacuum bag and vacuum pump, polyester resin is injected to impregnate the fibers. Once the semi-hexagonal profiles are cured, the specimens are cut and the chamfer type trigger is machined for each specimen in order to have progressive failure mode in the collapse. Finally, using structural epoxy based adhesives (Loctite® 9466 A & B Hysol®), semi-hexagonal profiles are bonded among themselves and to the metallic base plates.

Structures made of 2 mm and 3 mm thickness have been tested using an impact sled. They are attached in a rigid wall and a sled of 585 kg is impacted against the composite structure at 30 km/h. Force-Displacement curves of the Figure 11 are obtained integrating the information recorded by accelerometers.

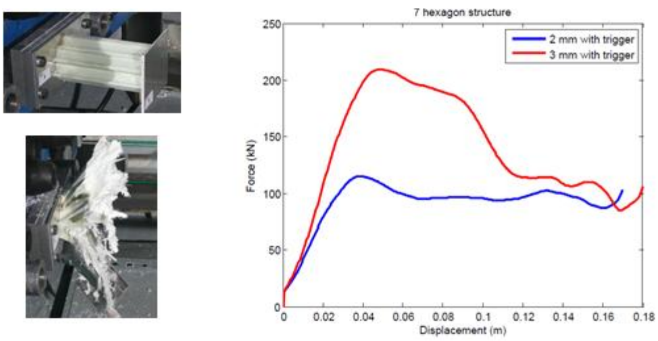


Figure 11: Composite impact structure before and after impact and obtained Force-Displacement curves

The following crashworthiness characteristics were measured and listed in Table 3:

- Peak load ➔ F_{peak}: maximum force of the first peak.
- Mean load ➔ F_{mean}: average load of the collapse, calculated with equation 1.

$$P_{mean} = \frac{\int_0^{l_{mean}} P(l)dl}{L_{max}} \quad (1)$$

- Specific energy absorption ➔ SEA: absorbed energy per unit of crushed specimen mass, equation 2.

$$SEA = \frac{\int_0^{l_{max}} P(l)dl}{m_t} \quad (2)$$

Table 3. Results of the impact tests at 30 km/h

	Fpeak (kN)	Fmean (kN)	SEA (kJ/kg)
2 mm with trigger	115,2	92,9	36,7
3 mm with trigger	209,4	125,6	36,6

Reparability

As a part of the design of the new vehicle structure a complete analysis regarding its damageability and reparability in order to guarantee a good performance was carried out. Development of new vehicle structures without the constraints derived from the internal combustion engine allowed defining optimum features. Then, different modules of the concept were analyzed to provide project with information related to the optimum damageability and reparability features. The analysis included different damageability/reparability tests.

Chassis

Given the weight restrictions, while maintaining the requirements of crashworthiness and safety of passengers, mainly two options were finally proposed. The first, a chassis completely made of aluminum beams (square profile) with inner reinforcements. The second one, a similar structure but, instead of aluminum, composites in the chassis legs were introduced.

The analysis showed that it is very difficult to repair any of the options that were considered, given the complexities that represent their reshaped. Therefore, only replacement for the damaged parts is possible so joints play an important role in the cost of repairing the damage. During the design phase it will be necessary to take into account different options in order to reduce the time spent on repair operations, making joints and access as simple as possible.

Cab structure

Once again weight constraints make that the use of aluminum beams cannot be excluded for the construction of the cabin structure, but always ensuring the safety of the occupants through a good sizing of the bars.

In any case, a good design for the joint between the cabin and the rest of vehicle will be essential, ensuring that it can be done as simple as possible, to enable their full and quick replacement if necessary.

Cab panels and add-ons

After analyzing damageability and reparability of different materials, a series of recommendations regarding the materials to be used in the cab panels and add-ons in the concept OPTIBODY, were given.

First, two types of materials were recommended for use both in the body panels and in the add-ons: plastics and composite materials (simple or sandwich panels).

Given the structural behavior, the following areas were distinguished:

- Parts with important structural functionality: Add-ons in protection zone, cab roof and floor.
- Parts with no important structural functionality: Add-ons in no-protection zone, non-structural panels of the cab.

For parts with a structural function, according to damageability and reparability criteria, the use of composite materials as PVC sandwich panels and non-flexible thermoplastics were considered as a good option, depending on the part to be applied.

For parts without structural function, the use of plastic materials with more elasticity (type PP) was considered a good alternative.

Conclusions

The OPTIBODY has been defined as a new modular structural concept for Electric Light Trucks and Vans (ELTVs) composed of a chassis (the key structural supporting element), a cabin and a number of specific add-ons, which will bring specific self and partner protection in case of front, rear, side impacts and rollover.

The L7e vehicle category was identified as the most convenient vehicle category to design the OPTIBODY vehicle. This vehicle category has an enormous lack of safety since in Europe and North America (Low Speed Vehicles) no crash test is mandatory to homologate this type of vehicle. In the US the maximum speed of the vehicle is limited while in the other geographical areas no restriction on speed is established. In Europe, the only passive safety requirement is the seat belt in all seated positions and the testing of the seat belt anchorages. This vehicle category also provides freedom to the engineers to innovate in the design since the homologation requirements are not excessively restrictive.

An initial accident analysis was carried out to identify the most common accident scenarios involving this category of vehicle. Despite the lack of harmonization when the different databases are considered, the frontal-side impact (frontal with offset) and rear impact are by far the most frequent types of accidents. However, frontal impact and pedestrian accidents are much more severe causing more casualties and injuries than the other types of prevailing accidents. **S**pecial effort needs to be done to reduce the number of pedestrian fatalities since the OPTIBODY vehicle will be mostly circulating in urban areas.

The main frame of the vehicle was design in aluminum and the frame was divided in two separated parts to enhance the modularity of the vehicle since it is possible to change the rear part of the vehicle (design for goods transportation) while keeping the same cabin and frontal protection structure.

Two different parts of the vehicle have been designed using composites: the frontal add-on and the frontal crash boxes. The frontal add-on is focused in pedestrian protection while the crash boxes improve safety performance optimizing the energy absorption. In both cases the composites seems to be a very good replacement of classic materials used in vehicle manufacturing such as steel and aluminum.

OPTIBODY is being defined as a new modular structure concept to take benefit of the singularities of electric vehicles to fully design a new ELTV focused in the improvement of self and partner protection, reparability and modularity.

References

1. Transport Safety Council, CARE: Community Road Accident Database http://ec.europa.eu/transport/road_safety/specialist/statistics/care_reports_graphics/index_en.html
2. International Transport Safety Data & Analysis Group. Annual report 2010. www.irtad.net/
3. *International Road Federation Global Database 2009, "World Road statistics 2002-2007" Geneva*
4. NHTSA. Traffic Safety Facts 2007: a compilation of motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System
5. The Aggressivity of Light Trucks and Vans in Traffic Crashes, Hampton C. Gabler and William T. Hollowell, SAE International, 1998. Paper: 980908
6. Gabler, H.C., Fitzharris, M., Scully, J., Fildes, B.N., Digges, K. and Sparke, L., "Far Side Impact Injury Risk for Belted Occupants in Australia and the United States", Proceedings of the Nineteenth International Conference on Enhanced Safety of Vehicles, Paper No. 05-0420, Washington, DC. 2005
7. Scarboro, M., Rudd, R., Sochor, M., "Near-Side Occupants in Low Delta-V Side -Impact Crashes: Analysis of Injury and Vehicle Damage Patterns". Enhanced Safety Vehicles 07-0225. Lyon, France: National Highway Traffic Safety Administration; 2007.
8. IATSS, Road Accidents Statistics, Japan 2007Contact Information

Acknowledgments

The authors would like to acknowledge the European Commission that co-funded this project through the FP7 program. The authors wish to acknowledge the Partners of the OPTIBODY consortium for their contributions.

The OPTIBODY consortium comprises: University of Zaragoza, Politecnico di Torino, PIMOT, IDIADA Automotive Technology, Centro Zaragoza, AMZ, Italdesign - Giugiaro, BELLA, SSAB and Mondragón Automoción.