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Improvement of crash behavior in a light urban electric vehicle

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Abstract

Urban-EV applies innovative manufacturing technologies and materials to produce a 2-seat urban electric vehicle with enhanced range: 150km. Attending to weight and power targets, the vehicle is classified as L7e, heavy quadricycle. The aim of the project is to design and test urban electric vehicles with crash behavior similar to conventional vehicles. The crash configurations considered for the design include both the ones in the Regulation and also the ones done by Euro NCAP. For achieving this target new materials and processes and also innovative joining processes have been optimized. The result is a very light multi-material structure that includes innovative solutions for energy absorption based on the use of low cost structural thermoplastic components. The paper includes the description of the structure optimization process and also of the restrain system that presents specific characteristics to be adapted to this kind of vehicles.

Keywords: crashworthiness, lightweight, restrain system, crash test, electric vehicle.

1. Introduction

The work described in this paper has been developed in the frame of the Urban-EV project. Urban-EV is a European Project from the Seventh Framework Programme funded by the European Commission [1].
In 2008, 50% of the World population lived in urban areas [2]; this trend is expected to continue growing to 70% in 2050 [3]. Air quality is becoming a health problem in many cities around the world and in Europe [4], so the traffic in several city centres is suffering restrictions in order to mitigate the pollution problems.
The use of small size electric vehicles together with the development of new mobility services are the most sustainable solution for the city. But small vehicles have the limitation that they are seen as unsafe vehicles by most of the users. Conscious of this problem, Urban-EV consortium has worked in several projects to enhance the crash behaviour of several urban vehicles of L7 category (quadricycles). At the same time important efforts have been done to reduce the vehicle mass in order to fulfill the weight restrictions of this category [5].
This paper shows the design evolution to fulfill the frontal and lateral crash tests required for conventional vehicles (M1 category) [6, 7]: the ones included in the regulation and the ones made by Euro NCAP [8].
Although Urban-EV can be categorized as L7 vehicle, the target fixed regarding crashworthiness has been ambitious and the crash tests simulated and experimentally performed have been the ones included in the European Regulation and the crash test included in the Euro NCAP protocol for M1 category.
The considered tests can be classified in two main classes. The frontal ones consist of

- Regulation 94: 50kph frontal crash against a deformable barrier with 40% overlap,
- Euro NCAP M1 full width: 50kph frontal crash against a rigid wall all the width of the vehicle,
- Euro NCAP M1 overlap: 64kph frontal crash against a deformable barrier with 40% overlap and
- Euro NCAP L7 full width: 50kph frontal crash against a deformable barrier all the width of the vehicle.

while at the lateral ones only two:

- Regulation 95: the vehicle is crashed perpendicularly by another vehicle, 950kg weight, with a deformable barrier in the front and
- Euro NCAP M1: the vehicle is crashed perpendicularly by another vehicle, 1300kg weight, with a deformable barrier in the front

are relevant for the investigations.

2. Starting point

The origin of Urban-EV is Casple-EV. It is an electric vehicle designed by the Spanish company Casple allocated in Burgos. The first step was to evaluate the stiffness of the original structure under torsional and bending loads and also its crashworthiness in several crash configurations.
Some of the results obtained can be seen in figure 1, which showed poor deformation behaviour. The deformation of the frontal form was very high and the structure was not able of absorbing an acceptable amount of energy. The intrusion of the A-pillar base was very high and the acceleration results absolutely inadmissible.

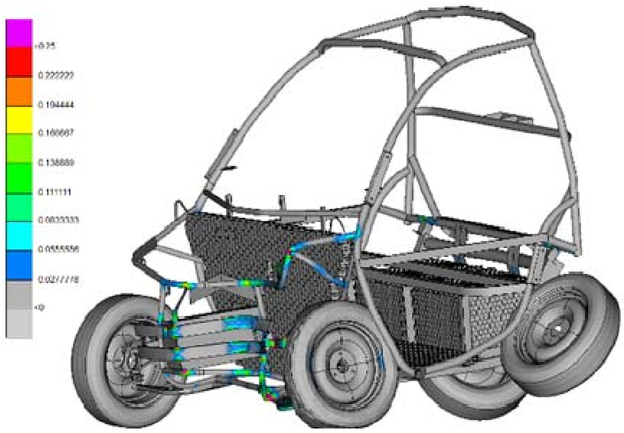

Fig. 1 Deformation of Casple-EV structure in the frontal crash under Euro NCAP M1 protocol

For this reason, it was decided to introduce a completely new subframe that integrated an innovative absorption system. At the same time the subframe incorporates a very stiff region under the seats of the vehicle, where the batteries are allocated. The subframe has been designed in such a way that the batteries do not suffer any deformation in any of the crash tests considered. The energy absorption system is based on a rigid box sized for allocating the rigid components of the power train in the event of a frontal crash. In this way it is avoided the intrusion of harmful elements in the passengers' cabin. In the frontal part of this rigid box four different energy absorbers are combined, two of them made of aluminum and the other two made of low cost structural thermoplastic. The inclusion of structural thermoplastic is an innovative solution that has demonstrated to be very effective thanks to the high ratio of energy absorbed to mass of this kind of materials. For achieving a good behavior, the work made to design the right geometry and assembly of these energy absorbers has been fundamental. The aluminum absorbers aim is to stabilize the behavior of the system during the crash event.

3. Structure optimisation

Before starting the definition of the optimization phase it is important to notice that Urban-EV presents several particularities related to the vehicle structure:

- The solution of the structure implies the use of different materials and different processes for each of the material:
  - Aluminum:
    - Rolled: For the floor of the vehicle, the battery chasing and the fire wall
    - Extruded: for the tubes of the main structure
    - Casted: for the rear control arms with a specific counter gravitatory process and for the roof nodes with low pressure die casting.
  - Magnesium:
    - Extruded: for the roof profiles
    - Casted: for the A nodes
  - Structural plastic:
    - Low cost structural thermoplastic for the frontal energy absorbing system.
    - Thermo set for the door structure and the vehicle exterior panels.
- This multi-material solution using magnesium and aluminum together in the same structure rises the need applying an innovative joining processes to put . The solution has been the use of electromagnetic forces to make mechanical joints between the parts, avoiding the heat input and the loss of mechanical properties in the heat affected zone.
- The vehicle is foldable to reduce the use of urban space during the periods that it is not used.

The distribution of the different materials and processes finally selected for Urban-EV are summarized in figure 2.

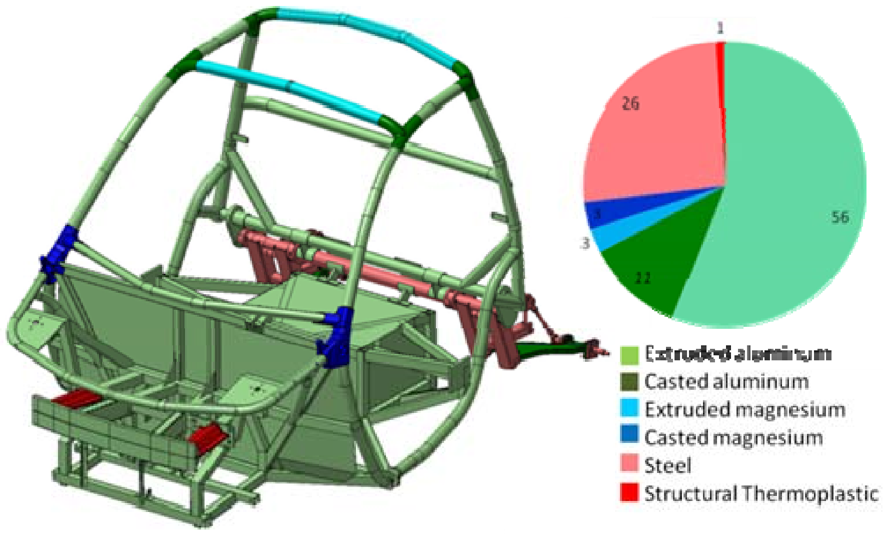

Fig. 2 Material distribution in the Urban-EV structure

During the structure optimization phase the work has been focus only on the vehicle structure. Different redesign cycles have been made considering at the same time the stiffness of the structure and the behaviour of the structure in all the crash configurations enumerated at the beginning of the paper. For doing it, two kind of targets have been fixed, the average acceleration of the structure has to be lower than 50g and the intrusion in different points of the cabin has to fulfill the same criteria than the conventional internal combustion engine vehicles. To obtain the average value of the acceleration six points are considered in the floor of the structure indicated in figure 3. The eight different points measuring the intrusion and the threshold values are shown in figure 4.

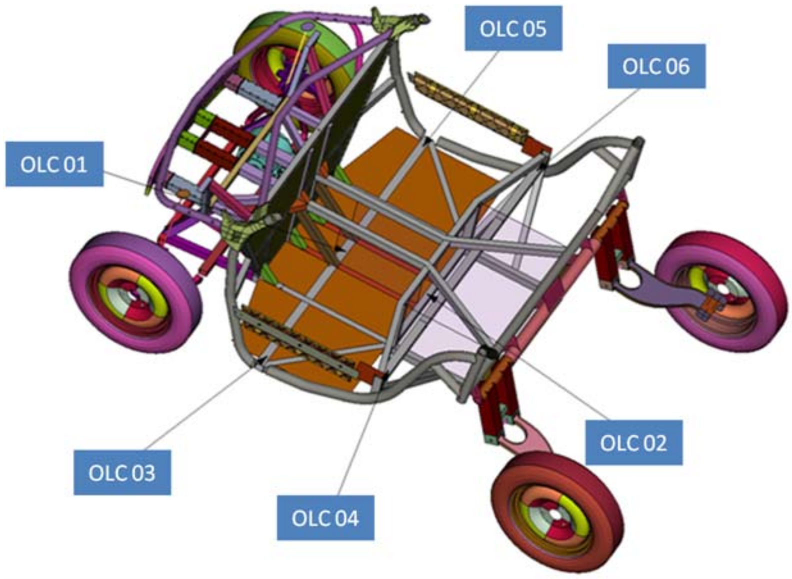

Fig. 3 Position in the vehicle structure of the six points used for measuring the average acceleration

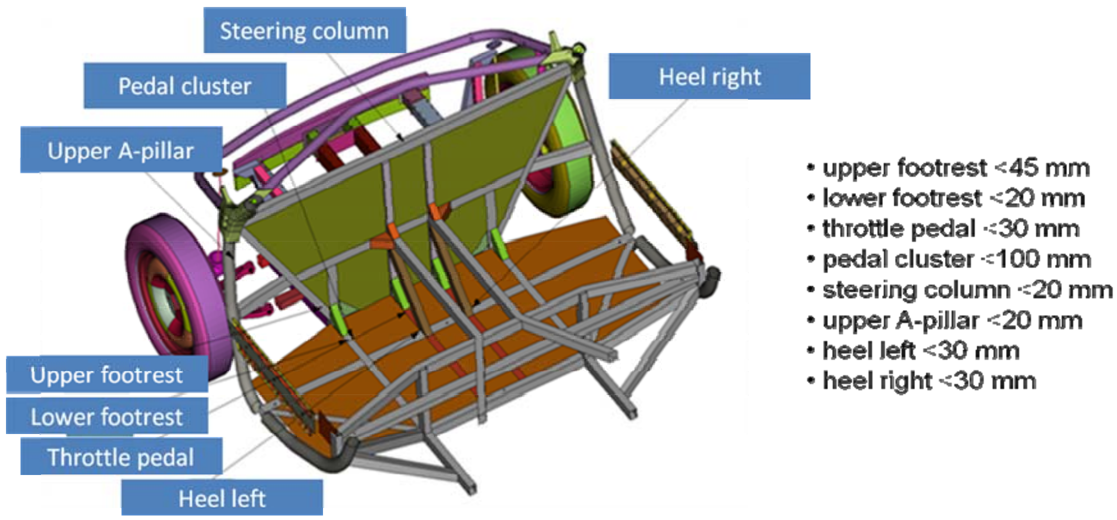

Fig. 4 Position of the eight points where the intrusion is evaluated and threshold values for acceptance of each of them

Figure 5 shows the intrusion in the passenger's cabin during the optimization process for the Euro NCAP M1 protocol test against a rigid wall at 50 kph.

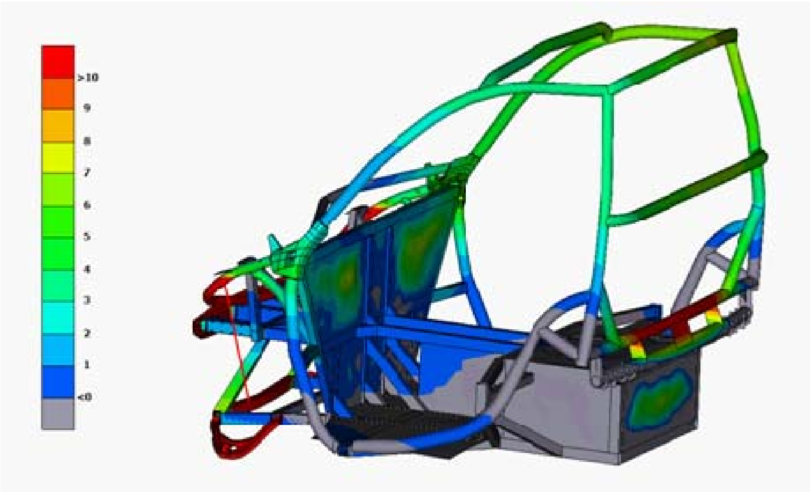

Fig. 5 Intrusion of the structure in the passengers' cabin during one frontal crash attending to Euro NCAP M1 protocol

It is important to notice that there is a difficult trade-off relationship between the acceleration and the intrusion behaviour. A stiff structure would reduce the intrusion in the cabin at the price of very high acceleration values in the other hand a softer structure would obtain low accelerations but at the cost of very high intrusions. For this reason, the optimization phase has been very important and it has allowed to design the structure in such a way that the front end of the vehicle absorbs the higher amount of energy possible and at the same time the energy not absorbed in the front is adequately addressed through the different tubes of the structure in order to minimize both the acceleration and the intrusion.
The structure optimization process has been considered as ended in the moment that the intrusion and acceleration targets have been fulfilled at the same time. The next step in the vehicle design has been to introduce all the bulky elements in the vehicle and all the components with some influence in the crash behaviour. This work has been made during the phase named as "Improvements in the design".

4. Improvements in the design

The first step has been the introduction of the high volume power train elements. As it has been explained before the subframe has been designed to serve as a safety box for the rechargeable energy storage system of the vehicle. The 44 battery modules, the battery management system and the chargers have been included in the model. The relative position in the vehicle is shown in figure 6.

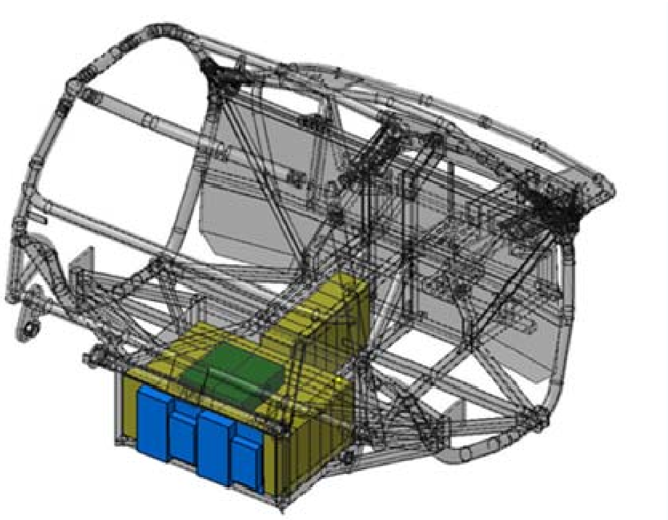

Fig. 6 Batteries, battery management system and chargers assembled in the subframe

Next elements to be introduced have been the ones under the hood: electric motor, reduction-differential and inverter have been allocated taking into account the space needed for the suspension and steering components and for their movement in any driving condition. In parallel, the position of the steering components has been calculated through multi-body analysis in order to ensure that the Ackermann relationship was fulfilled. The relative position of electric motor in pink, reduction-differential in blue, inverter in green and refrigeration system in brown are shown in figure 7.

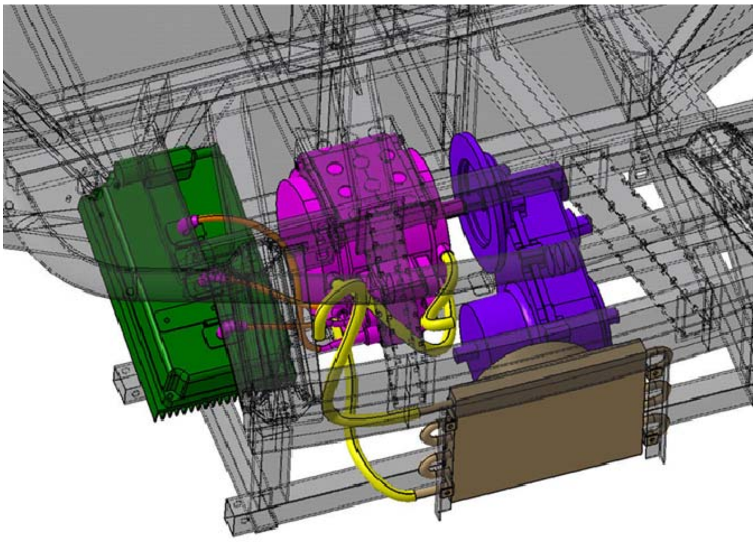

Fig. 7 Allocation of the electric motor, the reduction-differential, the inverter and the refrigeration system under the hood of Urban-EV

In parallel the rest of the components of the chassis have been positioned to warranty the right transmission of the motor power to the front wheels and to avoid any kind of interference. The elements responsible of transmitting the torque front the differential to the wheels, the suspension elements, the steering components and the brakes have been allocated as shown in figure 8. It is important to notice that the iteration cycles to optimize the crashworthiness of the vehicle have been very relevant for choosing the right packaging of all the elements under the hood.

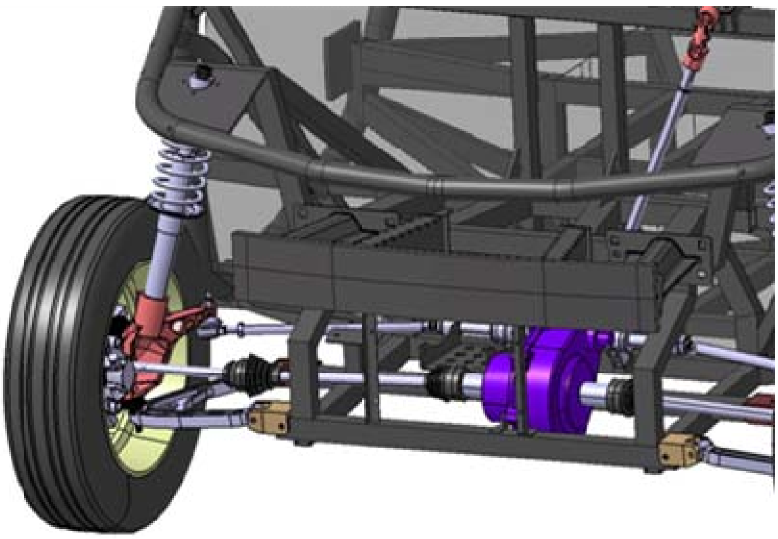

Fig. 8 Allocation of the transmission, suspension, steering and braking system under the hood of Urban-EV

Next steps in the improvement of the design have been the decision on the allocation of other important elements for the passive safety of the vehicle; mainly the fixing points of the seats and seat belts, the relative position of the steering wheel and other aspects related to ergonomics that are out of the scope of this paper. The final vehicle structure that includes all the components with responsibility in passive safety can be seen at figure 9.

Fig. 9 Urban-EV design with all the relevant elements for passive safety inside ready to be modeled for crash simulation

5. Crash simulation of the final model

All the vehicle characteristics have been introduced in the finite element model to accurately reproduce the behavior of the structure in the different crash configurations. The results shown in figure 10 correspond to different evolutions of the design when the vehicle suffers a frontal crash at 64kph against a deformable barrier attending to Euro NCAP protocol for M1 vehicles.

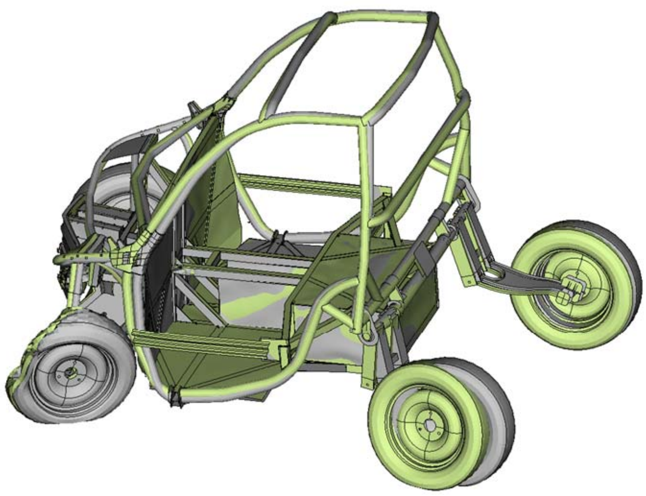

Fig. 10 Crash simulation of the Euro NCAP frontal crash test attending to protocol for M1 at 64kph. The yellow structure is the final solution and the grey one is the starting point for the last loop

The main criterion for obtaining the final design has been to find the best balance between the acceleration pulse suffered by the structure and the intrusion in the passengers' cabin. These parameters have been evaluated at the same time for three different configurations of frontal crashes and two different configurations of lateral ones. In this stage of the project the design of the lateral reinforcement bar and the detailed design of the energy absorbers have been of great importance.

The final results for intrusion and acceleration are shown in following figures to explain the main results reached. Figure 11 shows the value of the intrusion in the firewall of the vehicle. The maximum value in the scale corresponds to 40 mm, red coloured.

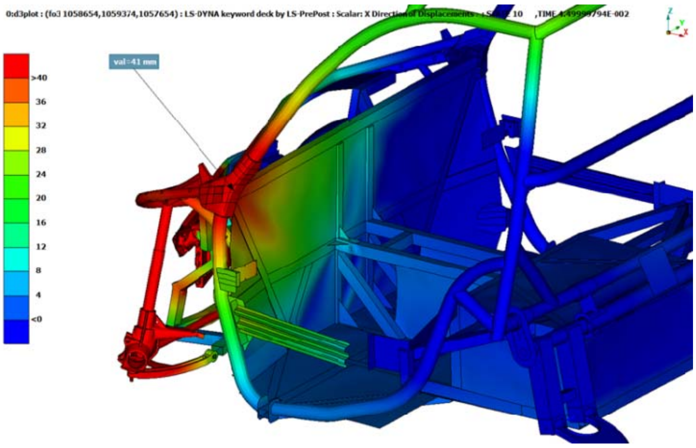

Fig. 11 Displacement in the moment of maximum intrusion

The evolution of the intrusion in the eight points indicated at the beginning of the paper is shown in figure 12. The threshold value is indicated with a dotted line to make possible the quick analysis of the results reached. It is important to notice that six out of eight measuring points fulfill the requirements with a high margin, one of them is very close to the limit, and the one related to the fixing point of the steering wheel to the fire wall has over passed the threshold value. The different optimization cycles have demonstrated that it was not possible to reduce this value without compromising the acceleration results. Finally it has been decided to correct the influence of this intrusion by the design of the restrain systems that is explained in the following part of the paper.

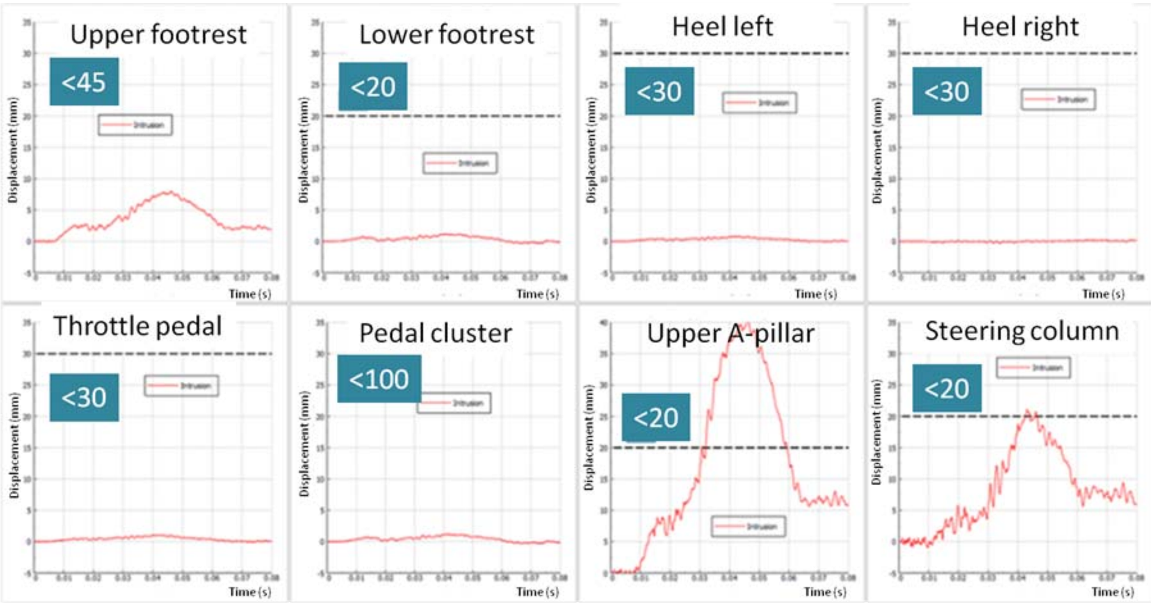

Fig. 12 Intrusion evolution in the eight considered points

Finally, figure 13 shows the evolution of the acceleration during the most critical of the crashes, the one under Euro NCAP protocol for M1 vehicles at 64 kph against a deformable barrier with a 40% overlap. To give an idea the acceleration values of the three last models considered during the optimization in order to show that the improvement capability was very close to the maximum. The 50g value is highlighted with a green dotted line in order to facilitate the reading of the figure.

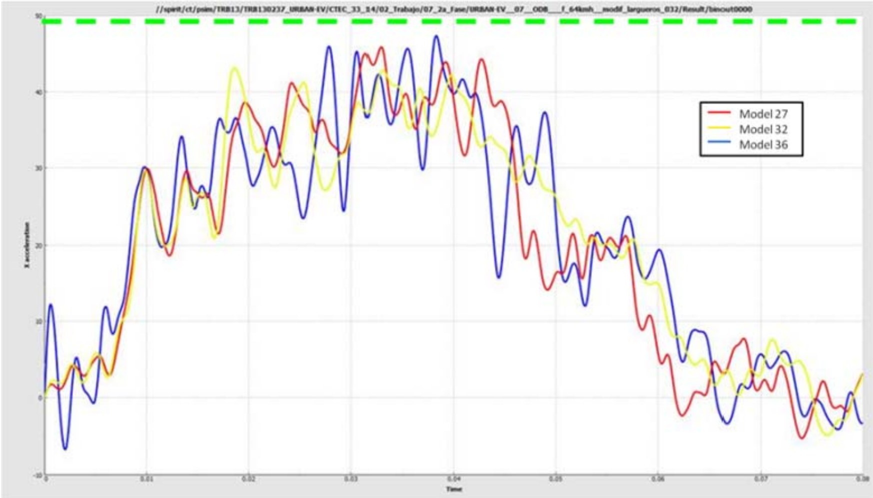

Fig. 13 Acceleration evolution for M1 Euro NCAP test in the three final models considered

6. Restrain system optimisation

Once the design has reached the most balance situation between intrusions and acceleration the design of the restrain system is tackled. In this kind of vehicles, and due to the small space available of energy absorption, the role of the restrain system is more important than in conventional vehicles.

At frontal crash simulation the deceleration pulse suffered by the occupants of the vehicle is obtained. This deceleration pulse is used for the design and optimization of the restraint systems of the vehicle, mainly airbag, seat belt, pretensioners, D-ring position, steering wheel position and inclination. The sequence of the simulation for restrain system optimization is shown in figure 14.

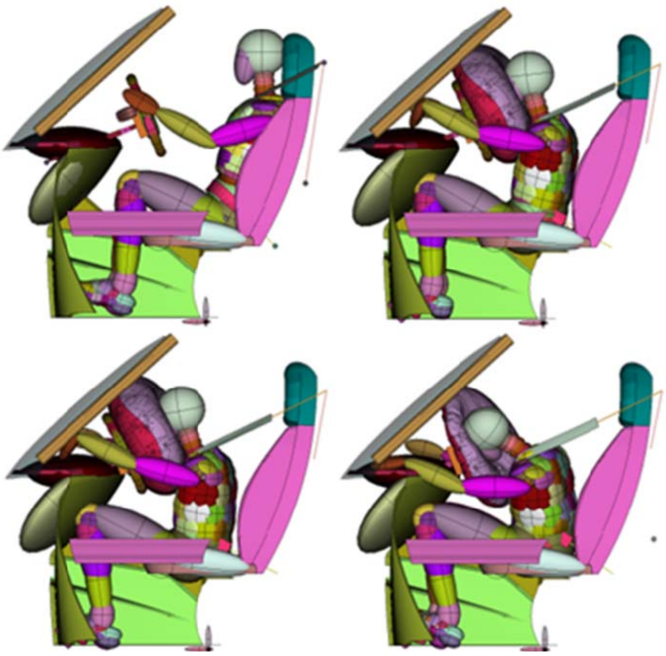

Fig. 14 Sequence of the simulation for the restrain system optimization

The main result of this kind of simulation is the evaluation of the damage suffered by the occupants of the vehicle that is the most important parameter to establish the number of star attending to Euro NCAP protocol. The results obtained after the optimization process for Urban-EV are shown in figure 15.

Driver Summary

Body Region	Rating
Head and Neck Assessment	2.62
Chest Assessment	1.67
Knee and Femur Assessment	3.00
Lower Leg assessment	0.00
Driver Frontal	7.29

Fig. 15 Summary of the driver damage after the restrain system optimization

The results shown in figure 15 correspond to the Euro NCAP protocol for M1 vehicles. There are two conclusions that can be highlighted, the results are equivalent to some conventional vehicles tested by Euro NCAP under the same protocol; and most important, the driver protection is clearly better than the one obtained by Euro NCAP for the 8 vehicles tested by now under the Euro NCAP protocol for L7 category vehicles. It has to be noted that the severity of the impact is more critical in the test considered in Urban-EV project than the one applied on the other L7e vehicles.

Urban-EV is an ongoing project, the final scope of the project is the manufacturing of three prototypes: one of them functional, another for frontal crash and the last one for lateral crash. In the moment of writing this paper the first prototype is in the state of assembly and crash tests are planned for February 2018.

7. Conclusions

The development of the present work has allowed establishing some important conclusions about the crash behavior of the urban electric vehicle developed within this project.

- The space available for energy absorption is limited.
- The cinematic of the vehicle during the crash is different to the M1 vehicles. In these small size-lightweight vehicles, the tendency of the vehicle to turn around the vertical axle is very much higher than in the standard vehicles.
- Also due to the lower weight of the vehicle, the vertical movement of the vehicle is higher than the one for the standard M1 vehicles.
- The restrain system has, proportionally, higher responsibility than in the case of M1 vehicles.
- The targets fixed for standard vehicles are very difficult to achieve and they may be not the right ones for lightweight vehicles.

In any case, after the whole optimization cycle, the occupant protection in a EuroNcap test, 64kph, 40% offset against a deformable barrier, is in the same level of some M1 vehicles tested in 2014 and 2015.

The direct comparison with other L7e vehicles is not possible because these vehicles have only been tested at 50kph full width against a deformable barrier, which is notably less restrictive. In any case, if the occupant protection is compared directly, the result obtained in Urban-EV is similar to the best L7e (Renault Twizy) and better than the rest.

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