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Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

Electric urban light vehicles structural integrity and occupant protection validation through experimental crash tests

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Abstract

Urban mobility decarbonisation requires new mobility solutions. Multi-Moby project, funded under H2020 nº 101006953, aims at developing technology for safe, efficient and affordable urban electric vehicles. The project covers aspects related to structure, safety, power train, vehicle dynamics, innovative battery and charging solutions, advanced electric electronic architecture and implementation of autonomous capabilities. The objective of the paper is to show the results achieved in relation to structural integrity and occupant protection in the first year of the project. In a first stage simulation tools have been used to optimise the vehicle structure crashworthiness at different crash configuration based on smart use of High Strength Steels focused to simplified and affordable manufacturing processes. Once the structural behaviour met requirements and expectations, the restraint system has been developed. After design optimisation, three vehicles have been prototyped to perform three crash tests, two of them frontal, corresponding to Regulation 137 and Regulation 94, and one lateral, corresponding to Regularion95.

Keywords: Urban light electric vehicles; structural safety; occupant protection; energy efficiency; affordability; homologation;

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Peer-review under responsibility of the scientific committee of the Transport Research Arena (TRA) Conference

1. Introduction

A few years ago, the European Commission (2011) was already drawing attention to the need for cleaner, smaller and lighter road passenger vehicles in order to achieve sustainable urban transport. Despite this, according to recent authors such as Gössling (2020), it is estimated that close to 40% of all cars in the world are Sport Utility Vehicles (SUVs). The smaller size of the required solutions and the need to offer affordable products make it very difficult for small vehicles to compete with larger M1 and N1 vehicles in terms of safety levels. Hence, their low market penetration.

In this line, the Multi-Moby project is a good example that this can be changed. By using the suitable material and optimising the structural design, the project demonstrates that safe and clean urban vehicles can be manufactured. Moreover, the focus is not only on the safety of occupants, but also on the safety of vulnerable road users. Here, Multi-Moby consortium is implementing several solutions, including the integration of two dual-band miniature gimbals which detect vulnerable road users and an AI based computational suite whose output drives both the steering and the braking systems. However, it is the structural design part that occupies the major part of the project.

This paper provides an overview of the steps taken to achieve the final vehicle structure and its validation.

2. Light and modular urban EV concept

Related to the above, the Multi-Moby vehicle concept relies on a vehicle architecture fully made of high-strength steel, characterized by best-in-class safety (for occupants and pedestrians) and cost-effectiveness, hence. The vehicle structure is based on an optimized tubular chassis, easily scalable and modular, in such a way that the dimensions and the purpose of the vehicle itself (passenger/cargo) can be shifted by only modifying a reduced number of elements of the chassis, as shown in Figure 1. With only 850 kg (passengers included), its dimensions fit into the categories L7, M1/N1 or Kei-car (Japan), therefore being ideal for urban mobility purposes. All these features are provided without the enormous investments needed to develop vehicles following conventional approaches. Outstanding safety performance is guaranteed thanks to a design methodology in which crashworthiness is the cornerstone of the vehicle design.

Fig. 1. Modular vehicle concept: very different vehicle architectures can be manufactured with minimal changes in the vehicle structure

In addition to the aforementioned features, the vehicle counts with high ergonomics, small environmental footprint compared to its competitors, high connectivity and interactivity and over-the-air software updates with the highest level of information security. Sustainability and energy efficiency are maximized thanks to the integration of high-efficiency solar panels.

3. Overview of standards

In sight of the peculiarities of the Multi-Moby vehicle, today the general consensus in the automotive world is that larger vehicles are safer than their smaller counterparts. After all, light urban vehicles have historically been characterized for a poor crash response. That lack of safety is primarily due to the lower demands of European Regulations (UE 168/2013) on the homologation of light vehicle impact safety requirements compared to larger M1 and N1 vehicles. However, with the trend towards smaller vehicles, this is changing.

The evidence is that Euro NCAP, a promoter of tests to evaluate the safety of different categories of vehicles, has already included a specific protocol to evaluate safety on quadricycles (L7 vehicles). The protocol, launched in 2014, includes two test configurations, frontal and lateral. The evaluation of both test configurations ranges vehicles from 0 to 16 according to its safety performance. In 2014, Euro NCAP tested four L7 vehicles available in the market, with quite poor scores: 2, 2, 4, and 6 respectively. In 2016, a new campaign was launched with similar results, the obtained scores were 2, 4, 4, and 6.

Aware of the results obtained by the commercial light urban vehicles in Euro NCAP tests, the vehicle developed in the context of the Multi-Moby project has been specifically designed to improve the average results achieved by the representatives of segment A and B M1 vehicles, which are the usual urban models in the cities. Multi-Moby's vehicle performance is not only better than that of L7 vehicles, but also better than that of some popular M1 vehicle models on the market. The preliminary analysis made has shown that there are models from segment A and B in the market with 0, 1, and 2 stars, while Multi-Moby is running in the good direction to get the four stars fixed as a target in the project.

The proofs are the results achieved by the developed vehicle in the crash tests attending to Regulations 137, 94 and 95, which are specific tests for the homologation of cars of category M1 and N1.

4. Structural design

In Multi-Moby project, the safest design of the vehicle structure has been achieved thanks to a methodology based on an intensive use of Finite Element Analysis (FEA) simulations together with redesign steps until ensuring that the stiffness, the durability and the crashworthiness performance meet the Key Performance Indicators (KPI) set, concretely 5.000 N/mm for bending stiffness, 40.000Nm/º for torsional stiffness, 200.000 km of hard use for fatigue and keeping structural integrity while complying with all biomechanical requirements of the Regulations for crash tests. All these objectives must be accomplished without being detrimental to the functionality, manufacturability or end-of-life management of the vehicle.

Each development loop relies strongly on the use of FEA simulations. Firstly, structural stiffness and durability are targeted so as to guarantee the expected performance of active safety systems such as suspension, steering and brakes. After that, a first proposal for the occupant protection system is made, considering restraint systems, airbags and design of the steering column. Once everything is defined and validated independently, the next step consists on analysing crashworthiness for ensuring that there is a part of the structure able to absorb impact energy and other part which protects occupants by being non-deformable (safety cells), following the guidelines of the most recent UNECE regulations and Euro NCAP protocols. Finally, when an adequate behaviour of the structure is obtained via simulation, real tests are performed, where crashworthiness performance is checked, further improvement routes are identified and data are generated so as to refine the correlation of the simulation model, closing the loop.

4.1. Bending and torsional stiffness

In order to ensure the correct performance of active safety systems (suspension, steering and braking systems), designing a sufficiently stiff structure is of vital importance. In this project, bending and torsional stiffness of the vehicle structure were evaluated.

Bending stiffness characterizes the robustness of the chassis, especially when it is subjected to vertical loads caused by the weight carried, braking and accelerating manoeuvres or potholes. As a worst-case scenario, the tests were performed without the suspension system, hence maximizing loads on the chassis. The loads were introduced through a tooling device connecting an actuator to a beam located in the vertical of the center of gravity of the structure.

Simulations and real experiments were performed for vertical loads of 25 kN and 15 kN respectively, obtaining in both cases a highly linear behaviour with maximum stress values around 400 MPa, far below the yield strength of the HSS used in the structure. The results are shown in Figure 2.

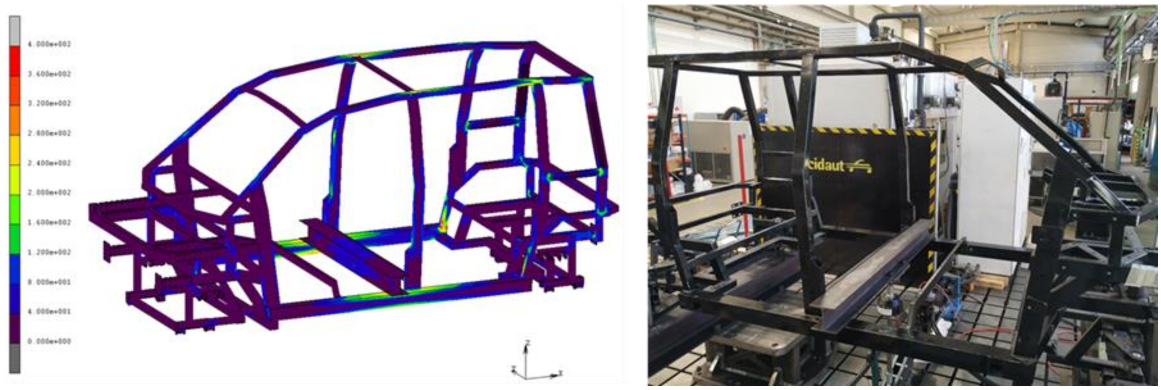

Fig. 2. Left: Equivalent von Mises stress (MPa) after bending test simulation. Right: Front part of the vehicle chassis during bending test.

Torsional stiffness is also employed to characterize the robustness of the chassis, as it is needed to ensure the appropriate behaviour of the vehicle in transversal manoeuvres like turning or braking in turn. In this case the vehicle structure must support the forces coming from the wheels through the suspension and steering systems with a limited deformation to ensure the wheels maintain the contact with the road in a position as close to the vertical as possible. Hence, the measurement of the torsional stiffness was performed without the suspension system of the vehicle, to test exclusively the performance of the structure.

Simulations and real experiments were performed for rotation angles of 2º and 1,5º respectively, obtaining a good correlation with maximum deviations of 7% between them, and a maximum stress of 350 MPa, which guarantees that no yield will take place in real driving scenarios. Simulation and experimental results are depicted in Figure 3.

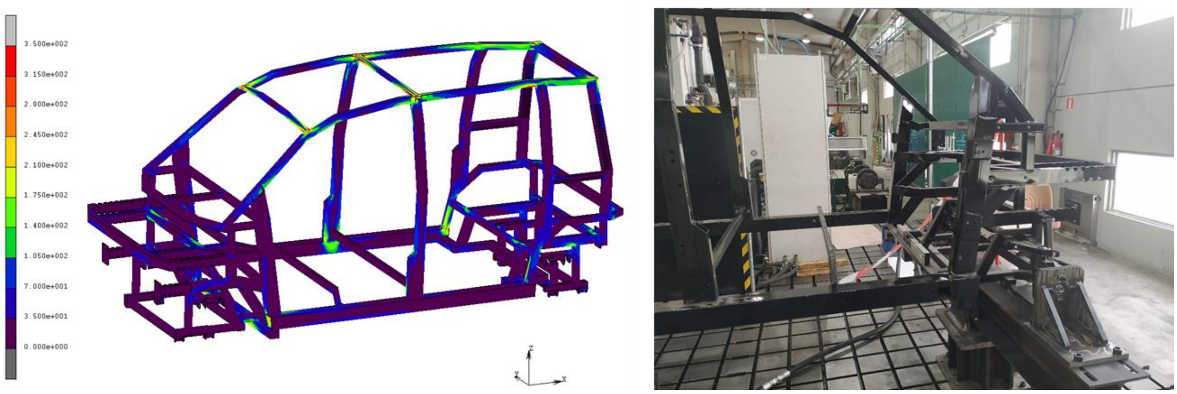

Fig. 3. Left: Equivalent von Mises stress (MPa) after torsion test simulation. Right: Front part of the vehicle chassis during torsion test.

Finally, a combination of bending and torsional loads was simulated by applying a vertical load of 25 kN and a 2º rotation of the front part of the vehicle, following the same approach used in the individual simulations. Even in this more demanding load case strain values do not reach the plastic region of the material where breakage may occur.

4.2. Fatigue behaviour

Fatigue analysis was performed to ensure the durability and performance of the vehicle throughout its life. Fatigue testing of the structure was performed taking into account daily driving manoeuvres. Representative loads were defined thanks to the development of a multibody vehicle model matching the characteristics of the Multi-Moby vehicle in terms of weight, centre of gravity, suspension, steering and braking. Using this model, different conventional manoeuvres (acceleration, braking in curve, speed bumper, moose test) were simulated to understand the dynamics of the vehicle and obtain data to calculate the loads transmitted through the wheels in the manoeuvres. All manoeuvres considered were simulated at three incremental intensity levels, according to different driver profiles.

Fatigue simulations are intended to analyse the less durable areas of the structure, where failure will likely start in real driving conditions, therefore strains reached will be lower than in the previous stiffness simulations, where conditions were critical. Fatigue test setup requires specific tooling considering vehicle dimensions and constraints. For this reason, the suspension system of the vehicle, including spring and shock absorber, was included. Furthermore, for a more realistic movement of the vehicle, frontal wheels supported by two pillars were included in the structure to restrict lateral movements.

In the simulation of the fatigue behaviour, a vehicle weight of 850 kg was considered. This value encompasses the real weight of the vehicle when in circulation, and includes elements such as batteries, powertrain and passengers. The simulation results show that maximum stress reached is under 50 MPa, which ensures the durability of the structure. The most stressed areas of the structure were also identified (profile joints at the bottom of C and B pillars) and analysed in further detail through sub-modelling techniques. In both cases maximum stress values are lower than 200 MPa, which is considered the threshold for infinite life of the profiles.

Experimental fatigue tests were performed for 1.000.000 cycles, equivalent to 250.000 km, distributed in three types of loads: everyday (800.000 cycles), sportive (190.000 cycles) and aggressive (10.000 cycles) manoeuvres. The structure underwent the whole fatigue testing program without visible damage. The only incident recorded was the breakage of one of the welds of the left frontal knuckle around cycle 750.000 under "aggressive manoeuvres" conditions. In any case, this component was out of the scope of the structure analysis, so it was repaired and the test resumed successfully. After the end of the test, an inspection of the structure was performed by applying penetrant liquids in order to detect possible cracks. No cracks were detected, and only some pores associated to the manufacturing process of the tubes were identified. A summary of fatigue characterization is shown in Figure 4.

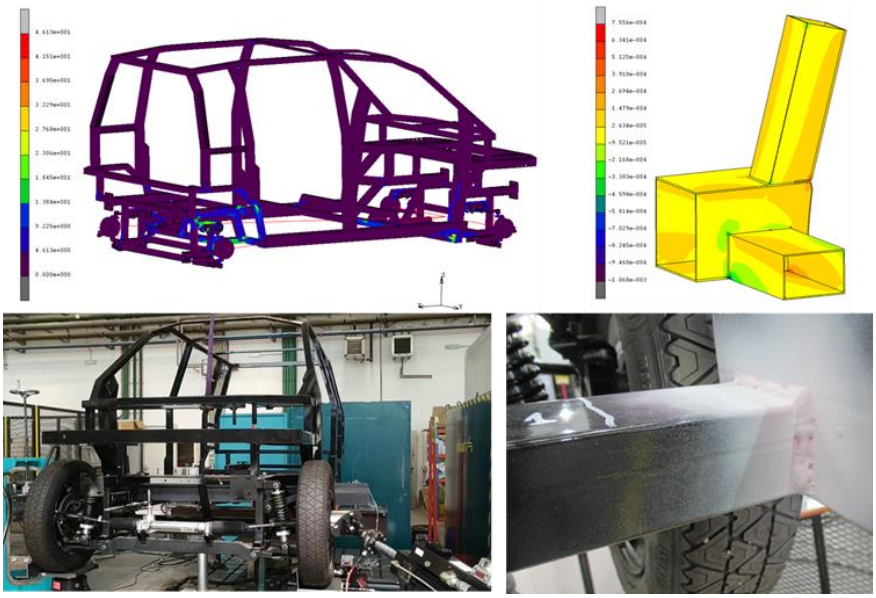

Fig. 4. Fatigue test results. Top left: equivalent von Mises stress results (MPa) during fatigue test simulation. Top right: strain distribution on a critical node. Bottom left: front part of the vehicle during fatigue experiments. Bottom right: penetrant liquids test on a critical node.

4.3. Crashworthiness

Once the vehicle structure has been validated, among the challenges of the project was ensuring the maximum safety in frontal and lateral crashes. For this purpose, several crash simulations were carried out according to different test regulation for M1 vehicles. Specifically, attending to the following:

- Regulation 137: full frontal crash configuration against a rigid barrier at 50 kph
- Regulation 95: lateral crash configuration against a mobile deformable barrier with a total mass of 950 kg at 50 kph.

The findings obtained on the final vehicle structure were validated by means of crash tests. Additionally, and due to the small size of the vehicle, it was decided to do another frontal crash test in order to ensure that the front part of the vehicle's structure was able to absorb all the energy in the case of collision. In this case, the test was carried out according to the directions of Regulation 94.

Thus, this section is structured in two main parts, one dedicated to the frontal crash and another to the lateral one. For its part, the section dedicated to frontal crash is split into 2 sub-chapters, one for each regulation.

4.3.1. Frontal crash

Rigid barrier full frontal crash

It corresponds to the configuration used in frontal crash simulations. In detail it considers a full-width frontal crash of the vehicle at 50 kph against a rigid wall.

Due to the fact that the vehicle hits against a rigid body, this is the most critical configuration of all because the whole energy of the impact must be absorbed by the vehicle. With this in mind, the final results after numerous design improvements can be seen in Figure 5, both from the simulations and the real test.

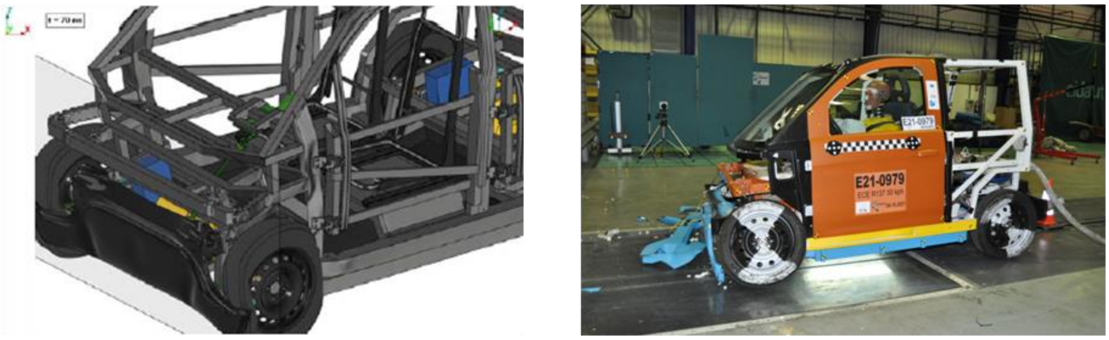

Fig. 5. Left: Vehicle status after frontal crash simulation. Right: General aspect of the vehicle after the frontal crash

To sum up, the obtained results were satisfactory. The vehicle maintains its integrity after the crash, with no important intrusion inside the cabin. However, there are aspects for improvement.

Due to the short length of the frontal par of vehicle's structure compared to standard vehicles, as a result of the collision the engine block tries to get into the passenger compartment; but it is stopped by the rigid structure of the floor. Consequently, the battery pack registers a peak in acceleration. Despite this failure, the biomechanical parameters registered on the dummy reconfirm the good behaviour of the vehicle in comparison to other similar vehicles. The simulations performed on the final design and the crash test results show that the vehicle can be classified to be the best-in-class in what concerns frontal impact.

Deformable barrier frontal crash

In view of the severity of frontal crash on vehicles of these characteristics, it was decided to do another frontal crash test. In this regard, the vehicle's structure was tested according to the directions of the UNECE R94 Regulations for M1 vehicles.

Similarly to the previous crash, the overall result of the test was satisfactory, with some aspects for improvement, but not so important. In this context, the fact that the collision is against a deformable barrier is relevant, because the energy is absorbed by both, the vehicle and the barrier. On the other hand, the crash happens at a higher speed, 56 kph instead of 50 kph, and it has an off-set, so only the 40% of the frontal structure is absorbing energy.

As it can be observed in Figure 6, despite these unfavourable aspects, the deformation suffered by the structure in this case was much smaller.

Fig. 6. Left: General aspect of the vehicle after the second frontal crash. Right: Deformation suffered by the structure after the second frontal crash.

Note that, due to the soft character of the part, the bumper absorbs almost no energy. Hence the deformation is suffered by the structure. Despite this, the motor does not penetrate into the passenger's compartment and the batteries are not damaged either.

4.3.2. Lateral crash

In closing, the following Figure 7 summarizes the results obtained in the simulations and the crash test carried out according to UNECE R95 Regulations.

Fig. 7. Left: Plastic strain results after lateral crash simulation. Right: Overview of the vehicle after the lateral crash.

Overall, both results were satisfactory, especially for the doors. Similar to the previous case, the fact that the collision was against a deformable barrier resulted that the structure experienced no deformation, because the barrier absorbs part of the energy. On the other hand, note that, in the case of the experimental test, owing to the doors are very rigid, there is almost no intrusion. Regarding the batteries, the design of the structure allows the barrier to slide over the sill. In fact, there is no damage in the battery casing, despite of being one of the most critical aspects together with the deformation of the doors.

5. Conclusions and future works

The work done within Multi-Moby project has demonstrated the viability of using high- and super-high strength steel in safe, light and affordable vehicle structures conceived for urban mobility purposes. Thanks to a robust design based on tubular solution, the chassis guarantees high levels of active and passive safety when subjected to demanding crash scenarios such as the ones within the scope of UNECE regulations and Euro NCAP procedures, and also great levels of structural integrity and durability as demonstrated in the stiffness and fatigue tests.

The simulation and physical experiments carried out on Multi-Moby vehicle have allowed defining the main working areas for ensuring the long-term technological and market impact of the project activities. Firstly, these results will be combined with other parallel developments made within the project in the field of ADAS in order to increase vulnerable road user protection. Secondly, it is intended to progress on the homologation of the vehicle, reaching 4 Euro NCAP stars and therefore exceeding the requirements for the homologation under categories M1/N1 and Kei-Car.

Acknowledgements

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No (101006953).

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