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ACHIEVING EURO NCAP BEST-IN-CLASS CRASH SAFETY FOR THE NEXT GENERATION OF LIGHTWEIGHT URBAN ELECTRIC VEHICLE (BEHICLE)

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1 INTRODUCTION

Electric vehicles are considered by many to be the future of personal transport. They are quick, quiet and do not emit pollutants produced by internal combustion engines. Although sales of fully electric vehicles accounted for less than 1% of total new car sales in the EU in 2013, it is clear that momentum towards the adoption of these vehicles is increasing. In Norway, electric vehicle sales made up 6.2% of the total market share while in The Netherlands, this value was 4% (Amsterdam Roundtables Foundation, 2014).

In order to meet performance and range targets required by the consumer, many manufacturers are designing purely electric vehicles that are compact and lightweight. Several different materials are investigated to produce a lightweight, multi-material Body In White. However, aside from achieving desirable performance targets, crashworthiness should be a major consideration when designing a lightweight electric vehicle.

Due to the limited numbers of electric vehicles on the roads, there are no electric vehicle accident statistics. However, an investigation into the safety risks of microcars (smaller than M1 vehicles) by the German insurance association found that the risk of an occupant in such a vehicle being killed in a collision event is up to ten times higher than in a conventional passenger car (Gwehenberger, 2009). A contributory factor to this statistic seems to be that

microcars do not have to meet the same regulatory passive safety requirements as conventional vehicles.

1.1 BEHICLE (BEST IN CLASS VEHICLE: SAFE URBAN MOBILITY IN A SUSTAINABLE TRANSPORT VALUE-CHAIN)

BEHICLE (BEst in class veHICLE: Safe urban mobility in a sustainable transport value-chain) is a collaborative project of the EC's Seventh Framework Programme. The project aims to deliver a safe, lightweight, performance-enhanced urban electric vehicle with the capability of obtaining a Best-in-Class vehicle rating in a full suite of Euro NCAP M1 category vehicle tests. *Figure 1* and *Figure 2* show images of the BEHICLE concept.



Figure 1: Images of the BEHICLE concept (Urban Electric Vehicle)

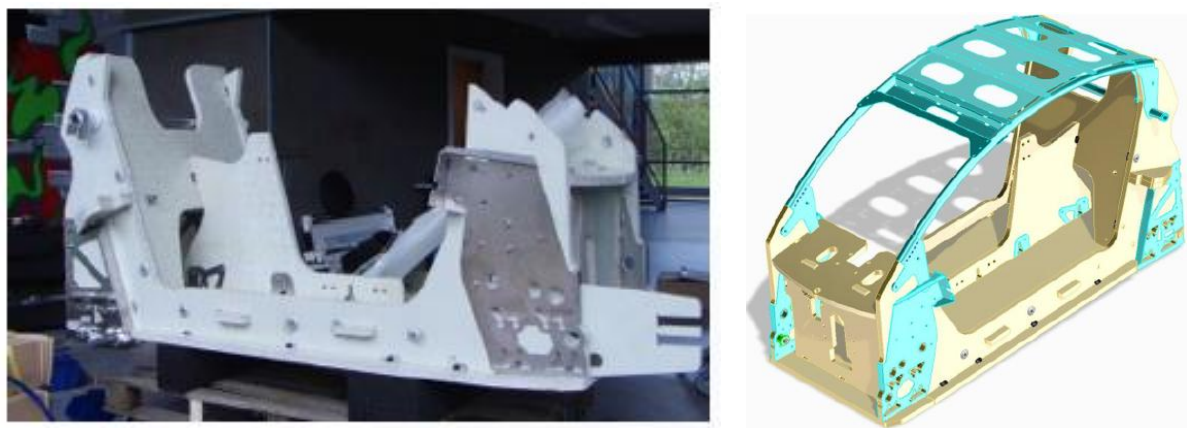


Figure 2: BEHICLE core chassis structure (left) and integration with roof frame (right). (Courtesy of ECOmove)

The BEHICLE has one central front seat and two rear passenger seats. The door beam travels down the length of the car and is hinged at the rear. The chassis is a novel multi-material design. It mainly consists of Acrosoma foam panels (3 to 6 times lighter than steel panels) and aluminium alloy. The structure is joined by a combination of techniques. The front and side crash protection structures are made from darker coloured EPP (Expanded Polypropylene) foam (which can be viewed in *Figure 5*). The roof tubing was also filled with EPP foam. The battery was placed underneath the floor of the rear compartment. Table 1 shows the main performance requirements of the BEHICLE.

Table 1: Performance requirements of the BEHICLE

Vehicle feature	Performance requirement
Maximum weight (including batteries and one occupant)	550 kg
0-100 km/h	Below 10 s
Average energy consumption	7 kWh/100 km
Urban energy consumption	8 kWh/100 km
Electric range	150 km
Euro NCAP score	4-5 stars

2 OBJECTIVES

The main objectives of the study were to:

- Conduct frontal and side impact tests, similar to the Euro NCAP test setup, using two fully instrumented BEHICLE rolling chassis and evaluate the structural crashworthiness of the first prototype.
- Use the results of the tests to validate an FE model so that the effect of further modifications (such as implementing tailor-made crash energy absorption modules and integrated innovative passive safety systems) could be simulated, giving an indication as to whether they further reduced the severity of the crash pulse transmitted to the occupant.

3 LITERATURE REVIEW

Vehicle design has advanced a great deal since early vehicle structures were manufactured using wood panels and steel brackets. In recent years, steel vehicle structures have been replaced with advanced high tensile aluminium alloys to reduce weight. Multi-material structures manufactured from a combination of high-strength steels, metal foams, plastics, aluminium and magnesium are now being considered. In order to meet weight targets, manufacturers are simultaneously forced to consider the structural improvements, such as optimised joint designs, and the optimisation of production processes, such as the reduction in the number of spot welds and lightweight joining techniques.

Some of the main barriers to the adoption of these materials and techniques are cost, energy to manufacture and crashworthiness performance. Multi-material vehicle structures, particularly for small, lightweight vehicles such as the BEHICLE, must meet crashworthiness requirements to convince consumers that there is no trade-off between size and safety. Additionally, BEHICLE must meet or exceed noise, handling and comfort standards consumers are accustomed to from conventional vehicles. According to Bois et al., vehicle structures must meet several crashworthiness requirements in order to provide good occupant protection performance during a crash event (Bois et al., 2014):

- The structure should be deformable yet stiff and contain crumple zones which are capable of absorbing a large amount of kinetic energy through controlled vehicle deformations.
- A deformable rear structure should protect the rear of the vehicle and the power source.
- A strong roof structure should be implemented to provide rollover protection.
- Protective side structures should be added which minimise compartment intrusion and prevent doors from opening during a crash.
- The structure should remove sufficient energy from the crash during the primary impact to ensure that the residual energy may be successfully managed by the restraint systems, minimising the load transmitted to the occupant.

Several research projects have been undertaken to investigate multi-material designs that are capable of meeting crashworthiness requirements. The Super Light Car (SLC) project is a European Commission project which carried out research to investigate automotive lightweight construction with a multi-material approach (Goede et al., 2009). One of the objectives of the projects was to reduce the weight of a body in white, front-end, floor and greenhouse while maintaining manufacturability, cost and crash safety. The project investigated manufacturing and joining technologies using the research approach in *Figure 3*.



Figure 3: Research approach during the Super Light Car project

The project consortium identified parts that were suitable for integration into a single cast part due to their arrangement, function and cost. The front end weight was reduced by 32% by implementing aluminium alloy longitudinal rails, and magnesium alloy strut towers. Applying this concept across the front structure reduced the weight by 24 kg. Design variants such as the wall thickness or changes were examined in LS-Dyna to determine whether crash performance during the offset deformable barrier was affected. The final multi-material structure was shown to decrease the footwell intrusion measurement by 50% compared to the reference vehicle. The cost implications of these design changes were not discussed but could be a factor which may prevent widespread adoption of this material.

Li et al. (2003) showed by computer simulation that it is possible to replace automotive metals with GMT (Glass Mat Thermoplastic) with minimal impact to the vehicle structural strength and crashworthiness. The total body weight was reduced by 41kg. The repairability of this material was not discussed, meaning the practicality of producing vehicles made out of this material is yet to be assessed. Wallentowitz et al. (2003) investigated the option of light weighting by replacing mild steel with a thinner sheet of high strength steel. An equation was developed and validated using a finite element simulation to determine the depth required of the high strength steel sheet required to maintain the structure's energy absorbing capabilities in a crash.

Christensen et al. (2012) developed a lightweight front end crash structure for hybrid electric vehicles using a technique entitled topology optimisation, which extracts the idealised load paths for a given loading. The topology optimisation assesses the structure by simulating six NCAP dynamic impact loading conditions in a Finite Element model (front, side, low speed rear, high speed rear, pole and roof crush) as well as torsional rigidity performance. Unnecessary material was identified and removed and supplementary material was added where the structure required reinforcement.

Christensen et al.'s assessment of the front crash structure commenced with a benchmarking exercise of vehicles of a similar size in NCAP tests. This allowed them to define performance requirements. The frontal impact crash pulse from five vehicles, representing the current state of the art of vehicle structural performance, was evaluated. An idealised pulse profile was developed based on several ideologies. The longitudinals should be as stiff enough to ramp up the acceleration pulse quickly so that the occupant engages with the restraint system early on. The acceleration peak duration should be kept as short as possible while the crash duration should be as long as possible to reduce the average deceleration.

MATISSE, an ongoing project by the European Commission to investigate the crash behaviour of composite structures of small electric vehicles, predicts that driver assistance programmes will be more efficient at preventing frontal impacts than side impact collisions (Svensson et al., 2014). This will cause protections from side collisions to be treated with higher priority than frontal impact protection. Future collision speeds are also expected to

decrease by 10 km/h due to driver assistance systems. The paper highlights the importance of side protection and the ability of the BEHICLE to protect occupants at a range of speeds.

Due to the increasing popularity of lightweight vehicles, Euro NCAP recently assessed the several heavy quadricycles against a new quadricycle Euro NCAP protocol. The results were presented in a safety campaign. This included a 50km/h frontal impact test into a full width deformable barrier and a 50km/h side impact test. All four were found to show serious safety problems and lacked the minimum safety features which are commonplace on modern cars. Three of these vehicles, the Renault Twizy (474 kg), the Tazzari ZERO (542 kg) and the Club Car Villager 2+2 LSV (541 kg) were purely electric.

Some of the common performance issues encountered during the frontal impact test were accredited to the very stiff nature of the structures and restraint systems. Dangerously high forces were recorded through the dummy neck and driver's knees were also exposed to hard structures causing high knee and femur loading. The battery pack was exposed in one of the vehicles and pushed backwards and into the footwell. Some of the vehicles were not equipped with an airbag, leading to a situation where the dummy's head hit the centre of the steering wheel at a force which was likely to cause a fatal injury

During the side impact test, the dummy head was exposed outside the passenger compartment in several tests – a very dangerous situation in the real world. Protection of the chest area was poor. The driver's door of one vehicle opened, compromising the integrity of the passenger compartment.

The papers show that there is growing interest in the use of non-conventional materials to reduce the mass of a vehicle structure. However, there are several factors that must be considered when evaluating the appropriateness of a material such as its cost, repairability, and its effect on vehicle handling, vibration and noise. Additionally, crashworthiness of the vehicle must not be compromised. Several papers used the vehicle acceleration pulse and intrusion measurements to determine how the addition of lightweight materials affects the vehicle crashworthiness. This method will be used while assessing the crashworthiness of the BEHICLE rolling chassis.

4 METHODOLOGY

Front and side impact tests, similar to those carried out by Euro NCAP, were conducted using the BEHICLE rolling chassis. The tests followed the Euro NCAP protocols in force during the start of the project (November 2013). An uninstrumented makeweight dummy was installed in the driver position during both tests. No restraint systems were installed on the BEHICLE apart from a three point seat-belt. The test results were analysed using acceleration

profiles, static deformation measurements, video footage and paint transfer observations between the dummy and the passenger compartment. The results were used to identify any areas of the BEHICLE which could be improved through design modifications.

4.1 FRONTAL IMPACT TEST

During a standard frontal impact Euro NCAP test, described in *Figure 4*, the test vehicle strikes a 40% offset deformable barrier at an impact speed of 64 km/h. Two Hybrid III dummies occupy the front seats and a Q1.5 and Q3 dummy are restrained in CRS systems in the rear. The deceleration of the compartment is measured using an accelerometer attached to the B-pillar. The displacement of the steering column and pedals is calculated using static measurements before and after the test.

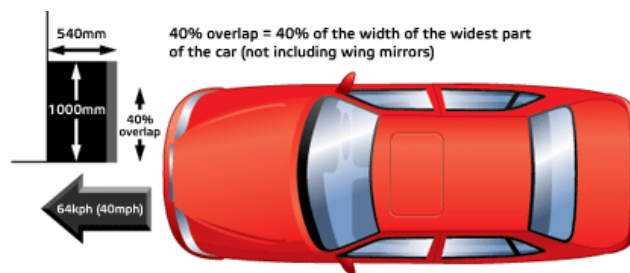


Figure 4: Standard Euro NCAP frontal impact configuration (source euroncap.com)

The BEHICLE rolling chassis struck a 40% offset deformable barrier at 64 km/h (*Figure 5*). The left side was chosen as the struck side in order to ensure that the passenger compartment experienced the maximum amount of deceleration possible caused by the 80 kg battery pack positioned at the rear of the car on the left-hand side. The battery was not fitted during the test but its mass was simulated using ballast.



Figure 5: BEHICLE frontal impact test (left) and areas of the BEHICLE fitted with accelerometers (right)

The test differed from a standard Euro NCAP frontal impact test in several ways. Additional instrumentation was fitted to the vehicle to measure deceleration readings across several areas of the passenger compartment (*Figure 5*). Readings from these areas would be used to validate a CAE model of the BEHICLE and inform the restraint system designers of the deceleration pulse which the restraint system must be capable of withstanding. Static measurement points were also recorded before and after the test to calculate deformation.

Due to the likelihood that a Hybrid III dummy would be severely damaged during the impact, a 50th percentile makeweight dummy occupied the front driver seat. The makeweight dummy was provided to simulate the mass of the driver and to give a visual indication of the kinematics of the driver during the impact. The dummy was belted in a basic three point seat belt arrangement to provide realistic loading to the vehicle structure and through the restraint anchorages. Two forward facing child restraint systems were fitted to the rear seats of the vehicle with ballast added to represent Q1.5 and Q3 child dummies. However, there was not enough space for a rear facing child seat.

4.2 SIDE IMPACT TEST

In a standard Euro NCAP car to car side impact test, shown in *Figure 6*, the side of the vehicle is struck by a deformable barrier moving at 50 km/h. The barrier is aligned to the car using the R-point, defined previously by the manufacturer.

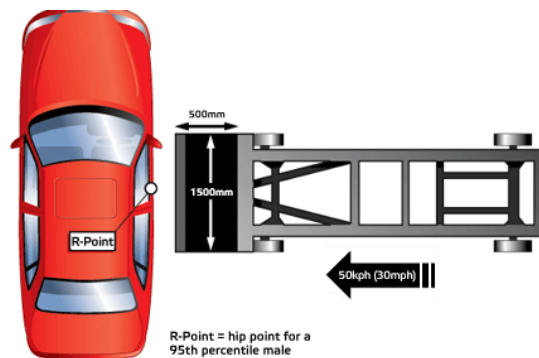


Figure 6: Standard Euro NCAP side impact configuration (source euroncap.com)

The BEHICLE rolling chassis was struck by the Euro NCAP deformable barrier at 50 km/h. The left-hand side of the vehicle was chosen as the struck side for consistency. Instrumentation was fitted to the BEHICLE in the same locations as the frontal impact test to measure decelerations across the compartment and the angular velocity of the seat mounting. Static measurement points were also recorded before and after the test to calculate deformation.

TRL provided the same 50th percentile makeweight dummy to replicate the mass of the ES-2 dummy typically used for the side impact test. Forward facing child restraint systems were also installed in the rear seats of the car with 11 kg and 15 kg weights added to represent Q1.5 and Q3 dummies. *Figure 7* shows the area of the BEHICLE which made contact with the moving deformable barrier.

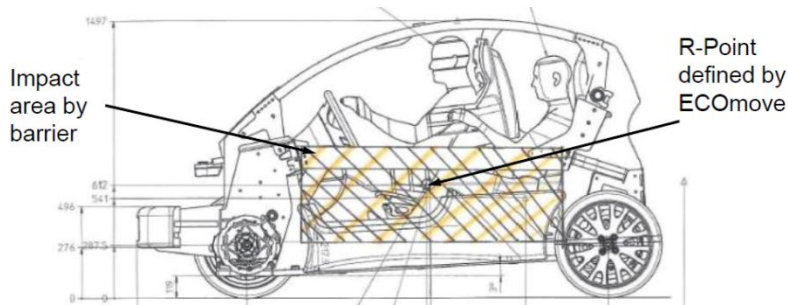


Figure 7: Barrier impact area of BEHICLE during side impact test

4.3 TEST OUTPUTS

The crash performance of the BEHICLE was analysed during both frontal and side impacts:

- The acceleration profiles at the compartment B-pillar measured during the frontal and side impact tests were compared with a high performing and lower performing supermini pulse to determine the severity of the pulse.
- The compartment integrity was analysed by taking static measurements at predefined locations before and after the test.
- Video footage allowed observation of the dummy kinematics in both tests.
- Paint transfer from the dummy to the interior of the vehicle showed any dummy interaction with hard structures.

The results were used to observe any areas of the structure requiring improvement such as the front foam crash structure.

5 RESULTS AND DISCUSSION

5.1 FRONTAL IMPACT TEST

The Euro NCAP offset deformable barrier test replicates a head-on collision between two cars of the same mass, travelling at 50 km/h with a 50% overlap (Euro NCAP, 2015). During the impact, the front bumper was completely destroyed and did not fulfil its energy absorption potential. *Figure 8* shows the front structure of the BEHICLE pre and post impact. The longitudinal part of the front structure mainly deformed through buckling during the test. The energy absorption capability of this area could be improved through decreasing its stiffness, making it more likely to crush.

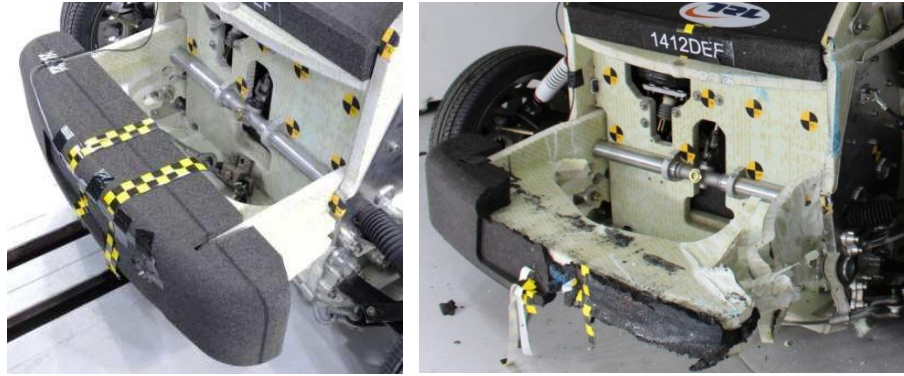


Figure 8: The front structure of the BEHICLE pre and post impact.

Figure 9 and Figure 10 compare the crash deceleration pulse of the BEHICLE with superminis that achieved five stars and three stars for adult occupant protection in the same test condition. The pulse is measured from the B pillar on both the struck and unstruck sides.

When a vehicle makes contact with a barrier, there is a primary and secondary impact. During the primary impact, the vehicle front end structure interacts with the barrier and absorbs a major portion of the crash energy through structural deformation. The amount of deformation is influenced by the stiffness of materials and crush depth available at the front end, as well as the location of non-crushable (e.g. powertrain) components. This influences the crash pulse that is transmitted to the occupant.

The secondary impact occurs as the occupant makes contact with the restraint system. In order to maximise occupant protection, the deceleration pulse should decay gradually during this phase (Bois et al., 2004). Any short duration deceleration peaks occurring during the secondary impact may result in forces transmitted through the restraint systems that are higher than human tolerance levels.

Figure 9 and Figure 10 show that the initial deceleration pulse of the BEHICLE during the first stage of the impact was more severe than the pulse recorded by both superminis. This was due to the fact that the front crash structure was too stiff and did not deform as originally intended. The severity of the initial deceleration pulse may be reduced through the addition of a more effective energy absorbing structure at the front of the car.

The decay of the BEHICLE crash pulse occurs over a short period of time than the two supermini crash pulses. This means that the restraint system has a shorter period of time within which to decelerate the occupant, leading to a greater risk of injury. The integration of an energy absorbing structure should mitigate this risk by reducing the severity of the crash pulse transmitted to the occupant. The three star supermini performs much better in this instance than the five star mini. This suggests that the restraint system installed in the five star supermini provides superior occupant protection performance.

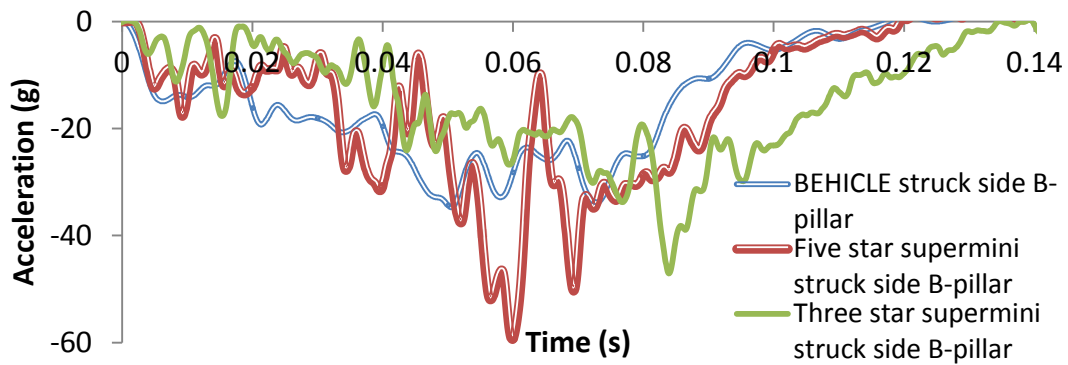


Figure 9: Comparison of the BEHICLE frontal impact pulse experienced at the B-pillar on the struck side with a high performing supermini pulse and a lower performing supermini pulse.

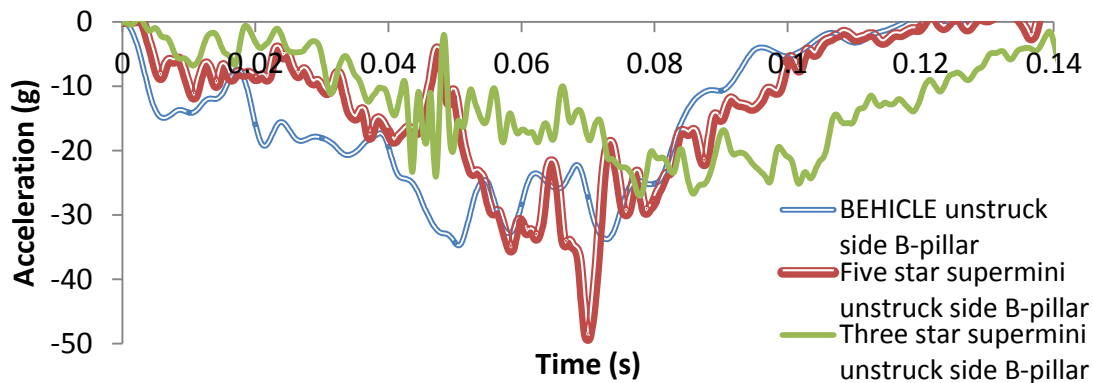


Figure 10: Comparison of the BEHICLE frontal impact pulse experienced at the B-pillar on the unstruck side with a high performing supermini pulse and a lower performing supermini pulse.

Figure 11 shows the deformation of the offset deformable barrier after the test. The impact caused the barrier to bottom out in the lower region. Using a rough estimate of the crushed volume, it was calculated that the barrier absorbed approximately 20 kJ of crash energy, 22% of the total crash energy.



Figure 11: Euro NCAP frontal impact offset deformable barrier post-test

Static measurements were recorded across the BEHICLE compartment before and after the test to measure static deformation. Figure 12 shows that a large amount of intrusion was observed at the front left region of the car, threatening the stability of the passenger compartment. This area could be reinforced through the use of a sill load path to transfer the force towards the rear of the vehicle.

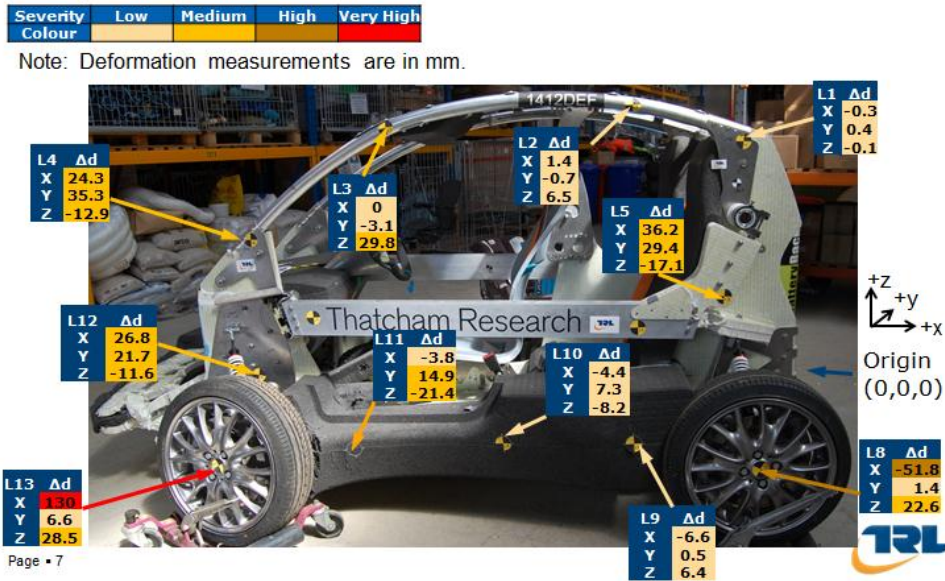


Figure 12: Static deformation of the BEHICLE after the frontal impact test. Colour scale is for visual representation only. Arrowheads point in the direction of deformation.

The impact caused the door latch mechanism to break, compromising the integrity of the passenger compartment, and the dummy was almost ejected. This is undesirable vehicle behaviour and would be heavily penalised by Euro NCAP. The dummy kinematics were also analysed during the test. The dummy head and chest both made contact with the steering wheel whilst the tibias and knees made contact with the dashboard. This is a point for concern since Euro NCAP applies modifiers in order to penalise manufacturers for such occurrences. During the project, the BEHICLE will be equipped with sophisticated bespoke restraint systems to ensure that the front occupant is protected in a frontal impact. However, the test highlights the need for a collapsible steering column to ensure that loading to the chest during impact will be minimised.

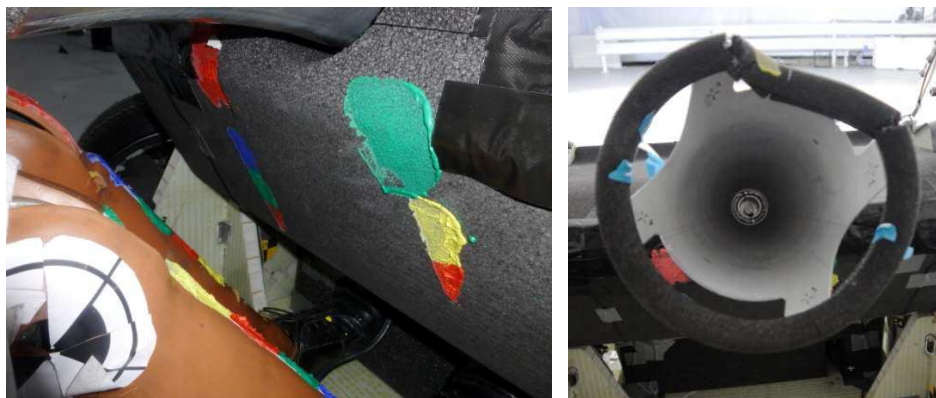


Figure 13: Dummy lower limb contact with the dashboard (left) and head contact with steering wheel (right)

Figure 14 shows the sill load paths which may be implemented to address some of the issues experienced during the frontal impact test. The dark green arrow at the front of the car represents the addition of a more effective energy absorbing module that collapses in a more controlled manner, producing a lower severity deceleration pulse. The design of the future

BEHICLE will incorporate the light green sill load path and dark blue door beam load path to reduce the amount of compartment deformation observed at the front left quarter.

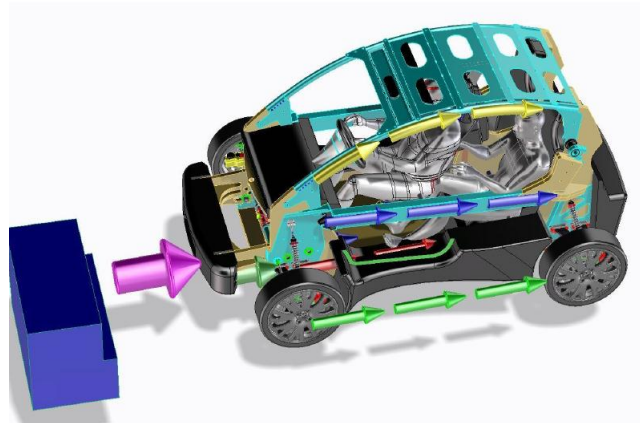


Figure 14: Sill load paths to be implemented to improve occupant protection performance of the BEHICLE

5.2 SIDE IMPACT TEST

The side impact test would be particularly challenging for the BEHICLE, which, unlike conventional vehicles, does not have a centrally located B-pillar. During the momentum exchange as the moving deformable barrier made contact with the BEHICLE, the barrier engaged well with the sill, although a large amount of the impact force was concentrated on the door beam. *Figure 15* shows the BEHICLE and the moving deformable barrier following the test.

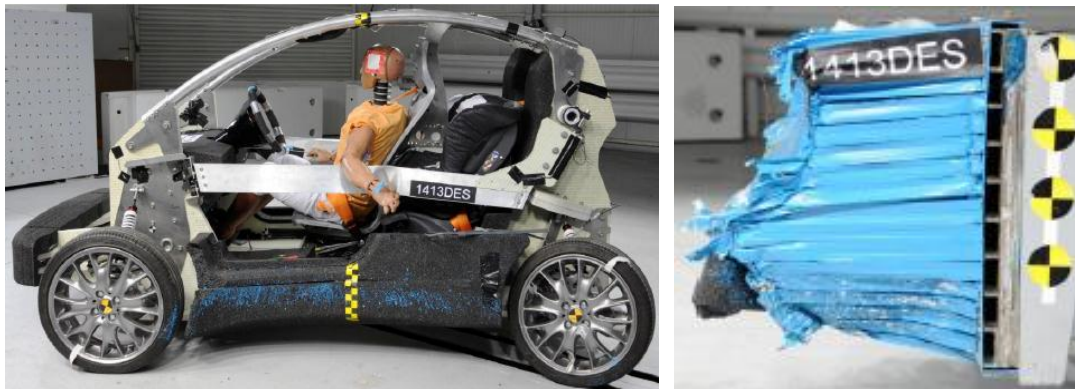


Figure 15: Images of the BEHICLE (left) and moving deformable barrier (right) after the test.

The door latch mechanism successfully held the door in place for the duration of the test. *Figure 16* and *Figure 17* compare the deceleration pulse and the velocity of the BEHICLE with the performance of a five star and a three star supermini.

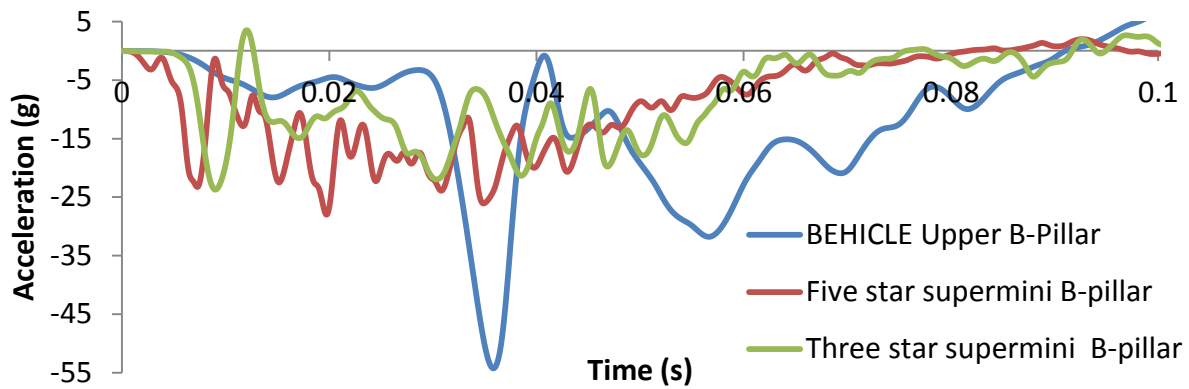


Figure 16: Comparison of the BEHICLE side impact pulse experienced at the B-pillar on the unstruck side with a high performing supermini pulse and a lower performing supermini pulse.

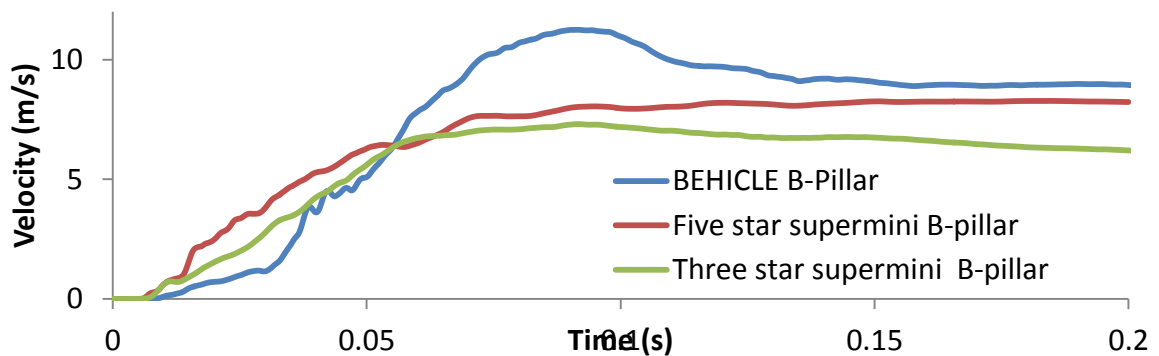


Figure 17: Comparison of the BEHICLE velocity during the side impact test with the velocity of a high performing supermini and a lower performing supermini.

Both the deceleration pulse and the velocity of the BEHICLE were considerably higher than those of the conventional superminis. This is due to the lower mass of the BEHICLE. The energy absorption characteristics of the side panels of the BEHICLE should be improved to reduce deformation. Due to the lack of restraint systems installed in the BEHICLE, the dummy kinematics were severe. The left leg and abdomen made contact with the door beam whilst the head and shoulder moved outside of the passenger compartment. These problems should be resolved with the introduction of side airbags and a four point seat-belt.

Figure 18 shows that the largest amount of deformation was observed at the central point of the door beam. The dynamic intrusion at this region was observed to be a lot higher. The distance between the car structure and the occupant should be kept as large as possible to ensure that there is sufficient time and space to decelerate and restrain the occupant. Therefore, additional structures should be installed along the side of the BEHICLE to prevent concentrated loading on door beam.

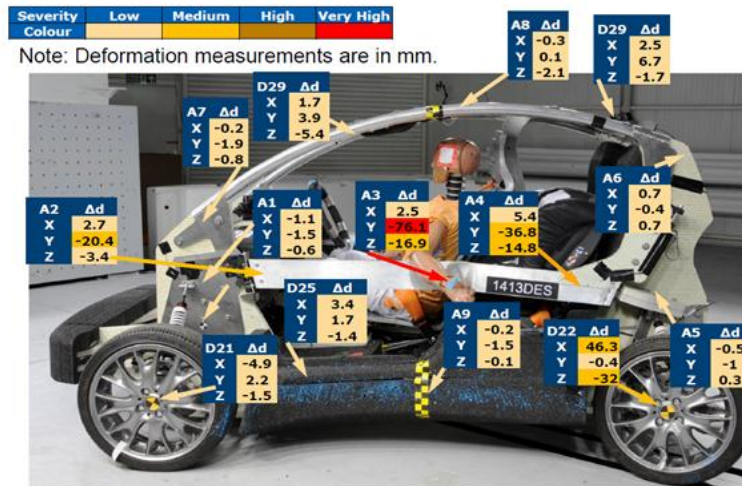


Figure 18: Static deformation of the BEHICLE after the side impact test. Colour scale is for visual representation only. Arrowheads point in the direction of deformation.

Figure 19 shows the load paths which should be implemented in order to improve the side impact protection performance of the BEHICLE. It is expected that the vehicle sill element will transfer the load through the floor panel of the chassis. The door beam will be reinforced by a load path through the firewall and the seat back panel.

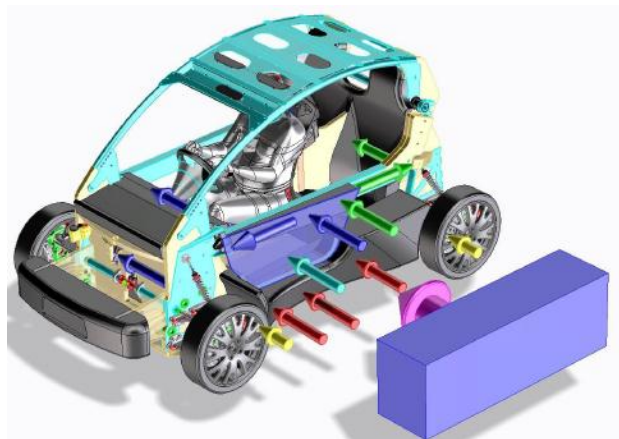


Figure 19: Load paths to be implemented in order to improve occupant protection performance of the BEHICLE during the side impact test.

6 CONCLUSION

Euro NCAP style frontal and a side impact tests were conducted using the BEHICLE rolling chassis to determine the crashworthiness performance of the multi-material design and to validate a FE model.

A literature review was conducted which provided the following findings:

- There is growing interest in the use of non-conventional materials to reduce mass.

- Factors such as cost, repairability, and the effect of modern materials on vehicle handling, vibration and noise insulation requires further investigation.
- Several papers used the vehicle acceleration pulse and intrusion measurements to determine how the addition of lightweight materials affects the vehicle crashworthiness.

Frontal and side impact tests were conducted. The following findings were observed:

- During the frontal impact test, a small amount of compartment intrusion was observed and the deceleration level experienced at the B-pillar was comparable to that of other superminis tested by Euro NCAP.
- A large amount of dynamic intrusion was observed during the side impact test. The pulse and velocity of the BEHICLE was much higher than those of conventional superminis. This may be attributed to the lower mass of the BEHICLE.

The study concluded with a set of design recommendations to improve the BEHICLE crashworthiness performance:

- The stiffness of the front crash structure should be decreased in order to improve the energy absorption capability of the structure.
- A sill load path should be implemented to decrease the deformation experienced around the front left area of the passenger compartment.
- A collapsible steering column should be implemented to ensure that the chest of the occupant does not experience loading.
- The door latch must be strengthened and reinforcement of the door beam is required to decrease the likelihood of the door opening during impact.
- Additional energy absorbing structures should be fitted at the sides of the car to prevent concentrated loading of door beam.

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