

PASSIVE SAFETY STRATEGY FOR ELECTRIC LIGHTWEIGHT VEHICLES WITH MULTI-MATERIAL BODY AND CENTERED DRIVER POSITION – OPPORTUNITIES AND LIMITATIONS

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Paper Number 17-0305

ABSTRACT

The growing market share of electric lightweight vehicles requires new passive safety strategies as these vehicles have different behavior in accidents compared to conventional vehicles. Due to their low weight they could experience high deceleration pulses and intrusion levels. The main objective of this study was to develop a passive safety strategy for a light weight electric vehicle to give best in class occupant protection.

Challenges involved in this study include, mainly focused on side impact:

- The use of alternative materials for the body structure (mainly sandwich panels and foam) due to their failure mechanism
- A novel seating layout with a centrally positioned driver, especially challenging for side impact

Within this study two baseline and four final prototypes were built. The development of the vehicle was accompanied by FE-simulation. Two of the baseline prototypes were subjected to Euro NCAP MDB side and ODB frontal impact crash tests. These baseline crash tests served as benchmark for the development of the passive safety strategy and the validation of the FE-model. For side impact two critical issues have been taken into account, namely a high Δv and a centered driver position which reproduces the current challenge for far-side protection. Firstly, FE simulations have been done to develop the restraint systems, followed by sled test development loops in the main Euro NCAP load cases (MDB, Pole and ODB). With the final prototypes a full Euro NCAP crash assessment was performed using the ‘year 2013’ rating protocols to allow comparison with the baseline crash tests.

The MDB side impact led to very high pulses, that couldn’t be addressed structurally due to the high mass ratio between barrier and vehicle. However, the results show that with the proposed restraint system using airbags and a four point seatbelt an adequate protection level could be reached for the centered driver for both MDB and pole side impacts, compared to standard vehicles. For frontal impact, the results showed that, using an approach of a strong compartment built from novel composite reinforced glass fiber / foam panels,

combined with a specially designed energy absorption module, an 'innovative' four-point seatbelt and a conventional driver airbag, resulting intrusion could be minimized and adequate protection could be offered to the driver. Overall occupant protection equivalent to a best in class Euro NCAP 'year 2013' rating was achieved for the vehicle.

The strategy developed demonstrated equivalent protection levels based on the Euro NCAP 'year 2013' suite of tests. Since then, the Euro NCAP assessment has been further improved in terms of representativeness of real-world accidents. These improvements include a heavier barrier for the MDB test and the addition of a full width frontal test.

With respect to growing market share of electric lightweight vehicles a passive safety strategy was developed for such vehicles based on Euro NCAP crash tests to give best in class occupant protection. Because of the centrally positioned driver, some challenges have been faced and solved, especially for side impact configurations.

INTRODUCTION

Current pollution issues in big cities in combination with mobility matters of conventional vehicles with petrol engines has resulted in an increment of electric lightweight cars on the roads, which have to coexist with the traditional kind of vehicles.

However, quadricycle versions of these vehicles do not need to fulfill the same legislation as conventional cars to be sold for road use, so basic, low level occupant restraint systems are in general developed for them.

Euro NCAP expected that quadricycles would show a very poor performance when they were tested using regular procedures for conventional cars, so Euro NCAP developed special protocols for testing heavy quadricycles through two crash tests, less stringent than protocols for passenger cars:

- A full-width frontal impact at 50km/h against a deformable element
- And a side impact test, also at 50km/h, in which a deformable barrier is driven into the side of the vehicle.

The assessment of 8 low weight vehicles according to these specific procedures [1], 4 of them assessed in 2014 and 4 additional ones assessed in 2016, as it can be seen in Figure 1 and in Figure 2, has shown the low protection capability of these vehicles, which are not able to exceed a 2 star rating.













2014	FWDB	MDB
Club Car Villager  0★		
Ligier Ixio JS Line4  0★		
Renault Twizy 80  2★		
TAZZARI Zero  1★		

Figure 1. Quadricycles assessed in 2014 according to Euro NCAP quadricycle protocols.













2016	FWDB	MDB
Aixam Crossover GTR  1★		
Bajaj Qute  1★		
Chatenet CH30  2★		
Microcar M.GO Family  1★		

Figure 2. Quadricycles assessed in 2016 according to Euro NCAP quadricycle protocols.

This paper describes the development and the results of a heavy quadricycle, included inside a Project of the Seventh Framework Programme developed by the European Commission called BEHICLE: “BEST in class VEHICLE: Safe urban mobility in a sustainable transport value-chain”; which has the target of fulfilling a rating of at least 4 stars according to Euro NCAP protocols for conventional cars of year 2013.

In addition to the activities performed inside the BEHICLE project, specific Finite Element crash simulations have been performed to evaluate BEHICLE against Euro NCAP 2016 protocols and Euro NCAP protocols for heavy quadricycles.

Although this paper is focused in side impact for a driver occupant in a Far Side configuration, results in frontal impact load cases have been also included in order to have a global view of the behavior of BEHICLE in Euro NCAP tests.

METHODS

In the BEHICLE program, the used method has been to perform as a first step preliminary crash tests with the non-optimized original BEHICLE vehicle according to Euro NCAP 2013 regular car protocols. These results have been used for the FE – Model correlation of the vehicle structure and as reference for the development of the passive safety strategy.

Afterwards, restraint systems (belt and airbags) have been included in the FE – Model with a dummy and intensive simulation runs have been performed. The best configuration has been evaluated via sled tests with real vehicle environment according to Euro NCAP 2013 regular car protocols (ODB, MDB and Pole).

Finally, three complete prototypes of BEHICLE have been crash tested according to the three load cases evaluated by Euro NCAP 2013 (ODB, MDB and Pole).

Nevertheless, assessment of BEHICLE would be incomplete if updated Euro NCAP protocols were not taken into account, so FE-Models have been also performed according to the Euro NCAP 2016 assessment (FW, ODB, AE-MDB and Pole), as well as Euro NCAP protocols for heavy quadricycles.

BEHICLE framework

BEHICLE has been designed as a 100% electric vehicle without petrol engine. Instead, it is powered by electric engines placed in the Wheel axis fed by a set of electric batteries placed in a false floor under the cabin ground [2].

As one requirement of the program is the low weight that BEHICLE needs to achieve, the materials in which it is mainly made is a light weight composite panel with a Core of hard foam and an external cover of glass fiber. These 3D composite panels, which mainly composes the lower platform, the firewall, the roof, the three seats and the doors, have all the advantages of standard sandwich panels, but posses enhanced properties since it is a 3D reinforced composite panel such as high strength-to-weight ratio, high buckling and impact resistance, absence of delaminating and high blast energy absorption capability.

Another light weight material is structural aluminum. Reinforcing elements between composite panels, like greenhouse structure or the door beams, are made of this material, which also offers an appropriate corrosion resistance, a good weldability and a proper cold formability.

The third main material in which BEHICLE is built up is black colored EPP foams (Expanded PolyPropilene) with a mass density of 58 g/l to 66 g/l, located in the front end cover, side sill covers, seats and interior parts.

Finally, Polycarbonate (PC) panels are used as glazing due to its thermal insulation properties and high resistance to impact. The outer shell is made of a combination of EPP parts and plastic panels, prototyped in BEHICLE by EPP parts.

Other important matters concerning vehicle stiffness in comparison with conventional vehicles is the lack of a B-Pillar, which makes BEHICLE more sensitive to lateral crash impacts; and the lack of petrol engine placed in the front of the car, which could cause different frontal crash pulses and intrusions. A general view of BEHICLE car can be observed in Figure 3.



Figure 3. Main view of BEHICLE.

Geometrically, as it is shown in Figure 4, BEHICLE has places for three adult occupants, in which the driver is centrally seated, while the two passengers are positioned on the rear seats behind the driver side by side making a triangular layout. Because of this configuration and the reduced space in the compartment, legs for rear occupants are placed on the right and the left of the driver.

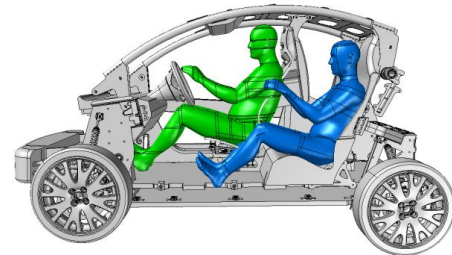


Figure 4. Rear passenger placed with legs on the side of frontal driver in BEHICLE.

Assessment and load cases

The driver safety performance in BEHICLE has been evaluated in accordance with the Euro NCAP procedures for conventional cars in 2013 and 2016 and the special protocols developed for testing heavy quadricycles [3 and 4].

Euro NCAP 2013 evaluates driver injuries according to three load cases (see Figure 5):

- A frontal impact test, in which the vehicle drives at 64km/h towards a Deformable Barrier, with 40% offset (ODB) and a HIII 50th dummy in the driver position.
- A side impact test, in which a Mobile Deformable Barrier of 950kg (MDB) is driven into the side of the vehicle at 50km/h, with an ES-2 dummy in the driver position.
- A side impact test, in which the vehicle is moved at 29km/h towards a rigid pole, with an ES-2 dummy in the driver position.

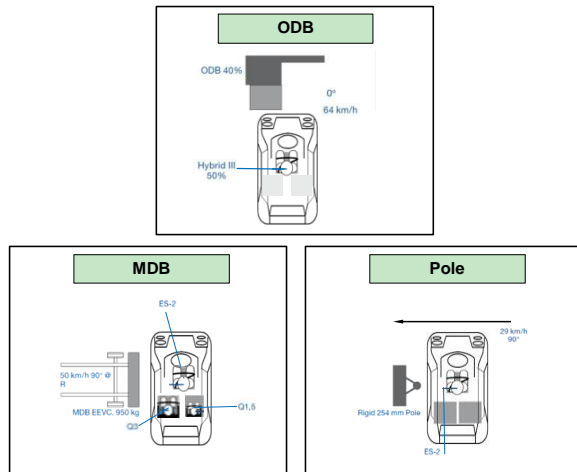


Figure 5. Euro NCAP 2013 load cases.

Euro NCAP 2016 evaluates driver injuries according to four load cases (see Figure 6):

- A frontal impact test, in which the vehicle drives at 64km/h towards a Deformable Barrier with 40% offset (ODB), and a HIII 50th dummy in the driver position.
- A frontal impact test, in which the vehicle drives at 50km/h towards a Full Width Wall, with a HIII 05th dummy in the driver position.
- A side impact test, in which an Advanced European Mobile Deformable Barrier of 1300kg (AE-MDB) is driven into the side of the vehicle at 50km/h, with a World SID 50th dummy in the driver position.
- A side impact test, in which the vehicle is moved at 32km/h towards a rigid pole with an angle of 75 degrees with respect to the lateral side of the vehicle, with a World SID 50th dummy in the driver position.

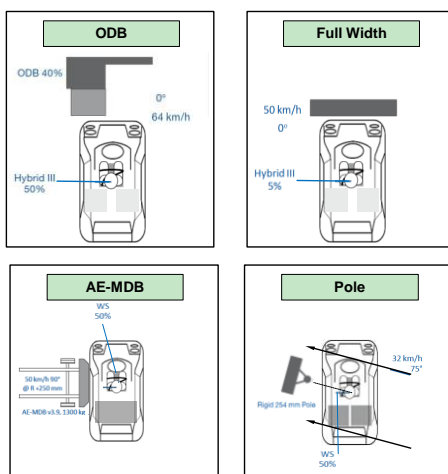


Figure 6. Euro NCAP 2016 load cases.

Heavy Quadricycles Euro NCAP evaluates driver injuries according to two load cases (see Figure 7):

- A full-width frontal impact at 50km/h against a deformable barrier (FWDB), with a HIII 50th dummy in the driver position
- And a side impact test, also at 50km/h, in which a deformable barrier of 950kg (MDB) is driven into the side of the vehicle, with an ES-2 dummy in the driver position.

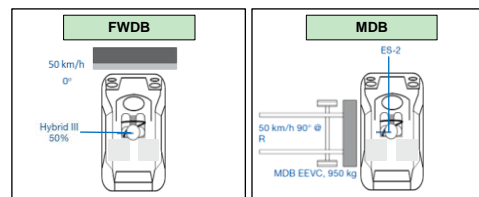


Figure 7. Euro NCAP tests for Heavy Quadricycle.

Devices and tools

FE-Models. The finite element simulation model used for this vehicle consisted of 1 to 1.5 million of degrees of freedom, depending on the load case [2]. The simulation was carried out with the finite element software LS-Dyna (Livermore Software Technology Corporation (LSTC), Livermore, CA).

The way to proceed has been firstly to transfer the linear and angular accelerations (crash pulse) of a point from the Full Crash FE-Models of BEHICLE into a BEHICLE substructure FEM to reproduce the global motion of the vehicle. The best area to get the pulse is one with high stiffness and low deformation and placed close to the occupants. In conventional vehicles, this point usually comes from the centre tunnel or the base of the opposite B-Pillar, but as BEHICLE has none of them, and because of the fact that the study will be focused on the driver and the floor of BEHICLE does not suffer high deformations, the optimal point to get the pulse is under the front seat close to the floor.

In addition, and according to the preliminary information, door intrusions will be important, so in addition to the pulse, it will be necessary to include in the model the intrusions of elements of the door as the inner door panel and the aluminum door beam, depending on the type of lateral load case:

- In MDB full crash simulation models, motion of the aluminum door beam and the motion of the door panel under the door beam have been included in the substructure models.
- In Pole full crash CAE simulation models, motion of the aluminum door beam, the motion of the door panel under the door beam and the motion of the roof have been included in the substructure models.

Sled Tests. As an intermediate step to perform crash tests, performance of passive restraint systems has been evaluated via sled test.

In these sled tests, real parts of BEHICLE which have a significant interaction with the dummy have been included in the set up to reproduce the internal environment of the car. In this way, and focused on lateral MDB and Pole load cases, frontal seat, Green House (roof), and left door with the aluminum beam, the EPP cover and the composite door panel have been implemented in the sled tests.

In addition, the acceleration (pulse) of a point under the frontal seat has been reproduced in Y direction; and the motion of two points of the door has been replicated.

In the case of sled tests with MDB configuration, it is possible to reproduce separately the deformation of the upper and lower part of the door due to the impact of the MDB barrier. Deformation of a selected point of the door beam has been used to reproduce the motion of the upper door, while deformation of a selected point of the composite door panel has been selected for the motion of the lower door.

In the case of sled tests with Pole configuration, it is possible to reproduce the pole intrusion into the cabin, directly via a real pole through the window, and the deformation of the door due to the intrusion of the pole. In this case, only one point of aluminum door beam will be used to generate the sled door pulse.

In addition, sled test can reproduce the V-shape deformation of the door caused by the pole penetration.

Crash Tests. Final step of BEHICLE program has been to perform Crash Tests according to Euro NCAP 2013 test protocols.

RESULTS

In the BEHICLE project, passive restraint systems have been developed focused on Euro NCAP 2013 test protocols (Frontal ODB, Lateral MDB and lateral Pole load cases), and the assessment has been done via FE-simulation models, sled tests and crash tests. However, although it is expected to perform three crashes according to each configuration with three final prototypes, only the results of the lateral crashes (MDB and Pole) have been included in this paper, as the planned ODB frontal crash test was not performed at the time this paper was written.

Additionally to the Euro NCAP 2013 assessment, further FE simulations have been performed to assess BEHICLE against the Euro NCAP 2016 protocols

and the Euro NCAP special protocols for testing heavy quadricycles.

Preliminary results

Prior to the integration of any restraint system, a lateral crash test according to MDB Euro NCAP 2013 procedures was performed with the original, non-improved BEHICLE vehicle as a baseline to get knowledge of the structural behavior and to define the strategy for the definition of the restraint systems. Main conclusion of this first crash test was the good integrity and stability of the BEHICLE compartment. The only significant intrusions have been observed in the door beam.

However, due to the low weight of BEHICLE, as shown in Figure 8, a high velocity of the car after the impact (delta-v) was observed (35 km/h). This high delta-v of the BEHICLE indicates a higher crash severity than typical for Euro NCAP side impact (22 km/h to 28 km/h).

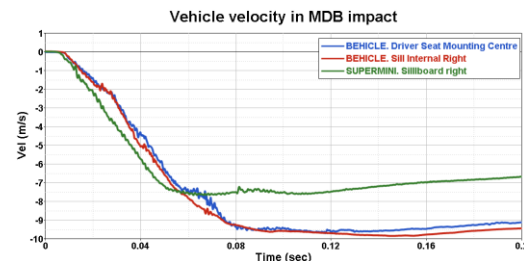


Figure 8. Velocity comparison with a Supermini vehicle.

Concerning dummy kinematics, the dummy's pelvis impacted the door glazing (which was pushed into the vehicle by the barrier). Also dummy head ejection outside the cabin was observed.

BEHICLE improvement

Previously to the inclusion of the passive restraint systems into the crash simulation models, the correlation of the BEHICLE simulation model to the preliminary MDB crash tests has been performed. As it was observed in the preliminary MDB crash test, important facts to be improved were the high intrusion of different door elements into the cabin and the control of the door bending.

In this way, the door area was redesigned in order to get an acceptable behavior of the door.

The final solution to improve these matters, schematized in Figure 9, was based on three main modifications of the side structure:

- Firstly, the material of the door panel has been replaced from glazing and / or EPP foam to a composite door panel.

- Secondly, a redesign of the sill area, in which also a composite panel has been included to increase the coupling of the door to the sill.
- Thirdly, the door beam has been slightly curved outwards to absorb the energy of the impact in a better way.

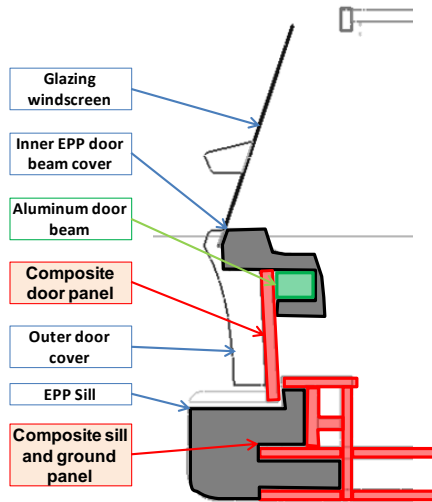


Figure 9. BEHICLE section in door area.

Simulation runs with this door modification have shown an improvement in the intrusion, avoiding that the door panel intrudes into the cabin in MDB and Pole configuration, and reduced the maximal door beam intrusion to a value of 140mm in MDB configuration and 115mm in pole configuration.

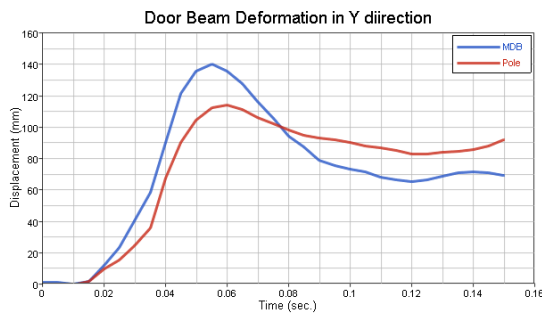


Figure 10. Maximal Aluminum door beam intrusion.

Restraint Systems

Innovative restraint systems were developed and integrated in BEHICLE [5]. These restraint systems were adapted to the specific BEHICLE architecture and crash behavior. Concerning side impact, the following restraint systems have been selected to be integrated in BEHICLE and adapted to the particular BEHICLE environment.

Driver four-point seat belt (Top Belt). Due to the particular characteristic of BEHICLE (without B-Pillars and with the driver in a central position) a new and innovative four point seat belt (Top Belt), with two retractors provided with load limiters and pyrotechnical pretensioners has been integrated in the car. Retractors are located at the roof in the rear part of the car. Two buckles are attached to both sides of the seat with the purpose of getting fastened to the latch plates. The two latch plates are stored at the roof in front of the driver in the unbuckled rest position. Figure 11 shows a dummy buckled with the four point seat belt system.



Figure 11. Top belt – Four Point Seat Belt.

Side airbag integrated in door (SAB). Due to the very thin BEHICLE seat backrest, it was not possible to integrate the side airbag in the front seat like in conventional cars; therefore it was integrated in the door and fixed to the aluminum door beam. The specific BEHICLE seat layout with the driver seat in the centre offers a new scenario for innovative side airbags because of the increased space between the side structure and the occupant. The airbag shape has been designed to cover all the different seat positions corresponding to different occupant sizes.



Figure 12. Side Airbag Module.

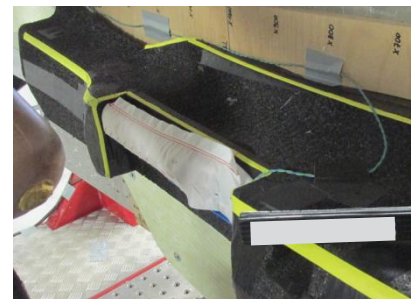


Figure 13. Side Airbag Module placed in door.

First Row Curtain airbag (CAB). (Figure 14). Main contribution of this curtain airbag is to avoid the front occupant's head contact against an external obstacle in pole test collisions, and to reduce the occupant's head excursion in barrier test collisions. The shape of the bag has been designed to cover the different occupant sizes.

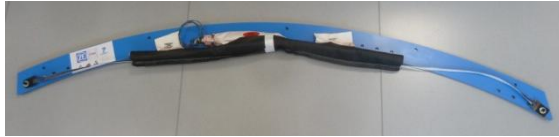


Figure 14. First row curtain airbag module.

Euro NCAP 2013 assessment

Three load cases according to the Euro NCAP 2013 procedures (ODB, MDB and Pole) have been evaluated in the BEHICLE program, including results of FE-models, sled tests and crash tests.

FE-models. FE-models according to Euro NCAP MDB load case have shown that in the case of no occupant restraint systems the ES-2 dummy's head contacts the composite Roof panel and the lower rib and abdomen area contact the BEHICLE door beam, see Figure A-1 of Annex A.

In a second step, it has been included a Top Belt with retractor pretensioners activated at a Time To Fire (TTF) of 8ms. In this case, the abdomen did not contact the door beam, showing the effectiveness of the Top Belt in terms of Pelvis and Abdomen restraint. However, the head still contacted the roof and the lower rib contacted the door beam.

Finally, in addition to a Top Belt, it has been included in the simulation models a side airbag placed in the door beam and a CAB placed in the roof. The TTF of both airbags, SAB and CAB, have been determined in order to be in position and filled with gas at the right time before the dummy contacts them. The optimal Time to Fire of the SAB was 10ms and of the CAB 40ms.

As shown in Figure A-1 of Annex A, the simulation showed that the head contact has been avoided as well as any dummy impact against the door beam thanks to the passive restraint systems. In addition, the CAB was able to avoid the head excursion outside the BEHICLE cabin and to provide a low neck bending.

As a summary, described in Figure 15, whereas the case without any passive restraint system provides a severe head contact to the roof metal plate and a high abdomen contact to the door, and the case with Top Belt only results in a contact between head and roof, in the case with all passive restraint systems these contacts are avoided and a good level of protection

close to the maximal Euro NCAP rating is provided (15.21 out of 16 points). Rating was only penalized in the back plate area due to the specific design of the frontal seat.

	No Passive Restraint Systems	Top Belt	Top Belt + SAB + CAB
Head assessment	0.00	0.19	4.00
Chest assessment	0.01	1.60	3.21
Abdomen assessment	0.00	4.00	4.00
Pelvis assessment	4.00	4.00	4.00
Total Rating	4.01	9.79	15.21

Figure 15. Dummy assessment in MDB configuration models without Passive Restraint Systems, with only Top Belt and with all Passive Restraint Systems.

FE-models according to Euro NCAP pole load case have shown similar results as FE-models with MDB configuration. It can be seen in Figure A-2 of Annex A that a contact of the dummy head, chest and abdomen to the BEHICLE interior parts is noticed in the baseline models. The Top Belt is able to reduce the dummy values in the abdomen area, and the inclusion of SAB and CAB reduces additionally the dummy values in head and chest area.

Therefore also in the pole load case, a good protection level is achieved close to the maximal Euro NCAP rating (15.03 out of 16 points) with the passive restraint system, only penalized by the influence of the frontal seat in the Back plate area of the dummy (see Figure 16).

	No Passive Restraint Systems	Top Belt	Top Belt + SAB + CAB
Head assessment	0.00	0.00	4.00
Chest assessment	0.00	2.99	3.03
Abdomen assessment	0.00	4.00	4.00
Pelvis assessment	4.00	4.00	4.00
Total Rating	4.00	10.99	15.03

Figure 16. Dummy assessment in Pole configuration models without Passive Restraint Systems, with only Top Belt and with all Passive Restraint Systems.

In case of Far Side impact, the integration of a 4 point seat belt system with pretension function helps significantly to control the pelvis and abdomen motion, improving the occupant kinematics. In addition, a thick SAB in combination with a CAB offer a good protection of the chest and head area due to its early contact with the occupant and large thickness. As a conclusion, restraint systems integrated in

BEHICLE allows to provide a good occupant protection of the centered driver in the case of far side impacts.

Sled tests have confirmed similar results than in previous FE-models. Apart from getting an acceptable reproduction of the BEHICLE behavior in both MDB load case, illustrated in Figure B-1 of Annex B, and Pole load case, illustrated in Figure B-2 of Annex B, the dummy injury values have reached similar results. All passive restraint systems have worked in a proper way: dummy is well coupled to the frontal seat thanks to the Top Belt System, the side airbag avoids any contact of the dummy torso to the door and the curtain airbag protects the dummy head.

In both MDB and pole cases back plate forces have been reduced in comparison with FE-models thanks to the smoothing of the frontal seat section, minimizing the interaction of the ES-2 dummy back plate with the lateral part of the seat and achieving the maximal rating of 16 points in the MDB and Pole load cases (see Figures 17 and 18).

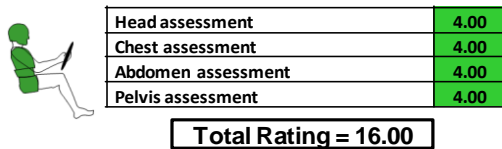


Figure 17. Dummy Assessment in MDB sled tests.

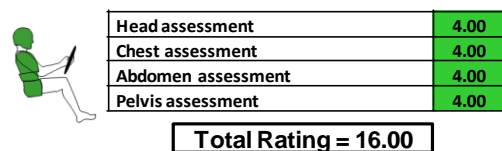


Figure 18. Dummy Assessment in Pole sled tests.

Crash Tests. Similar to the results of FE-Models and sled tests, final crash tests according to lateral MDB and pole Euro NCAP 2013 protocols achieved good dummy injury results, reaching a total of 15.24 points out of 16 in MDB configuration, and 15.66 points out of 16 in Pole load case, only penalized in both cases by the back plate of the dummy. This fact points out the necessity of smoothing the profile of the backrest of the frontal seat in order to improve back plate values. Results according to MDB load case are shown in Figures 19 and C-1 (Annex C); and results according to pole load case are shown in Figures 20 and C-2 (Annex C).

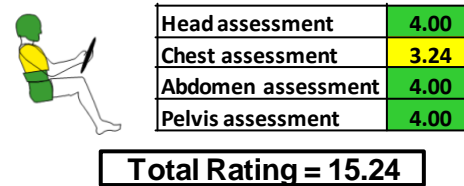


Figure 19. Dummy Assessment in MDB crash test.

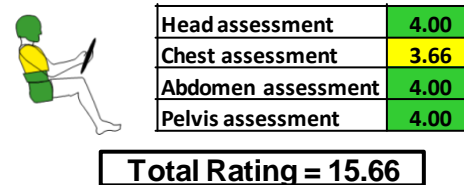


Figure 20. Dummy Assessment in Pole crash test.

Frontal ODB Assessment. In addition to lateral MDB and pole load cases, it has been assessed the BEHICLE performance in frontal impact according to Euro NCAP 2013 protocols in order to get the complete occupant protection assessment. Results in sled tests provided a rating of 14.20 points out of 16 points, which are shown in Figure 21. In a further step in the project a frontal ODB crash test will be done to confirm those results.

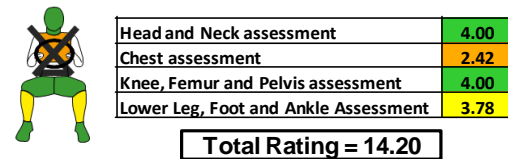


Figure 21. Dummy Assessment in ODB sled test.

Sled test were performed with a rigid steering column without collapsibility and energy absorption function; therefore, results in chest area could be significantly improved by implementing a collapsible steering column, absorbing occupant energy and increasing the distance to chest.

Euro NCAP 2016 assessment

Crash tests in BEHICLE program were performed according to the 2013 Euro NCAP protocols.

Additionally, in order to complete and update the investigation, the BEHICLE performance was also evaluated according to Euro NCAP 2016 protocols via FE-Models. Figure 22 presents the Assessment according to the four Euro NCAP 2016 load cases. Driver assessment reached the full score of 16 points in lateral load cases (AEMDB and pole), whereas it reached 13.56 points out of 16 on Frontal ODB load case and 12.26 points out of 16 points in Frontal FW load case.

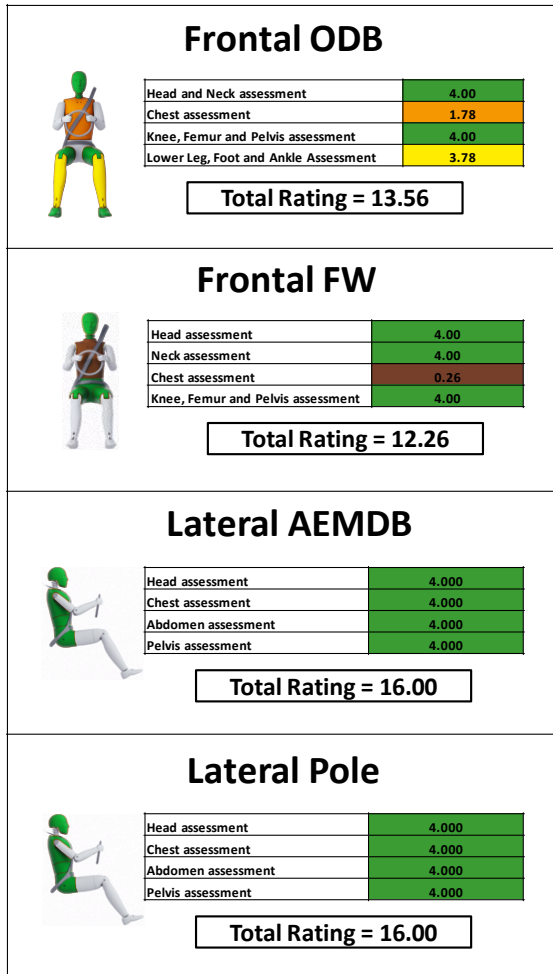


Figure 22. BEHICLE's Driver Assessment according to Euro NCAP 2016 protocols.

Euro NCAP quadricycle assessment

BEHICLE was originally conceived as a lightweight, subcompact urban electric car, aiming at balanced energetic performance whilst ensuring top-notch safety performance. According to the car classification standards it would fall within the supermini category. But with lower engine power it would fall into the L7e category; therefore, the BEHICLE was also additionally assessed according to the Heavy Quadricycle rating protocol by FE simulation: Figure 23 illustrates the dummy assessment, reaching 12 out of 16 points in FWDB load case and 14 points out of 16 in MDB load case.

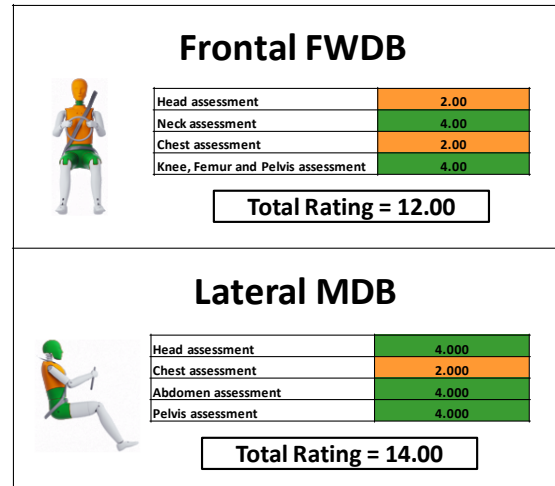


Figure 23. BEHICLE's Driver Assessment according to Euro NCAP protocols for quadricycles.

Benchmarking

BEHICLE has reached, according to Euro NCAP 2013 protocols, a rating of 14.20 points out of 16 points in ODB load case, 7.68 points out of 8 points in MDB load case and 7.83 points out of 8 points in pole load case, with a total rating of 29.64 points out of 32 points. BEHICLE is 0.91 points over the average of M1 – Supermini vehicles evaluated in 2013 according to Euro NCAP 2013 rating protocols (average rating 28.73 points) [1]. This is shown in Figure 24.

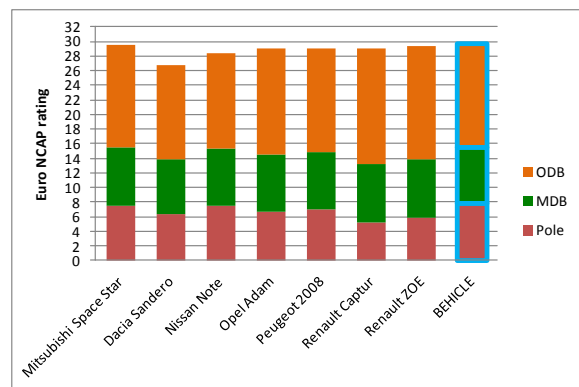


Figure 24. ODB + MDB + Pole Euro NCAP rating of M1 supermini vehicles and BEHICLE in 2013.

Comparing ODB, MDB and Pole rating assessment of BEHICLE's driver occupant with the average of M1 – Supermini vehicles evaluated in 2014 according to Euro NCAP 2013 protocols [1], which reached an average rating in the three load cases of 27.66 points out of 32 points, also illustrates that

BEHICLE is close to two points above the average (see Figure 25).

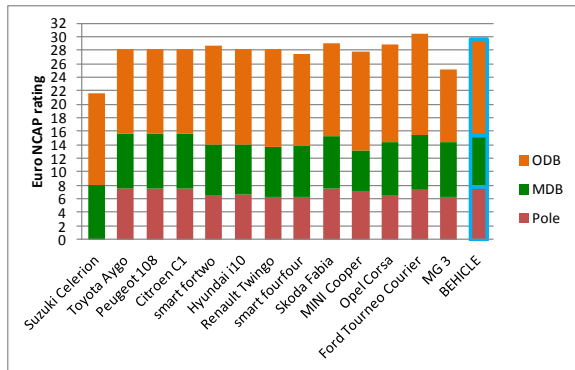


Figure 25. ODB + MDB + Pole Euro NCAP rating of M1 supermini vehicles and BEHICLE in 2014.

Regarding Euro NCAP 2016 [1], BEHICLE’s driver has reached 13.56 points out of 16 points according to ODB load case, 12.30 points out of 16 points according to FW load case and 16 points out of 16 points according to AEMDB and Pole load cases. Making a comparison with all M1 - Supermini vehicles assessed according to this Euro NCAP protocols, it can be observed that the driver BEHICLE rating in ODB and FW load cases is placed inside the range of the cars evaluated by Euro NCAP (see Figures 26 and 27).

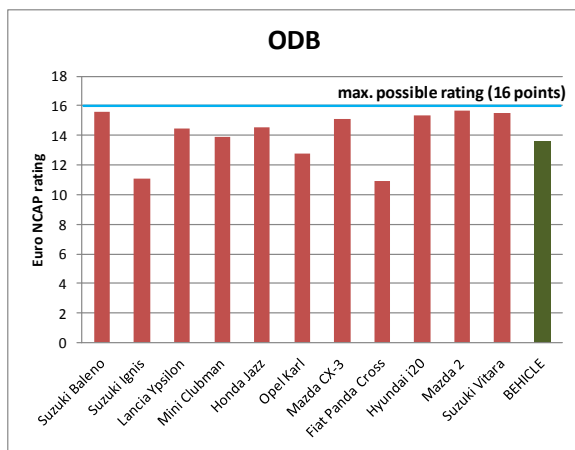


Figure 26. ODB Euro NCAP 2016 rating of all evaluated vehicles and BEHICLE.

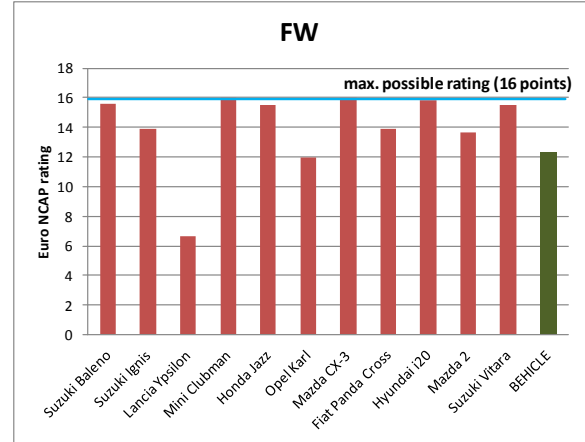


Figure 27. FW Euro NCAP 2016 rating of all evaluated vehicles and BEHICLE.

Concerning lateral load cases, BEHICLE has achieved the highest possible score in AE-MDB and Pole load cases (see Figures 28 and 29).

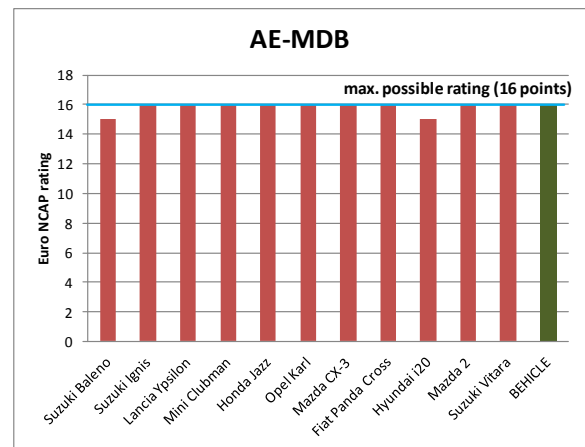


Figure 28. AE-MDB Euro NCAP 2016 rating of all evaluated vehicles and BEHICLE.

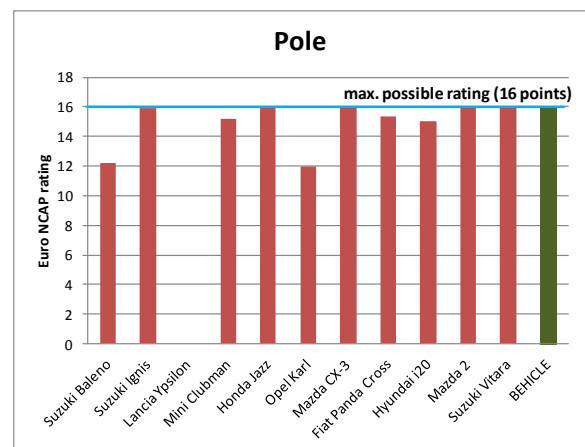


Figure 29. Pole Euro NCAP 2016 rating of all evaluated vehicles and BEHICLE.

Finally, according to the special protocols for testing heavy quadricycles [1], BEHICLE is able to achieve a total rating of 12 points out of 16 points in FWDB assessment, twice as high as the best quadricycle tested by Euro NCAP (see Figure 30: vehicles assessed in 2014 in blue, vehicles assessed in 2016 in green and BEHICLE in orange). In MDB assessment, BEHICLE has achieved 14 points out of 16 points, 4 points more than the best tested quadricycle, as indicated in Figure 31. With these results, as shown in Figure 32, BEHICLE is able to reach a total rating of 5 stars, far higher than the best quadricycle evaluated by Euro NCAP, which only reached 2 stars.

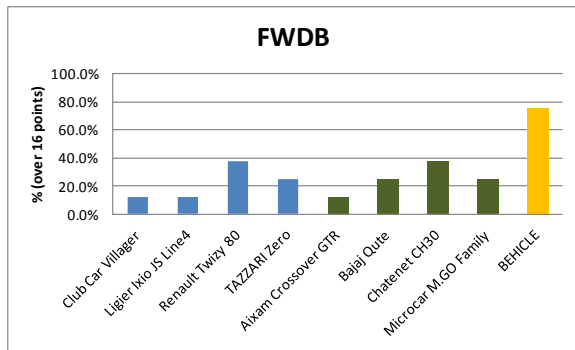


Figure 30. FWDB quadricycle assessment.

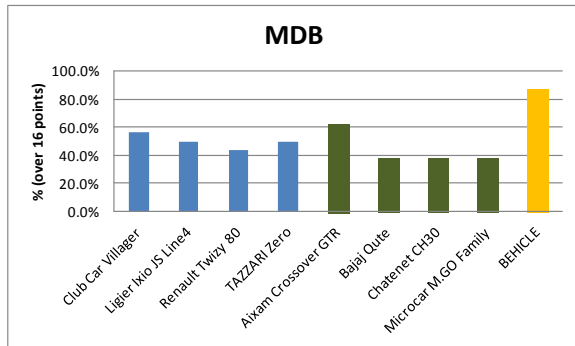


Figure 31. MDB quadricycle assessment.

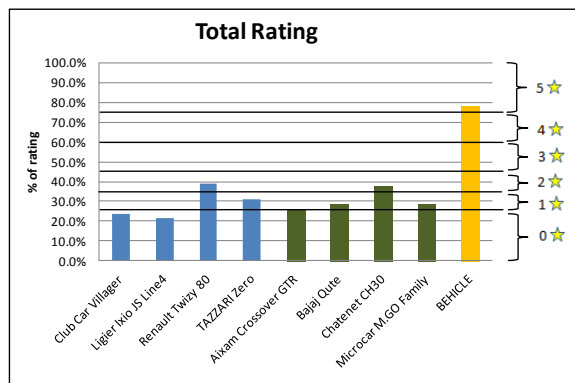


Figure 32. Total quadricycle assessment.

DISCUSSION AND LIMITATION

The presented development has demonstrated an equivalent protection level of BEHICLE in comparison with conventional Supermini cars based on the Euro NCAP ‘year 2013’ suite of tests, via FE – models, sled tests and crash tests. Since then, the Euro NCAP assessment has been further improved in terms of representativeness of real-world accidents. These improvements include a heavier barrier for the MDB test and the addition of a full width frontal test. BEHICLE was also evaluated according to Euro NCAP 2016 assessment, but only with FE simulations. In a similar way, BEHICLE evaluation according to protocols for Heavy Quadricycle was performed by FE – Models, not being validated in crash tests during this investigation. Even if the BEHICLE was not developed neither against the Euro NCAP 2016 assessment nor the Heavy Quadricycle assessment, it also has achieved a very good rating.

Occupant restraint strategy (in special concerning lateral impact) has been developed for the specific BEHICLE occupant seating layout with only one centred occupant in the first seat row. The case of light weight vehicles with a different seating layout with two occupants in the first seat row would need to be object of a specific study, due to the limited space from the occupant to the door.

BEHICLE offers a similar side protection level independently of the side of impact (near side or far side) due to the centred driver position, in combination with a symmetrical four point seat belt with pretensioning function, a thick side airbag and a curtain airbag.

Therefore, results in terms of occupant safety for far side impact will be equivalent to the results for near side impact.

Finally, other matter to be taken into account is the absence of collapsible steering column in BEHICLE. Experience in conventional vehicles has demonstrated that a collapsible Steering Column reduces the loads on the chest in the case of frontal impacts of vehicles, so it offers possibilities to improve the actual BEHICLE results in frontal impact load cases.

CONCLUSIONS

Despite the fact that light weight cars are limited by their low weight, composite materials have evolved to achieve a high resistance and reduced weight in comparison to traditional materials. This fact, in combination with a good passive restraint system strategy, as in BEHICLE, can offer a good level of occupant safety for the driver, similar to conventional

Supermini vehicles that are now on the streets, assessed according to Euro NCAP 2013 and Euro NCAP 2016 procedures, and much better than heavy quadricycles driving along the cities. Also good occupant protection in the case of far side impact was demonstrated.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to the European Commission for its financial support of the project BEHICLE: Best in class vehicle: Safe urban mobility in a sustainable transport value-chain. (Grant Agreement N°605292), a Seventh Framework Programme Project, THEME [GC.SST.2013-3.] within which the work presented here has been carried out. The authors also extend their thanks to all the BEHICLE project consortium members for their help, cooperation, open discussion and continued support.

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APPENDIX A. Dummy kinematics in FE-Models

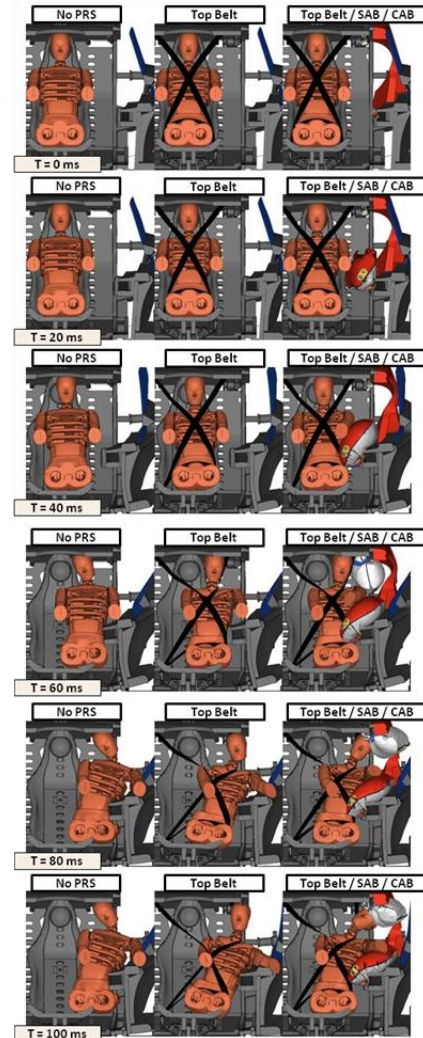


Figure A-1. Dummy kinematics in MDB configuration models without Passive Restraint Systems, with only Top Belt and with all Passive Restraint Systems.

APPENDIX B. Dummy kinematics in sled tests

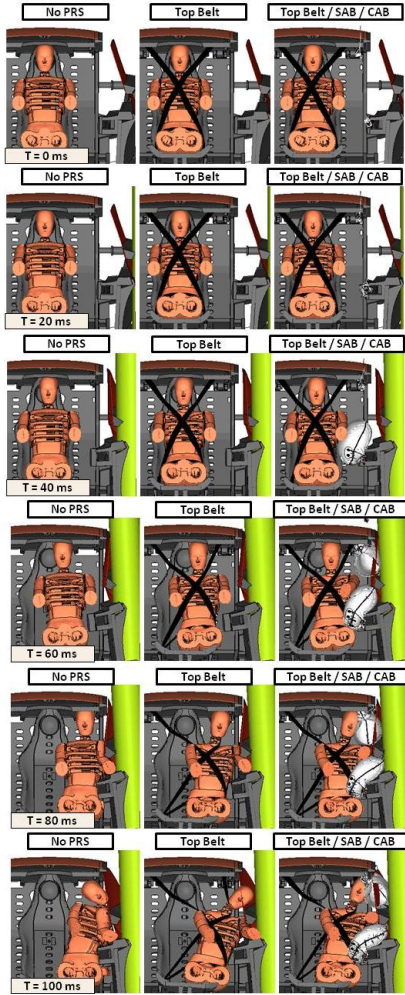


Figure A-2. Dummy kinematics in Pole configuration models without Passive Restraint Systems, with only Top Belt and with all Passive Restraint Systems.

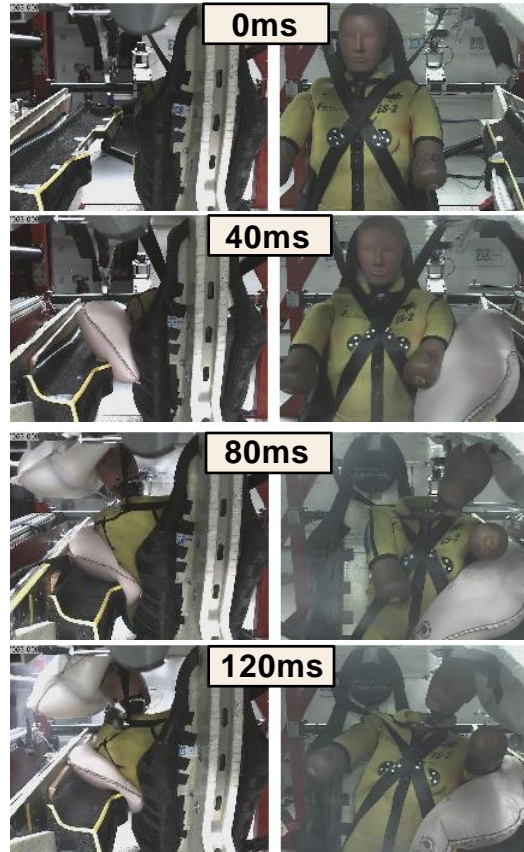


Figure B-1. Dummy kinematics in MDB sled tests.

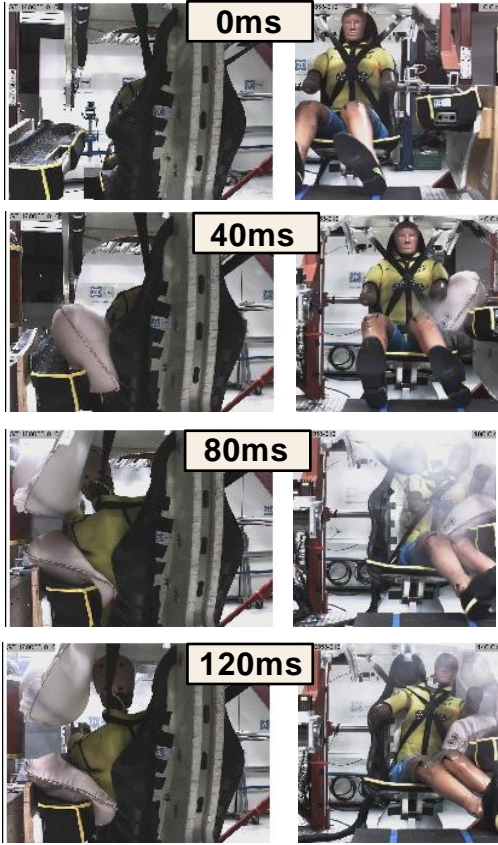


Figure B-2. Dummy kinematics and Assessment in Pole sled tests.

APPENDIX C. Dummy kinematics in crash tests



Figure C-1. Dummy kinematics in MDB crash test.



Figure C-2. Dummy kinematics in Pole crash test.