Mathias Stein, Heiko Johannsen, Johannes Holtz, Emiliano Core, Lothar Zink

Abstract Within this study the conceptual design requirements for lateral occupant protection for a light-weight electric vehicle with a centred driver seat are analysed. Based on the development of this vehicle two critical issues had to be taken into account: relative high Δv and known problems from occupant protection in far-side crashes. Due to the seating concept and the large space between occupant and interior, the neck kinematic and loadings were added to the standard Euro NCAP assessment of the investigated concepts. Therefore, a comparison with neck loadings that can be typically measured in Euro NCAP was done. The developed concepts are a combination of separate countermeasures (double pretensioner, side bag with increased thickness (thick airbag) and inflatable curtain) which were added to a standard 3-point belt with retractor pretensioning. The results show that only the combination of the countermeasures fulfilled the requirements. The thick airbag is able to fill the large space between occupant and interior to reduce chest, abdomen and pelvis loadings to an acceptable level. The inflatable curtain supports the head motion which leads to low head loadings and a reduced bending moment in the lower neck. Furthermore, the proposed concept offers good occupant protection in cases where the impact location altered from one to the opposing side.

Keywords centred driver, lateral impact, occupant protection, numerical simulation, electrical vehicle

I. INTRODUCTION

Following the political discussion of global warming and the political objective to support green mobility there is the objective to particularly support electrical mobility. One of the considered options for electric mobility is the use of small electric vehicles, i.e. L7e vehicles. While in principle for L7e vehicles no dynamic crash protection requirements are defined, there is an increasing demand for these vehicles with appropriate safety level. However, the current work focuses on the development of a light electric vehicle which offers the same passive safety level as conventional cars do.

BEHICLE – Best in class veHICLE

This study was undertaken to support the EC funded FP7 project BEHICLE[1] that is developing an electric vehicle with one front and two rear seats. The scope of the BEHICLE research project is to achieve a “best-in-class” rating with regard to the passive safety requirements as defined by Euro NCAP for a battery-powered electric vehicle (EV) with enhanced performance and a maximum total weight of 550 kg, including the driver as well as the battery pack. The starting point for the development of the BEHICLE is an existing urban EV, namely the QBEAK [1], manufactured by ECOmove. A special characteristic of the BEHICLE is the seating concept, see Figure 1. The example shows a 95%ile dummy used for ergonomic studies that was placed at the centred driver seat. The main advantage of this seating concept is the maximum comfort for almost all movements.

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[1] BEHICLE: Best in class veHICLE: Safe urban mobility in a sustainable transport value-chain (Project Number: 605292); http://behicle.eu/

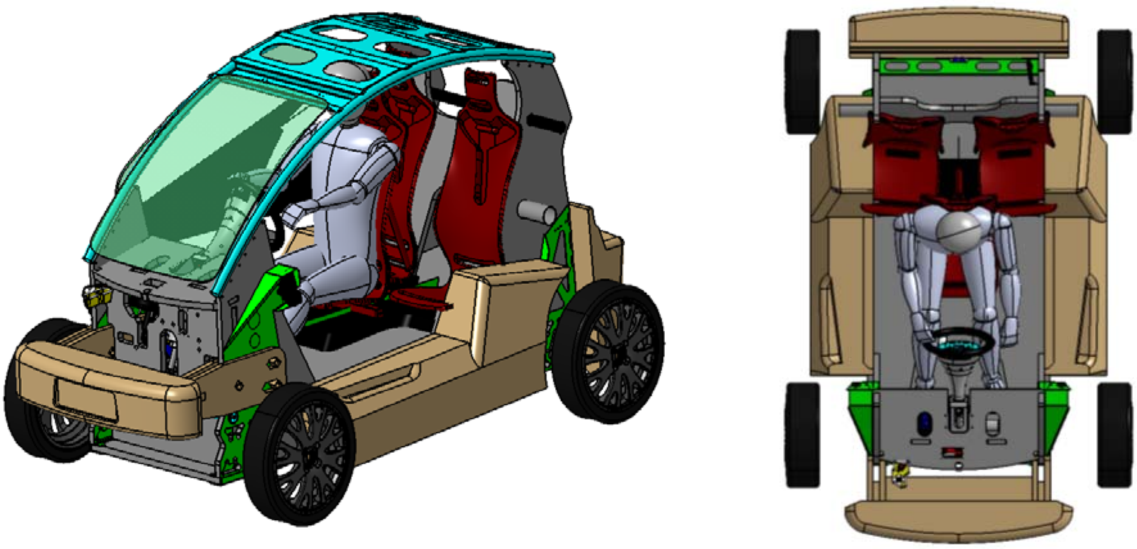


Figure 1: First BEHICLE design showing seating concept with centred driver (95%ile dummy)

To achieve the intended Euro NCAP rating special focus is on the occupant protection system for lateral impact. At this early stage of the BEHICLE development process, two critical issues were identified which necessitate the development of new concepts for protection systems:

- very low vehicle mass which leads to a high Δv
- centred seating position of the driver which leads to problems from far-side crashes

A third critical issue for the self-protection level of the BEHICLE is the integrity of the compartment. Former projects focussing on light-weight vehicles indicate that the relevance of the compartment integrity is not as important as the resulting change in velocity (Δv) [2-3]. Therefore, the assumption was made that the compartment of the BEHICLE can be defined as rigid for the assessment of the investigated concepts. Thus, a worst case scenario for the conception of the occupant protection systems for lateral impact was specified. Consequently, only the first two issues ((Δv) and centred seating position) will be taken into account for the present study which will be described more precisely in the following sections.

Crash Severity – Δv

One of the main objectives of the BEHICLE project is the compliance to the target weight of 550 kg. The assessment of the self-protection level of the BEHICLE in lateral impacts is done with Euro NCAP impact conditions. Where normally the mass of the test vehicle is higher than the mass of the barrier, here the weight of the BEHICLE is 550 kg against 950 kg of the barrier which is a mass ratio of 1:0.57 with regard to the BEHICLE mass. For the change in velocity this means a Δv of approx. 35 km/h (for k=0.1) and approx. 38 km/h (for k=0.2), respectively, for the BEHICLE, see Equation (1).

$$\Delta v_1 = v_1' - v_1 = -\frac{m_2 \cdot (1+k)}{m_1 + m_2} \cdot (v_1 - v_2) \qquad (1)$$

where:

$m_1;\ m_2$ masses of body 1 (BEHICLE) and 2 (side impact barrier)
$v_1;\ v_2$ velocities of body 1 and 2 before impact
$v_1';\ v_2'$ velocities of body 1 and 2 after impact
$\Delta v_1;\ \Delta v_2$ change in velocity of body 1 and 2
k restitution coefficient ($k = 1$ ⇨ fully elastic impact; $k = 0$ ⇨ fully plastic impact)

Thomas et al. [4] mention typical Δv values in Euro NCAP side impact conditions ranging from 22 km/h to 28 km/h, depending on the vehicle structures and the mass ratio. Hassan et al. [5] analysed the crash severity in lateral impacts of three different European crash databases (CCIS, LAB, GIDAS) for the years 1997 to 2004 and developed MAIS 2+ injury risk curves based on these data. According to this analysis the estimated Δv values for the BEHICLE were compared with typical Δv values in Euro NCAP side impacts, see Figure 2. While the risk to sustain a MAIS 2+ injury with typical Δv in Euro NCAP is approx. 10% to 30%, the risk for the BEHICLE occupant is approx. 30% to 60%. Taking into account an average vehicle mass of 1500 kg [6], the injury risk for MAIS 2+ injuries increases to 50% to 70%. Regarding the estimated Δv for the BEHICLE in Euro NCAP side impact, this means for the BEHICLE a more severe crash configuration than normally used within the development process.

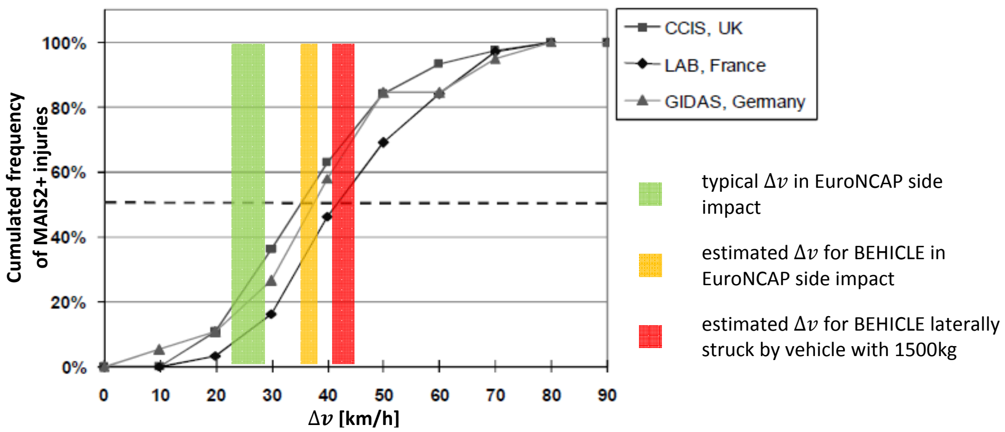


Figure 2: Estimated injury risk for BEHICLE in Euro NCAP side impact and struck by a vehicle with 1500 kg according to the cumulative frequency of MAIS 2+ related to Δv acc. to Hassan et al. [5]

However, the direct comparison of the crash severity based on a delta-v metric between conventional cars and the BEHICLE has to be made carefully. Generally the data shown in Figure 2 do not represent vehicles with a total mass comparable to the BEHICLE. Thus, the correlation between Δv and injury risk may vary as for standard cars higher delta-vs are normally correlated with greater intrusion while less intrusion from an identical delta-v is expected for the light-weight vehicle.

Due to the special seating concept of the BEHICLE, normal injury mechanisms that can be observed in lateral impacts with conventional cars (contact with the intruding side structure) may not occur in that specific case for the front seat occupant. However, the concept may result in other risks. Therefore, an analysis of the influence of an altered seating position is made in the following section.

Centred Driver – Far Side Crash

Theoretically, the centred seating position of the driver should offer a number of advantages in lateral impacts, which can be typically found as disadvantages for the occupants on the struck side in conventional vehicles. For example:

- a deformation zone is available,
- a large distance exists between occupant and vehicle structure,
- longer time is available to detect the impact and to activate the restraint systems.

However, analyses of far-side occupants in vehicles with conventional seat concepts indicated that occupants on the non-struck side of the crash are also at relative high injury risk [7-8]. Both studies specify chest and abdomen as well as the head as the most frequently injured body regions. Digges et al. [7] analysed NASS/CDS data and identified an injury risk for MAIS 4+ injuries of 45% for the head and 39% for the abdomen and chest. For the driver the contact with the opposite-side interior was the most frequent injury causation for AIS 3+ and the safety belt the second most frequent injury causation. Fildes et al. [8] mention that contact with the seat back of the adjacent seat caused nearly half of all AIS 2+ injuries of the chest, because the seat of the struck side moves into the trajectory of the occupant on the non-struck side. Furthermore, Fildes et al. proposed to improve the safety belt loading which should bring the most benefit to decrease the severity of abdominal and chest injuries. Fildes et al. observed that the safety belt or buckle caused 25% of AIS 2+ chest injuries and 86% of AIS 2+ abdominal injuries.

In several studies Bostrom et al. [9-10] and Rouhana et al. [11] investigated countermeasures to address the injury mechanisms observed in far-side crashes. The investigated countermeasures involved modified standard safety belts and side airbags. Regarding the safety belt systems, modified pretensioners and altered belt geometries were investigated to reduce the belt slack and restrain the occupant from moving inboard. The usage of side airbags focussed on avoiding direct contact between the occupant and the deformed side structure for the near-side occupant. As examples, the kinematics of different ATDs with different countermeasures (standard 3-point belt and 3-point belt upgraded with side airbag, extra shoulder belt and inflatable curtain) and test severities are shown, see Table 1.

Table 1: Comparison of dummy kinematics restrained with different restraint systems and different test severities acc. to Bostrom et al. [9]

	t = 001ms (t = 001ms)*	**t = 075ms (t = 050ms)***	**t = 150ms (t = 100ms)***
• 3-point belt • BioSid spring spine • $\Delta v = 24\ km/h$			
• 3-point belt + side airbag • BioSid spring spine • $\Delta v = 24\ km/h$			
• 3-point belt + additional shoulder belt • Thor • $\Delta v = 30\ km/h$			
• 3-point belt + inflatable curtain • WorldSid • $\Delta v = 50\ km/h$ • *			

Based on the kinematics of the ATDs shown in Table 1 and the corresponding dummy loadings, Bostrom et al. [9] could show that for Δv of 20 km/h to 30 km/h the risk of serious or fatal head injuries was reduced by 19% and 57%, respectively, assuming a 100% effectiveness of the restraint system. Regarding the higher test severity of 30 km/h to 50 km/h, the inflatable curtain has a potential to reduce the number of fatalities by 30%, assuming again 100% effectiveness of the countermeasure.

Assessment of neck loadings for centred driver in lateral impact

In preparation of this study the relevance of the neck loadings was observed. This led to the problem that the neck could not be taken into account for the overall assessment of the restraint system. Relative to the Euro NCAP rating scheme, the neck loadings are not relevant. However, due to the centred driver and the door geometry of the BEHICLE, the neck loadings become more relevant than in conventional cars.

In general no official injury assessment reference values (IARV) for the neck in lateral impact are available. Nevertheless, some proposals for the upper neck IARVs can be found in the literature. Referring to Lund [12] Fildes et al. [8] mention an IARV for lateral bending of the upper neck that has to be smaller than 143 Nm. Yoganandan et al. [13] conducted PMHS tests which indicate that the head-neck complex can tolerate 75 Nm at low axial loading without sustaining injuries. However, no description as to how to transfer these values to the dummy (ES2) used within this study was made.

Another approach is the comparison of the neck loads with those measured in Euro NCAP side impact crashes. Table 2 shows the upper and lower values of the neck measurements of seven vehicles in Euro NCAP side impact crashes, based on internal data of TRW [14].

Table 2: Upper and lower boundaries of neck injury values measured in Euro NCAP side impacts of seven vehicles [14]

	Injury values	min	max
Upper Neck	F_y [kN]	-0.3	0.5
	F_z [kN]	-0.4	0.8
	M_x [Nm]	-45	25
Lower Neck	F_y [kN]	-0.6	0.2
	F_z [kN]	-0.4	0.7
	M_x [Nm]	-30	40

Even though no estimation of an injury risk for the neck is possible, the comparison offers the possibility to assess the neck loadings with typical loadings in Euro NCAP side impact testing and thus to flag unusually high loadings. Due to the small number of cases used to estimate typical neck loads these reference values are more an indicator than a valid threshold value. To ensure robust conclusions further cases need to be analysed.

Objectives

The primary objective of this study was to identify an appropriate concept to ensure good occupant protection in a lateral impact, which has the potential for a “best-in-class” rating in Euro NCAP side impact testing in a light-weight vehicle with a centred driver seat, using the BEHICLE as an example. In addition to the primary objective a secondary objective was formulated to take the neck kinematic and the resulting neck loadings into account as well. Furthermore, the evaluation of the occupant protection concept from an altered impact location was proposed. Therefore, due to the centred seating position the performance of the restraint system for both side impact directions (from the left and from the right) was examined.

The estimated Δv of the BEHICLE (35 km/h to 38 km/h) in Euro NCAP side impact indicates a higher crash severity than typical for Euro NCAP side impact (22 km/h to 28 km/h). Looking at the centred seating position of the driver and the resulting relative high lateral distance between the interior and the occupant, analyses of occupant protection in far-side crashes were reviewed. Based on the knowledge of countermeasures proposed for far-side crashes, different types of restraint systems were used as a starting point for the development of final concepts, which are a 3-point belt with adapted pretensioner and a thick airbag instead of the head-thorax airbag. In addition the benefit of an inflatable curtain was analysed.

II. METHODS

The method section is divided into two main parts. First, a brief description of the simulation models is given. Two models are described which were used to compute the crash pulse of the BEHICLE and to assess the restraint system components. Second, the methodology used to analyse the occupant protection potential of the single countermeasure is explained. Based on these results concepts of combined measurements were defined and finally assessed.

Structural Simulation Model

As already explained in the introduction section, some assumptions were made for the FEM model. To compute a crash pulse that can be used for occupant simulation the BEHICLE model was simplified, see Figure 3, and is further referred to as simplified BEHICLE model. The compartment and all attached parts, except the tyres, were defined as rigid. Thus no intrusions into the cabin were simulated. One of the self-protection concepts of the BEHICLE is to use energy absorption modules with a high energy absorption capacity, attached to the front and rear as well as to the side structures. Because material characteristics of the final energy absorption modules (EA modules) are still unknown, it could not be taken into account for the side impact crash simulation. However, when assuming that no intrusion will occur, a rigid compartment can be assumed to represent the worst case with regard to the crash pulse. Another important assumption is the absence of the suspension system. Thus, the typical rolling due to the relative displacement between compartment and wheels also cannot be simulated.

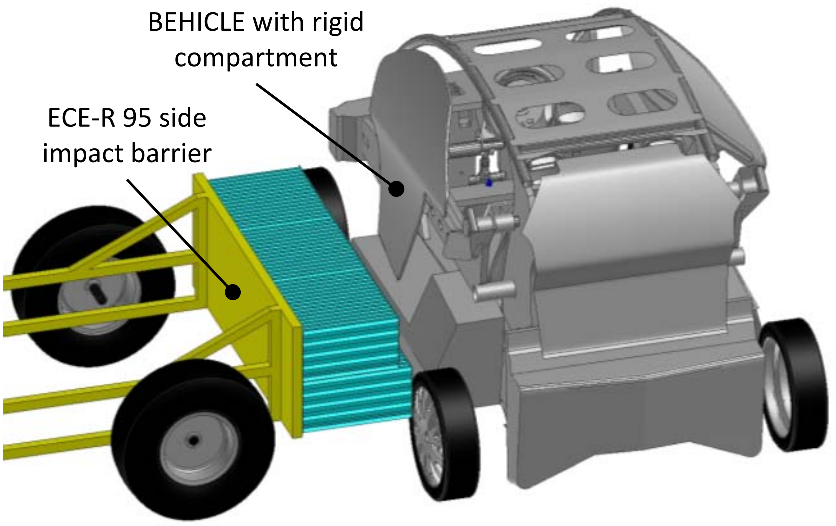


Figure 3: Structural simulation model to compute the crash pulse of the simplified BEHICLE FEM model in Euro NCAP side impact

Figure 4 shows the computed crash pulse of the simplified BEHICLE FEM model in a Euro NCAP side impact. Acceleration and velocity are displayed in lateral direction for the BEHICLE and in longitudinal direction for the barrier model. Up to 50 ms the acceleration loading was mainly controlled by the crush element of the side impact barrier. The acceleration peak of 25 g at 55 ms resulted due to the direct contact of the trolley with the rigid vehicle structures. The computed Δv is 32 km/h which is a little bit lower than the estimated Δv, but still higher than typically in Euro NCAP side impact crashes.

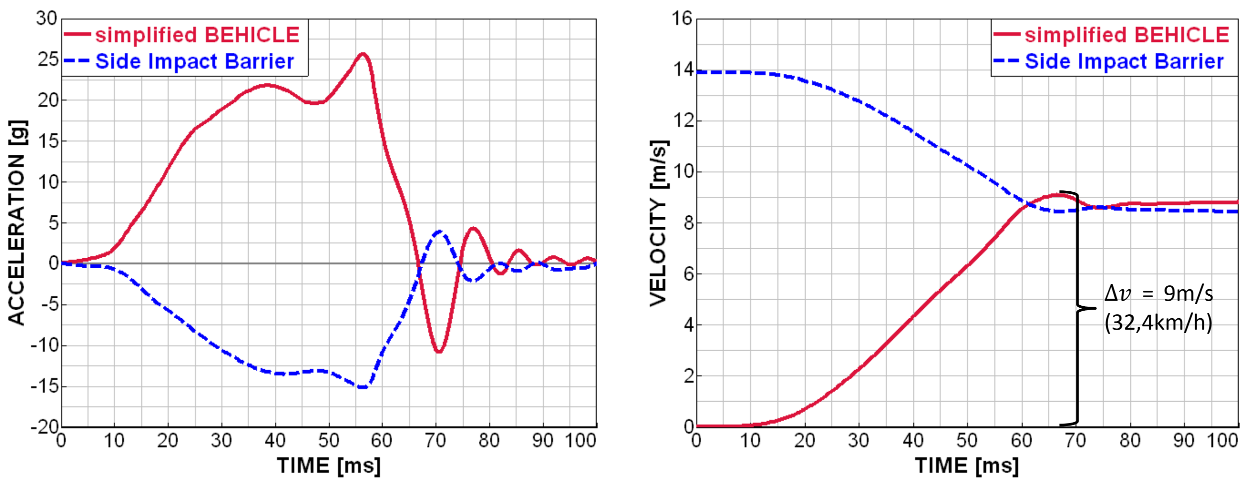


Figure 4: Computed crash pulse (a-t – left; v-t – right) of simplified BEHICLE FEM model in Euro NCAP side impact

The computed crash pulse (including components in x-, y- and z-direction) for the BEHICLE was transferred to a separate occupant simulation model which is explained in the following section.

Occupant Simulation Model

For the simulation of the occupant loadings the original seat of the BEHICLE was replaced by a generic seat model which represents important characteristics like compression of the seat foam and friction between occupant and seat, see Figure 5. Thus, a more generic occupant behaviour can be simulated.

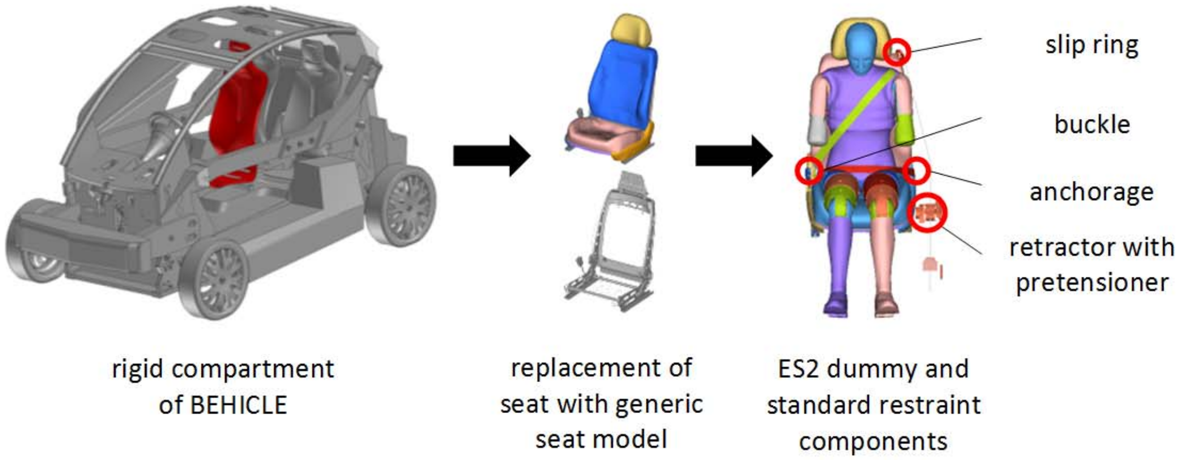


Figure 5: Components of the occupant simulation model

The dummy used for this study is an ES2 which is placed in a standard seating position according to the Euro NCAP side impact protocol. The dummy was restrained by a standard 3-point belt which was used for all investigations but modified and supplemented with additional components.

Countermeasures for Centred Driver in Lateral Impacts

An overview of the investigated countermeasures for a centred occupant is shown in Figure 6. In addition to the new restraint system components a baseline model was created containing standard restraint components that can typically be found in super-mini cars. These basic components are a 3-point belt with one retractor pretensioner and a conventional head-thorax side airbag.

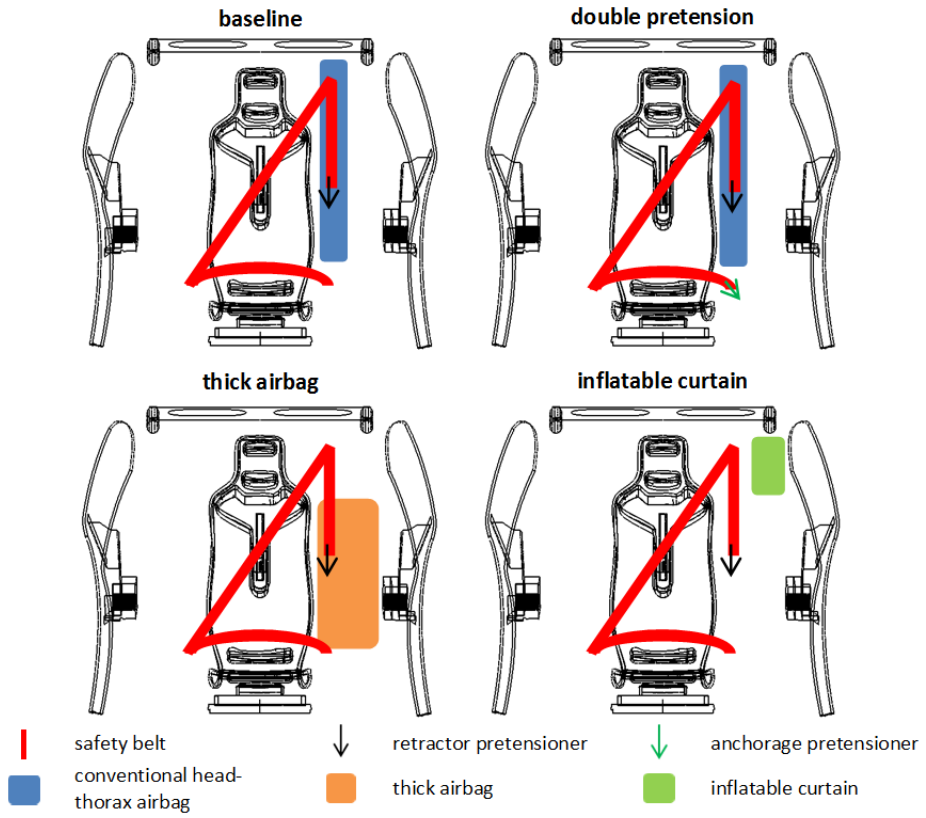


Figure 6: Schematic diagram of the baseline restraint system and the three investigated countermeasures

The first countermeasure is a modification of the baseline concept by using an additional pretensioner located at the belt anchorage and is further referred to as double-pretension concept. The basic idea is the better coupling of the occupant to the seat and the high reduction of the belt slack. In particular, the anchorage pretensioner helps to minimise the remaining slack in the lap belt. The second countermeasure uses a side bag with increased thickness referred to as a thick airbag instead of the conventional head-thorax airbag. The large volume of this airbag was designed to fill the available space between occupant and door. Therefore, the thick airbag covers the complete pelvis, thorax and shoulder of the driver. Currently the airbag module is integrated in the seat backrest like the conventional head-thorax airbag, but it could also be integrated into the door. Due to the higher volume the thick airbag enables higher impact energy absorption and a sufficient cushion. The third countermeasure is an inflatable curtain that should address potential contact between head and vehicle interior or intruding external parts. Furthermore, the inflatable curtain aims for improved head and neck kinematics of the driver.

III. RESULTS

The assessment of the dummy loadings was done with respect to the Euro NCAP side impact performance limits [15] proposed to achieve a maximum rating for the corresponding body regions. In addition, the kinematic of the dummy was analysed to assess the overall occupant behaviour and to identify critical configurations that are not covered by Euro NCAP assessment. In particular, the neck performance was observed and assessed according to typical neck loadings that can be found in cars in Euro NCAP side impact tests, see Table 2.

Initial simulations of the baseline model showed that the standard restraint system used was not able to provide an acceptable safety level. Due to the early time to fire (TTF) of 10 ms the internal pressure of the head-thorax airbag at the time of contact at 78 ms was already too low. Therefore, the baseline model was adjusted to create a better scenario. Simulations with a TTF of 40 ms showed the best results of the baseline restraint system, but due to the centred seating position and the large distance between occupant and interior, the conventional head-thorax airbag was not in an optimal position to support the head and thorax during the impact (e.g. head - HIC_{36}=1166; chest-T12 – M_x=323 Nm). An overview of the computed injury values of the adjusted baseline restraint system is given in

Table 3. In the following section an assessment of the separate countermeasures is done. Based on these findings, new concepts were created as a combination of the countermeasures which were assessed individually. Furthermore, the influence of an impact from the opposing vehicle side to the occupant restraint with a 3-point belt was done. These results were compared to the final occupant protection concept that was also simulated with an altered 3-point belt.

Results of Separate Restraint System Components

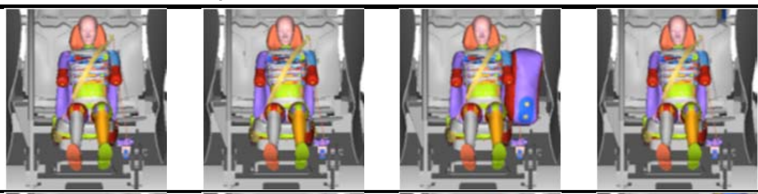
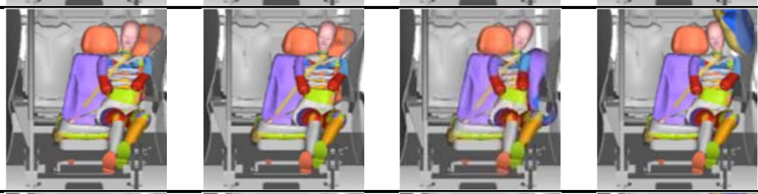
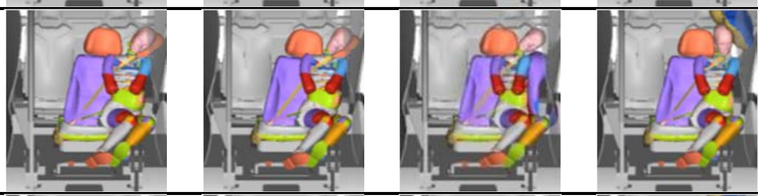
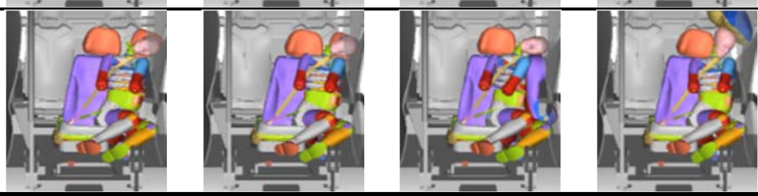
The following analysis was done with regard to the calculated injury values which are listed in Table 3. In addition the dummy kinematic is shown in Table 4. The analysis of the simulation results indicates that the design of the door beam is a critical part of the door. Due to the additional distance between the inner surface of the door beam and the door glazing, the door beam contacts the dummy between middle and lower rib which leads to a relative high compression of the ribs while the head has still no contact to the door glazing. This leads to a relative high bending of the neck in all four cases but only the inflatable curtain reduced the lateral head motion as well as the neck bending. The head-thorax airbag was not able to support the head kinematic in both cases, neither with retractor pretension nor with double pretension. The thick airbag provided the best protection of the chest. The thick airbag filled the large space as intended and could protect the dummy from contact with the door beam. The high forces of the backplate are due to the interaction with the seat frame. This effect is increased in case of double pretension. Even though the coupling to the seat was improved, the calculated backplate forces are increased. The abdomen was identified as being not critical in the BEHICLE. Due to the relative high position of the door beam no contact with the abdomen was observed which results in low injury values (0.1 kN to 0.5 kN). The loadings measured at the pelvis are on a relative low level (about 2.8 kN to 3.6 kN). However, as already mentioned the double pretensioner provided the best coupling of dummy and seat and therefore the pelvis loads show the best injury values of all four investigated countermeasures.

Table 3: Injury numbers of adjusted baseline restraint system and analysed countermeasures

	Injury values	Baseline	double pretension	thick airbag	inflatable curtain
Head	HIC_{36}	1166	1917	172	107
	Resultant $a_{3\,ms}$ [g]	79	75	33	28
Upper Neck	F_y [kN]	1.2	1.0	1.0	0.9
	F_z [kN]	1.5	1.6	1.3	1.0
	M_x [Nm]	47	49	64	52
Lower Neck	F_y [kN]	1.4	1.0	0.6	1.7
	F_z [kN]	1.4	1.4	1.2	1.4
	M_x [Nm]	156	185	164	108
Chest	Rib Compression [mm]	35	34	21	45
	Rib Viscous Criterion [-]	0.72	0.60	0.12	1.04
	T12 F_y [kN]	1.2	0.9	0.8	1.8
	T12 M_x [Nm]	323	225	146	435
	Backplate F_y [kN]	2.3	3.1	2.8	3.3
Abdomen	Lateral Force [kN]	0.1	0.1	0.5	0.1
Pelvis	Pubic Symphysis Force [kN]	3.4	2.8	3.0	3.6

pass higher performance limit | borderline values | failed higher performance limit

Table 4: Dummy kinematics for adjusted baseline restraint system and analysed countermeasures

	baseline	double pretension	thick airbag	inflatable curtain
40ms				
82ms				
98ms				
114ms				

The analyses of the kinematics show that in cases without the inflatable curtain the head kinematics are relatively poor. Therefore, a large bending in the neck occurs which results in a high bending moment in the lower neck (108 Nm to 185 Nm). Compared to typical values in Euro NCAP side impact testing, see Table 2, the loadings are two to four times higher. Even though this is not crucial for the Euro NCAP assessment, the assessment of the neck seems to be necessary in terms of a centred driver.

Assessment of Separate Countermeasures

A qualitative assessment of the simulation results is shown in Table 5. The assessment was done with regard to results of the adjusted baseline model. It can be seen that each countermeasure has advantages in different areas. The double pretensioning provides a very good coupling between dummy and seat. The thick airbag is the only countermeasure which offers acceptable protection to the chest and the inflatable curtain improves the head and the neck loadings as well.

Table 5: Qualitative assessment of the simulation results of the separate countermeasures

Body region	double pretension	thick airbag	inflatable curtain
Head	o	+	++
Upper Neck	o	o	+
Lower Neck	-	o	++
Chest	-	++	--
Ribs	o	++	--
T12	+	++	-
Backplate	--	-	--
Abdomen	o	-	o
Pelvis	++	+	o

-- high degradation - degradation o no change + improvement ++ high improvement

Theoretically, equipping the BEHICLE only with the thick airbag has a high potential to achieve the demanded "best-in-class" rating in the Euro NCAP test. However, according to the secondary objective to ensure acceptable neck kinematics and loadings, this countermeasure does not fulfil the requirements. Therefore, a combination of the countermeasures was done which is described in the following section.

Final Concepts and their Occupant Protection Potential

Based on the findings of the protection potential of the separate countermeasures, three final concepts were created, see Figure 7. The main objective of the new concepts is to improve the neck kinematic which was identified as critical even though the assessment of the neck loading could not be made objectively due to missing IARVs for the neck. Because the double pretension in combination with the thick airbag was not analysed yet, the combination of both countermeasures was analysed as well. However, focus is on Concepts 2 and 3 because the combination of the thick airbag and the inflatable curtain are the most promising concepts to achieve a good neck kinematic. The difference between these two concepts is the double pretension of the seat belt.

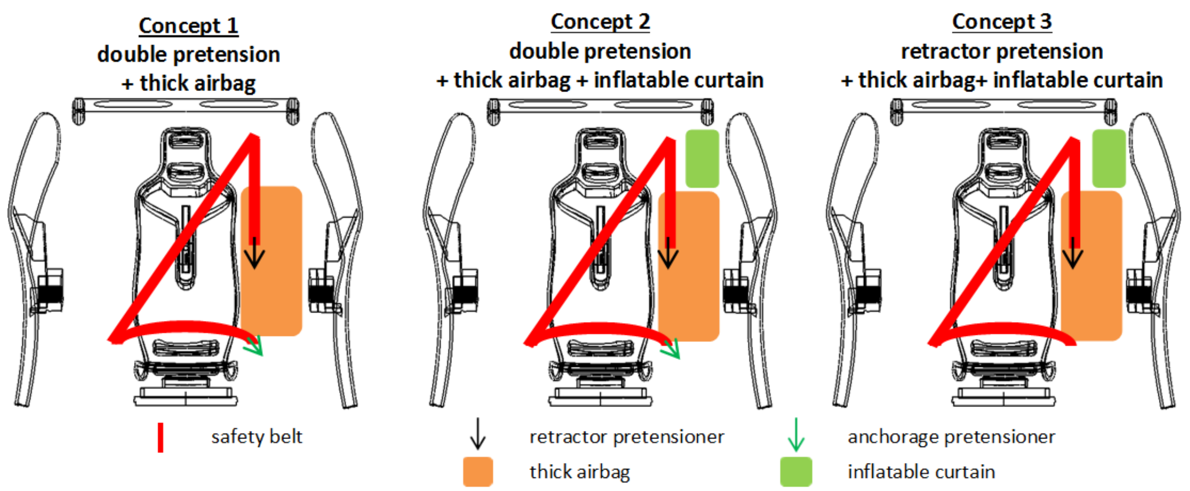


Figure 7: Schematic diagram of the three final concepts

The results of the simulated concepts are shown in Table 6. The injury values show the benefit of Concepts 2 and 3 in comparison to Concept 1. Due to the inflatable curtain the head loadings are smaller than without the curtain. However, due to the missing head contact with the interior the injury values are on an uncritical level. For the chest no critical issues could be observed. As already identified, the double pretension provides a good coupling between occupant and seat but causes higher backplate loadings due to the interaction with the seat frame. Without double pretension the measured forces in the pelvis are a little bit higher due to the interaction of pelvis and thick airbag.

Table 6: Injury numbers of the three final concepts

	Injury values	Concept 1	Concept 2	Concept 3
Head	HIC_{36}	212	129	127
	Resultant $a_{3\,ms}$ [g]	38	30	34
Upper Neck	F_y [kN]	0.7	1.0	0.9
	F_z [kN]	1.4	0.6	0.8
	M_x [Nm]	52	37	41
Lower Neck	F_y [kN]	0.9	0.5	1.0
	F_z [kN]	0.8	0.9	1.2
	M_x [Nm]	194	121	122
Chest	Rib Compression [mm]	23	23	21
	Rib Viscous Criterion [-]	0.13	0.13	0.12
	T12 F_y [kN]	1.0	0.9	0.7
	T12 M_x [Nm]	110	85	85
	Backplate F_y [kN]	3.5	3.5	2.9
Abdomen	Lateral Force [kN]	0.4	0.4	0.4
Pelvis	Pubic Symphysis Force [kN]	2.2	2.2	3.0

pass higher performance limit | borderline values | failed higher performance limit

With focus on the neck kinematics Concepts 2 and 3 show the expected benefit, see Figure 8. The inflatable curtain supports the head resulting in a reduced bending of the head. The decreased bending moment of the lower neck confirms the analysis of the kinematics. Compared to the neck reference values used within this study, see Table 2, the calculated values are still higher, but a clear improvement with regard to the separate countermeasures could be observed.

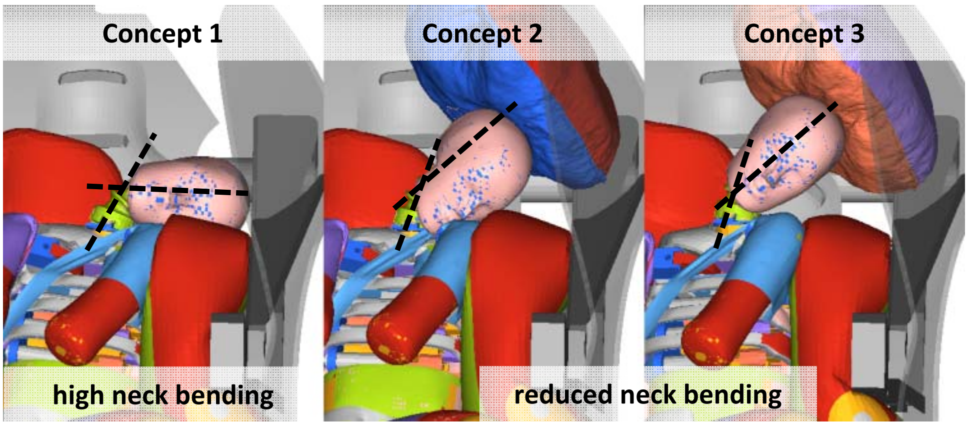


Figure 8: Neck kinematics of the three final concepts at 120 ms

Summarising the results from the simulated concepts, the main finding is that the combination of a thick airbag to protect the thorax and pelvis and an inflatable curtain to protect the head provides good protection to the centred occupant. In addition, the neck kinematic could be improved and the neck loadings compared to proposed threshold values indicate an acceptable performance.

Altered Impact Configuration – Mirrored seat belt geometry

One important question relative to a centred driver is the influence of an asymmetric belt geometry in the case that the impacted vehicle side altered. Basically the design of an occupant restraint system aims for an excellent rating in Euro NCAP. In this case the impacted vehicle side is clear. Furthermore, conventional cars always have the shoulder belt geometry going from the upper side structure to the lower tunnel in the middle of the car. In terms of the centred driver in the BEHICLE, an impact from the opposite side of the vehicle can be compared to a far-side crash configuration. To analyse the occupant protection potential for that case, the belt geometry of the 3-point belt was mirrored, see Figure 9. Two models were used to investigate the influence of the altered impact location, the adjusted baseline model (TTF=40 ms) and the Concept 2 (double pretension, thick airbag and inflatable curtain).

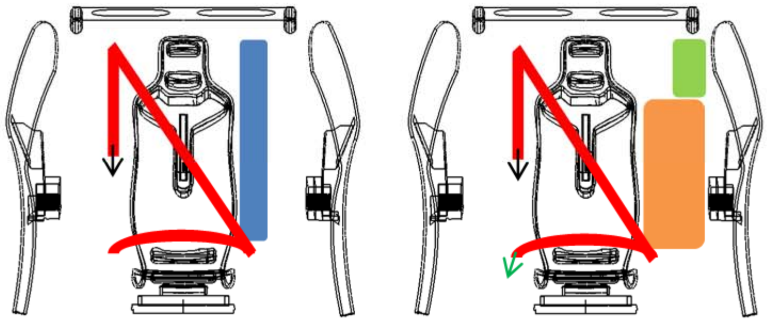


Figure 9: Schematic diagram of the baseline restraint system and the three investigated countermeasures

The analysis of the simulations with the mirrored seat belt clearly shows the advantage of the newly developed occupant protection concept. Due to the altered impact location the shoulder belt does not restrain the dummy, which results in a poor coupling between dummy and seat, see Table 8. However, the examined Concept 2 provided acceptable protection due to the thick airbag and the inflatable curtain. With no head contact, low head loading could be achieved, see Table 7. Due to the missing effect of the shoulder belt, the lateral movement of the dummy is higher than in the other cases. This affects the chest loadings due to the more severe impact of the door beam of the BEHICLE and the dummy.

Table 7: Injury numbers for altered impact location

Injury values		baseline	Concept 2
Head	HIC_{36}	7906	89
	Resultant $a_{3\,ms}$ [g]	116	25
Upper Neck	F_y [kN]	1.2	0.8
	F_z [kN]	6.6	0.8
	M_x [Nm]	65	50
Lower Neck	F_y [kN]	2.1	0.8
	F_z [kN]	7.2	1.0
	M_x [Nm]	161	127
Chest	Rib Compression [mm]	62	31
	Rib Viscous Criterion [-]	2.10	0.2
	T12 F_y [kN]	3.0	0.6
	T12 M_x [Nm]	237	147
	Backplate F_y [kN]	0.9	2.5
Abdomen	Lateral Force [kN]	0.1	0.4
Pelvis	Pubic Symphysis Force [kN]	3.9	2.1

pass higher performance limit | borderline values | failed higher performance limit

Table 8: Dummy kinematics for altered impact location

	40ms	82ms	98ms	114ms
baseline				
Concept 2				

The simulations of an altered impact location show that the investigated Concept 2 is able to provide good occupant protection in both impact scenarios. The inflatable curtain was able to protect the head, even in the case where the lateral restraint effect of the shoulder belt was insignificant.

IV. Discussion

The objective of this study was to deliver basic information about the occupant protection requirements for a centred driver in a light-weight vehicle and how they could be addressed by different types of restraint systems. Although FEM simulation is a standard tool within today's product development processes that provides reliable results, the limitations of numerical simulation and the validity of the FEM models need to be discussed. All presented results are based on numerical simulation only. Up to now no confirmation of the computed crash pulse as well as the investigated countermeasures and combined occupant protection concepts was done. Therefore all assumptions, in particular the rigid compartment, have to be evaluated within the development process of the BEHICLE.

Another relevant point is the usage of the reference values to classify the neck loadings. The assessment was done according to neck loadings of only seven cars in Euro NCAP side impact testing. The small number of cases does not allow a robust comparison to typical loadings in that impact scenario. Furthermore, no estimation of the injury severity for the neck could be made.

Finally, it is important to note that this study is based on investigations with a unique vehicle called BEHICLE. All results were derived with regard to the structural design and the special seating concept. Thus, the assessment of the countermeasures and the examined concepts cannot be transferred to conventional cars without review of the assumptions and boundary conditions.

V. Conclusions

The main objective of this study was to identify a concept for lateral impact protection of a centred driver in a light electric vehicle. The analysis was done according to the 2014 Euro NCAP side impact configuration. Due to the special car used for this study, two critical issues had to be taken into account: the relative low vehicle mass of the vehicle which results in higher Δv than typical for Euro NCAP and the centred driver which leads to problems known from far-side crashes. Additionally, the asymmetric belt geometry of the 3-point belt was analysed in two different impact scenarios with altered impact location (left and right side).

Three different countermeasures were analysed: a double pretensioner, a thick airbag and an inflatable curtain. The results show that each countermeasure provided individual benefits in different areas. While the double pretensioner provided the best coupling between occupant and seat, only the thick airbag was able to protect the chest on a relative low load level. Even though the thick airbag prevents the head from contact with the vehicle interior, the inflatable curtain provided the best head protection and improved the head kinematics as well.

In a next step a combination of the most promising countermeasures was analysed. The results showed that the concepts including a thick airbag and an inflatable curtain have the potential for the demanded “best-in-class” rating in Euro NCAP. Although the investigated double pretensioner decreased the assessment rating of the backplate due to the interaction with the seat frame, it is necessary to reduce the pelvis loadings.

Depending on the struck side of the vehicle, the protection potential of the shoulder belt of a 3-point belt can be insignificant, taken into account the centred position of the driver. Thus, the thick airbag and the inflatable curtain are the only effective restraint systems in the case when the impact location altered. However, the better pretension of the lap belt limited the lateral motion of the pelvis in both impact scenarios which is more relevant when the shoulder belt does not restrain the occupant in the case with the slip ring at the non-struck side.

The following conclusions can be summarised:

- basically the thick airbag is able to provide acceptable occupant protection in a lateral impact with a centred driver;
- due to the large space between occupant and side interior, the neck loadings are more relevant than in a lateral impact with conventional cars;
- to address the neck kinematic and loadings, a combination of thick airbag and inflatable curtain is necessary to reduce the rotation of the head and the resulting bending moment in the lower neck;
- the double pretensioner improved the coupling between occupant and seat but increased the backplate loadings.

Based on these findings the proposed concept is a combination of the following restraint systems: 3-point belt with pretensioner located at retractor and anchorage, thick airbag and inflatable curtain. This will provide good overall protection to all relevant body regions including the neck. To achieve the demanded “best-in-class” rating according to Euro NCAP assessment, the proposed restraint system needs to be optimised.

VI. Acknowledgement

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