Side-impact simulation study to investigate the protection of older child occupants in lightweight vehicles

Johannes Holtz, Michelle Tress, Christian Sobotzik, Heiko Johannsen, Jolyon Carroll, Steffen Müller

Abstract From 2016, the Euro NCAP side-impact test will be conducted with Q6 and Q10 child dummies installed in the rear of the vehicle. The use of larger dummies is likely to produce a much more challenging test due to the generation of larger head excursions and the greater likelihood of body contact with the vehicle interior. This scenario is particularly applicable to lightweight vehicles due to the limited space available in the passenger compartment and the typically high crash pulses experienced by this vehicle type.

This paper investigates the challenges of designing a lightweight electric vehicle that provides sufficient protection for older child occupants in side-impacts. Side-impact simulations, based on the Euro NCAP 2016 side-impact setup, were performed at 50 km/h in LS-DYNA using the mobile deformable barrier (MDB) instead of the Advanced European-MDB (AE-MDB). The results were analysed to examine the influence of crash pulse and compartment intrusion on dummy injury severity, and also to address the trade-off between pulse severity and intrusion level. The study is maintained by an accident data analysis with German In-Depth Accident Study data and installation tests with Child restraint system (CRS).

Keywords Lateral impact, occupant protection, numerical simulation, older child occupants, lightweight vehicle

I. INTRODUCTION

Due to their size, smaller cars are more likely to experience higher deceleration pulses and greater intrusion during side-impacts. This means that an occupant is more likely to make contact with intruding parts of the vehicle. It is important to solve this issue considering that future trends suggest that the number of small vehicles driven in urban areas is expected to increase.

In addition to a strong compartment structure, when designing such vehicles, designers must consider the use of deformable areas that absorb energy to reduce the vehicle pulse. However, the level of intrusion caused by this deformation must also be considered so that the risk of severe contact between occupants and the vehicle interior can be reduced. It would be useful to understand whether vehicle designers could increase the level of protection offered to larger child occupants by providing the right balance between pulse and intrusion. It is also important to consider whether there is currently an issue causing the protection of larger child occupants to be compromised due to a lack of compartment space, leading to interactions between a CRS and the vehicle interior.

Euro NCAP now has a strong focus on vehicle safety for occupants within small lightweight vehicles and for larger child occupants in conventional vehicles. In 2014, Euro NCAP launched a safety campaign, introducing new tests for quadricycles in a bid to increase safety. Additionally, from 2016, the Euro NCAP side-impact test must be conducted with larger child occupant dummies situated in the rear of test vehicles. The Q3 and Q1.5 child dummies, used in previous tests, have been replaced with the Q6 and Q10 dummies. In tests involving the smaller child dummies, the protection of Q3 and Q1.5 dummies is mainly influenced by the CRS and its installation. However, in cases involving the Q6 and Q10, the interaction between dummies, child restraint system (CRS) and vehicle interior is more important.

Due to the larger size and greater potential head excursion of these dummies, designers may no longer rely on the good performance of the CRS to ensure sufficient protection of child occupants. Therefore, vehicle design

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features (e.g. airbags, pretensioners) are expected to have much greater influence over the injury outcome of the larger child occupant.

Recent studies involving rear seat occupants tested in the 2016 Euro NCAP configuration mainly focus on frontal impact scenarios. Results have shown that in the Euro NCAP 2016 frontal impact test configuration, the Q6 and Q10 dummies are sensitive to restraint system parameters [1][2]. The side-impacts scenario is especially challenging for lightweight vehicles due to the high pulses expected [3]. No publication was found that investigates injury criteria of Q6 and Q10 dummies with respect to the Euro NCAP side-impact configuration. Additionally, the trade-off between pulse severity and intrusion level with regard to older child occupants has never been studied in side-impact tests.

II. METHODS

This study consists of an accident data analysis, CRS fitting analysis and a numerical simulation analysis in order to investigate the protection of older child occupants in lightweight vehicles. The accident data analysis investigates the injuries sustained by older child occupants in lateral impact cases. It also gives an overview of the general accident behaviour of small cars in side-impact accidents. The CRS fitting assessment studies the likelihood of interaction issues between a single CRS and the vehicle interior for several vehicle types. The aim of the assessment is to identify general geometrical issues at the vehicle-CRS-interface for the selected vehicle class. The numerical simulation analysis investigates the effect of altering pulse and intrusion levels on the performance criteria of the Q6 and Q10 dummies in Euro NCAP lateral impact tests. The outcomes of these analyses include recommendations to vehicle designers of small lightweight vehicles to prioritise specific design features in order to improve the protection offered to larger child occupants.

Accident data

The German In-Depth Accident Study (GIDAS) is the largest and most comprehensive in-depth road accident study in Germany. Since mid-1999, the GIDAS project has been investigating about 2,000 accidents per year in the areas of Hannover and Dresden, and it records up to 3,000 variables per crash. The project is supported by the Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT) [4]. The sponsors and the investigation teams have access to the data.

In GIDAS, road traffic accidents involving personal injury are investigated according to a statistical sampling process using the “on-the-scene” approach.

For this study, the accident data analysed was for the years 2005–2014 and relating to children using booster type CRS (high-back booster and backless boosters), sitting in a passenger car that collided with another car, a duty vehicle or with an object. Due to the low number of lateral impact cases involving children sitting in a struck passenger car using a booster type CRS, particularly when separated into car size classes, the data from lateral impacts without child occupants but meeting all other requirements mentioned above were included. The aim of this study was to investigate the general intrusion level and pulse severity of side-impact accidents depending on car classes.

CRS fitting Analysis

In order to analyse intrusion in a side-impact loadcase, it was necessary to analyse the available space and geometrical issues encountered during the installation of large CRSs recommended for large child occupants. Within the fitting analysis, various CRSs were statically tested in different vehicles. Until 2013 no requirement for car manufacturers was in force to offer good compatibility between high-back Booster CRS and the vehicle interior. Since then, the Euro NCAP child assessment protocol has required a CRS from the top pick list defined by Euro NCAP to be statically tested within the car and rated depending upon whether the seat may be installed in each position [5]. A high-back Booster CRS is included amongst the CRS that are installed during these tests. This study aims to examine whether small vehicles with limited space in the rear compartment area may be more likely to suffer from geometrical ‘fitting’ issues between CRS and vehicle interior when attempting to install high-back Booster CRS compared to other M1 vehicles.

CSC Car Safety Consulting has conducted fitting tests within vehicles since 2009, including semi-universal ISOFIX Booster CRS tested in various car models from between 1995 and 2015. The results included observations of geometrical interference between the CRS and the car, such as the reduction of CRS height adjustability caused by contact between the CRS and the car body.

This study compared the behaviour of very small M1-vehicles to larger M1 vehicles. Four models of ISOFIX high-back Booster CRS, approved according to ECE R 44/04, were selected based on the fact that they had previously been tested in a relatively high number of different car models. The selected CRSs do not fit in the envelope ISO N1068 due to issues with the headrest, which is in the highest position not inside the envelope. However, all of them were introduced in the market before the development of the new ISO envelope.

Fig. 1. CRS in lowest position.

Fig. 2. CRS in highest and widest position.

Figures 1 and 2 show images of the CRS used for the fitting tests in their smallest and largest adjustment positions. The car models studied within the database were classified into three classes based on their size according to the Federal Office for Motor Vehicles in Germany [6]. Investigated classes are mini (e.g. VW Up!, Ford Ka, Toyota Aygo), small (e.g. VW Polo, Ford Fiesta, Toyota Yaris) and other (all larger cars). The fitting analysis was performed to indicate geometrical issues between vehicle interior and CRS that affect the adjustment range in height or width of the CRS. The idea is to derive from the vehicle class and size problems in fitting CRSs.

Numerical simulation

In order to achieve good occupant protection in a side-impact scenario, vehicle designers aim to keep the side-impact pulse and intrusion as low as possible. However, for conventional vehicles under Euro NCAP test conditions, low crash pulse and low intrusion are mutually exclusive. Therefore, designers must strike a balance between pulse and intrusion in order to achieve good occupant protection, especially for supermini vehicles. FE-simulations were conducted to study different pulse severities with different intrusion levels.

The simulation model for this investigations is derived from the BEHICLE project (Best in class veHICLE), a 7th Framework Programme project, that has the ambition of creating a 'best in class' vehicle when tested against the Euro NCAP requirements within the protocols in force in 2013. The BEHICLE is a 600 kg electric M1-vehicle including batteries and driver. This FE-model is validated with a full scale side-impact crash test with the mobile deformable barrier (MDB) following the Euro NCAP protocol in force in 2013. To provide a good level of safety the vehicle was optimised within the progress of the project, which led to better intrusion behaviour of the door. These optimisations are within the validation corridor. This optimised full vehicle model was used for this investigation in a simplified derivate. The simplification left out the parts that had no contact to the child occupants (e.g. suspension, external body shell, powertrain). The chassis is a rigid body, only parts that may have contact to the dummies are deformable (e.g. door parts, rear seats and mid panel).

The load on the simplified model was implemented with prescribed motions that were derived from the full scale MDB-simulation. The pulse was simplified to allow better alteration, because the recorded pulse was highly oscillatory (Fig. 3). The initial pulse (Pulse 0) is now 25 g instead of 28 g. The intruding doorbeam was implemented with a prescribed motion loaded on the centre of the doorbeam (Fig. 4). The level of intrusion was directly derived from the full scale MDB-simulation (Fig. 3). For this study intrusion was implemented and measured at the middle of the doorbeam so that the intrusion observed in the rear seat was about a quarter of the numeral applied intrusion. The amount of intrusion in Pulse 0 is 155 mm in the centre of the doorbeam, an intrusion of 30 mm is observed in the rear seat region (Fig. 4). The simplified FE-model shows for the initial pulse good correlation to the full vehicle model.

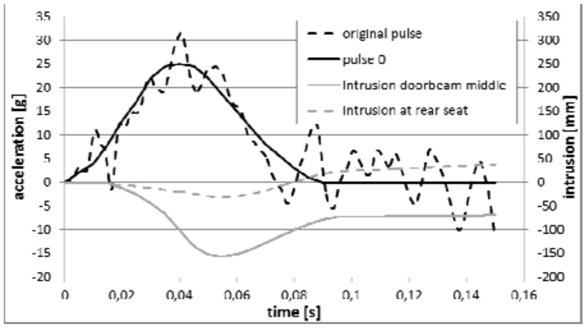

Fig. 3. Simplification of the pulse and intrusion.

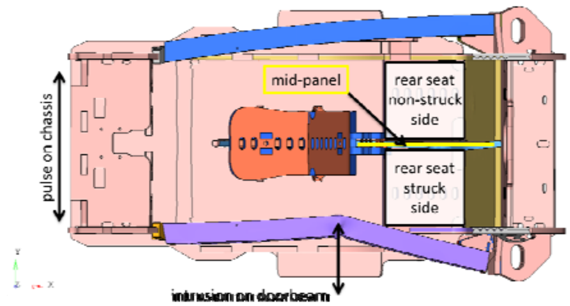

Fig. 4. Simplified FE-model and its prescribed motions.

Within the simplified model the pulse was scaled between 10 g and 40 g, with increments of 10 g. Intrusion was scaled between no intrusion and 300 mm, with increments of 100 mm. To begin with, the initial simplified pulse (25 g and 155 mm intrusion) was simulated. Table I shows the test matrix of the studied pulse and intrusion configurations. The initial pulse serves as base to evaluate the safety level of the investigated pulses.

Figure 4 also indicates the characteristics of the investigated vehicle with respect to the rear seat occupants. Both rear seats are separated from each other by a so-called 'mid-panel' that is manufactured from a sandwich panel. Due to this separation the movement of the non-struck-side occupant towards the struck side is restricted, preventing occupant-to-occupant contact. The driver seat is situated in the centre of the vehicle. This provides more legroom for the rear seat occupants but also provides a higher risk of lateral contact with the lower extremities. Initial simulations showed that the booster cushion raised the position of the Q10 higher, making head contact with hard structures close to the roofline more likely. It is recommended that the manufacturer of the vehicle take preventative steps to eliminate this harsh contact. To address this in the test, padding was added, which could also be replaced by a curtain airbag.

TABLE I
TEST MATRIX OF THE INVESTIGATED PULSES AND INTRUSION

		acceleration of chassis				
		10 g	20 g	25 g	30 g	40 g
intrusion of door beam	0 mm	Pulse 1	Pulse 5		Pulse 9	Pulse 13
	100 mm	Pulse 2	Pulse 6		Pulse 10	Pulse 14
	155 mm			Pulse 0		
	200 mm	Pulse 3	Pulse 7		Pulse 11	Pulse 15
	300 mm	Pulse 4	Pulse 8		Pulse 12	Pulse 16

According to the Euro NCAP protocol, the Q10 is positioned on the struck side and the Q6 dummy on the non-struck side to allow the greatest potential for high head excursions [7]. The Q6 dummy is required to be seated in a CRS with back rest, and the Q10 on a booster cushion CRS [7]. Within this investigation the use of the CRS was extended. In order to analyse its conflicts with intruding parts during a lateral impact, both dummies were investigated with a CRS with back rest, on a booster cushion CRS and without any CRS. Preliminary simulations showed that the contact within the first 120 ms was prevented due to the mid-panel, so it is not required to investigate all CRS variants with each other.

The CRS used within the simulations was the generic class 2/3 CRS developed in the CASPER project, which has movable wings in the head and chest area and a removable back rest [8]. This CRS is based on the Jane Indy Racing model and is applicable for basic kinematics analysis [8]. With respect to the availability of FE-models and the range of application, this CRS model is most suitable for this study. In Figure 5, the CRS is shown as booster cushion CRS (*left*) and CRS with back rest (*right*). A benefit of this seat is its general size. It was possible to position the seat within the vehicle without revising the vehicle interior or the CRS. In order to fit the Q10 dummy in the CRS, the maximum headrest position was beyond its adjustment range of 160 mm by an additional distance of 80 mm. The side wings of the CRS were moved upwards by 50 mm and 150 mm, so that the upper point of the wings had the same height level as the shoulder of the Q6 and Q10, respectively (Fig. 6).

The process of placing the CRS in the vehicle caused the inner chest wing of the CRS to bend towards the dummy (Q6 and Q10) due to contact with the mid-panel in between the two rear seats (Fig. 6). The outer wing of the headrest for the Q10 dummy was also bent towards the dummy due to contact with the B-pillar (Fig. 6).

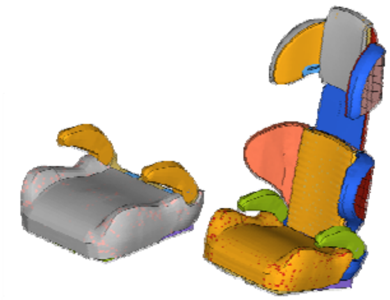

Fig. 5. Generic CRS as booster cushion (*left*) and with back rest (*right*).

Fig. 6. CRS placed in vehicle on struck side for Q10 dummy (interaction with B-pillar and mid-panel).

In the process of placing the dummies into the CRSs, the position of the legs for both dummies had to be adjusted due to interaction with the driver seat which caused the inner leg to move outwards. To prevent intersection between the upper arm of the Q10 dummy and the chest wing of the CRS, it was necessary to move the upper arms towards the thorax in the seating process. The CRS model used in this study does not fit in the envelope ISO N1068 for booster seats, nor do the CRSs from the fitting analysis, due to issues with the headrest. This envelope does not fit in the rear seat of the vehicle since there are several conflicts between the seat and the midpanel, the driverseat and outward chassis parts. This shows that the FE-Model of the CRS is geometrically comparable to the CRSs of the fitting analysis, but the installation of larger CRSs in cars with limited space in the rear seat should be checked individually.

The Model included a simple three-point belt with the buckle located at the outer edge. No retractor, load limiter or pretensioner was included, to simplify the model and to address all dummy responses to the pulse and intrusion level. Also, previous studies have shown that the effect of pretensioner and load limiter in comparison to a standard three-point belt shows no consistent pattern in side-impacts [9]. Figure 7 shows all simulations settings at t0.

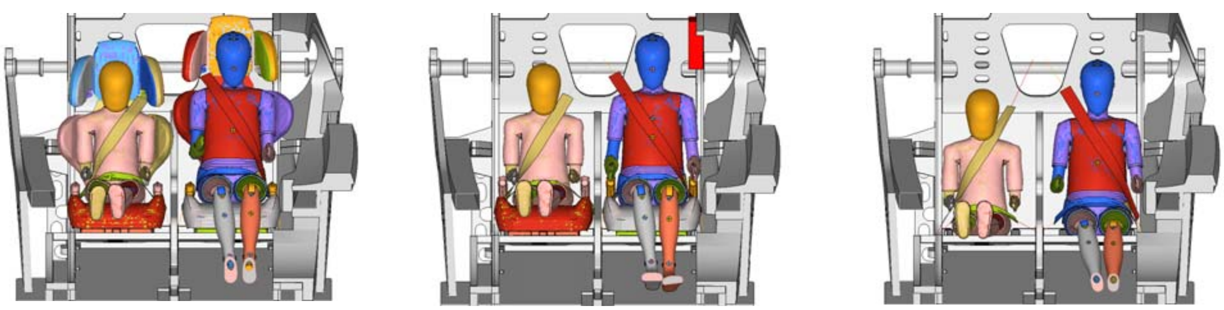

Fig. 7. Final position of all dummy-CRS combinations. *Left*: with back rest, *middle*: with booster cushion, *right*: without CRS.

The simulation data was analysed by assessing the dummy injury metrics against the criteria set by Euro NCAP. Table II shows the Euro NCAP higher and lower performance limits stated within the Child Occupant Assessment Protocol [5]. The simulations recorded additional dummy injury metrics, such as the pelvis a3ms, the chest deflection (for Q10 the maximum value from the upper and lower measurements), the shoulder force Y, the shoulder force resultant and the internal energy of the abdomen. All results were normalised to the results obtained from the initial pulse in order to determine the influence of pulse severity and intrusion level.

TABLE II
EURO NCAP INJURY CRITERIA FOR Q6 AND Q10 DUMMY [5]

	Q6		Q10	
	Higher	Lower	Higher	Lower
HIC15	500	700	500	700
Head a3ms	72 g	88 g	72 g	88 g
Chest a3ms	-	67 g	-	67 g
Neckforce resultant	-	2,4 kN	-	2,2 kN

III. RESULTS

Accident data

The analysed accident data showed a considerably low injury risk for children using booster seats in a passenger car in any kind of accident (Fig. 8). However, it is important to keep in mind the low number of cases available that fulfilled the inclusion criteria. The results were categorised using the same car size classes as used previously for the CRS compatibility assessment. The differences between the car size classes were not found to be relevant looking at the low number of cases and the possible variety of accidents. When looking at cases involving children that were seated in booster seats in cars that were struck laterally the number of cases drops down to 16 for children at the struck side and 23 for children sitting at the non-struck side. All sustained either no injury or MAIS 1 injuries. Therefore, no further investigation of these cases was carried out.

By including all lateral accidents (including cases without the involvement of children) it is possible to observe the different occupant loading conditions depending on the vehicle. For adults, only a small difference was identified between the different car sizes (Fig. 9). Although the differences were not statistically significant using the chi square test, the risk of severe injury for non-struck-side occupants tended to be larger in small vehicles.

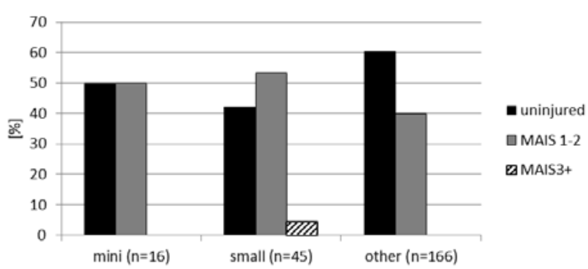

Fig. 8. Injury risk for children in booster type CRS in GIDAS lateral impact accidents 2005-2014.

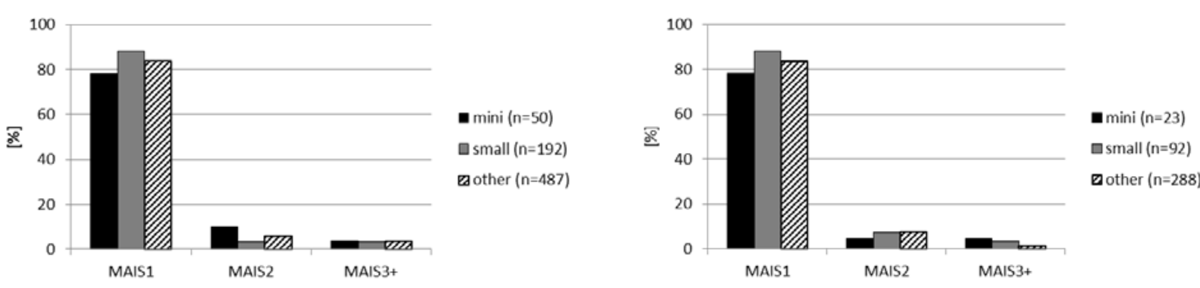

Fig. 9. Injury risk for adults in GIDAS lateral impact accidents 2005-2014.

The slightly higher injury risk for non-struck-side occupants in smaller vehicles and the similar injury risk at the struck side can likely be explained by the expected higher delta-v in lighter cars, as explained above, in combination with a smaller crush distance (Fig. 10). This is likely to be due to the compact design of the smaller vehicle, resulting in a greater involvement of structural parts such as A- and C-pillar.

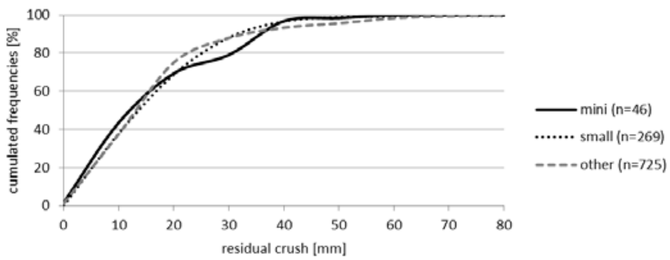

Fig. 10. Maximum residual crush in GIDAS lateral impact accidents 2005-2014.

CRS fitting Analysis

Table III shows the relative number of small, medium and other cars in which geometrical fitting issues between the car and the CRS occurred. A fitting issue means that the full use of the CRS adjustment range in height or width could not be accommodated. However, minor contact between the full height and width-adjusted CRS and a part of the vehicle interior was tolerated.

Figure 11 shows an example of a common fitting issue that occurs with high-back Booster CRSs. It was not possible to use the CRS in the highest position due to a contact between the upper part of the CRS and the C-pillar of the large family car shown.

TABLE III
COMPARISON BETWEEN CAR SIZE AND OCCURRENCE OF ISSUES WITH HIGH-BACK BOOSTER CRS

	CRS 1		CRS 2		CRS 3		CRS 4	
	Total no.	% of cars with geom. issues	Total no.	% of cars with geom. issues	Total no.	% of cars with geom. issues	Total no.	% of cars with geom. issues
Mini	24	33.3	16	43.8	28	3.6	10	10
Small	53	47.2	29	69.0	41	7.3	33	0
Other	317	25.2	279	31.9	384	8.9	178	0

Although in the majority of cases the CRS was tested in the same car models, the number of instances that each CRS encountered geometrical issues varied by a large amount. This could be caused by an apparent lack in geometrical guidance in UN Regulation 16 for Booster CRS, as the ISOFIX garbarits to check the geometrical compatibility are only applicable for integral ISOFIX CRS. Initiatives to address this issue are currently under consideration in the upcoming UN Regulation 129 Phase 2 and the analogue adaptation of Regulation 16 with the inclusion of a geometrical test device for high-back booster CRS [10].

Fig. 11. No full height adjustability possible due to contact between CRS and C-pillar in a large family car.

The results in Table III showed that CRS 1 and CRS 2 encountered the most fitting issues within smaller vehicles. With CRS 4, only one issue in one mini car occurred. All tests showed that problems were more likely to be encountered in mini vehicles than in small vehicles, although the total number of mini cars involved in the fitting study is too low to draw a definitive conclusion. Overall, no major differences in the ability to install CRS in mini cars were detected compared to the other M1 vehicles.

Numerical simulation

A large number of numerical simulations were analysed with respect to the initial pulse. The numerical simulation results from the initial pulse (25 g, 155 mm) showed that the use of a CRS with backrest gave the best protection for both the Q6 and the Q10 dummies when rated against the Euro NCAP protocol criteria (Table IV). Even with padding added to represent a curtain airbag, the head impact for the Q10 dummy on the booster at the struck side was very high, meaning that no points were awarded for head protection. The sum of the Euro NCAP rating for the Child assessment protocol (Q6 with CRS, Q10 with booster) shows that the general safety level of the vehicle is acceptable with 5 out of 8 points in Euro NCAP side-impact rating for both rear seat occupants. The analysis of the other simulation data gives an indication how altering the pulse and intrusion changes the safety level of this vehicle.

TABLE IV
EURO NCAP RATING FOR INITIAL PULSE (25 G AND 155 MM INTRUSION)

CRS	Q6 (unstruck)	Q10 (struck)
CRS with backrest	3.75	3
Booster	2	2
No CRS	1	2

Kinematic analysis

The kinematics of the Q6 dummy (non-struck side) were consistent. In simulations involving a Booster cushion and in simulations without CRS the head moved towards the struck side, while the thorax was stopped by the mid-panel. In these cases, high neck force and moment measurements were recorded. At higher pulse severities, the head made contact with the mid-panel, leading to high head accelerations. In simulations involving the CRS at the non-struck side, the head was protected by the headrest. It is important to note that the heads of the dummy did not remain contained in the CRS at pulses with 30 g or more. During the simulations at 40 g, the head of the Q6 dummy made contact with the CRS restraining the dummy at the struck side.

Kinematics of the Q10 dummy (struck side) with CRS were similar to the non-struck side. The head of the dummy was protected by the headrest, but at higher pulses and at the highest investigated intrusion the head of the dummy was not contained within the CRS. This also led to high neck loads, especially at simulations without CRS. Due to the higher seating position of the Q10 dummy on the booster cushion, the head made contact with the foam padding. This caused the head and thorax to be loaded equally by the side wall and the padding. This produced much lower neck loadings, but increased head acceleration readings. The kinematic analysis of the dummies showed that especially at higher pulses the coupling between CRS and dummy was not ensured. This could cause heavy impacts on interior parts. Due to the lack of coupling to the vehicle in absence of a backrest or the whole CRS the interaction with interior parts was even higher in simulations with booster and without CRS on both dummies. Especially the highest pulse with 40 g led to complex kinematics. Figure 12 show the kinematics at 75 ms for all simulation settings for the initial pulse.

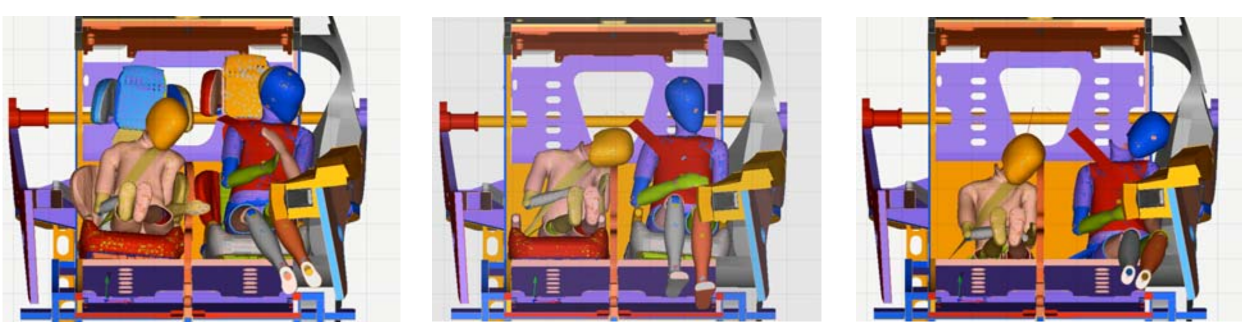

Fig. 12. Kinematics at 75 ms of all dummy-CRS combinations of the initial pulse. *Left*: CRS with back rest; *middle*: with booster cushion; *right*: without CRS.

Euro NCAP ratings for all load cases

Table V shows the Euro NCAP ratings for pulse 1 – 16 (see Table I) from all CRS variations with both dummies.

The points awarded correspond to the findings from the analysis of the kinematic behaviour. It is obvious that by reducing the pulse the rating is better. At pulses of 10 g a top rating is achievable without using a CRS. Pulses at 40 g were awarded with 1 or 0 points, with the exception of the Q6 secured in a CRS with backrest. The influence of intrusion level was not detected using the Euro NCAP ratings.

TABLE V
EURO NCAP RATING FOR PULSES 1-16 OF BOTH DUMMIES. *GREEN*: BETTER OR EQUAL TO PULSE 0; *RED*: WORSE THAN PULSE 0

			Acceleration in g											
			10			20			30			40		
			CRS	Booster	No CRS	CRS	Booster	No CRS	CRS	Booster	No CRS	CRS	Booster	No CRS
Q10	Intrusion in mm	0	4	3,70	4	3,44	2,60	3,42	2,58	2	2	1	1	1
		100	4	3,20	4	3,35	2,17	3,47	2,73	2	2	1	1	1
		200	4	3	4	3,70	2	4	2	1	2	1	1	1
		300	4	3,62	4	3,42	1	3,57	1	1	1	0,10	1	0
Q6	Intrusion in mm	0	4	4	4	4	2	2	3,79	1	1	2	0	1
		100	4	4	4	4	2	2	3,98	1	1	2	0	1
		200	4	4	4	4	2	2	2,72	1	1	2	0	1
		300	4	4	4	4	2	2	2,72	1	1	2	0	1

Relative injury data of all load cases

Beyond the Euro NCAP dummy assessment areas, other body regions of the dummy are interesting with regard to other injury criteria. To compare lots of injury criteria of various simulations it is helpful to concentrate the injury criteria of one dummy into one value. This was done by comparing each value with the corresponding value from the initial pulse simulation, to gain a percentage:

$$IC_{rel\_pulsei} = \frac{IC_{pulsei}}{IC_{pulse0}} \cdot 100\% \tag{1}$$

Where IC is one injury criteria of the recorded data (head a3ms, HIC15, maximum of resultant neckforce, maximum of lateral shoulder force, chest a3ms, maximum of chest deflection, maximum of inner abdomen energy or pelvis a3ms). To get one value for each load case, the mean value from every relative injury criteria was calculated. In table VI these mean values are specified for Q10 and Q6 dummy.

When comparing this data with the Euro NCAP rating the same trend is apparent: By reducing the pulse the injury criteria are better. By analysing this data, a lower intrusion level resulted in a lower injury criteria mean. This was also seen in the separated channel data of each injury criteria.

To summarise, the data in tables VI the secondary diagonal (pulse 4, pulse 7, pulse 10 and pulse 13) of every load case was observed (Fig. 13). The results show that by reducing the pulse but raising the intrusion level, the level of the investigated injury criteria will be lower also. With respect to the initial pulse it is possible to reduce the mean of all injury criteria by 20 % if the pulse will be decreased from 25 g to 20 g, but allowing 200 mm instead of 155 mm of maximum intrusion.

TABLE VI
MEAN VALUES OF ALL INVESTIGATED DUMMY READINGS RELATIVE TO INITIAL PULSE (VALUES IN %)

			Acceleration in g											
			10			20			30			40		
			CRS	Booster	No CRS	CRS	Booster	No CRS	CRS	Booster	No CRS	CRS	Booster	No CRS
Q10	Intrusion in mm	0	34	30	30	65	59	65	96	88	109	127	112	145
		100	41	36	30	68	68	71	98	96	114	140	121	143
		200	58	41	33	81	79	78	127	110	113	195	133	150
		300	98	58	48	128	95	103	185	123	141	247	151	192
Q6	Intrusion in mm	0	28	22	25	61	56	59	90	99	99	128	141	144
		100	35	24	26	69	64	64	97	105	101	131	143	144
		200	45	26	27	80	68	67	110	115	111	155	162	151
		300	82	40	30	110	75	75	145	127	113	180	200	160

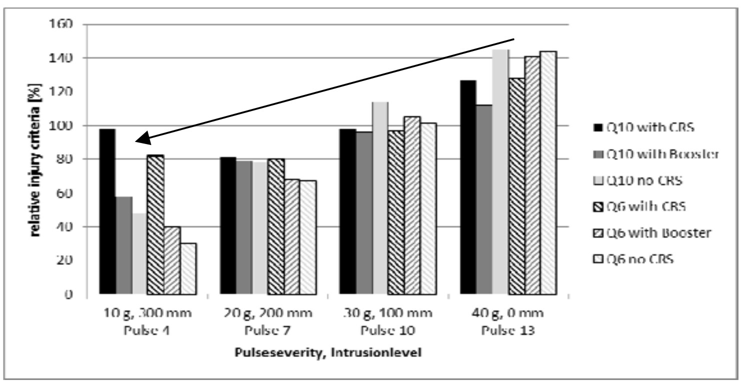

Fig. 13. Mean values of the secondary diagonal of the dummy loadings relative to the initial pulse (values in %).

Kinematic sequence

The dummy loading caused by intrusion is dependent on the kinematic sequence (e.g. the movement of the dummy towards the door beam whilst it is intruding into the car). If the thorax and head are loaded by intruding parts, the dummy measurements could be very high, even if the pulse was set very low. For example, Figure 14 show plots of relative shoulder force and chest deflection. The loading on the dummies positioned in a CRS on the struck side is higher for a 10-g-Pulse with 300 mm intrusion, than for a 40-g-pulse with no intrusion. The values for all other analysed dummy readings showed the opposite trend. This example and the analysis of the kinematics show that an intrusion that is too high will cause complex interaction with intruding parts and it is possible that some body regions will have lower injury criteria, but other body regions that interact directly with the intruding parts will be loaded more severely.

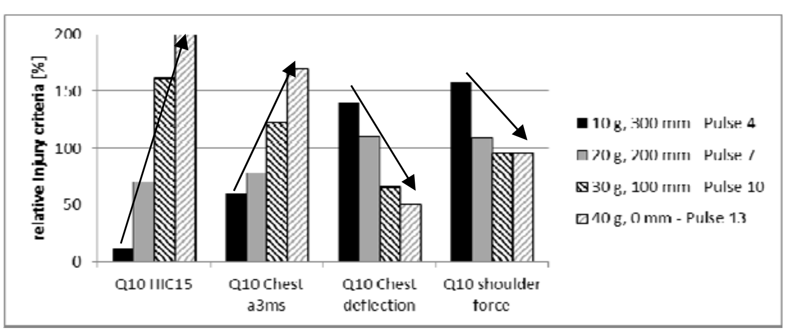

Fig. 14. Chest deflection and shoulder force show the opposite trend by altering the pulse and intrusion level than all other recorded dummy readings for Q10 on a CRS with backrest.

IV. DISCUSSION

The three phases of the study presented interesting outcomes worthy of discussion. The accident data analysis showed that, although case numbers are too low to make firm conclusions, children appear to be relatively well protected in lateral impacts in small cars. Furthermore, cases involving adults showed only minor differences in injury risk when comparing cases involving different car sizes.

The findings from the CRS fitting analysis indicated that there was no significant increase in fitting issues observed for Mini M1 vehicles in comparison to Small M1 vehicles. This suggests that vehicle designers of small cars design with a minimum compartment space in mind. However, this study did not evaluate the ability to install CRS either in multiple rear seat locations simultaneously or at the same time as another rear seat occupant. A much greater number of fitting issues would likely have been encountered in a study assessing vehicles where CRS must be fitted in all rear positions capable of having CRS installed at the same time – especially for cars with three seats in the rear row.

The numerical simulations showed that changing the pulse had a more influential effect over injury criteria than changing the intrusion. The effects of increased intrusion were minimal with low vehicle acceleration, but amplified in higher pulse cases. This effect was observed using dummy readings, the application of a Euro NCAP rating and through visual analysis. The results indicated that minimising the side-impact pulse should be a key consideration for lightweight vehicle designers. Designers may also consider compromising on an increased level of intrusion to reduce pulse severity.

Lowering the pulse was also shown to provide a benefit for the non-struck-side occupant. Visual analysis of the simulations showed that lowering the pulse could also reduce the amount of interaction between both occupants, such as head contact between the dummy Q10 and the other CRS.

Additionally, the kinematic sequence of the Q10 and Q6 dummies provided interesting results as unequal loading of different body regions caused some regions to show opposing effects (e.g. chest deflection and shoulder force in low pulse, high intrusion cases). This also shows that uninstrumented areas and areas that are not assessed by Euro NCAP should be taken into consideration. Additionally, due to the limited space in the rear seating positions, a lateral interaction between the centred driver seat and the legs occurred. The injury risk associated with this interaction was not classified within this study.

It is clear from initial simulations that hard structures close to the roofline of the BEHICLE presented a risk of harsh head contact for larger rear seat occupants. Remedial action in the form of a curtain airbag or padding is required to improve the head protection for the occupants. The aim of the BEHICLE project is to create a 'Best in class' vehicle. The performance of the car in comparison to other vehicles could not be conducted due to the lack of published results at the time of writing (March 2016). Additionally, the simulations were conducted using the pre-2016 MDB instead of the updated AE-MDB used in tests beyond 2016. This barrier is heavier and stiffer than the MDB, leading to higher deceleration pulses encountered during the side-impact test. This will provide an even greater challenge for smaller lightweight vehicles.

Based on the results of this study, it is recommended that designers of lightweight mini cars aim to lower the lateral pulse. To do this, designers should consider raising the intrusion level by 50 mm. When raising the intrusion level, the kinematic sequence should be considered to avoid injury risk from unequal loading of different body regions. Despite the limited space in the rear seats, it is recommended that designers ensure there is space to install a CRS with backrest for Q6 and Q10, either by considering the latest booster-seat envelopes or a CRS from the Euro NCAP top pick list.

The main limitation of this study was the simplified restraint system used in the numerical simulations. For future work, the interaction with a more realistic restraint system (e.g. curtain airbag and pretensioner) should be analysed. Also, an investigation with a CRS from the actual top pick list will produce results that are more comparable to the Euro NCAP 2016 results. In order to consider more designs of car interiors, it would be interesting to expand this study with a parametric car interior. Additional future side-impact studies with human body models could also provide more representative results.

V. CONCLUSIONS

In light of recent modifications to the Euro NCAP lateral impact assessment protocol, this study aimed to identify the main design considerations for small lightweight vehicles to protect larger child occupants effectively in the rear of vehicles. This study consisted of an accident data analysis, CRS fitting analysis and a numerical simulation analysis.

The accident data analysis does not support the expected higher injury risk in smaller cars.

The CRS fitting analysis investigated the likelihood of issues arising when installing CRS with backrests in vehicles of different sizes. Overall, the results showed that there was no significant increase in fitting issues observed for Mini M1 vehicles in comparison to Small M1 vehicles.

The numerical model was used to simulate several configurations of the Q6 and Q10 dummy in the rear of the vehicle during a side-impact. The dummies were analysed following the Euro NCAP protocol seated in two types of CRS and without any CRS. The effect of altering the pulse and intrusion levels on the injury assessment values of the Q6 and Q10 dummies was analysed against criteria set out in the Euro NCAP child occupant assessment protocol.

The investigation showed that reducing the pulse had a greater influence over improving the dummy injury values currently assessed during Euro NCAP tests. Therefore, the results indicated that minimising the side-impact pulse should be considered the top priority for lightweight vehicle designers. The results also show that an acceptable solution could be to allow some level of intrusion in order to reduce pulse severity and improve dummy injury readings.

Based on the results of this study, it is recommended that a CRS with backrest for Q6 and Q10 dummy is used to contain the dummy and, in particular, the head. Equally, curtain airbags should also be available in the rear of the vehicle to ensure sufficient protection of the head. A good coupling between the CRS and the dummy leads to controlled and uniform acceleration of the dummy, even with interaction from intruding parts. A good Euro NCAP score for the protection of both child dummies seems to be achievable for lightweight cars where designers have considered these recommendations.

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