Dummy Kinematics and Head Containment in Far-side Impact of Child Restraint Systems

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Abstract The assessment of child restraint systems in side impact has tended to focus on struck-side impact. However, far-side impact collisions also contribute to overall side impact injury rates. This study investigated the ability of different child restraint system designs to contain the head in far-side impact. Fourteen sled experiments were carried out with instrumented Q-Series dummies in a range of different child restraints, i.e., rear-facing, forward-facing, boosters. A test bench, used in European consumer (struck) side impact testing of child restraints, was mounted on the sled at 80° to the direction of travel. The sled acceleration pulse was derived from ISO/DTS 13396:2021.

Child restraint systems subject to a regulatory struck-side impact test achieved a basic level of performance in far-side impact. One exception was observed with the Q10 dummy in a booster seat. The struck-side regulatory requirements are reduced for this size dummy, which may have been a factor in the far-side performance we observed. There was a trade-off between the motion of the child restraint towards the far-side impact and head containment. Greater child restraint motion, particularly a sweeping motion around the vertical axis, was associated with better head containment than more limited rotation about the longitudinal axis only.

Keywords Child occupant protection, child restraint systems, far-side impact, non-struck side impact.

I. INTRODUCTION

Regulatory and consumer test procedures that evaluate the protection afforded by child restraint systems in side impact collisions tend to focus on the struck-side seating position. United Nations (UN) Regulation No. 129 replicates struck-side vehicle intrusion in a perpendicular, i.e., 90°, side impact sled test. The test conditions are intended to be broadly consistent with those of the vehicle side impact test for adult occupant protection in UN Regulation No. 95. UN Regulation No. 129 applies in the European Union as well as several other countries around the world, including Japan, Malaysia and Russia. The regulation was introduced in phases from 2013 and was mandatory for new child restraint type-approvals from 2020. Prior to this, child restraints approved to the previous regulation, UN Regulation No. 44, were not required to undergo side impact testing of any kind. However, European consumer testing of child restraint systems carried out by the European Test Consortium (ETC) has included a struck-side impact test in their child restraint system rating since 2015 [1]. The ETC side impact test procedure is carried out at 80° with slightly higher severity than the regulatory test. The United States has issued a notice of proposed rulemaking to amend Federal Motor Vehicle Safety Standard (FMVSS) No. 213 to adopt a side impact sled test for child restraints [2]. The proposed test procedure replicates vehicle intrusion in an 80° impact.

Efforts to develop a side impact test procedure for child restraint systems were initiated by the International Organisation for Standardisation (ISO) in the late-1990s. At that time, the risk of serious injury in a side impact was greater compared with other impact directions [3]. Although side impacts accounted for only 25% of collisions involving children, they represented over 40% of all injury costs [4]. The European Enhanced Vehicle safety Committee (EEVC) recommended that increasing protection of the head should be the priority, following a wide-ranging review of European collision databases [5]. EEVC also reported that intrusion was an important parameter and influence on the injury severity level. Similar findings were observed in the United States, where a significantly higher injury risk was observed for children seated on the struck-side of a crash compared with those on the non-struck side or in frontal impacts [6]. These findings, along with other studies from the time,

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informed ISO's work on a side impact test procedure for child restraints, which ultimately led to the development of the struck-side impact test in UN Regulation No. 129 [7].

More recently, interest has grown in the risk of injury to occupants on the non-struck side, or far-side, of a side impact collision. Much of the research focus has been on adults, where clear risks for far-side occupants have been observed. As far back as 2002, Reference [8] reported a high risk to far-side adult occupants from head contacts with struck-side structures. A study by EEVC found that 55% of occupants in single side impacts were on the far-side and 45% were on the struck-side [9]. Studies such as these, led to the development of the European New Car Assessment Programme (Euro NCAP) far-side occupant test and assessment procedure, which was introduced from 2020 [10]. However, the situation for children is less clear. Recent collision studies from Europe have found low rates of serious injury to children in child restraints in all impact directions [11-12]. However, the sampling strategies of the in-depth databases probably means that too few cases of children are being collected to draw meaningful conclusions [13].

Laboratory studies of the performance of child restraint systems in far-side impact have typically been carried out in the United States using products certified to FMVSS 213. These have observed poor head containment and the potential for head contact with intruding surfaces in some configurations [14-19]. However, the child restraint systems used in these studies were unlikely to have been designed for side impact or undergone significant side impact testing for either the struck- or the far-side. Furthermore, the child restraints often featured attachment methods that are specific to the United States, such as lap-only seat belts or flexible lower attachment straps and booster seats appear not to have been investigated at all. The main aim of this study was to investigate the ability of a broad range of common child restraint types to contain the head of the dummy in far-side impact. The secondary aim was to investigate whether struck-side impact protection in child restraints, as required by UN Regulation No. 129, or encouraged by ETC consumer testing, is also likely to convey a degree of far-side protection.

II. METHODS

Experiment Overview

Fourteen far-side impact experiments were carried out on an acceleration sled at the CYBEX Safety Centre in Germany. Q-Series child dummies were restrained in a convenience sample of child restraint systems installed on a test bench mounted on the sled at 80° to the direction of travel. The sled pulse represented the struck vehicle chassis acceleration of a passenger car struck by another car at 50 km/h. The experiment matrix is shown in Table I.

TABLE I
TEST MATRIX

		Child restraint system			Consumer	Dummy
Seat #	Orientation	Type	Attachment	Type-approval	test score	
A1	RF	Infant carrier	ISOFIX & SL	R129	3.2	Q1
A2	RF	Infant carrier	ISOFIX & SL	R129	1.4	Q1.5
A3	RF	Infant carrier	Adult belt	R129	1.0	Q1.5
B1	RF	Child seat	ISOFIX & SL	R129	1.0	Q3
B2	RF	Child seat	ISOFIX & SL	R129	3.1	Q3
B3	RF	Child seat	Adult belt & LT & SL	R44	2.5	Q6
C1	FF	Child seat	ISOFIX & SL	R129	1.0	Q3
C2	FF	Child seat (shield)	ISOFIX & SL	R129	1.0	Q3
C3	FF	Child seat	ISOFIX & SL	R129	3.1	Q3
C4	FF	Child seat	Adult belt	R44	2.0	Q3
D1	FF	Booster seat	Adult belt	R129	1.3	Q10
D2	FF	Booster seat	ISOFIX & adult belt	R129	1.3	Q10
D3	FF	Booster seat	ISOFIX & adult belt	R129	1.8	Q10
D4	FF	Booster cushion	Adult belt	R44	n/a	Q10

SL (Support Leg); LT (Lower Tether)

ETC Consumer test score: 0.6 - 1.5 (Very Good); 1.6 - 2.5 (Good); 2.6 – 3.5 (Satisfactory); 3.6 – 4.5 (Sufficient); 4.6 – 5.5 (Inadequate)

Far-side Test Set-up and Conditions

The European consumer side impact test bench was used in the study, primarily because it is already configured for mounting at 80°. This orientation was used to provide a more challenging test environment than purely lateral impact. The consumer test combines the test bench with a real vehicle three-point seat belt. This was replaced with the retractor and seat belt system used in UN Regulation No. 129. The consumer test mounting points were used to avoid making adaptations to the test bench. In the consumer test, the retractor is mounted on the bench just behind the top of the seat back.

The struck vehicle acceleration corridor in ISO/DTS 13396:2021 was used to replicate the far-side impact conditions [7]. The corridor peaks between 10 and 14 g and was derived from impact tests of vehicles according to UN Regulation No. 95 (50 km/h impact with the 950 kg trolley with the EEVC Mobile Deformable Barrier face). The sled velocity change was 25 km/h. This represents the theoretical velocity change of a car being struck by another car of the same mass travelling at 50 km/h.

Dummies and Child Restraint Systems

Five instrumented Q-Series dummies were used: a Q1, Q1.5, Q3, Q6 and a Q10. The dummies were manufactured by Humanetics, Germany, and certified and prepared for testing in line with their user manual. The specific dummy chosen for each experiment corresponded to the upper stature limit for each child restraint as this was likely to be the worst-case for head containment. A convenience sample of child restraint systems from different manufacturers were used comprising infant seats, child seats and boosters, with the aim of covering all of the main types from birth to 150 cm (the legal threshold for adult belt use). The sample included different seating orientations (rear- or forward-facing) and attachment methods (ISOFIX or three-point seat belt). The ETC side impact test score was obtained from Reference [20] for all of the child restraints to ensure that a range of struck-side impact performance was covered where possible. This led to several child restraints being chosen for the study primarily due to having a lower ETC score than other child restraints of the same type, e.g., Seats A1, B2, C3 and D3. An ETC score was not available for Seat B3, so the score from a similar, but now discontinued seat from the same manufacturer is shown in Table I.

Most of the child restraints were type-approved to UN Regulation No. 129. Three exceptions were Seat B3 (rear-facing belt-attached child seat), Seat C4 (forward-facing belt-attached child seat) and Seat D4 (booster cushion), which were all approved to UN Regulation No. 44. At the time of the study, UN Regulation No. 129 had only recently been extended to include these child restraint types and it was impossible to find any examples on the market. Instead, best-performing belt-attached child seats, according to the ETC side impact score, were chosen to give a level of struck-side impact performance consistent with the other, i.e., Regulation No. 129, child restraints in the sample. However, booster cushions are not typically rated by ETC and are not required to undergo side impact testing in UN Regulation No. 129, so a common Regulation No. 44 product was chosen.

All dummies and child restraint systems were installed according to the procedure specified for impact testing in UN Regulation No. 129. In addition, for each installation, particular care was taken to ensure the centreline of the dummy and child restraint were aligned with the centreline of the seating position. This provided a consistent starting position for each test.

Data Analysis and Assessment Measures for Far-side Impact

All measurement and data analysis conformed to ISO 6487. The main UN Regulation No. 129 assessment criterion for side impact was calculated for each experiment, namely the resultant head acceleration (cumulative 3ms value). HIC_{15} is also specified in Regulation No. 129, but was not used as significant head contact was not expected in these experiments. The upper neck tension force is specified in the regulation for *monitoring purposes* and was used in this study due to the inertial nature of the neck loading expected in these far-side impact experiments.

The peak lateral head excursion was determined relative to the centre of the seating position on the test bench. Video analysis was carried out from the top view high-speed camera, using commercial software with automatic parallax correction (FalCon eXtra). Two fixed five-point MarkerXtrackT (MXT) markers on the backrest of the test bench were used to identify a 2D coordinate system oriented parallel to the test bench. As the markers were positioned symmetrically, their half-distance defined the centre of the seating position, i.e., x = 0 mm. The excursion of the leading edge of the head relative to the centre of the seating position was tracked by hand for each frame. Due to uncertainties in the variation of the height of the head during the test, the measurement uncertainty of the excursion values was in the region of ± 10 mm.

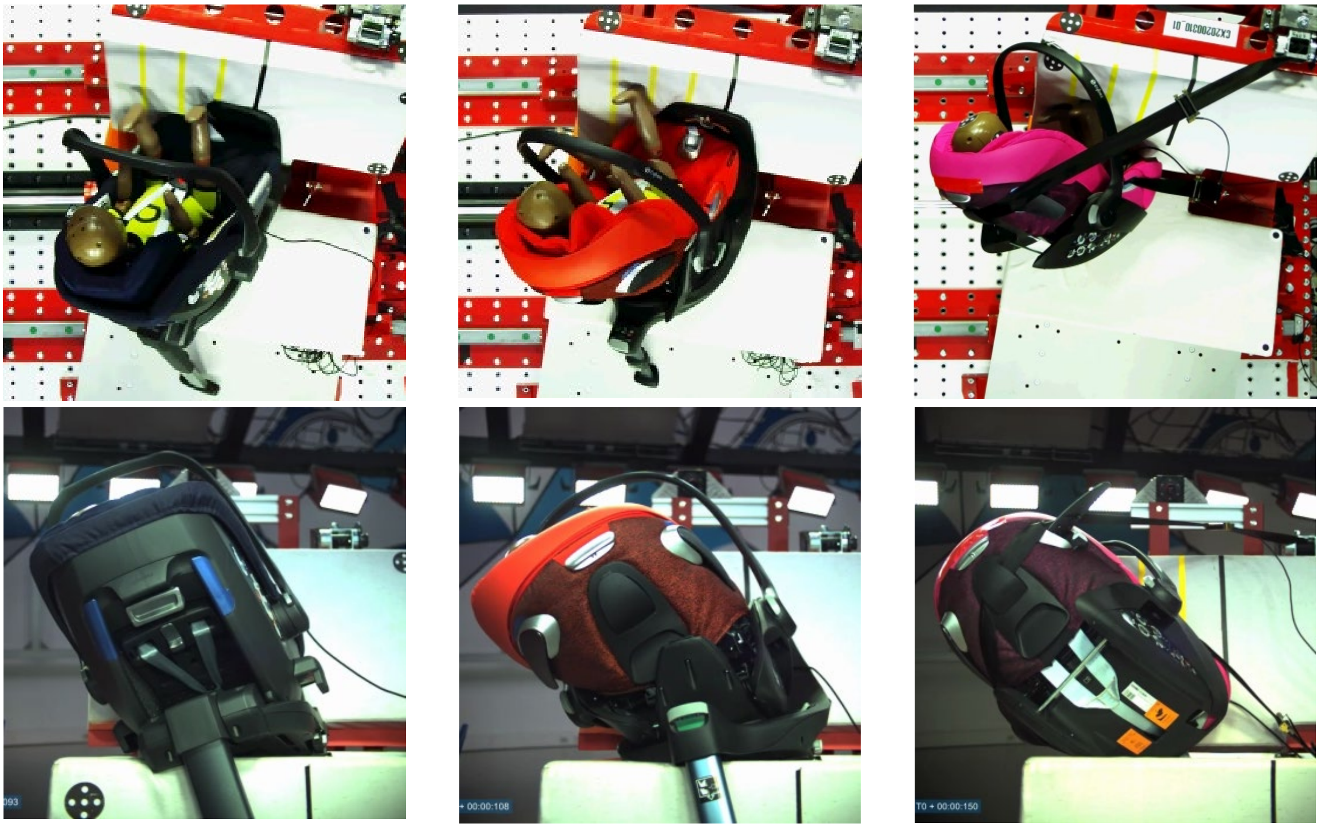
Four excursion lines or distances were generated to contextualise the measurements in terms of a real vehicle: a VW Polo, a popular European Supermini (or B-Segment or Subcompact, depending on the vehicle classification system used). In increasing distance from the far-side seat centreline, these excursion lines comprised the vehicle centreline, the struck-side seat child restraint line, the struck-side seat centreline and the maximum intrusion line. The struck-side seat child restraint line was established at 220 mm inboard from the struck-side seat centreline as this represents the size limit for an i-Size child restraint system in UN Regulation No. 129. The maximum intrusion line was set at 250 mm inboard from the distance to the inner door skin of the VW Polo from the centre of the far-side seating position.

III. RESULTS

Kinematic Observations

The motion of the dummy during far-side impact depended primarily on the orientation of the child restraint, but also its method of attachment. The rear-facing child restraints (Figures 1 and 2) swung and rotated towards the impact about the vertical and the longitudinal axes (with respect to the test bench). This sweeping motion of the restraint appeared beneficial in containing the head. The belt-attached infant carrier (Seat A3) rotated almost completely into the seat back of the test bench. However, the carry handle of the infant carrier passed beyond the upper corner of the seat back and into free space behind the test bench. This motion would likely be more limited in a real bench seat typical of the rear of a car. Similar motion was prevented in the other belt-attached rear-facing seat (Seat B3) by the lower tether straps. However, this seat, rotated substantially into the cushion of the test bench and may have bottomed-out on the structure below. In ISOFIX-attached rear-facing child restraints, the seating unit experienced much greater rotation than the base. Nevertheless, no significant structural failures or detachments were observed. Despite these kinematic differences, the integral harness straps remained on the shoulder of the dummy in all of the rear-facing child restraints, regardless of their type or method of attachment.

Forward-facing child restraints rotated about the longitudinal axis only (Figures 3 and 4). This placed greater strain on the side wing and the head became somewhat exposed above the upper surface of the wing. The belt-attached integral seat (Seat C4) translated towards the impact, which possibly led to reduced rotation compared with the ISOFIX child seats. As a result, the head seemed better contained in this seat. The harness straps remained on the shoulder of the dummy in all forward-facing integral child restraints. One booster seat (Seat D3) lost Q10 head containment entirely, while the booster cushion (Seat D4) had no structure with which to contain the dummy and was therefore reliant only on the seat belt for containment. The seat belt slipped off the shoulder in all of the booster systems. In general, the reduced motion of forward-facing restraints meant that the overall excursion towards the impact tended to be lower than rear-facing models, but seemingly at the expense of containment.



Seat A1 (Q1) Seat A2 (Q1.5) Seat A3 (Q1.5)

Fig. 1. Dummy and child restraint kinematics in infant carriers.

Seat B1 (Q3) Seat B2 (Q3) Seat B3 (Q6)

Fig. 2. Dummy and child restraint kinematics in rear-facing child seats.

Seat C1 (Q3)

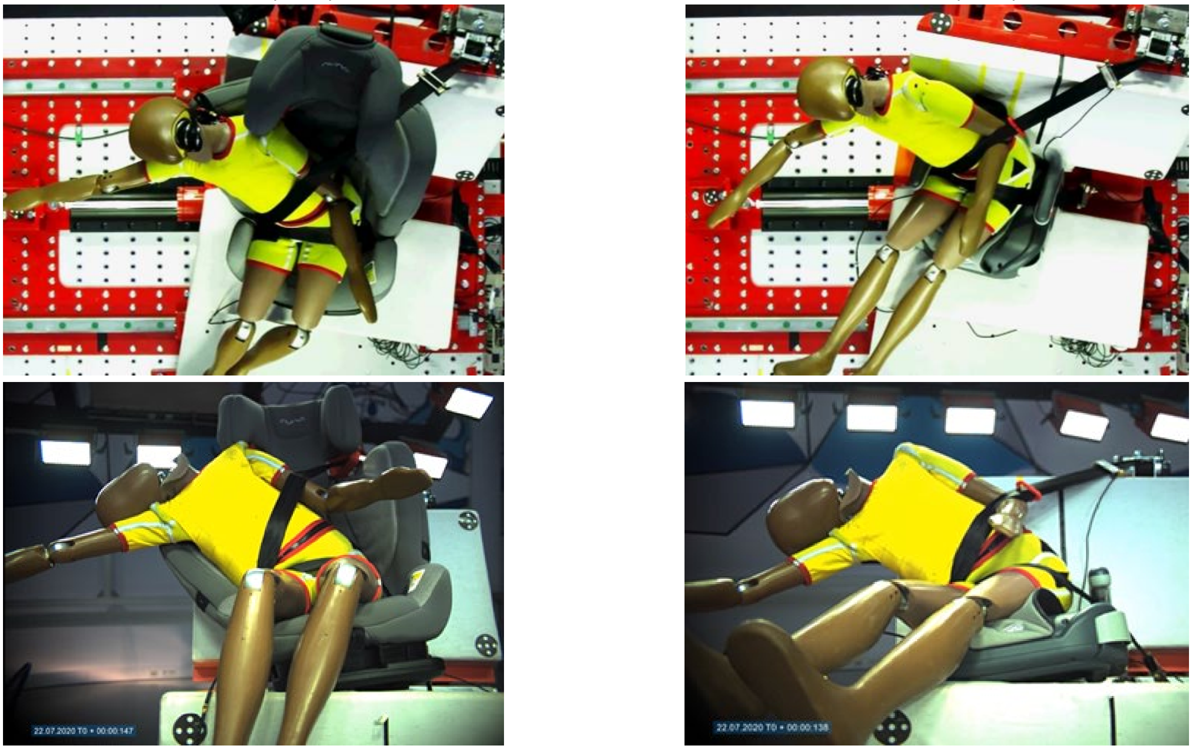
Seat C2 (Q3)

Seat C3 (Q3)

Seat C4 (Q3)

Fig. 3. Dummy and child restraint kinematics in forward-facing child seats.

Seat D1 (Q10) Seat D2 (Q10)



Seat D3 (Q10) Seat D (Q10)

Fig. 4. Dummy and child restraint kinematics in booster systems.

Lateral Head Excursion

Figure 5 shows the peak head excursion from the centreline of the dummy’s far-side seating position with the four excursion lines generated to contextualise the measurements in terms of a real (Supermini) car environment. The head excursion was not sufficient to reach maximum intrusion line in any of the child restraints. However, the booster cushion, Seat D4, was relatively close; 45 mm from the region where vehicle intrusion would be plausible for a Supermini car. The head excursion in the rest of the child restraints did not pass beyond the struck-side seat centreline, but in most cases, did pass beyond the struck-side child restraint line. This suggests there might be some interaction with another child restraint seated in the struck-side position, although that seat itself would also move towards the point of impact. As previously described, these excursion lines were indicative only, based on comparative measurements in a small car.

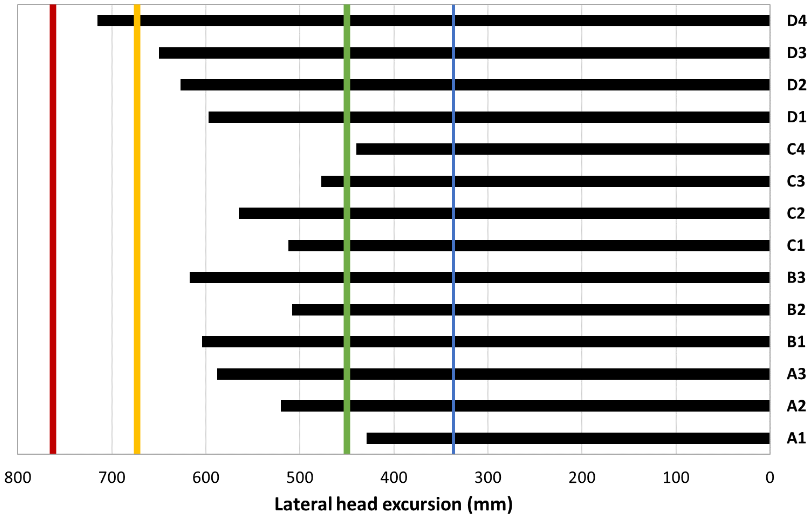


Fig. 5. Lateral head excursion from the centreline of the dummy's seating position. Lines are marked to show the distances from the far-side seating position of a supermini car to the vehicle centreline (blue), child restraint interaction line (green), struck-side seat centreline (amber) and vehicle intrusion line (red).

Head and Neck Loads

The resultant head acceleration (3ms value) was relatively low in all experiments, falling within the range of 20 to 45g (Figure 6). This corresponded to 25% to 56% of the (struck) side impact test limit in UN Regulation No. 129[1]. Seats B2 (56% of the regulatory limit) and C4 (50% of the limit) measured slightly higher head acceleration than most other child restraints, but the head excursion tended to be lower. However, there was limited evidence for a trade-off between head acceleration and head excursion across the full sample of tests. For example, the worst-performing child restraint for head excursion, Seat D4, also measured high acceleration. While Seat C2 delivered low head excursion and acceleration.

The upper neck tension force displayed a spread in values from 251 to 1,386 N (Figure 7). No regulatory or other validated injury limit values are available for the Q-Series neck with which to interpret the magnitude of these measurements in terms of neck injury risk. The lowest values were recorded in the infant carriers (Seats A1 to A3), which were occupied by the smaller dummies (Q1 or Q1.5). The largest values occurred where head containment was lost (particularly in Seat D3 and D4).

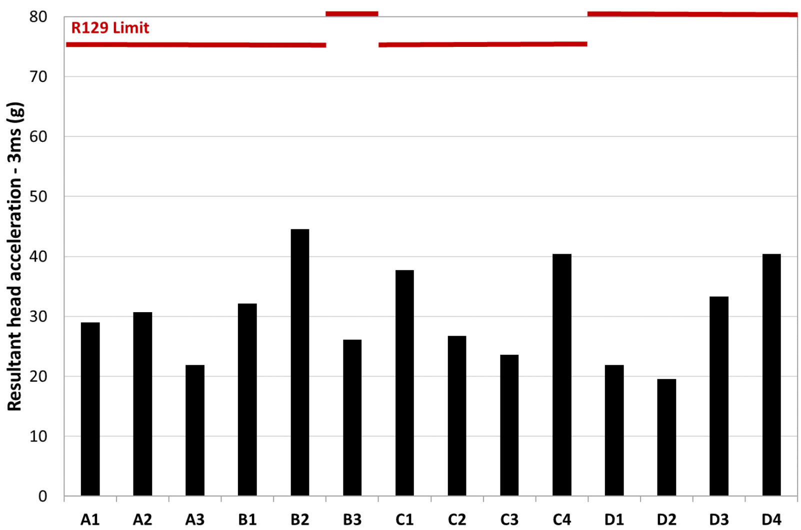


Fig. 6. Resultant head acceleration (3ms exceedance value) shown with the corresponding dummy limit in UN Regulation No. 129 struck-side impact test.

[1] 75g for the Q1 and Q1.5; 80g for the Q3 and Q6; no limit is specified for the Q10, but 80g was recommended for the dummy by the European Enhanced Vehicle Safety Committee (EEVC).

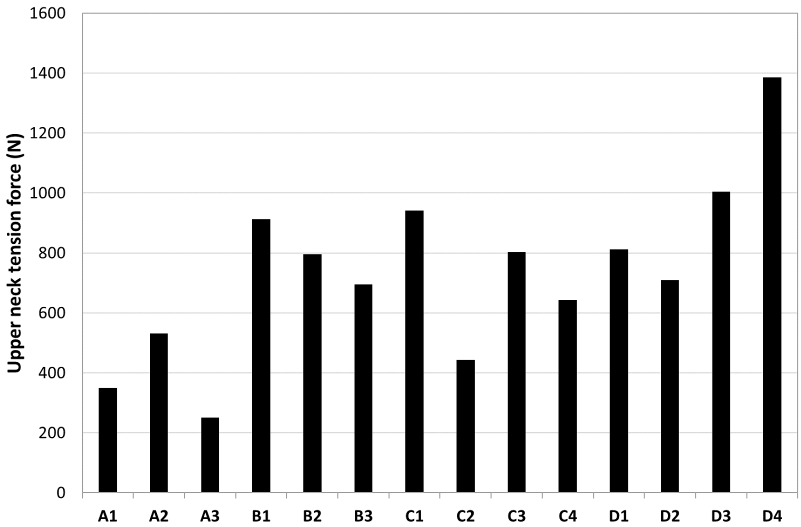


Fig. 7. Upper neck tension force. No limit values available.

IV. Discussion

There are no regulatory or consumer test requirements for far-side occupant protection in child restraint systems. Side impact test and assessment procedures for struck-side protection necessitate child restraint designs capable of containing the head whilst mitigating loading to the child under direct vehicle intrusion. When restrained on the struck-side, very little movement of the child restraint towards the impact is observed due to the intruding surfaces. In contrast, a child restraint installed in a far-side seating position is subjected to somewhat different loading conditions. In the absence of adjacent intrusion, the child restraint is, in principle, more free to move towards the impact. This places inertial loads on the attachment mechanism to the car as well as any points of connection between different parts of the child restraint, such as a base and seating unit. No significant failures or detachments were observed in our study, which suggests that meeting front and/or struck-side impact requirements provides some measure of structural integrity in far-side impact, at least at this severity. However, all of the ISOFIX-attached child restraints displayed relative motion between the base and the seating unit. ISOFIX is a rigid attachment system and although some rotation of the base about the longitudinal axis was observed, the seat rotated towards the impact to a greater degree than the base in each experiment. Reference [15] observed a similar seat disengage from its base in a far-side impact test, albeit with a product not designed or assessed for side impact, but other instances do not appear to have been reported. Notwithstanding the lack of failures observed in our study, or others, this highlights a potentially vulnerable point in infant carriers and child seats that include a base from which the seat can be removed or rotated.

The motion of each child restraint was a factor in its ability to contain the head and limit head excursion. In general, rotation about the longitudinal axis was decisive and meant that the top of the head could become partially exposed above or in front of the side wing. This was most noticeable in forward-facing child seats, but was also observed in some rear-facing child restraints, particularly with larger dummies, i.e., Q3 and Q6. Lateral motion without rotation, as observed in the forward-facing belt-attached child restraint, did not seem to influence head containment and excursion unduly. In booster systems, rotation of the seat combined with motion of the dummy led to the diagonal belt slipping off the shoulder and the head being exposed, or in some cases, containment being lost altogether. Although head containment was not always fully achieved in this study, the level of lateral head excursion, when related to a small Supermini car (a VW Polo), was unlikely to result in head contact with vehicle intrusion for child restrained on the far-side. Some interaction with adjacent child restraints or occupants might be possible, but is difficult to assess purely from excursion measurements as these other occupants would also move towards the impact. Other studies have associated containment with child restraint rotation [14-15][17][19]. Head excursion with the potential for injurious contacts with intruding door structures were observed in [17-18]. However, these studies used child restraints certified in the United States featuring a single webbing LATCH attachment system. The child restraints were installed in the centre rear position, rather than the far-side. Similar research using child restraints with either rigid ISOFIX, or a dual webbing LATCH system, limited head excursion before such contact occurred [19]. Although these studies share some findings with our study, it is difficult to compare them directly due to fundamental differences in child restraint (and vehicle) regulations between United States and the United Nations and their implications for product design.

The capacity to limit head excursion appears to be the main priority for far-side seated children in child restraint systems. Significant dummy loading was not observed in this study. The head acceleration (3ms value) fell well below the limit for (struck-) side impact in UN Regulation No. 129, which suggests a low risk of inertial head injury at this severity level. Although no regulatory neck limits or validated neck injury criteria are available for the Q-Series, the neck tension force also appeared to be relatively low, based on typical measurement levels expected in front and struck-side impact tests. Neck tension tended to be lower when the head was contained by the child restraint, which was also reported in [15] and [18]. Investigations of occupant loading to the head and neck in far-side seating positions appear to be warranted only when the excursion is sufficient to generate contact with the intruding surface, or with adjacent occupants, and such contact is replicated in the test. In these cases, measurement of the dummy loads would be necessary to determine whether such interactions are potentially injurious.

Child restraint systems that are subject to struck-side impact test and assessment procedures appear capable of achieving a reasonable level of performance when installed on the far-side. Although the head was not always contained fully, it was unlikely to strike the intruding surfaces in a small car. That said, some of the booster systems did not perform particularly well with the Q10 dummy. One booster seat with UN Regulation No. 129 type-approval and a side impact score of 1.8 (*Good*) lost head containment completely. The Q10 dummy is exempt from some of the struck-side impact requirements in UN Regulation No. 129 and is not currently used by ETC in their side impact test of child restraints. With the limited use of the Q10 in these procedures, it follows that this seat may feature reduced countermeasures for struck-side impact, which in turn may have influenced its performance in far-side impact. Similarly, the booster cushion, with no backrest structure, was unable to prevent substantial head excursion that came close to the likely intrusion surface in a small car. This study was carried out with a basic three-point seat belt and retractor. Seat belt pretensioners have been found to reduce head excursion in booster systems installed on the far-side, albeit with greatest benefits for booster seats [21]. Such vehicle-based countermeasures may be the only option for improving far-side protection in booster cushions.

The ETC (struck) side impact score did not necessarily translate to far-side impact performance in the child restraint systems in our study sample. For example, integral child restraints with worse ETC ratings tended to record lower lateral head excursion than comparable restraints with better ETC ratings. A larger sample of child restraints would be needed to determine whether any relationship exists between the ETC side impact score and far-side impact parameters such as lateral head excursion. Nevertheless, our study suggests that the ETC struck-side impact test and rating method does not discriminate the far-side impact performance of child restraints. It was not developed for that purpose, and it seems likely, therefore, that a dedicated far-side test, similar to that carried out in our study, would be needed to evaluate and compare child restraints in this respect.

Limitations

No other studies were found that investigated the performance of UN Regulation No. 129 type-approved child restraints in far-side impact. With no clear baseline or starting point for this study, a broad range of representative products covering most of the main child restraint types from birth through to 150 cm stature were included in the experiment matrix. This approach gave a more complete picture of typical child restraint performance in far-side impact and highlighted some general trends. However, the limitation of such a broad product matrix was that restraint parameters could not be investigated in detail. Future research may concentrate on specific restraint types in order to conduct a more comprehensive investigation of potential influences on child restraint performance in far-side impact and potential countermeasures.

The Q-Series dummy family was developed as an omnidirectional tool and is specified for both front and side impact testing in UN Regulation No. 129. It is capable of distinguishing differences in head protection afforded by child restraints in struck-side impact [12]. However, the Q-Series does not meet all of its lateral biofidelity targets [22] and a side impact version (Q3s/Q6s) has been developed for use in the United States [23]. Although the findings of this study are dependent on the Q-Series' capabilities and limitations, [24] found that none of the current child dummy options (Hybrid III, Q or Qs) displayed sufficient biofidelity to replicate volunteer kinematics in low-speed far-side tests.

This study used the sled pulse corridor recommended for side impact testing of child restraint systems by ISO/DTS 13396:2021. The ISO corridor is basically equivalent to a typical vehicle pulse in a UN Regulation No. 95 side impact test for adult occupant protection. An oblique (80°) angle was used to make the test conditions more demanding and to reflect far-side consumer testing of cars by Euro NCAP. However, it was a limitation of the study that no other pulse severities were investigated. This approach seemed appropriate for a first investigation of UN Regulation No. 129 type-approved child restraints in far-side impact, i.e., in the absence of previous research or regulatory or consumer test requirements. Nevertheless, future research may verify the findings of this study with a more aggressive pulse, for example, one that is typical of a Euro NCAP side impact test.

Observations of head containment by the child restraint systems were made based on several different camera views. In general, it was very clear when containment was lost completely, for example, if the head of the dummy was fully exposed beyond the side wings of the child restraint. However, in most cases, an objective assessment of containment was impossible, due to the complex motion of the child restraint and its effects on the interaction between the side wings and the dummy's head. The assessment of head containment is also challenging in more established struck-side impact test procedures, which did not offer a ready solution for our far-side tests. If a far-side impact test is introduced in future test and assessment procedures for child restraint systems, a clear definition of head containment will be needed if it forms part of the assessment criteria, along with an objective method of determining it from video analysis. It was beyond the scope of our study to develop such a definition of head containment and we focussed our analysis on more objective measures such as lateral head excursion.

V. CONCLUSIONS

This study provides a snapshot of far-side occupant protection in a sample of child restraint systems. Dummy head containment and excursion were influenced greatly by the motion of the child restraint system relative to the test bench. ISOFIX attachment, combined with a support leg, offered some stability versus the seat belt; however, rotation was still observed, due to motion of the seating unit with respect to the base. Rear-facing child restraints swung and rotated towards the impact about the vertical and the longitudinal axes (with respect to the test bench). This sweeping motion of the restraint appeared beneficial in containing the head, particularly for smaller dummies. Forward-facing child restraints rotated about the longitudinal axis only. This placed greater strain on the side wing and the head became somewhat exposed above the upper surface of the wing. Although this motion or tipping of the child restraints undermined their capacity to contain the head fully, the lateral excursion was not sufficient to risk head contact with the likely location of intruding surfaces in a small car.

An important difference from previous studies was that all of the child restraints (except the booster cushion) had likely been designed to deliver at least a baseline level of struck-side impact protection, as required by UN Regulation No. 129, or European consumer testing. This appeared to bestow a reasonable level of performance in far-side impact. However, far-side impact appeared to be challenging for one booster seat with the Q10 dummy. The struck-side regulatory requirements are reduced for this size dummy, which may have been a factor in the far-side performance we observed. Similarly, the booster cushion offered limited protection beyond restraining the pelvis. Booster cushions are exempt from struck-side impact testing in UN Regulation No.129, but are subject to dimension requirements to ensure they position the head adjacent to the side impact airbag. Vehicle restraints, such as seat belt pretensioners, or centre airbags, may be the only countermeasure to provide far-side protection in booster cushions.

VI. ACKNOWLEDGEMENT

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