Investigation of Different Methods of Improving the Assessment of Booster Seats in Light of Dummy and Sensor Capabilities

Costandinos Visvikis, Christoph Thurn, Thomas Müller

Abstract Q-Series dummies, with Abdominal Pressure Twin Sensors, have shown limited ability to discriminate differences in booster seats. This study investigated whether alternative static and/or kinematic measures could supplement the Abdominal Pressure Twin Sensors and improve the capacity of the dummy to discriminate between boosters. A series of sled experiments was carried out with Q3, Q6 and Q10 dummies. The dummies were seated directly on the test bench (with no booster) and in a range of boosters that generated different belt paths over the pelvis and different levels of belt guidance.

None of the dummies submarined when seated directly on the test bench and all regulatory test requirements were met (including abdomen pressure). The initial static belt path and knee-head excursion were both capable of discriminating differences between boosters. Furthermore, both parameters would require a booster to achieve a basic level of performance in the regulatory test. They may be useful tools, therefore, to supplement the current requirements and ensure that good restraint design principles are followed.

Keywords Abdominal pressure twin sensors (APTS), booster seats, child occupant protection, Q-Series dummy.

I. INTRODUCTION

A booster seat is a type of child restraint system that raises the child to improve the fit and position of the adult seat belt over their body. Booster seats are intended for children that have outgrown child restraints with an integral harness or shield and are at the final stage before using the seat belt alone. Booster seats have proven to be very effective in positioning the seat belt and reducing the risk of injury in older children compared with the adult seat belt alone [1]. Nevertheless, injuries are still observed in children using these child restraint systems [2-3]. Whilst being the principal means of restraint in a booster, seat belts can also cause injury if they are ill-fitting or used inappropriately [4-6]. Literature on the potential for seat belt induced injuries tends to focus on the lap part of the belt. The lap belt should pass over the top of the thighs with the anterior-superior iliac spines (ASIS) of the pelvis acting as an anchor point [7]. This routing helps to keep the belt in position and avoids loading to the anterior abdominal wall and underlying organs and soft tissues [8]. The diagonal part of the seat belt should pass over the centre of the shoulder and sternum before meeting the lap belt at the hip [7]. Without effective positioning, the diagonal belt can be close to the neck. Although there appears to be little, if any, literature on diagonal belt induced cervical spine injuries, the discomfort can lead children to place the belt behind their back or under their arm [9]. This misrouting compromises the restraint of the torso and increases the risk of head contact [9]. It can also lead to lumbar spine injury, particularly when combined with poor lap belt placement [10]. Similarly, if the diagonal belt is too close to the edge of the shoulder, there is a greater chance it can slide off, reducing the restraint of the torso leading to greater head excursion [11].

United Nations (UN) Regulation No. 129 (on Enhanced Child Restraint Systems) assesses the capacity of booster seats to protect children whilst minimising the risk of belt induced injury. The risk of lap belt induced injury is addressed by an abdomen pressure threshold that is applied to measurements made with Abdominal Pressure Twin Sensors (APTS) within the abdomen of the Q-Series dummies. The sensors were evaluated extensively and the peak pressure injury criterion developed from accident reconstruction [12-13]. Nevertheless, the dummies appear to display limited capacity to submarine under conditions in which it might be expected [14]. Further, the APTS do not seem to detect borderline situations in which the belt is high on the Anterior Superior Iliac Spine (ASIS) or partially loading the abdomen [15]. This means that the regulatory test is

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not particularly effective in discriminating differences between booster seats [14-16]. Other potential sensors, such as ASIS load cells, offer complimentary information to the APTS, but do not improve the capacity of the dummy and regulatory test to discriminate [15]. The risk of diagonal belt induced injury is not addressed fully in UN Regulation No. 129. Although the abdomen pressure can by influenced by the diagonal belt [14-15] and therefore offers some measure of control, the other regulatory performance criteria cannot detect concentrated loading to other parts of the torso. Chest deflection is one parameter with the potential to assess and/or control loading to the torso by the diagonal belt, but the location of the sensors tends to penalise good belt paths over the torso [17-19]. Further, it appears to be influenced greatly by chin-to-chest contact [20].

A recent amendment of Regulation No. 129 was made to include booster cushions, i.e., backless boosters. These boosters also raise the child, but the extent to which they position and influence the diagonal belt path, if at all, varies considerably [21]. Furthermore, booster innovations are emerging that offer lighter, more transportable solutions, often with new mobility services in mind. These innovations sometimes sacrifice ideal restraint practice in favour of convenience [22]. This has led regulators to propose that certain design approaches are explicitly forbidden because the performance requirements have been unable to discriminate products they deem unsafe [23]. Whilst such a retrospective approach might deal with specific issues observed in the field, it is unlikely to be sustainable. It seems far preferable to have test procedures that are effective in assessing booster systems. This study investigated whether alternative static and/or kinematic measures could supplement the APTS and improve the capacity of the dummy to discriminate between booster systems.

II. METHODS

Experiment Overview

Fourteen front impact experiments were carried out on an acceleration sled at the CYBEX Safety Centre in Germany. The experiments were performed according to the procedure specified in the 03 series of amendments to UN Regulation No. 129. The regulatory test conditions comprise an impact speed of 50^{+0}_{-2} km/h and a deceleration corridor that peaks between 20 g and 28 g. The experiments are summarised in Table I.

TABLE I
TEST MATRIX

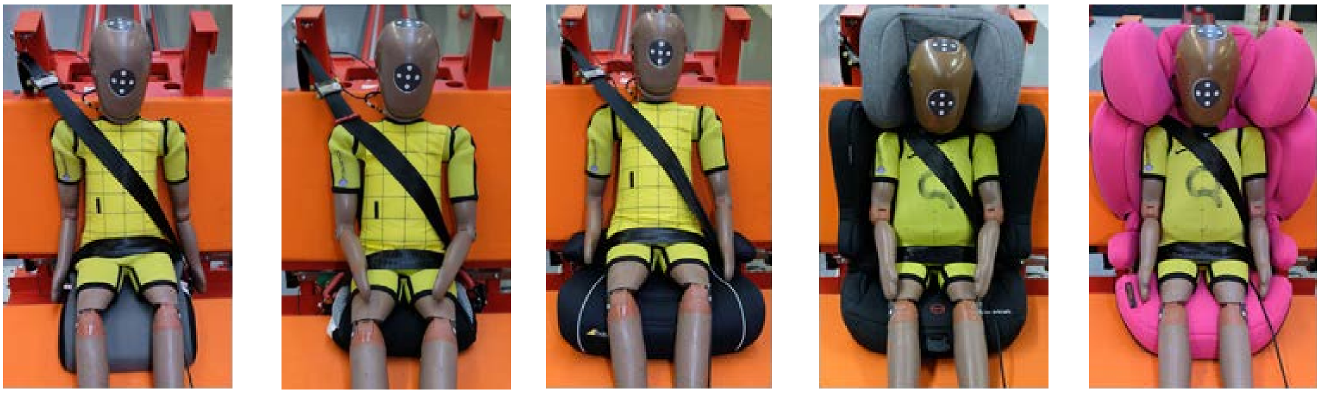
CRS type	CRS installation	Q3	Q6	Q10
No CRS	n/a	✓	✓	✓
Booster cushion 1	Seat belt	-	✓	✓
Booster cushion 2	Seat belt	-	✓	✓
Booster cushion 3	Seat belt and ISOFIX	-	✓	✓
Booster seat 1	Seat belt and ISOFIX	✓	-	✓
Booster seat 2	Seat belt and ISOFIX	✓	✓	✓

Dummies and Booster Systems

Three instrumented Q-Series dummies were used: a Q3, Q6 and a Q10. The dummies were manufactured by Humanetics, Germany, and certified and prepared for testing in line with the regulatory procedure. Accordingly, each dummy was equipped with a hip liner accessory, below the suit, to prevent the lap part of the seat belt from becoming trapped in the gap between the legs and the pelvis. The hip liner was manufactured by Humanetics.

Baseline experiments were carried out with each dummy seated directly on the test bench (with no booster). These were included as a surrogate for a poor performing booster and under the assumption that it would be desirable for a booster to be needed to meet the regulatory requirements. These were supplemented with a convenience sample of booster cushions and booster seats selected to generate different belt paths over the torso and different levels of belt guidance. These are shown in Figure 1. The selection of dummies for each experiment was determined by the type-approval test procedure in Regulation No. 129. For example, booster cushions can be approved from 125 to 150 cm, which necessitates testing with the Q6 and Q10. Booster seats can be approved from 100 to 150 cm and necessitates testing with the Q3 and Q10. A supplementary experiment with the Q6 was included with Booster Seat 2.

The booster systems were all type-approved to UN Regulation No. 44 (Child Restraint Systems). This was due primarily to the very limited availability of booster systems approved to the newer regulation (No. 129) at the time of this study. This meant that none of the boosters were developed or optimised for the Regulation No. 129 test environment and were approved using a different dummy (the P-Series) and a different test bench.



Booster Cushion 1
Low cost, basic design, typical of online marketplaces

Booster Cushion 2
Inflatable, convenient for car- and ride-share

Booster Cushion 3
Large base, with ISOFIX

Booster Seat 1
Low cost booster seat

Booster Seat 2
High-performing in consumer tests

Fig. 1. The booster systems used in the study.

Data Analysis and Potential Assessment Measures for Booster Systems

All measurement and data analysis conformed to ISO 6487. The UN Regulation No. 129 assessment criteria were calculated for each experiment. These comprise head excursion, resultant head acceleration (cumulative 3ms value), resultant chest acceleration (cumulative 3ms value) and abdomen pressure. Knee excursion was also calculated for the purpose of this study.

Two potential assessment measures were examined: the initial, static position of the seat belt and the difference between the knee and head excursion, subsequently referred to as ‘knee-head excursion’. These measures previously showed promise in discriminating between adapted booster seats with the Q6 and Q10 dummies [15].

The static position of the lap and diagonal belts were measured prior to each experiment using a procedure developed in [24]. This procedure was proposed for use in UN Regulation No. 129, but has not been implemented to-date (UN Informal Document CRS-58-04e *Belt Path Assessment Text*). In this procedure, the position of the seat belt is measured relative to reference points on the Q-series grid suit. In the case of the lap belt, this is measured in three places; in the centre and at a specified distance to the left and right of the centre. Although the grid suit is not available for the Q3, landmarks were drawn on the suit for our study in equivalent positions to those of the Q6 and Q10, and as indicated in [24]. All three dummies were fitted to their suits according to the user manuals. The centrelines of the suit and dummy were aligned for each measurement.

Head and knee excursions were measured relative to the fixed Cr point on the test bench, as used in the head excursion measurement in UN Regulation No. 129. The Cr point marks the intersection of the surface planes of the seat cushion and backrest of the test bench. The head and knee excursions were determined by video analysis (FalCon eXtra) using a 2D coordinate system with automatic parallax correction. The excursion of the leading edge of the head from the Cr point was tracked by hand for each frame. The knee excursion was tracked automatically using a marker placed on the dummy knee joint. The knee-head excursion was calculated by subtracting the peak forward head excursion measured at the leading edge of the head from the peak forward excursion of the knee joint.

III. RESULTS

Baseline Dummy Response with no Booster System

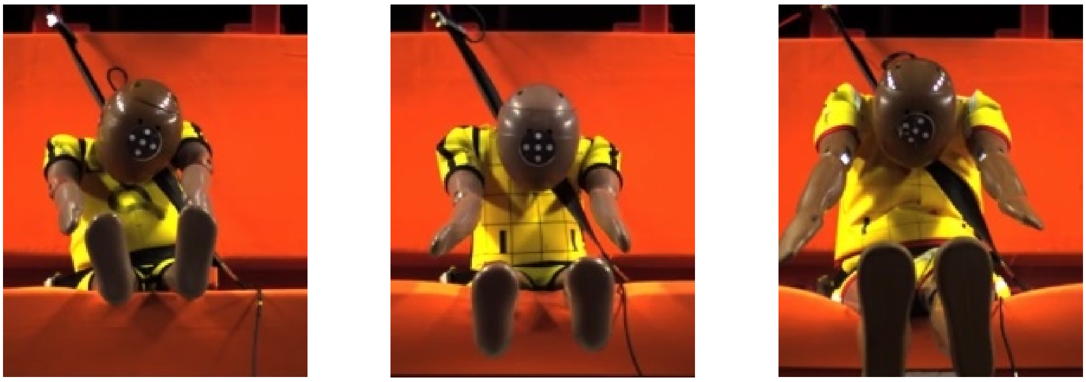
Table II shows the principal results when the dummies were seated directly on the test bench with no booster. It compares the peak dummy measurements with the corresponding UN Regulation No. 129 assessment criteria for front impact. The regulatory requirements were all met with the Q3 and Q6 dummies. The resultant head acceleration limit was exceeded by 3 g with the Q10, but all other requirements were met.

TABLE II

UN REGULATION NO. 129 ASSESSMENT CRITERIA

Measurement criterion		Limit	Q3	Q6	Q10
Head excursion (mm)	Horizontal	500 (550 for Q10)	258	319	328
	Vertical	800 (840 for Q10)	570	638	689
Head resultant acceleration (g)	3 ms cum.	80	50	55	83
Chest resultant acceleration (g)	3 ms cum.	55	39	43	40
Abdomen pressure (bar)	Left	1.0 (1.2 for Q10)	0.47	0.55	0.62
	Right	1.0 (1.2 for Q10)	0.30	0.52	0.51

Figure 2 shows the interaction between the dummy and the seat belt at the time of peak head excursion. The lap part of the seat belt remained on the pelvis of each dummy throughout the impact. The lap belt adopted a relatively shallow angle, and was visibly high on the pelvis, but there was no indication of submarining or abdominal loading. The diagonal belt moved towards the neck in all dummies, and in doing so, moved up the chest. This belt movement was particularly noticeable with the Q3 and the Q6 dummies, where the belt wrapped under the opposite arm.



Q3 dummy **Q6 dummy** **Q10 dummy**

Fig.2. Dummy kinematics and belt interaction at peak head excursion with no booster.

Abdomen Pressure

The lowest overall peak abdomen pressure across the left and right side of the APTS was measured when the three year old dummy was seated on the test bench with no booster seat (Figure 3). The lap belt remained on the pelvis in all experiments with the Q3 with no indication of submarining or loading to the surface of the abdomen by the belt; nevertheless, the pressure reached 47 percent of the abdomen pressure threshold with no booster and 75 percent of the threshold with Seat 2. In each case, the left-side APTS, i.e., the buckle-side of the seat belt, measured the greatest abdomen pressure. This suggests the pressure may have been generated by the diagonal part of the seat belt. However, Figure 4 shows the left and right side abdomen pressure overlaid with the resultant external head contact force in Seat 2. The head contact force was determined according to the procedure specified in SAE J2502 in order to highlight the timing and duration of contact. During each test, the chin of the Q3 struck the chest. Both the left and right side abdomen pressure show substantial increases that coincide with the period of chin-to-chest contact. The same trend was observed in the test with no CRS and with Seat 1.

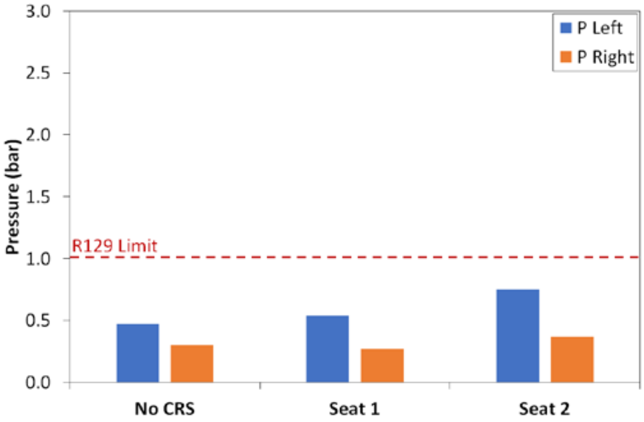


Fig. 3. Peak left and right side abdomen pressure – Q3.

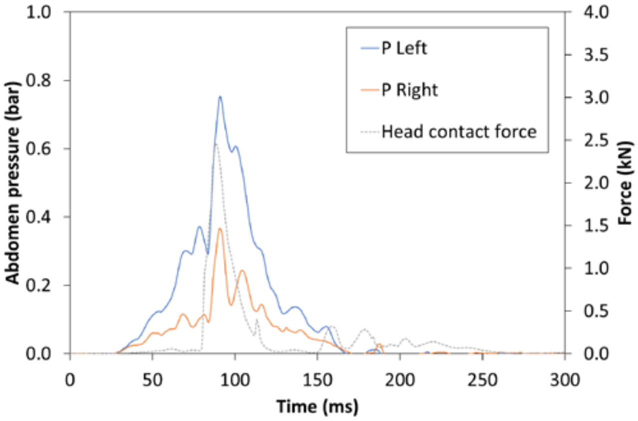


Fig. 4. Left and right side abdomen pressure and head contact force (Q3 in Seat 2).

The booster systems measured lower abdomen pressure than the baseline experiment with the Q6 dummy seated on the test bench (Figure 5). With this dummy, the pressure tended to be balanced between the left and right side APTS, with the exception of Seat 2, which was greater on the left-side (i.e. the buckle-side of the belt). The diagonal belt passed across the centre of the torso and down to the hip in this booster seat. In contrast, in the booster cushions, the diagonal belt was higher on the torso, above the abdomen (and above the APTS), which may have influenced the pressure measurement. The lap belt remained on the pelvis, away from the area of the APTS, in all experiments with the Q6. Chin-to-chest contact did not seem to affect the abdomen pressure measurements greatly in the Q6. For example, this is illustrated in Figure 6, which shows the abdomen pressure overlaid with the external head contact force in Seat 2. The peak abdomen pressure occurred before the period of chin-to-chest contact.

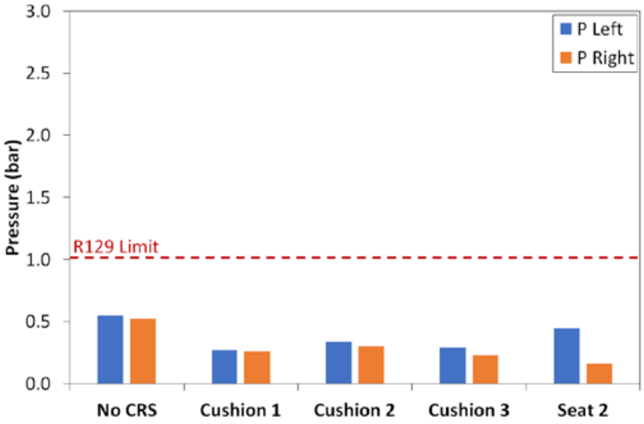


Fig. 5. Peak left- and right-side abdomen pressure, Q6.

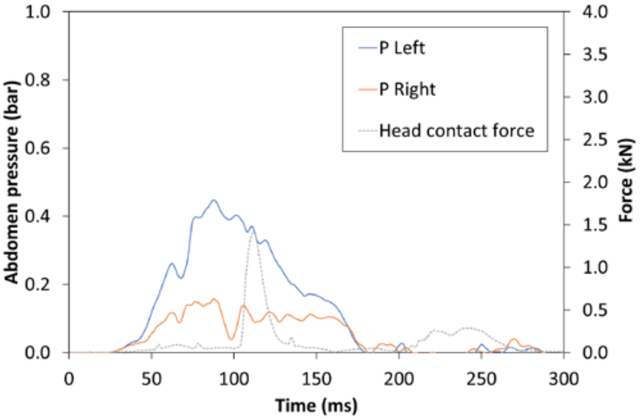


Fig. 6. Left- and right-side abdomen pressure and head contact force (Q6 in Seat 2).

The booster seats measured abdomen pressure that was consistent with the baseline experiment with the Q10 dummy directly on the bench (Figure 7). Once again, the lap part of the belt remained on the pelvis with no apparent abdomen loading (by the belt), but the pressure reached around 50 percent of the threshold in UN Regulation No. 129. The booster cushions displayed relatively high abdomen pressure on the left, i.e., buckle, side that was substantially higher than that on the right side. This peak abdomen pressure exceeded the threshold in Regulation No. 129. The lap part of the seat belt remained on the pelvis in the booster cushions and there was no evidence from the videos that the lap belt loaded the abdomen on the left side. Only the diagonal part of the seat belt was visible on the abdomen over the period of pressure measurement and hence it appears this pressure resulted solely from loading by the diagonal belt. Once again, chin-to-chest contact was observed, but did not influence the peak pressure in any of the booster systems. This is illustrated in Figure 8, which overlays pressure and head contact force in Seat 2.

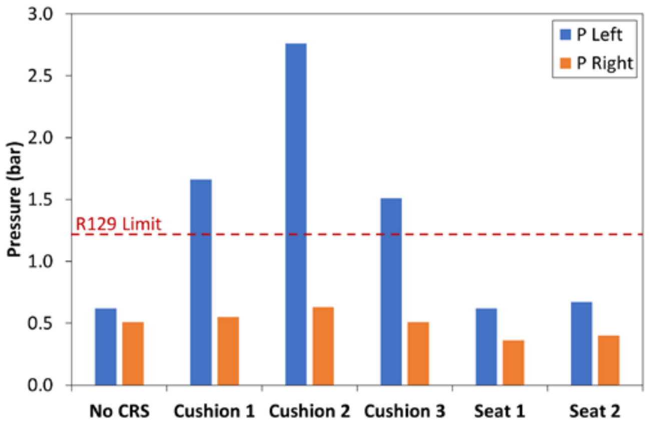


Fig. 7. Peak left- and right-side abdomen pressure, Q10.

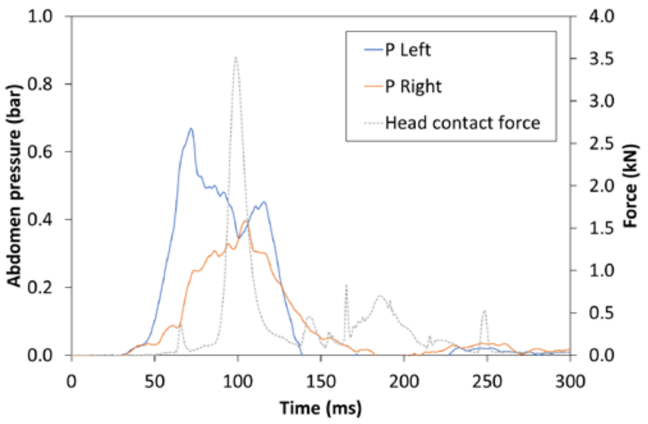


Fig. 8. Left and right side abdomen pressure and head contact force (Q10 in Seat 2).

Static Belt Path Assessment

Figure 9 shows the static lap belt measurements made prior to each dynamic test with the Q3 dummy. Figures 10 and 11 show the corresponding charts for the Q6 and Q10, respectively. A potential belt position criterion was specified for these dummies in the proposed procedure (UN Informal Document CRS-58-04e *Belt Path Assessment Text*) and is overlaid on the chart (the green area denotes the acceptable position). The development of this criterion for the Q6 and Q10 is explained in [24]. No criterion was developed for the Q3 because it uses landmarks on the grid suit, which is not currently available for that dummy.

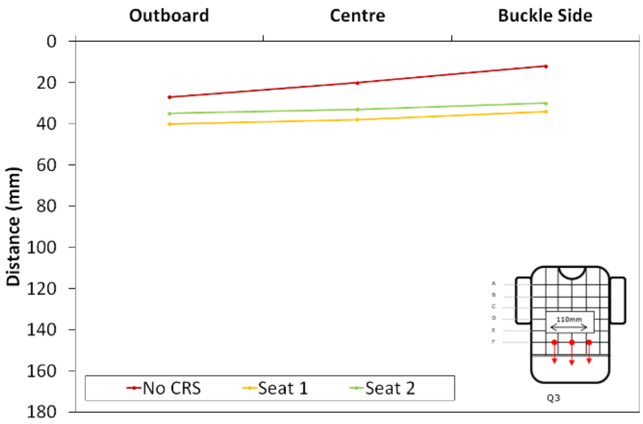


Fig. 9. Static measurements of lap belt fit with the Q3.

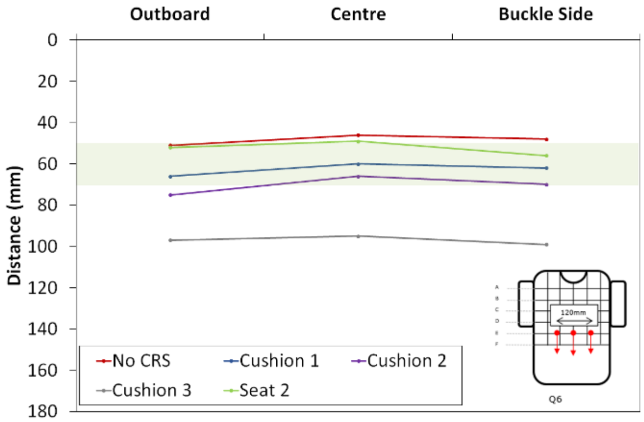


Fig. 10. Static measurements of lap belt fit with the Q6

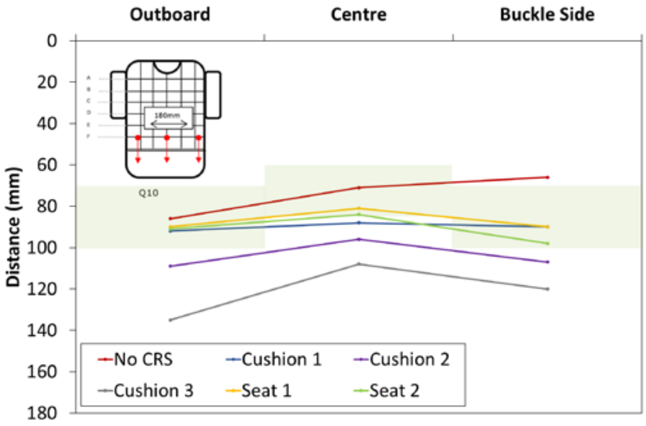


Fig. 11 Static measurements of lap belt fit with the Q10.

The highest lap belt path occurred when the dummies were seated on the test bench with no booster. This was observed consistently across all three dummies. With the Q3, the belt path with no booster was visibly higher than the booster seats used in the study. This is illustrated in the left and centre images in Figure 12. With the Q6 and the Q10, the path with no booster was also higher than the booster systems and passed above the acceptable zone in the centre (Q6 only) and buckle-side (both dummies). A spread of belt paths were observed among the different booster systems, suggesting the measure is capable of distinguishing differences between products. Where the booster paths fell outside the acceptable zone, they tended to be below the zone and were far forward on the thighs (as judged by the procedure used in this study). An example is shown on the right of Figure 6.

Fig. 12. Examples of initial static belt path, from left to right: Q3 with no CRS; Q3 in Seat 2; Q6 in Cushion 3.

Static measurements of the diagonal belt path were also made and are shown in Appendix A.

Knee-head Excursion

Larger values of knee-head excursion suggest poor restraint of the pelvis, with the potential for submarining [25]. In our study, the lap belt remained on the pelvis in all experiments with no indication in the videos of submarining or abdominal loading by the lap belt. Nevertheless, a range of different knee-head excursion values were recorded (Figure 13). The measurements with the Q3 and Q6 fell within a similar/overlapping range (Q3: 78 to 128 mm and Q6: 18 to 137 mm), whereas the Q10 measurements were higher (243 to 315 mm). Taking the Q3 and Q6 together, the baseline experiments measured the highest knee-head excursion for these dummies (with the exception of Seat 1 and the Q3). This trend was not observed with the Q10, where several boosters displayed greater knee–head excursion than the baseline, albeit with some spread in the excursion values. For example, the booster with the highest Q10 knee-head excursion (Cushion 3) did result in kinematics that might be considered unfavourable (i.e. forward pelvis and reclined torso at peak dummy excursion) compared with the other boosters.

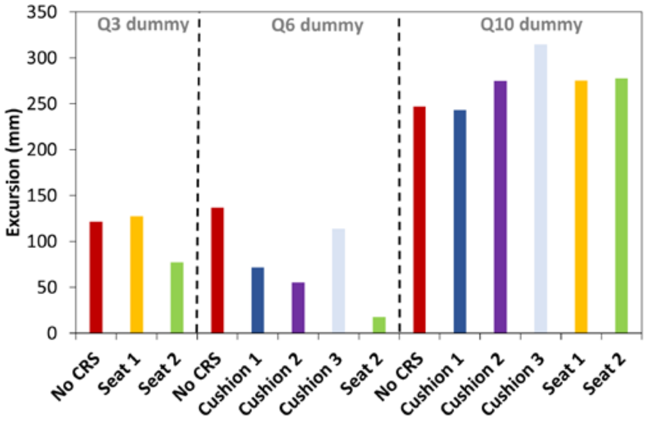


Fig. 13. Knee – head excursion.

IV. DISCUSSION

The Q3, Q6 and Q10 dummies did not submarine when they were restrained directly on the test bench with no booster. The belt interaction was unfavourable (i.e. towards the top of the pelvis and close to the neck), but the front impact performance requirements in UN Regulation No. 129 were largely met. The only exception was the Q10, which exceeded the head acceleration limit marginally. Similar outcomes were observed with the Q6 in [14] and the Q6 and Q10 in [15], but to our knowledge, these are the first experiments to examine all three booster-sized dummies (Q3, Q6 and Q10) directly on the test bench. This finding suggests that the current regulatory performance requirements are not a strong basis from which to assess booster systems as they can be met without raising the dummy or influencing the seat belt position. The APTS lack sensitivity at the border between the bottom of the abdomen and the top of the pelvis [26]. However, if the dummy does not submarine under conditions where it is expected, or at least desired (i.e. with no booster), it is perhaps not surprising that the APTS and abdomen pressure criterion do not detect risks fully.

The capacity of the Q-Series dummies to submarine and generate meaningful loading to the abdomen has been the subject of considerable research [13][15][20][27]. Two principal issues have emerged: firstly, the gap between the legs and pelvis, which traps the belt, regardless of booster design, and secondly, the extent to which the pelvis can rotate rearwards, which is thought to be an important part of the submarining mechanism in real children [27]. The hip liner accessory, particularly in its prototype form, showed promise in preventing belt entrapment and appeared to facilitate submarining and loading to the APTS [28]. However, the dummy, the APTS, or perhaps more accurately, the regulatory procedure in its entirety (including the bench characteristics, anchorage positions, dummy positioning, test pulse, etc.), still does not discriminate differences fully among booster seats [14-16]. This was reinforced in our study, whereby the abdomen pressure did not appear to be sensitive to differences in lap belt path and belt guidance between the boosters, and more importantly, there was no abdomen pressure performance advantage of a booster seat compared with the test bench and seat belt alone. Furthermore, with the Q3, the booster seats performed worse than the seat belt alone, generating higher abdomen pressure, although this may have been influenced by chin-to-chest contact. That said, one notable exception was the Q10 dummy in the booster cushions, where the APTS was sensitive to loading from the diagonal part of the seat belt. The contribution of diagonal belt loading to injury risk for children on booster cushions does not appear to have been quantified, but on the basis of these experiments, the abdomen pressure criterion discriminated very clearly between booster seats and booster cushions with the Q10 (since all cushions in this study measured higher abdomen pressure than the booster seats and exceeded the regulatory pressure threshold).

Although the Q-Series dummies and APTS can detect some extreme examples of poor belt path and unfavourable kinematics [15], an abdomen pressure criterion alone seems insufficient to assess boosters under the current regulatory test conditions. The initial static belt path over the pelvis was a better discriminator than abdomen pressure in our study. Not only was the worst performance (i.e. highest belt path) observed when each dummy was seated on the test bench and restrained with the seat belt alone, but a spread of different belt paths was observed between the boosters. These ranged from high paths towards the top of the pelvis to lower paths on the thighs that were forward of the pelvis. These different belt paths did not lead to different dynamic behaviour in our sled tests (in terms of the likelihood of submarining, or of increased abdomen pressure). However, that may have been due to the dummy and other test procedure characteristics mentioned above. The dynamic performance of a booster is key, but a good static belt position and fit may be important pre-conditions [21]. It may not capture all situations, for example, some boosters can optionally be installed with ISOFIX or without, which may influence their dynamic behaviour. Nevertheless, a static belt path assessment could be a useful interim measure if the dynamic assessment is not able to discriminate boosters fully [29]. There appears to be no precedent for a static belt assessment in other global child restraint legislation, but the Insurance Institute for Highway Safety (IIHS) assesses and rates boosters in the US market for their capacity to provide good lap and diagonal belt fit. The range of static belt fits has narrowed considerably amongst the boosters tested by IIHS since the procedure was introduced in 2009 [30]. The IIHS procedure uses a specific measurement tool, whereas the procedure we used is carried out on the crash test dummy prior to the dynamic test. This reduces the need for additional test tools and means the belt fit and dynamic behaviour can be evaluated together; however, it relies on the dummy suit being fitted in a consistent way.

Knee–head excursion also showed value as a potential discriminator of booster systems, particularly for the

Q3 and Q6. In each case, the highest values of knee-head excursion were observed when the dummy was restrained by the seat belt alone and the parameter also displayed differences between the boosters. Reference [25] concluded that knee–head excursions of 200 mm and greater were associated with *submarining kinematics*. Furthermore, since values approaching 200 mm were thought to have *submarining tendencies*, only values less than 150 mm were deemed to have *desirable kinematics*. As this previous study used a different child dummy (Hybrid III 6YO) and a different regulatory environment (FMVSS 213), their findings may not translate readily to the Q-Series in the UN Regulation No. 129 environment. The Q6 did not reach that excursion level in our study; however, considering we observed a knee-head excursion of 137 mm with no booster, and taking account of experiments with poor-performing adapted boosters in [15], an indicative threshold of around 100 - 110 mm may be appropriate for the Q6. Although fewer experiments were performed with the Q3, the knee-head excursion with no booster was 121 mm and hence this threshold might be suitable for that dummy too. A threshold at this level would ensure a booster is needed, and would discriminate those with borderline behaviour. In our present study, the parameter did not work particularly well for the Q10, as all of the boosters displayed greater excursion than the seat belt alone. Nevertheless, the parameter discriminated adapted boosters in [15], albeit with more extreme characteristics than those used in our study (i.e. higher lap belt paths or more forward on the thighs).

The main limitation of this study was the small sample of boosters. This was due, in part, to the need to investigate different dummy sizes, as required by UN Regulation No. 129. The initial belt path and knee-head excursion showed promise as potential additional performance measures to supplement abdomen pressure in detecting potential issues of belt fit and interaction. However, a much larger programme of validation would be needed to assess their benefits and readiness for use in booster test procedures and to develop robust criteria. Any such criteria would likely be pragmatic only as the link between these parameters and real-world injury outcomes for children in boosters is not currently proven and would be difficult to verify. A programme of validation would also need to investigate the reproducibility of each parameter across different test laboratories and type-approval technical services. This was beyond the scope of this study and hence any findings, particularly with respect to indicative thresholds that might have emerged from our data, should be treated with caution.

Another limitation was the underlying assumption that the Q-Series should submarine in the regulatory environment when restrained on the test bench with no booster. Although this suited the practicalities of assessing boosters, the human response in this environment (i.e. seat and belt characteristics) and pulse conditions is unknown. Injuries to children restrained only by the seat belt are observed in the real world [4-6], but the threshold for submarining, i.e., impact severity, seating and belt anchorage characteristics, child characteristics, are not quantified in the literature. Human body modelling may play a role in future to understand what behaviour is expected from the dummy.

Finally, this study identified large increases in Q3 abdomen pressure that coincided with chin-to-chest contact. Chin-to-chest contact has been observed with the Q-Series dummies, but previous research has tended to focus on its effect on chest deflection [14] [16] [24]. The mechanism by which contact to the chest of the dummy loaded the abdomen sensors needs further investigation. Within our study, it was possible only to identify increased pressure over the period of contact. Computer simulation in which chin-to-chest contact is prevented, or in which the contact stiffness is varied, is necessary to verify a causal relationship exists and whether any mitigating actions might be feasible.

V. CONCLUSIONS

The performance requirements for booster seats in UN Regulation No. 129 can be met with the dummy seated directly on the test bench and restrained by the seat belt alone. There is little incentive, therefore, for boosters to improve the position of the belt and little discrimination between boosters. Although the abdomen pressure criterion detects significant loading to the abdomen, under the current regulatory test conditions, borderline interactions where the lap belt is visibly high on the pelvis, or forward of the pelvis, are not discriminated from more favourable belt paths. Added to this, the Q-Series dummy does not readily submarine.

The initial static belt path and knee-head excursion were both capable of discriminating differences between boosters. Although the link between either parameter and the real-world booster performance and risk of injury has not been established, both parameters would require a booster to be present and to achieve a basic level of performance in the regulatory test. They may be useful tools, therefore, to supplement the current performance requirements and ensure that good restraint design principles are followed.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX A

The static position of the lap belt was presented in the paper. However, the position of the diagonal belt was also measured prior to each experiment using the same procedure proposed for UN Regulation No. 129 (UN Informal Document CRS-58-04e *Belt Path Assessment Text*). The position of the seat belt is measured relative to a reference point on the Q-series grid suit. As the grid suit is not available for the Q3, similar landmarks were drawn on the suit in equivalent positions to those of the Q6 and Q10. In the case of the diagonal belt, the measurement is usually made from a reference point on the opposite shoulder to that of the belt. However, in our tests with the Q3, we measured from a point on the same shoulder as the belt, as illustrated in Figure A1, below. In this case, a larger measurement, i.e., the larger distance to the belt, means the belt is further to the neck.

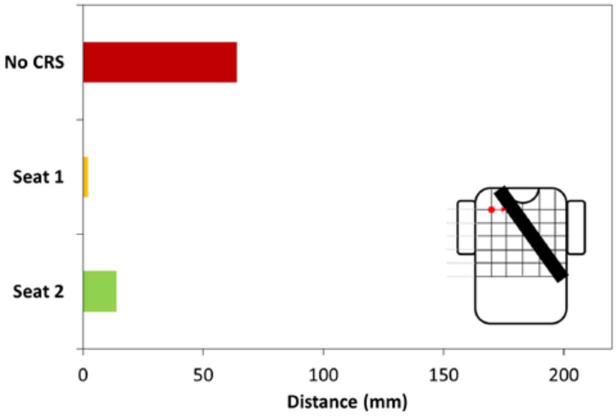

Fig. A1. Static measurements of diagonal belt fit with the Q3.

In Figure A2 (Q6) and Figure A3 (Q10), the correct reference point was used on the opposite shoulder. In this case, a lower measurement indicates the belt is closer to the neck and a larger measurement indicates it is close to the edge of the shoulder. A belt position criterion was specified for these dummies in the proposed procedure and is overlaid on the chart (the green area denotes the acceptable position).

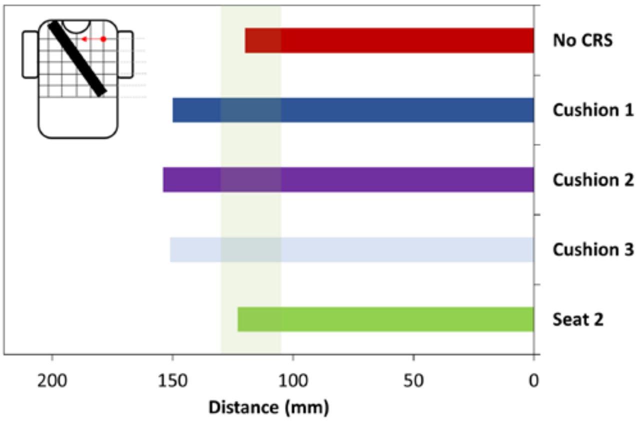

Fig. A2. Static measurements of diagonal belt fit with the Q6.

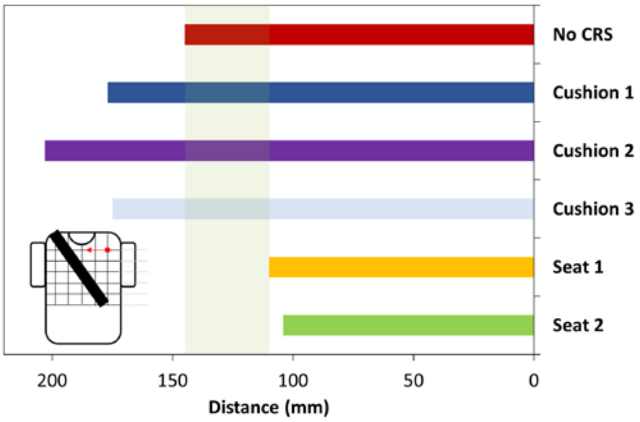

Fig. A3. Static measurements of diagonal belt fit with the Q10.