Effect of Crash Pulse Characteristics on Child Restraint System Performance in Front Impact Sled Tests

Costandinos Visvikis, James Ellway, Christoph Thurn, Thomas Müller

Abstract The front impact pulse used to test child restraint systems in United Nations (UN) regulations has not been updated since it was introduced in the 1980s. However, vehicle tests established later have led to stiffer structures with greater passenger compartment deceleration than vehicles from the 1980s. The aims of this study were to derive an experimental sled pulse corridor from European New Car Assessment Programme (Euro NCAP) full-width tests of modern vehicles and to investigate the effect of this pulse, alongside established corridors (UN R129, UN R16, FMVSS 213), on the performance of child restraints. The Euro NCAP sample highlighted that the UN R129 corridor is not representative of modern vehicles. Other regulatory corridors replicate some aspects of a full-width test, but do not offer a good fit overall. A new corridor would be needed to more closely match an average full-width vehicle pulse, in terms of the peak deceleration, time-to-peak, and the pulse duration. The effect of the pulses on child restraint performance depended on the type of child restraint and the dummy size, but the UN R129 corridor tended to generate the lowest measurements. Any new corridor would challenge current child restraints, particularly if the current UN R129 performance limits are maintained.

Keywords Child occupant protection, child restraint systems, child safety, vehicle crash pulses

I. INTRODUCTION

A front impact test of child restraint systems is specified in United Nations (UN) Regulation No. 129 (R129). This comprises a 50 km/h impact with a deceleration corridor that peaks between 20 g and 28 g. This pulse was carried over from UN Regulation No. 44 (R44), the predecessor to UN R129. UN R44 entered into force in 1981 and the front impact pulse was representative of production vehicles at that time [1]. Precise details of how the pulse was derived appear to have been lost to history. However, it is understood that a series of rigid wall crash tests were carried out in which the impact face extended across the full width of the car [2]. This scenario, where the vehicles overlap by 100 % of their width, is demanding of restraint systems because the impact force is spread widely over the frontal structures thereby limiting deformation [3]. This results in a short stopping distance and high passenger compartment deceleration compared with offset collisions [4]. The UN R129 pulse is well-established in UN Regulations and is also specified in UN Regulation No. 17 (strength of seats), UN Regulation No. 100 (electrical safety) and UN Regulation No. 126 (partitioning systems).

Vehicles were subject to very rudimentary crash requirements when the UN R44 pulse was derived. Since then, mandatory offset crash tests were introduced in European Union (EU) vehicle type-approval legislation in the late 1990s, and at around the same time, the European New Car Assessment Programme (Euro NCAP) began rating vehicles with increasingly more stringent requirements than the legislation [5]. These legislative and Euro NCAP offset crash tests were very demanding of the passenger compartment integrity of vehicles from that period and led to stiffer vehicle structures that minimised intrusion [6]. However, a potential artefact of stiffer vehicle structures is greater passenger compartment deceleration, particularly in full-width conditions [3]. Studies of vehicle crash pulse characteristics over time appear to confirm this, not only in Europe [7], but in different regulatory jurisdictions, such as the United States [8].

During the development of UN R129, the UN Informal Group on Child Restraint Systems compared the UN R44 corridor with vehicle pulses from regulatory and Euro NCAP tests [9-10]. Although there were some differences in timing and duration, they concluded that the UN R44 corridor was generally comparable in

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severity to vehicle pulses of that time, i.e., around 2008 [11]. However, full-width crash testing was not specified in Europe until later and so their analysis drew on offset tests only. Recognising that full-width conditions would be more appropriate for the assessment of child restraint systems, a 2010 study derived an alternative corridor from National Highway Traffic Safety Administration (NHTSA) full-width tests at 48 km/h [12]. This new corridor, developed in [12], peaked between 25 g and 32 g, with a shorter duration than the UN R129 corridor. Shortly after, a moving car to moving car full-width test with a European Supermini generated vehicle pulses that fitted closer to the corridor proposed by [12] than the R129 corridor [13]. In the same study, matching sled tests were carried out with child restraints that had also been installed in the car-to-car experiment. This found that the dummy responses generated with the pulse in [12] were more consistent with those in the car than sled tests with the R129 pulse. Nevertheless, no changes were made to the pulse specified in UN R129, but over the last decade, Euro NCAP has further increased the stringency of their offset test, whilst also introducing a full-width test in 2015.

In 2021, the European Commission funded research to review crash pulses across all type-approval legislation, with the aim of identifying where changes might be needed [2]. To this end, a new analysis of full-width crash test data was performed using a sample of 22 tests provided by Euro NCAP. The study found that individual peaks in the vehicle pulses were higher than the UN R129 corridor, as was the mean pulse. A potential new corridor was derived, which was similar to that proposed in 2010 in [12], but featured a wider initial rise. Despite developing a potential new corridor, [2] proposed instead that the corridor specified in UN Regulation No. 16 (UN R16) on safety belt systems should be adopted in UN R129. However, the UN R16 corridor is potentially more severe than a pulse derived from Euro NCAP full-width tests because it is shorter in duration and the peak deceleration is maintained for longer. Furthermore, the dynamic test in UN R16 assesses seat belt systems with a basic, rigid dummy. The main performance requirements are specified in terms of dummy displacement. No biomechanical criteria or limits are applied. The validity of this pulse for assessing child restraint systems with advanced dummies such as the Q-Series is unknown.

Although the research described in [2] focussed on the UN regulatory situation, similar activities have taken place in the United States. For example, statistically significant differences were found between the Federal Motor Vehicle Safety Standard (FMVSS) 213 sled pulse and vehicle crash test pulses obtained from NHTSA [14]. Nevertheless, NHTSA recently evaluated the FMVSS 213 pulse against real world collisions involving restrained children and concluded there was no pressing safety need to update the pulse [15]. However, although the FMVSS 213 pulse peaks at a similar level to that of UN R129, the initial rise is steeper, the peak is maintained for longer and the overall duration is shorter. The FMVSS 213 pulse may therefore be more severe for the assessment of child restraints than the UN R129 pulse, although no recent studies seem to have been conducted to verify this. In light of these developments, the aims of this study were (1) to derive a sled pulse corridor from full-width crash tests of modern European vehicles and (2) to investigate the effect of this pulse, alongside established pulse corridors (UN R129, UN R16, FMVSS 213), on the performance of child restraint systems in regulatory-type tests.

II. METHODS

Vehicle Crash Pulse Analysis

Anonymised base of B-pillar deceleration time-histories were provided by Euro NCAP from a sample of 144 official Euro NCAP 50 km/h full-width rigid barrier crash tests. No further inclusion criteria were defined. For example, all vehicle model years were considered on the basis that the full-width test is a relatively recent addition to the Euro NCAP rating scheme in 2015. Similarly, all vehicle size classes were included and no attempt was made to target worst-cases or vehicles commonly used to transport children. Although Euro NCAP assigns each vehicle to a class, e.g., supermini, small off-road, etc., these are typically declared by the manufacturer. Marketing or other considerations may factor into the decision, rather than genuine vehicle characteristics, which makes analysis of specific classes unreliable.

A mean time-history and mean±3g corridor were calculated from the Euro NCAP sample and compared visually and qualitatively with the UN R129, UN R16 and FMVSS 213 front impact corridors to determine how well these regulatory pulses represent modern vehicle tests. A new sled pulse corridor, intended primarily as a visual aid, was estimated to fit around the mean±3g corridor in a uniform way appropriate for a standardised test. Essentially, the new corridor was hand-drawn to follow the mean±3g corridor, but with straight lines to minimise the number of data points, as befitting for a laboratory test corridor. The corridor characteristics were also compared in terms of the change in velocity (km/h), peak deceleration (g), time of peak deceleration (g) and the pulse duration (ms).

Experimental Testing

Thirty front impact experiments were carried out on an acceleration sled at the CYBEX Safety Centre in Germany. The tests were performed according to the procedure specified in the 03 series of amendments to UN R129. The performance of three child restraint systems was assessed across four test pulses (see Table I). These comprised the baseline UN R129 pulse, alongside pulses derived from UN R16, FMVSS 213 and the Euro NCAP full-width sample (Euro NCAP FW). Further tests were carried out with the dummy seated directly on the regulatory test bench. The FMVSS 213 pulse was not used in this condition after reviewing the results with the other pulses.

TABLE I
TEST MATRIX

Child restraint system		Dummy	Front impact test pulse			
Type	Installation		UN R129	UN R16	FMVSS 213	Euro NCAP FW
RF integral harness	*ISOFIX & SL*	Q1.5	✓	✓	✓	✓
		Q3	✓	✓	✓	✓
FF integral harness	*ISOFIX & SL*	Q1.5	✓	✓	✓	✓
		Q3	✓	✓	✓	✓
Booster seat	*Seat belt and ISOFIX*	Q3	✓	✓	✓	✓
		Q10	✓	✓	✓	✓
No CRS	*n/a*	Q3	✓	✓	-	✓
		Q10	✓	✓	-	✓
Total number of tests per pulse			8	8	6	8

RF (rear-facing); FF (forward-facing); SL (support leg)

The child restraint systems were all type-approved to UN R129. They comprised a rear-facing toddler seat, a forward-facing toddler seat and a booster seat. The toddler seats were equipped with an integral five-point harness and were attached with ISOFIX and a support leg. The booster seat included a backrest and was attached with ISOFIX, in addition to the three-point seat belt. The child restraint models were chosen for convenience, but shared characteristics with many others on the market today. All dummies and child restraint systems were installed according to the procedure specified for impact testing in UN R129 (see Figure 1). This procedure was also followed when the dummy was seated directly on the test bench.

Fig.1. Typical test set-up - Q3 in forward-facing toddler seat (left) and Q10 in booster seat (right).

Three instrumented Q-Series dummies were used: a Q1.5, Q3 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. All sled and dummy measurement and data analysis conformed to ISO 6487. The UN R129 assessment criteria were calculated for each experiment. These comprise head excursion, resultant head acceleration (cumulative 3ms value[1]), resultant chest acceleration (cumulative 3ms value) and abdomen pressure. Neck tension force and flexion moment are specified in R129 for *monitoring purposes* and were measured in this study. No limits are currently applied to the measurements; however, a proposal has been submitted to introduce limits for the Q0, Q1 and Q1.5 dummies and is currently in discussion at the UN [16].

Head excursion was measured relative to the fixed Cr point on the test bench, as specified in UN R129. The Cr point marks the intersection of the surface planes of the seat cushion and backrest of the test bench. The head excursion was determined by video analysis (FalCon eXtra, Falkner Consulting für Messtechnologie GmbH, Germany) 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.

III. RESULTS

Vehicle Crash Pulse Analysis

The study sample comprised 144 Euro NCAP full-width rigid barrier tests on new cars intended for the European market. The tests were performed between 2015 and 2019 at one of six test laboratories accredited by Euro NCAP. The target speed at the point of impact was 50 ± 1 km/h. The vehicle pulse characteristics are shown in Table II.

TABLE II
VEHICLE SAMPLE PULSE CHARACTERISTICS

Euro NCAP full-width tests (n=144)	Peak acceleration (g)	Time of peak acceleration (ms)	Velocity change (km/h)
Mean ± SD	37.5 ± 5.9	46.6 ± 12.9	57.9 ± 4.6

Figure 2 shows the mean acceleration-time history of the full sample of 144 Euro NCAP full-width tests. In addition, the sub-sample of 22 acceleration-time histories used in [2] is shown on the figure to illustrate the highly oscillatory nature of typical vehicle acceleration responses, despite a relatively *heavy* filter being used, i.e., Channel Frequency Class 60. Each individual vehicle pulse typically comprised a series of short duration peaks and troughs, some reaching as high as 45 g, whilst also dipping below 5 g. The time to reach the overall peak acceleration was variable. Some pulses were front-loaded, i.e., the peak was relatively early with respect to the total duration, whereas other pulses were back-loaded. The mean pulse smoothed out the oscillations of the individual vehicles and was moderately back-loaded, which suggests this was the most common pulse shape in the vehicle data. This *smoothing effect* meant that the mean acceleration time-history peaked at 30.5 g and was lower, therefore, than the mean of the peak acceleration values across the actual vehicle pulses (37.5 g, Table II).

The ±1 standard deviation of the Euro NCAP acceleration-time histories formed a very wide corridor around the mean (Figure 2). The mean ± 3g was therefore used as a more precise basis for comparing vehicle pulse characteristics with current regulatory corridors and for developing a new corridor (Figures 3 to 6). The mean of the Euro NCAP pulses exceeded the upper limit of the UN R129 corridor by around 2.5 g (Figure 3). The mean vehicle pulse also displayed a steeper initial slope and a shorter duration than the UN R129 corridor. Although the time to reach the peak acceleration was within the range of the UN R129 corridor, the back-loaded shape of the mean vehicle pulse differed from the more evenly-loaded, almost triangular, regulatory corridor.

[1] The cumulative 3ms value is the highest acceleration level with a cumulative duration of at least 3ms. It can be calculated from one peak or across a series of peaks and is often specified in UN Regulations for vehicle occupant protection.

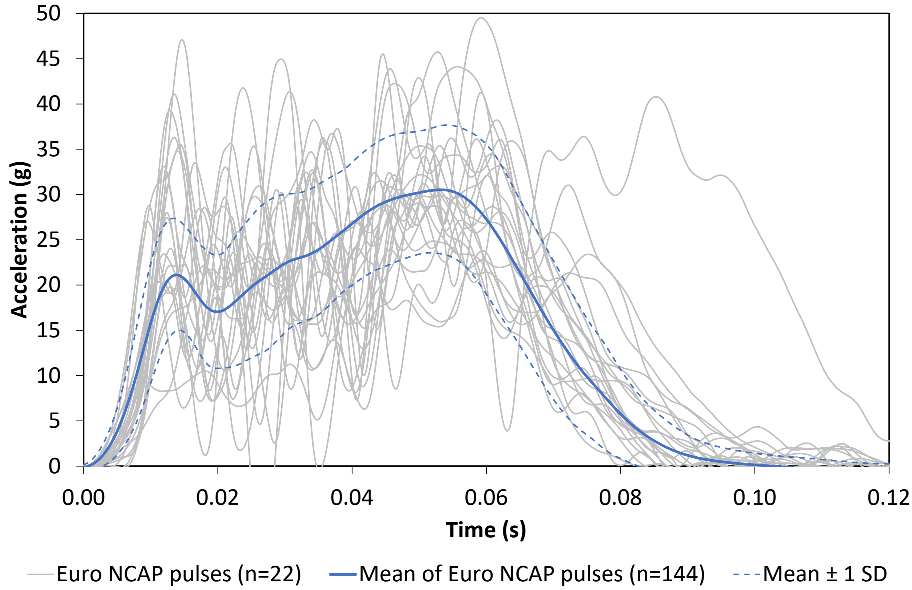


Fig.2. Base of B-pillar acceleration-time histories from Euro NCAP full-width rigid barrier crash tests at 50 km/h compared with the mean and mean ± 1 standard deviation (SD)

The peak acceleration of the mean of the Euro NCAP pulses was consistent with the UN R16 corridor (Figure 4). The initial slope also matched the corridor; however, the mean vehicle pulse displayed a more gradual rise to the eventual peak, which was maintained for a much shorter period than the UN R16 corridor. In addition, the duration of the mean vehicle pulse was slightly longer than that of the corridor. The mean of the Euro NCAP pulses followed the FMVSS 213 corridor very closely until around 40 ms (Figure 5). From this point, the mean vehicle pulse increased and reached the peak at around 5 g above the corridor. Although the duration was similar, the FMVSS 213 corridor is a regular trapezoid shape and is more evenly-loaded than the mean vehicle pulse.

The mean Euro NCAP pulse was an irregular trapezoid with the peak occurring towards the rear, just prior to the down slope. A new corridor was drawn that followed the mean Euro NCAP pulse very closely, taking account of the ±3 g bands (Figure 6). This new corridor replicated the rapid initial gradient over the first 10 ms, followed by a more gradual rise to the ultimate peak towards the back end of the corridor. The corridor was intended to be feasible with a total velocity change of 51 $^{+2}_{-0}$ km/h.

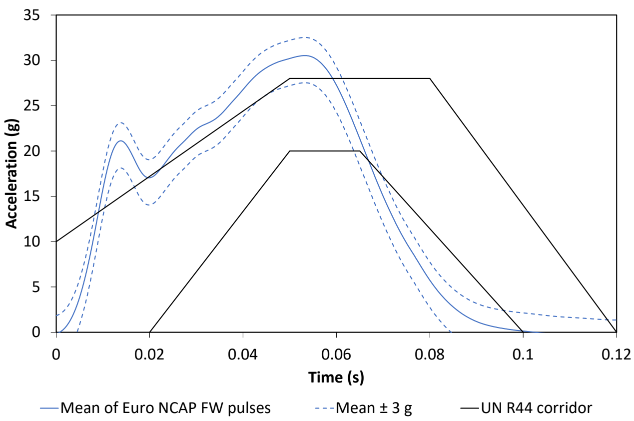


Fig.3. Mean of the acceleration-time histories from Euro NCAP full-width tests compared with UN R129 corridor.

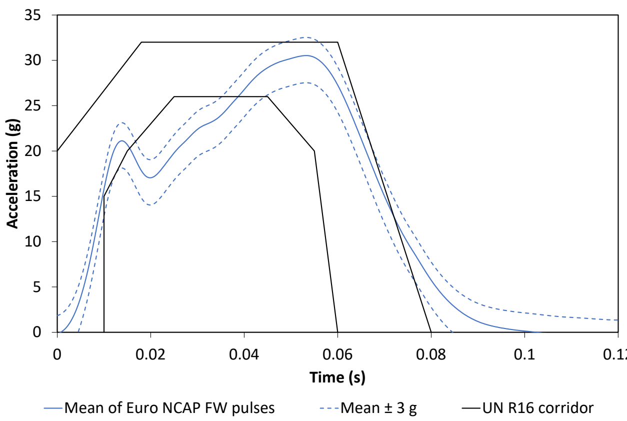


Fig.4. Mean of the acceleration-time histories from Euro NCAP full-width tests compared with UN R16 corridor.

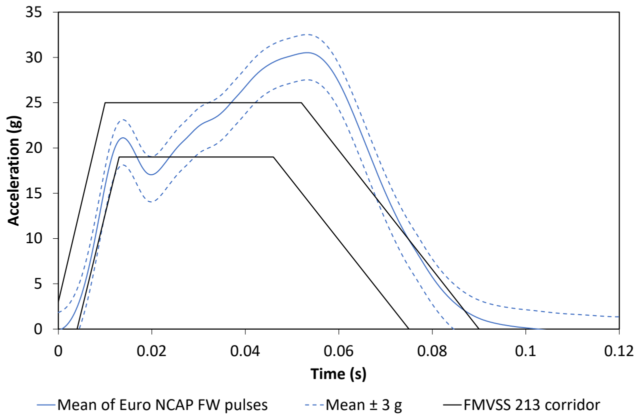


Fig.5. Mean of the acceleration-time histories from Euro NCAP full-width tests compared with FMVSS 213 corridor.

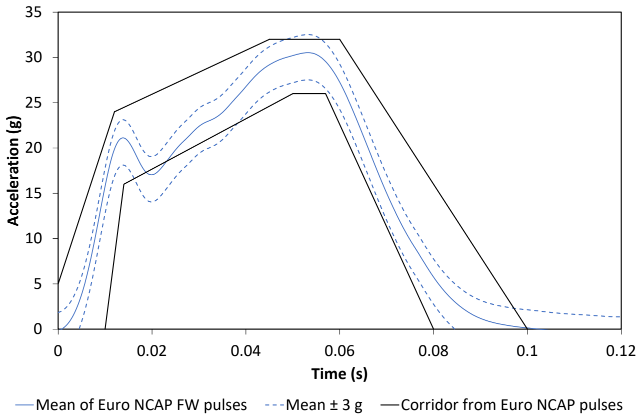


Fig.6. Mean of the acceleration-time histories from Euro NCAP full-width tests with a matching corridor.

Experimental testing

Sled pulses

Each of the sled pulses specified in the test matrix (Table I) fitted within the corresponding corridors shown in Figures 3 to 6. In addition, the total velocity change of the sled complied with the requirement of each regulation. An example of each of the four sled pulses is shown in Figure 7. The mean and coefficient of variation (CoV) of the key pulse parameters across tests with the same pulse are shown in Table III. Very high repeatability was observed for each pulse.

Although every effort was made to pass through each corridor in a consistent way, i.e., through the middle, this was not always possible due to the need to comply with a combination of acceleration and velocity conditions. The pulses for the UN R129 and Euro NCAP FW corridors typically passed through and/or peaked in the centre of the corridor, whereas the pulses for the UN R16 and FMVSS 213 corridors tended more towards the top of the corridor.

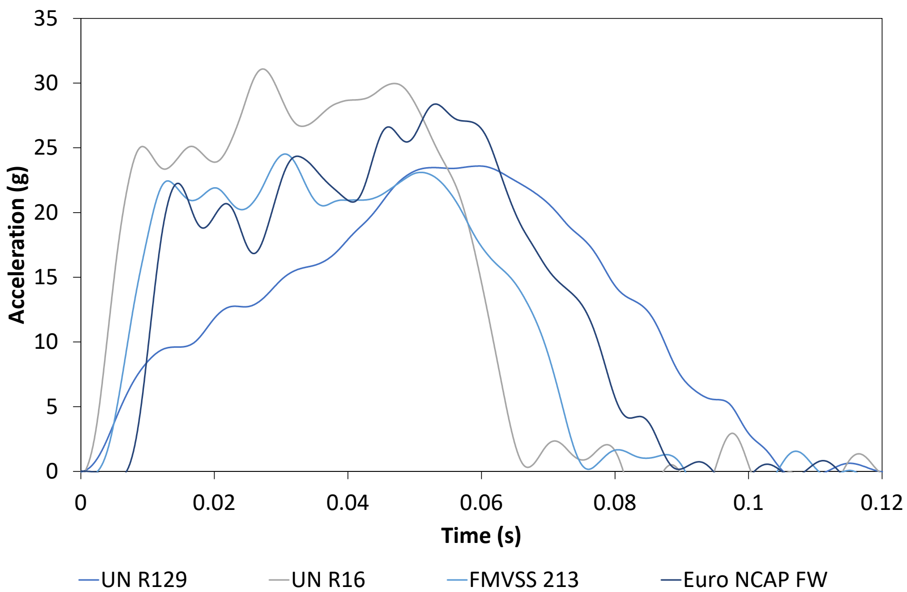


Fig. 7. Example sled pulses used in the experimental testing.

TABLE III
SLED PULSE CHARACTERISTICS

Front impact test pulse	Peak acceleration	(g)	Time to peak acceleration (ms)		Velocity change (km/h)	
	Mean (g)	CoV (%)	Mean (g)	CoV (%)	Mean (g)	CoV (%)
UN R129 (n = 8)	23.7	0.42	54.3	4.37	50.8	0.49
UN R16 (n=8)	31.3	1.20	27.0	0	53.5	0.38
FMVSS 213 (n=6)	24.6	0.65	30.3	1.70	46.6	0.60
Euro NCAP FW (n=8)	28.5	0.54	53.0	0	52.8	0.53

Dummy response

Peak horizontal head excursion was influenced by the sled pulse to some extent, but the differences were often marginal (Figure 8). For example, the UN R16 pulse increased head excursion by around 100 mm with both the Q3 in the rear-facing harness seat and the Q10 in the booster seat, compared with the UN R129 pulse. In both cases, the type-approval limit was almost reached. However, this trend was not replicated across other child restraint system and dummy combinations. Although some pulse effects were observed, such as moderate increases in head excursion with the UN R16 and Euro NCAP pulses, the level of difference tended to be in the order of 20 mm to 30 mm and therefore potentially also explained by normal test to test variation and error. The pulse did not appear to influence the capacity of the child restraints to achieve the current horizontal head excursion limit in UN R129. That said, all of the horizontal head excursion measurements in the forward-facing integral seat were at or just above the limit, including those with the UN R129 pulse. This child restraint was equipped with an internal load-limiting device, which has since been withdrawn due to inconsistent performance. Peak vertical head excursion showed almost no sensitivity to pulse in the forward facing child restraints (Figure 9). All of the alternative pulses generated slightly higher vertical head excursion than the UN R129 pulse in the rear-facing integral seat, particularly with the Q3, but all values remained within the UN R129 limit.

The cumulative 3ms value of the head resultant acceleration showed marked effects of the sled pulse, although the trends were somewhat inconsistent across the different child restraint and dummy combinations (Figure 10). The clearest effect was observed in the integral harness child seats where the UN R16 pulse increased head acceleration by 20 g to 30 g compared with the UN R129 pulse. The Euro NCAP pulse also increased head acceleration in these child restraints, typically by around 20 g compared with UN R129. Both of these pulses generated head acceleration that exceeded the UN R129 limit for the Q1.5 dummy by some margin. More moderate effects of the sled pulse were observed in the booster seat. In this case, the Euro NCAP pulse tended to have the greatest influence for both the Q3 and Q10 dummies (10 g to 15 g, compared with UN R129).

The effect of the sled pulse on the peak neck flexion moment was highly variable (Figure 11). In general, the alternative pulses tended to increase the flexion moment, but not in every child restraint and dummy combination. Where relatively large increases were observed, e.g., 5 Nm to 10 Nm, these were typically generated by the UN R16 and Euro NCAP pulses. Nevertheless, none of the pulses generated flexion moments that were close to the draft limit proposed for UN R129 in [16]. The peak neck tension force also displayed inconsistent trends (Figure 12). Where a large difference was observed between the UN R129 pulse and one of the alternatives, e.g., in the range 500 N to 1,000 N, it tended to be generated by the UN R16 pulse or the Euro NCAP pulse. However, there were notable exceptions, such as the Q3 dummy in the forward-facing integral harness child restraint and both dummies in the booster seat. Across these three cases, no single pulse consistently generated greater neck forces. Removing the potential influence of chin-to-chest contact by calculating the purely inertial neck force reduced the value to a similar level across all pulses, with the exception of the UN R16 pulse, albeit for the Q3 in the integral seat and the Q10 in the booster (Figure 13).

The cumulative 3ms value of the chest resultant acceleration was influenced greatly by the sled pulse (Figure 14). The UN R16 pulse in particular led to substantial increases in chest acceleration compared with the UN R129 baseline, often beyond the limit specified in R129. This was particularly noticeable in the forward-facing harness seat where the chest acceleration doubled and exceeded the UN R129 limit by around 40 g for both dummies. The FMVSS 213 and Euro NCAP pulses generated similar chest acceleration values, typically 10 g to 20 g greater than the UN R129 pulse and just above the UN R129 limit in some tests.

Peak abdomen pressure displayed inconsistent trends in its response to the sled pulse (Figure 15). Although the pulse appeared to influence pressure in some child restraint and dummy combinations, the measurements were typically quite far below the UN R129 limit, regardless of the pulse. Relatively low pressure, well within the R129 limit was also observed in the tests with the dummy seated directly on the test bench with no child restraint system. In these tests, the abdomen pressure did not differ notably from corresponding tests in a booster seat for any of the pulses used in the study. Furthermore, the dummy kinematics showed no evidence of submarining or unfavourable interaction with the seat belt in any of the tests with no child restraint system (Figure 16).

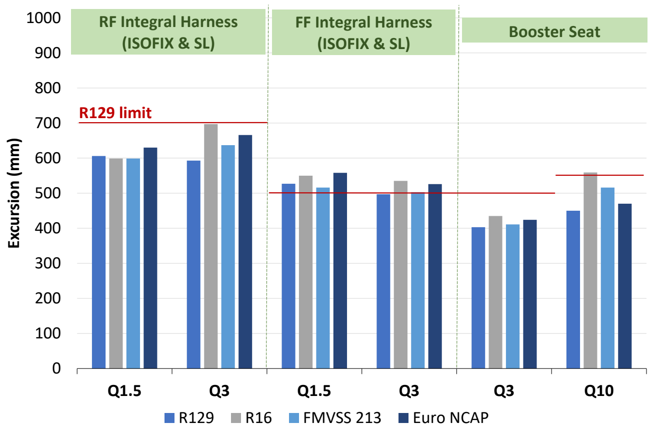


Fig.8. Horizontal head excursion (peak).

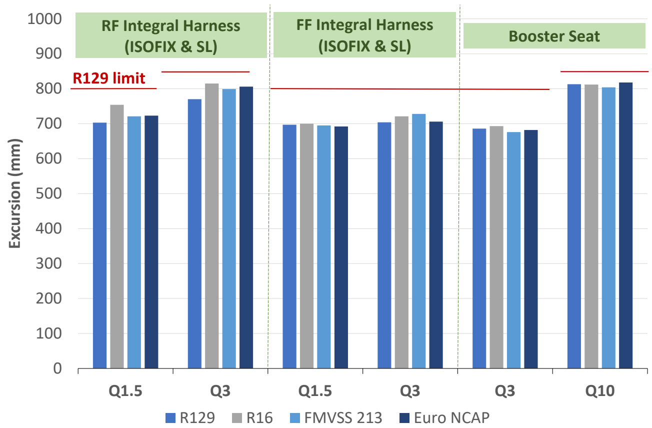


Fig.9. Vertical head excursion (peak).

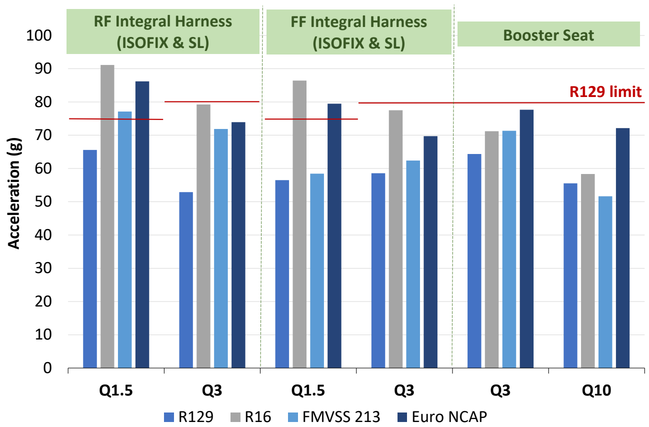


Fig.10. Resultant head acceleration (3ms value).

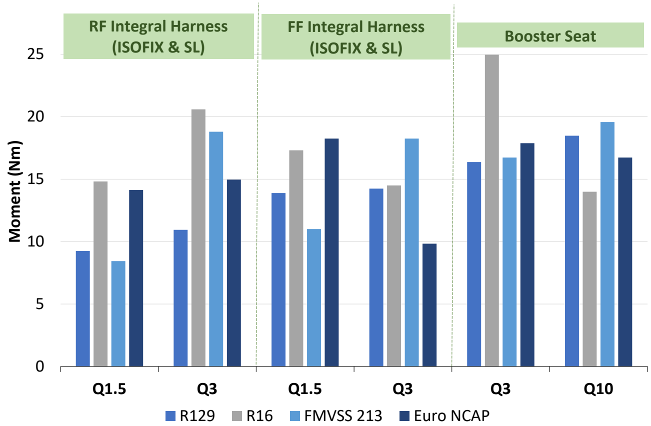


Fig. 11. Neck flexion moment (peak).

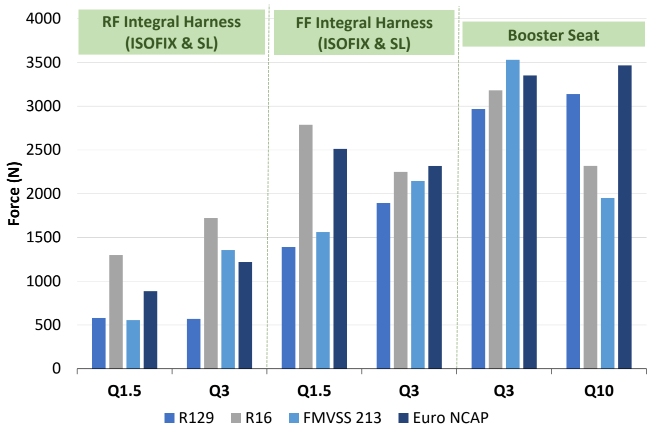


Fig.12. Neck tension force (peak).

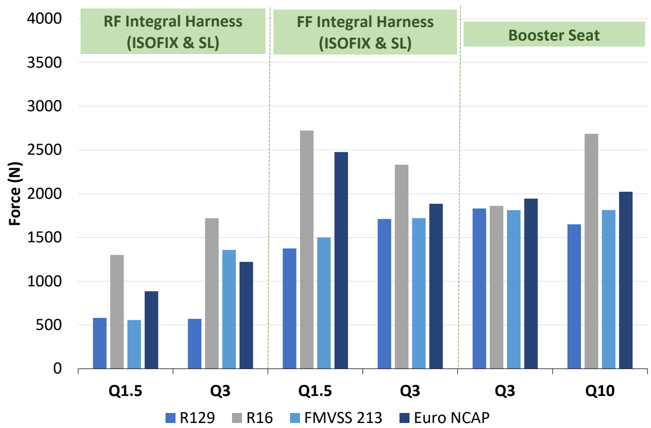


Fig.13. Neck tension force – inertial forces only (peak).

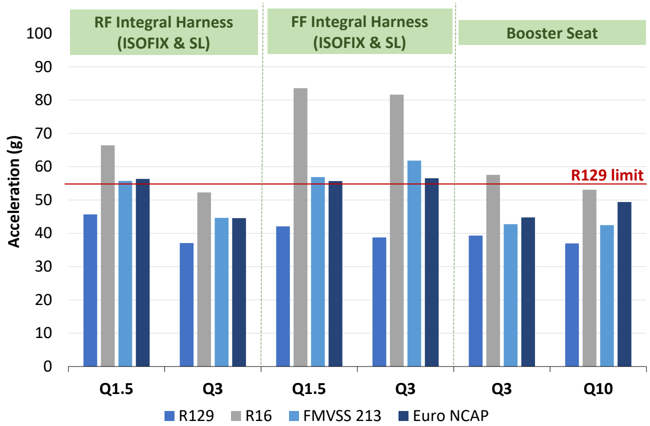


Fig. 14. Resultant chest acceleration (3ms value).

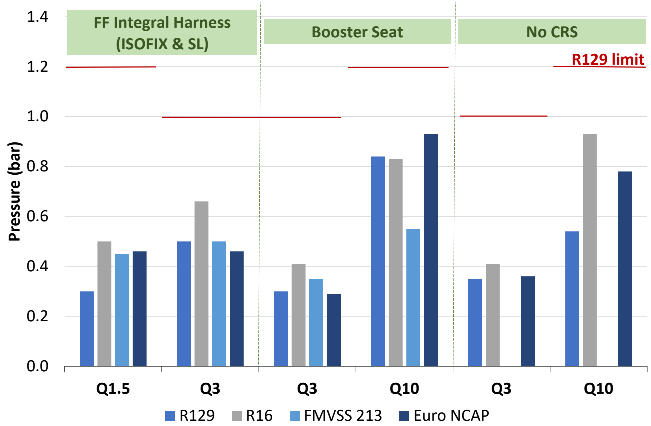
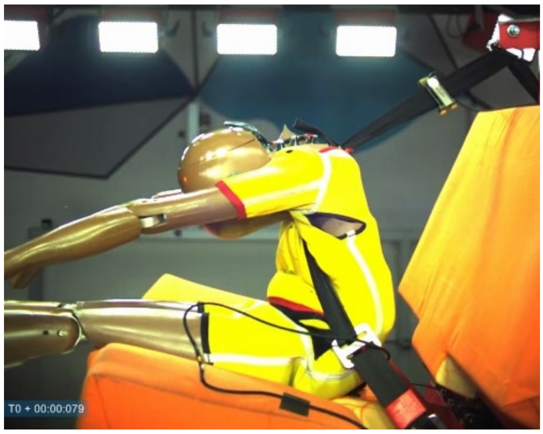


Fig.15. Abdomen pressure (peak left or right side).

Q3 dummy UN R129 pulse

Q10 dummy UN R129 pulse

Q3 UN R16 pulse



Q10 UN R16 pulse

Q3 Euro NCAP derived pulse

Q10 Euro NCAP derived pulse

Fig.16. Dummy kinematics and belt interaction at peak head excursion with no booster.

IV. DISCUSSION

The vehicle crash pulse can be a dominant factor affecting injury risk in a collision [17]. The vehicle pulse determines how much work the restraint system must do for the occupant to ride-down the collision without serious injury. It is important, therefore, that sled pulses, particularly those used in regulatory tests, are set at an appropriate level to target injuries without increasing the cost and complexity of the restraint system. This is especially important for child restraint systems, which are usually an accessory purchased by parents in addition to the vehicle. Although a sled pulse will always be a standardised representation of a real vehicle pulse, it must replicate the essential characteristics, such as peak acceleration, pulse shape and duration. The Euro NCAP sample demonstrated that a large variation in peak acceleration and pulse shape can be generated in vehicles subject to a 50 km/h full-width rigid barrier crash test. Much of this variation is caused by relatively short duration oscillations that may not be crucial to the performance of a restraint system. However, the large range in peak acceleration and the mix of front- and back-loaded pulses observed in the sample suggest it is unlikely that a regulatory sled pulse corridor could ever replicate all vehicles precisely.

Our study builds on that of [2] by examining a larger sample of tests, i.e., 144 vs. 22. That said, the mean pulse from our analysis was similar to [2], which suggests that analysing a more manageable sub-sample of vehicle tests can also be meaningful, provided no biases are introduced. The vehicle sample characteristics from our study were also similar to those of [14]. Euro NCAP assesses vehicles for the European market that are type-approved using UN Regulations for most of the technical requirements. The United States operates a different regulatory framework. Nevertheless, the pulse characteristics derived by [14] from NHTSA full-width rigid barrier tests at 48 km/h were similar to our study. For example, [14] reported a slightly lower mean peak acceleration (33.8 g vs. 37.5 g), but the study sample included tests from year 2000, whereas ours began in 2015. Although the sled pulse in UN R129 is different from that of FMVSS 213, these vehicle data suggest that a single pulse might be capable of covering both regions.

The peak acceleration of the mean Euro NCAP test pulse (30.5 g) exceeded the upper limit of the UN R129 corridor. The difference was only around 2.5 g, but a typical UN R129 pulse is unlikely to follow the upper limit of the corridor closely as the other test conditions would not be met. For example, the upper limit of the corridor represents a total velocity change of around 80 km/h whereas UN R129 specifies the velocity change must be 52^{+0}_{-2} km/h for acceleration sleds. The relatively large duration of the UN R129 pulse (120 ms for the upper corridor) is a factor that serves to keep the peak acceleration lower than the upper limit and within the total velocity change requirement during a typical test. The real vehicle pulses in the Euro NCAP sample typically displayed a pulse duration of around 80 to 100 ms. Of the existing regulatory corridors, the mean Euro NCAP test pulse arguably displayed the best fitting to the UN R16 corridor. However, the mean vehicle pulse dipped below the corridor between approximately 20 to 40 ms, which may be important as during this period, any residual slack has been removed and the occupant is typically coming into full contact with the restraint system. The mean of the Euro NCAP test pulse exceeded the upper limit of the FMVSS 213 corridor by around 5 g, after following the corridor quite closely for the first 40 ms. This contrasts somewhat with where the mean of the NHTSA 48 km/h tests displayed a similar peak acceleration to the FMVSS 213 corridor, if somewhat later and also did not replicate the initial rapid slope of the corridor.

The shape of the mean Euro NCAP pulse was an irregular trapezoid with the peak occurring towards the rear, just prior to the down slope. Although the existing regulatory pulse corridors shared some characteristics with the mean Euro NCAP pulse, none achieved as good a fit as the new corridor derived from the mean ± 3g. This new corridor appeared to be sufficiently different from the existing regulatory corridors to warrant including it in our test programme. One characteristic that the new corridor derived from the Euro NCAP tests shared with those of UN R16 and FMVSS 213 was a rapid initial slope. This was replicated in the vehicle pulses as well, but may be an artifact of the longitudinal rails interacting with the rigid wall. Car-to-car crash pulses typically display a more gradual rise; nevertheless, a more rapid rise is associated with a higher severity [15] and may therefore be a reasonable worst-case for testing a restraint system.

The effect of the sled pulse on child restraint performance depended somewhat on the type of child restraint and the dummy size. Nevertheless, the UN R129 pulse tended to generate the lowest dummy measurements. All of the child restraints were type-approved to UN R129 and although they were developed primarily to perform well in European consumer testing, which specifies a different pulse, it is also possible that some degree of historical optimisation played a role as well, for example if long-standing design practices were followed that were developed over many years of UN R44 and then UN R129 type-approvals. The UN R16 pulse tended to generate the highest dummy measurements. The head and chest acceleration showed particularly marked increases with the UN R16 corridor compared with the UN R129 baseline. Although it might be feasible to develop child restraint designs that bring these measurements back below the current regulatory performance limit, that might come at the expense of head excursion which was already close to the limit in several of the UN R16 tests. Given that protection of the head from contact with the vehicle interior remains a priority for injury reduction, adopting the UN R16 pulse without revaluating the performance thresholds might lead to unintended consequences for head impact protection.

The FMVSS 213 corridor often resulted in similar measurements to the UN R129 corridor; however, whenever there was a difference, the FMVSS 213 corridor tended to be higher. Although the UN R129 corridor peaks above the FMVSS 213 corridor, the steeper initial rise, and longer period of peak acceleration, may have played a role, or it could simply have been inadvertent optimisation. Given that the FMVSS 213 corridor was better at replicating some of the vehicle pulse characteristics than the UN R129 corridor, it may present an opportunity to harmonise without reducing safety or placing undue demands on child restraints. The corridor derived from the Euro NCAP tests resulted in measurements that approached those of UN R16 in some dummy and child restraint combinations, but they were more often lower than UN R16 and in some cases consistent with FMVSS 213. Nevertheless, this pulse presents an opportunity for testing child restraints with a pulse that represents the mean pulse of UN-approved vehicles in a 50 km/h full-width test.

Recent studies have highlighted the limited capacity of the Q-Series dummy to submarine in conditions under which it might be expected [18-19]. For example, it would be desirable for the dummy, particularly the smallest booster-sized dummy, i.e. the Q3, to submarine when seated directly on the test bench as this requires any booster seat being type-approved to actively control and improve the belt interaction. Currently, it appears not to be the case and the dummy displays submarining tendencies only in relatively extreme cases of poor initial belt placement or geometry [18]. In our study, the crash pulse offered no influence on the behaviour of the dummy in this regard. This contrasts with one previous study in which the pulse did appear to improve the capacity of the dummy to submarine [19]. However, a prototype hip liner was used in that study and it is possible that the production version, in becoming more durable, is now less effective in improving this aspect of the dummy behaviour. Unfortunately, no comparative testing appears to have been carried out and the prototype no longer seems to be available.

Regulators in the United States, i.e. NHTSA, recently decided not to increase the test velocity of FMVSS 213 to 56 km/h [15]. One of their reasons was that child restraint design changes may be needed that increase the weight, cost and size of child restraints potentially reducing their usability. Increasing the test velocity in this way would likely translate to a greater increase in stringency than the pulse adjustments discussed in this paper. Nevertheless, none of the child restraints in our study sustained significant damage in any of the pulses. It seems unlikely, therefore, that significant changes to the size or weight of child restraints would be needed if any of these pulses were introduced in the future. That said, as noted above, the UN R16 pulse might necessitate significant innovations to meet some of the current regulatory limits, which could add to the complexity and cost of child restraints. NHTSA also noted that child restraints are “highly effective in preventing injuries and fatalities” and when serious injuries occur these typically result from gross misuse of the child restraint or exceedingly severe collisions [15]. Similar data from countries that follow UN R129 supports the view that child restraints are currently very effective [21-22]. The proportion of children in child restraints receiving serious injury was very low in [21] and [22]. However, the absolute numbers were also very low, which makes it difficult to draw reliable conclusions about the causes and mechanisms of injury at a population level. Furthermore, the limited-area sampling strategy used by the European in-depth collisions databases that [21] and [22] drew from, combined with low case numbers, means that trends, such as those associated with vehicle age, or any other factor, may be being missed.

Limitations

A large sample of Euro NCAP crash pulses were analysed to derive a mean pulse for comparison with current regulatory sled corridors. The sample comprised a broad range of vehicles, which was reflected in the variation of pulse shapes and peak accelerations. No effort was made to evaluate the pulses by vehicle mass. Separating or grouping by mass might allow specific vehicle classes or sizes to be targeted. However, to be useful, it would also require knowledge of the type and/or mass of vehicles that children travel in in order to highlight reasonable worst-cases or most common cases. Further, this may vary from country to country.

The investigation of the effect of the sled pulses on the performance of child restraint systems was limited to a small convenience sample of child restraints. Although these shared common characteristics with many child restraints on the market today, different makes and models might respond differently to crash pulses. For example, lower cost child restraints, which play an important role in ensuring child restraint use is high, might respond differently and require further engineering to withstand these pulses. Further, some child restraint types were not investigated at all, such as harness seats for larger children, belt-attached child restraints, or booster cushions. All of these child restraint types may respond differently to pulse changes than those used in this study.

V. CONCLUSIONS

The front impact corridor specified in UN R129 is not representative of modern vehicle pulses in a 50 km/h full-width rigid barrier test. Real vehicles typically experience a shorter duration pulse with a more rapid initial slope and higher peak acceleration than the UN R129 corridor. Other regulatory corridors replicate some aspects of a full-width test, but do not offer a good fit overall. For example, the UN R16 corridor was somewhat similar in shape but maintained the peak acceleration for longer, whereas the FMVSS 213 corridor also displayed a similar shape for part of the pulse, but ultimately did not reach the same acceleration as the cars. A new corridor would be needed to replicate all of the key characteristics of an average full-width pulse, such as peak acceleration, time-to-peak and pulse duration.

Changing the UN R129 corridor would challenge child restraints, particularly if the current performance limits are maintained. The UN R16 corridor was particularly severe for the dummy head and chest acceleration and would likely require significant harness redesign with potential implications for dummy head excursion. The corridor derived from the Euro NCAP tests would also increase the stringency of the test for some body regions in some child restraints; however, this was also the case for the FMVSS 213 corridor, which also offers the opportunity for harmonisation between the US and UN requirements. However, determining the most appropriate pulse for assessing child restraints is a matter for regulators who need to balance any potential benefits against any wider implications for child restraint performance at lower (and more common) severities, child restraint cost, usability and weight.

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VII. REFERENCES

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