

Estimation of injury risk of different child restraint systems in realistic frontal impact tests for future mobility applications

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Abstract

Motorized vehicle crashes represent the highest injury risk for children. Furthermore, new devices and new transportation applications potentially bring new challenges and injury risks. Therefore, the main objective of this work is to analyze the safety performance of seat belt alone, booster seat and belt guide only devices in frontal impact tests under regulatory and realistic conditions. We analyzed the kinematics of the dummy, calculated the injury risks and compared it with the meta-analysis of past published crash analysis complemented with the most recent accident data retrieved from the EU CARE database. We calculated the risk attributable to the studied restraint solutions and test conditions.

Test on belt guide only devices show that they are statistically equivalent to seat belt alone solutions. Therefore, replacing an appropriate booster seat with belt guide only devices potentially increase the number of injured children by 33% (95 confidence interval:16%, 50%).

Finally, we performed gap analysis to improve the fitness-for-purpose of regulations for future mobility applications.

Keywords: child restraint system, passive and active safety, motorized vehicle crash, vulnerable users, crash statistics

1. Introduction

The use of child restraint systems (CRS) is mandatory in all Member States of the European Union (Directive 91/671/EEC) for children less than 150 cm tall. The technical criteria of CRSs are regulated by UNECE Regulation 44 which was replaced by UNECE Regulation 129.

In spite of the widespread use of CRS, road fatalities are a leading cause of death of children (defined as 14 years old or younger persons) both in the EU (EU Observatory, 2018a) and in the US (NHTSA, 2019). In the EU 50% (Dovile Admaite *et al.*, 2018) and in the US 74% (NHTSA, 2019) of all dead children in road crashes were car occupants.

According to the European Road Safety Observatory (EU Observatory, 2017, 2018b) child fatality in motorized vehicle crashes (MVC) decreased from 1,888 to 615 between 2007 and 2016, but leveled off around 500 fatalities in the recent years. In the US the decline of child fatality (NHTSA, 2019) is smaller compared to EU data and it has flattened in the recent years too. Since MVCs are a consistent part of overall child fatalities, the effectiveness of CRS has a major influence on the reduction of injured and dead children.

New devices, such as belt guide only have been provided on the market as a cheaper/lighter alternative to child seats. However; testing procedures and regulations were not developed for such devices and are not always sensitive enough to determine their safety performance. Previous findings showed that Q-series dummies are less sensitive in regulatory tests (Visvikis, Thurn and

Müller, 2020) on the abdominal region when the dummy is placed on the test bench without a CRS and even the adult seat belt can pass the regulatory limits of UN ECE R129. We investigated the effectiveness and estimated the efficacy of belt guide only solutions in real car seat, as it is prescribed in UN ECE R129 comparing its safety performance with a booster seat.

The efficacy of different CRSs can be estimated from accident data by comparing the odds ratio (OR) of injury and fatality between CRS and no restraint use. However, accident databases can be used if an intervention or protection device is widespread enough to have measurable statistical significance. Alternatively, safety performance of new devices can be estimated by establishing causal relationships between the kinetics of a simulated crash and injury severity. However, this latter method is not able to assess the change of injured children attributable to the device. Therefore, in this work we combined accident statistics with injury assessment of simulated crash data applying machine learning techniques to calculate the potential risk of belt guide only devices on the population of 8-12 years old children in frontal impact MVC.

1.1. Efficacy of child restraint systems

Elvik et al. (Elvik *et al.*, 2009) applied meta-analysis of 19 accident studies originated from 1977 to 2006 and concluded that any restraint, including the car seat belt alone, reduces injuries; however, CRS had beneficial advantage over the (adult) seat belt alone for kids between 0-9 years old. A proper CRS can reduce the number of injuries by 33% more than the car's seat belt alone.

The correlation between age and CRS types was studied in a NHTSA technical report (Robert Sivinski, 2010) by analyzing crash data between 1998 and 2008. It was found that the injury reduction for 4 to 8-year-old kids in CRS was 14% (95% CI 10-19%) compared to seat belt alone. Furthermore, the analysis suggested that for 3 to 4-year-old kids, the booster seat, which is not designed for this age, may have caused more injuries than the child safety seat. For older kids, Anderson (Anderson, Carlson and Rees, 2017a) analyzed Washington state data of 8 to 12-year-old kids and found 29% reduction in the odds of experiencing any injury in a booster seat than with the seat belt alone (OR=0.709, 95% CI=0.675, 0.745). The adjusted estimation resulted in 19% (OR=0.814, 95% CI=0.749, 0.884) reduction of the odds of injury. Children in side impact crashes benefitted the most from booster seats showing an 82% and 62% reduction in injury risk for far side and near side, respectively, compared to seat belt alone (Arbogast, Jermakian and Ghati, 2009).

On the contrary, Ma et al. (Ma *et al.*, 2013) reported that 0 to 10-year-old children using booster seats experienced equal risk of injury but higher risk of neck and thorax injury than children restrained by seat belt only. Despite kids up to 10 years were added to the analysis, 0-4 years were also included in the data, hence the average age was 4.7 years. A previous NHTSA study (Robert Sivinski, 2010) found that booster seat for smaller kids (<4 years) is not safe and they should be restrained in child safety seat rather than in a booster seat only, therefore the analysis of Ma et al. (Ma *et al.*, 2013) measured most probably the effect of misused booster seats for smaller kids.

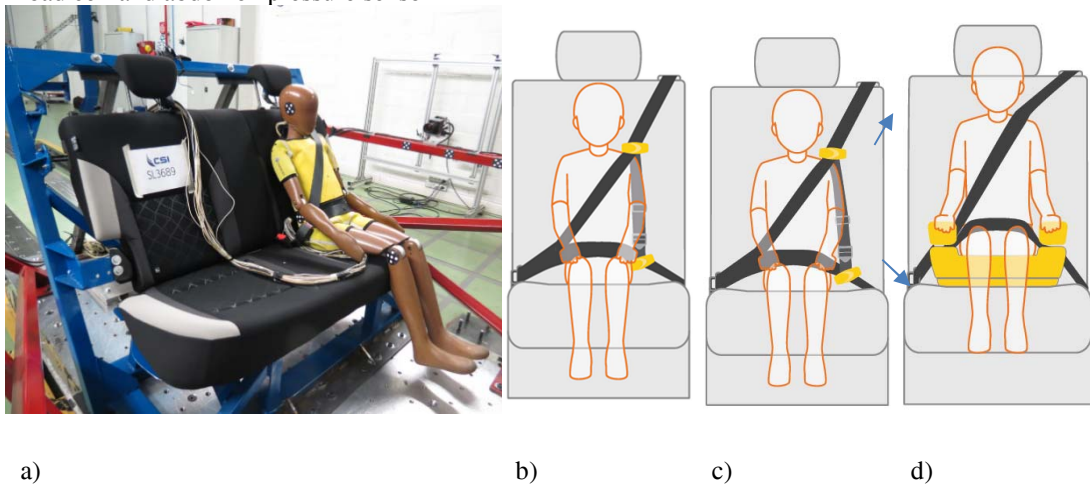
Obviously, any restraint, which prevents child occupants from free flying and from hitting the interior of a vehicle, provides protection from many injuries. However, the restraint itself can cause injuries if it is not properly designed for the occupant. The "seat belt syndrome" described by Garrett and Braunstein (Garrett and Braunstein, 1962) in 1962 identified a distinctive pattern of injuries associated with the lap belt. The immaturity of the pelvic structure of kids to properly anchor the lap belt combined with the tendency to scoot forward so that their knees bend at the edge of the seat create a constellation in which the lap belt directly compresses the abdominal organs against the spinal column. Furthermore, the child's body may "jack-knife" around the belt (Durbin *et al.*, 2011), putting high tension force on the lumbar spine increasing the risk of distraction injuries of the posterior elements of the spine. A lap belt that starts out too high can lead to a kinematic pattern known as submarining, in which the pelvis slides down under the belt and the

body is restrained through abdominal soft tissue, rather than through loads applied to the bony pelvis (Reed *et al.*, 2009).

Arbogast *et. al* (Arbogast, Jermakian and Ghati, 2009) studied the occurrence of injuries by body regions between seat belt alone and booster seat users. Head injuries represented ~65% of injuries and showed the same prevalence for both groups. For booster seat users, face and lower extremity injuries were the next most common at 9% and 8%, respectively, while children in seat belt alone sustained injuries to the abdomen and face at 12% and 9%, respectively.

2. Assessment methodology

We tested three restraint devices: 1) a universal category booster seat, 2) a seat belt alone, and 3) a belt guide only device in two installation configurations as Figure 1 depicts. All devices were type approved according to the respective UN ECE regulations. We performed frontal impact tests in real a car seat (vehicle body shell) with a Q10 dummy (equivalent of a 12 year-old child) according to the UN ECE Regulation 129. We installed the dummy in its rear seat with its seat belt system buckled according to the installation instructions of each type of device tested as it is seen in Figure 1. Because the instruction was not fully clear for the belt guide device, we tested two different webbing positions (Figure 1b and c). The Q10 dummy was equipped with head, thorax and pelvis accelerometers, lower and upper neck tension load cell, rib deflection sensor, lower lumbar spine load cell and abdomen pressure sensor.



a) Figure 1 Picture of the equipment used: the reproduced steel frame of Nissan Micra 5th Generation with Q10 manikin a). Schematics of the tested belt guide only configuration #1 b), belt guide configuration#2 c) and booster seat d). Arrows in inset c) show the differences from the configuration in inset b).

3. Results

We measured 48 different parameters during frontal impact tests. We recorded the tests with five high-speed, high-resolution cameras (1000 fps), which measured the displacement of the manikin's head and knee in the vertical and horizontal directions and analyzed potential submarining. Then we used the injury limits of UN ECE R129 or estimated limits from literature data to assess the risk of the different restraint devices.

We compared the kinematics acquired from all tests by using machine learning techniques such as principle component and cluster analysis, to classify the behavior of the dummy under different conditions and in different devices.

Finally, we calculated the risk ratios (RR) from previous studies by using meta-analysis of published motorized vehicle crash studies. Since these data were sometime more than 10 years old, we complemented the analysis with uncorrected accident data involving children and where the use of child restraint system has been recorded in the EU CARE and NHTSA databases in the last 5 years.

3.1. Frontal impact tests

Figure 2a shows that the behavior of head acceleration for both installations of the belt guide only (BGO) device and the seat belt alone (SBA) have a very similar pattern. The resultant head acceleration of belt guide only and seat belt alone show ca. two times higher head acceleration than a booster seat (BS) at around 100 ms, i.e. at the time of the maximum horizontal head excursion. The maximum of head acceleration for BGO and seat belt alone is above the head acceleration threshold of 80 g. Another sharp peak appears at ca. 220 ms for BGO and seat belt alone when the dummy bounces back and the head hits the back of the seat. In Table 1 the head performance criterion (HPC as it is defined in R129) is also calculated which indicates a significantly higher values for BGO and SBA than for booster seat, although all values remain below the injury threshold (800) .

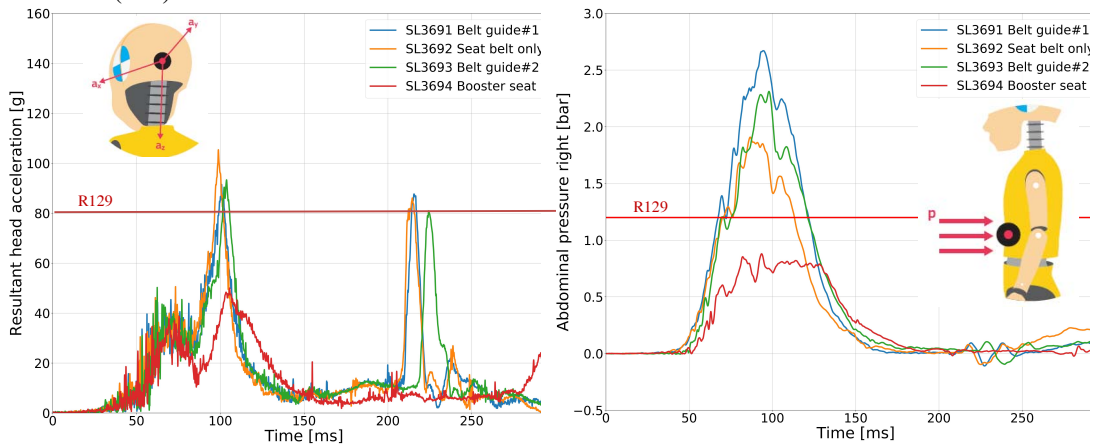


Figure 2. Resultant head acceleration a) and abdominal pressure on the right side b). The inset of the dummy shows positive directions of the acceleration in each direction.

Figure 2b shows that the abdominal pressure is much higher than the threshold of 1.2 bar in the case of belt guide only with both configurations and in the case of seat belt alone. The high abdominal pressure together with the visual observation (not shown here) that the lap belt fully passes the pelvic structure, is a strong indication of excessive stresses on the weak parts of the child’s abdomen that could lead to serious injuries (Johannsen and Schindler, 2007; Beillas *et al.*, 2012; Lesire, 2012). For the BS the pressure is never higher than 0.88 bar, consequently below the threshold of R129.

Table 1 Injury thresholds and measured values of each dynamic test. Limit values with * are from R129 paragraph 6.6.4.3. others are estimation from literature.

	Limit AIS \geq 3	Belt guide #1		Belt guide #2		Seat belt alone		Booster Seat	
		SL3687	SL3691	SL3690	SL3693	SL3689	SL3692	SL3688	SL3694
Head performance	800*	545.65	558.96	669.38	570.73	667.72	668.46	271.57	180.58

criteria									
Head acceleration 3 ms [g]	80*	86.32	85.48	100.67	85.22	96.36	91.37	57.35	47.24
Upper neck tension force F_z [kN] (max)	3.7 (2.8-4.6)	5.85	5.65	6.09	6.00	6.52	6.30	3.89	2.69
Upper neck flexion moment [Nm] (max)	135 (113-156)	13.78	12.44	12.89	10.11	14.9	3.17	5.86	6.19
Chest acceleration [g]	55*	45.30	46.58	46.66	45.26	47.42	44.23	42.16	39.43
Abdominal pressure [bar] Left/Right	1.2*	2.40 2.09	2.92 2.67	2.45 2.06	3.09 2.31	1.82 1.73	2.59 1.91	0.38 0.39	0.28 0.88

Table 1 summarizes the absolute values of the relevant injury limits and measured values. The BS values are lower than the thresholds for all parameters; however, for BGO and the SBA tests, the abdominal pressure and the head acceleration exceed the threshold by 250% and 25%, respectively. The red values in Table 1 indicate that the respective injury threshold is exceeded. Orange values are higher than the reference booster seat case and indicate the possibility of serious injuries despite no threshold has been defined in R129 paragraph 6.6.4.3.1.

Furthermore, we extracted 96 features from the times series of the measured values to compare the overall behavior of the different devices. Then we applied principal components analysis and we performed K-means clustering with 2, 3, 4 centroids using Wide method with covariance (using JMP statistical software, USA). The 2-centroid case yielded the optimal cluster numbers that is shown in Figure 3c. The density plot clearly shows that both configurations of the belt guide only and seat belt alone devices are in the same cluster while the booster seat is in another one. Injury assessment, ANOVA and principal component analysis unequivocally indicate that belt guides (regardless of the installation) behave similarly to seat belt alone, but differently from booster seat.

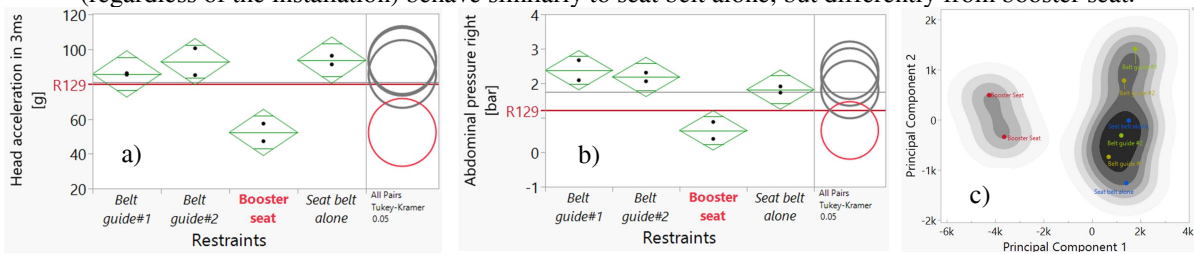


Figure 3 ANOVA analysis of resultant head acceleration a) and abdominal pressure b). Principal components analysis of all features c).

3.2. Population attributable risk of belt guide only solutions

Beside the already published relative injury risk ratio (RR) and odds ratio (OR) in literature, we supplement the data calculated from the latest available data sources from 2015 to 2018. We aggregate accident data of EU (CARE) and the USA (NHTSA, 2019) related to children and then we calculate the population attributable risk (PAR) of belt guide alone (PAR_{BGO}) in the following way:

- Unadjusted risks of injured, killed and seriously injured children are estimated from the number of injuries, fatality and serious injury of children, respectively, as a car occupant in different restraining solutions on children travelled km basis
- The exposure to different restraining solutions is estimated from CRS usage in the USA and EU member states from data of NHTSA (NHTSA, 2019) in 2017 and of ESRA (Nakamura *et al.*, 2020), European Transport Safety Council in 2018 (Dovile *et al.*, 2018), respectively. The EU exposure is averaged by weighing the use of restraints in each member states by children population data accessed from the OECD statistical portal, Historical Population Data (HPD) of ages between 5-14 years old and between 2015 and 2018 (Organization for Economic Co-operation and Development, 2021).
- In the EU, the number of injured, died or seriously injured children is aggregated between 2015-2018 for all EU countries and grouped by seat belt alone, CRS and no seat belt categories.
- The PAR_{BGO} is predicted from the RR and the use/penetration of belt guide alone among CRS for the investigated vehicles

Unadjusted injury risk ratio between CRS and seat belt alone is calculated by using the following formula:

$$RR_{CRS} = \frac{\frac{\#_{SBA}}{V_{km} KID_{vehicle} p_{Belt\ alone}}}{\frac{\#_{CRS}}{V_{km} KID_{vehicle} p_{CRS}}} = \frac{\#_{Belt} p_{CRS}}{\#_{CRS} p_{SBA}} \quad (1)$$

where $\#_{CRS}$ and $\#_{Belt\ alone}$ are the number of injured, died or seriously injured children when CRS or seat belt alone were used in the reported crash, respectively. V_{km} is the total driven km by all vehicle in a region/country in a year [km], $KID_{vehicle}$ is the average number of kids in a vehicle, and p_{SBA} and p_{CRS} are the EU weighted average of usage of CRS [%] and seat belt alone [%] respectively in the same period.

Despite vehicle km and the average number of kids per vehicle can be calculated from other sources (e.g. IRTAD by OECD), the risk ratio RR_{SBA} does not necessitate the knowledge of these parameters assuming that V_{km} and $KID_{vehicle}$ are independent from the usage of any restraint.

Unadjusted injury risk ratio between CRS and no restraint is calculated in the similar way

$$RR_{No\ restrain} = \frac{\#_{No\ restrain} p_{CRS}}{\#_{CRS} p_{No\ restrain}} \quad (2)$$

The different restraint use ratios are calculated from ESRA (Nakamura *et al.*, 2020) as follows

$$\begin{aligned} p_{CRS} &= (1 - ESRA_{no\ restrain}) * (1 - ESRA_{CRS}) \\ p_{SBA} &= (1 - ESRA_{no\ restrain}) * (ESRA_{CRS}) \\ p_{no\ restrain} &= ESRA_{no\ restrain} \end{aligned} \quad (3)$$

where $ESRA_{no\ restrain}$ is the perceived social normative of transport of children in the car without securing them and $ESRA_{CRS}$ is transport of children (under 150cm) without using child restraint systems.

The US fatality data and restraint use were accessed from NHTSA Traffic Facts (NHTSA, 2019). The numbers were aggregated for all types of CRS i.e. rear-forward facing, booster and high back booster seat data into “CRS used” category. “Seat belt” and “no restrain” were used as they are.

The EU accident data was accessed from CARE database on 15/03/2021, which contains the number of injured (killed and injured), died and seriously injured children between 5-12 years old from 29 EU member states from 2015 to 2018 as a function of different safety solutions. First, the data summarized for all EU member states, then aggregated to categories “CRS used” (backward, forward, not specified), “Belt used” (seat belt worn and air bag released, seat belt worn no airbag released, seat belt worn) and “No restraint” (no use of safety equipment) categories. The category “Belt alone” is calculated as the difference between “CRS used” and “Belt used”, since when CRS is used belt should be used as well. The unspecified cases and incomplete data were omitted from the analysis.

The population attributable risk quantifies the increase of injuries in a population taking into account the exposure to the scenario. We calculate PAR in accordance to the WHO (Chisholm and Naci, 2008) methodology by using the Levin's formula:

$$PAR_{BGO} = \frac{p_{BGO}(RR_{SBA}-1)}{p_{BGO}(RR_{SBA}-1)+1} \quad (4)$$

where p_{BGO} is the use ratio of the belt guide alone among other CRS, i.e. exposure to belt guide alone in the population. Figure 4 shows the calculated PAR from the different data sources. As it is expected from $RR>1$ relationship, PAR_{BGO} is positive, therefore the use of the device potentially increases the number of injury and death. The current unadjusted estimation is in line with the latest study about booster seats in the age group 8-12 by Anderson et. al (Anderson, Carlson and Rees, 2017b) as Figure 4 shows the that lines of unadjusted data are in close proximity with the EU data. Therefore, these data do not show significant changes in the efficacy between historical and recent data.

Table 2 Calculation of unadjusted relative risks for different age groups and regions in 2018 for US in the period 2015-2018 for EU, with the corresponding 95% CI. RR and CI are calculated by a Python script

Number incidents	CRS used	Belt alone	NO restrain	All
USA 8-12 year-old				
Fatality				
CRS usage (2017) (p)	9	96	89	194
Relative risk (RR)	12%	75%	14%	100%
	Ref	1.70 (0.8-3.8)	8.72 (4.3-19.1)	
USA 4-7 year-old				
Fatality				
CRS usage (2017)	72	43	55	170
Relative risk	69%	21%	11%	100%
	Ref	1.97 (1.3-2.9)	4.94 (3.3-6.9)	
EU 5-12 year-old				
Accidental injury				
Weighted CRS usage	7050	1610	695	9355
Relative risk	83%	13%	3%	100%
	Ref	1.40 (1.3-1.5)	2.5 (2.3-2.7)	
EU 5-12 year-old				
Serious injury				
Weighted CRS usage	379	637	132	1148
Relative risk	83%	13%	3%	100%
	Ref	10.8 (9.5-12.2)	8.5 (7.0-10.4)	
EU 5-12 year-old				
Fatality				
Weighted CRS usage	33	32	17	82
Relative risk	83%	13%	3%	100%
	Ref	5.8 (3.6-9.1)	16.3 (9.3-27.6)	

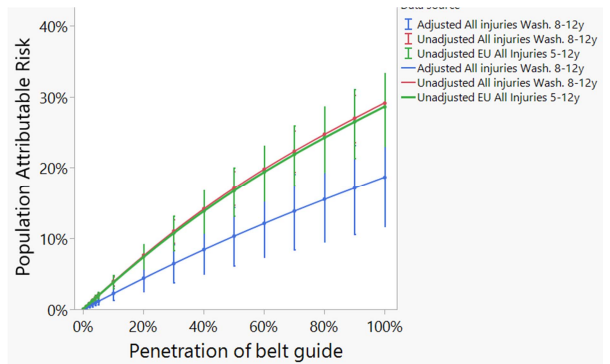


Figure 4 Estimated attributable risk of using belt guide only instead of a CRS (booster seat) for older children. The error bar shows the 95% CI calculated from the 95% CI of the risk or the odds ratios (RR and OR). The respective ORs (Adjusted/Unadjusted All injuries Wash. 8-12y) are taken from Anderson et. al (Anderson, Carlson and Rees, 2017b).

4. Conclusions

Previous findings showed that Q-series dummies are less sensitive in regulatory tests on the abdominal region; however, we showed that this does not hold for real conditions. By performing frontal impact tests in realistic conditions, we showed that booster seats provide the highest level of safety for children in motorized vehicle crashes. The belt guide only device investigated exceeded the abdominal injury and the resultant head acceleration threshold by 250% and 25%, respectively.

Therefore, new types of child restraint systems, which may provide more flexibility, need to be investigated in more detail not just under regulatory criteria but also under real conditions. This lack of sensitivity of regulatory tests potentially increases the risk that unsafe CRSs are able to enter the market. Therefore, new regulatory research is suggested to assess whether alternative child restraint systems provide enough protection in future mobility applications where the seating and hence child restraint devices can have higher variability.

For comprehensive study, tests on the Q3 and Q6 dummy, with other car seats, seating positions (e.g. according to UMTRI), different pulse combinations will be necessary to improve the assessment of submarining effects. Finally, the comparison of the behavior of the dummy in real car crash with regulatory test bench results is desirable to develop fit-for-purpose regulations suitable for new transport systems to guarantee protection under non-fixed testing conditions.

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