ANALYSIS OF THE PERFORMANCE OF DIFFERENT ARCHITECTURES OF FORWARD FACING CRS WITH INTEGRAL RESTRAINT SYSTEM

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ABSTRACT

The use of an appropriate Child Restraint Systems (CRS) is mandatory in Europe for children up to at least 135 cm. CRS are currently homologated according to the regulation ECE R44. A draft for a new ECE Regulation has been proposed. According to ECE R44, children with a weight between 9 and 18 kg shall use a CRS with integral restraint system, which are normally forward facing. Two architectures fulfilling the integral restraint system requirements can be found on the European market: 5-point-harness systems and shield systems. In principle the same systems can be homologated according to the future regulation.

While shield systems were very popular in the beginning of the CRS epoch, they disappeared in the end of the 1990s. Today they are subject of a revival. Although a considerable number of shield systems are offered in the market today and it is estimated that they have today a market share of 10% of the CRS group in question, they are seldom observed in field data, i.e. accident data and misuse studies, and biomechanical studies on the topic are limited.

The aim of this study was to analyse the performance of shield and harness systems in dummy tests, to analyse the limited accident data available and discuss the possible impact on future child safety.

While shield systems are advertised to protect the neck better than 5-point harness systems, this is overall not supported by the test results, especially for neck moments which appear to be higher with shield systems for most of the tests. However, for the long duration ADAC pulse shield systems show clearly lower neck loadings. Based on the observed injuries, it is questionable whether or not the Q dummy neck instrumentation is sufficient to fully understand the injury mechanisms. Mainly small children in forward facing CRS are suffering from neck injuries. These are mainly represented by Q1 and Q1.5. These dummies only offer upper neck load cells, which is in principle compliant with the injury pattern observed for this age group. However, lower neck injuries are appearing to be more of an issue for shield systems.

Dummy readings are also considerably higher for thorax and abdomen for shield systems than 5-point-harness systems. Based on the limited accident data available, this seems associated with more frequent injury to these regions with shields.

The head excursion, an important factor for head injuries, is lower for shield systems than for 5-point-harness systems in dummy tests.

Overall, the results from the current study do not clearly indicate a benefit of shields for the head and neck. However, they raise questions about possible risks to the thorax and the abdomen.

INTRODUCTION

The use of appropriate CRS is mandatory in Europe for children up to at least 135 cm. CRS are currently homologated according to the regulation ECE R44.

According to ECE R44, children with a weight between 9 and 18 kg are supposed to use a CRS with integral restraint systems. Integral restraint system for the child means w.r.t. Regulation 44 that either belts, that are connected to the CRS restrain the child or the child is restrained by an impact shield that may be connected directly to the vehicle's belt. Two architectures fulfilling these requirements can be found on the European market: 5-point-harness systems and shield systems.

harness system
the child is restrained by the red 5-point-harness

impact shield system
the child is retrained by the blue impact shield which is secured by the red vehicle's belt

Figure 1. Types of integral CRS [TCS, 2012].

Shield systems were common in the past before being almost completely replaced by harness systems. Currently, shield systems are subject to a revival and becoming more and more popular either by combined group I/II/III CRS where the use of the shield is mandatory or by group I shield CRS only. However, 5-point-harness systems still represent the largest proportion of group I CRS on the road.

Shield systems are advertised to offer better neck protection in frontal impacts than 5-point-belt harness systems. In recent European consumer information campaigns they are often rated good, e.g., the only good rated group I/II/III CRS in 2012 were shield systems [ADAC 2012]. Following the success in consumer rating programs and in the market, the number of CRS manufacturers that are offering shield systems is increasing.

The passive safety capabilities of CRS in Europe are mainly tested within the framework of UNECE Regulation 44, and the automobile clubs and Consumers International (CI) joint consumer rating programme. Both test procedures are using sled tests to assess the safety performance of CRS.

The Regulation 44 procedure consists of a test bench that is decelerated according to a generic corridor representing an impact speed of 50 km/h. Dummy resultant chest acceleration, chest acceleration in Z direction (as a representative for neck loads) and head excursion are assessed. No sensors are used to assess the abdominal loading and chest compression, as the P dummies which are used do not have instrumentation in these regions. It is therefore unclear if a fully informed opinion on shields or harness systems can be made with these limitations.

In the consumer rating procedure a specific car body is used and the acceleration of the sled is derived from the pulse of the car in Euro NCAP test (40% offset, 64 km/h, deformable barrier face). Dummy head and chest resultant acceleration, chest acceleration in Z direction, resultant neck forces and head excursion are rated.

While P dummies are used for the regulatory assessment, the consumer rating programme utilises the newer Q dummies. In both test procedures, the dummies representing the smallest and the largest child for each weight group are used in the tests. That means that for Group I CRS the P3/4 and the P3 are used in Regulation 44 tests and Q1 and Q3 are used in the consumer rating programme, respectively.

P dummies were developed in the 1970s for use in Regulation 44. Originally they were equipped with a three axial accelerometer in the chest. Later on it was possible to also equip the head and pelvis with accelerometers and to use a neck load cell. The P dummy spine consists of a central cable that is pretensioned and rubber discs around the cable. This construction allows flexibility of the spine. However, it also leads to some instability, especially for larger P dummies (e.g. the P10).

Q dummy development was started in the 1990s in order to replace the P dummies in Regulation 44 and consumer testing programmes. They initially aimed to be omni-directional i.e. suitable for frontal, lateral and rear impact tests. The Q dummies offer multiple instrumentation options: head, chest and pelvis three axial acceleration, head angular velocity, 6 axial neck load cell at upper neck and for Q3 and older also for the lower neck, lumbar spine 6 axial load cell and chest compression in X or Y direction [Johannsen, 2012]. Furthermore abdominal sensors were developed and used in Q3, Q6 and Q10 dummies [Beillas, 2012a, 2012b]. In comparison to the P dummies, the spine of the Q dummies consists of a stiffer lumbar spine, a similarly rigid thoracic spine and a stiffer neck. For the Q dummies, frontal impact injury criteria including injury assessment reference values (IARV) are proposed for the head and the neck. In addition chest deflection has been proposed but no injury risk curve could be calculated based on the available accident reconstruction data [Johannsen, 2012].

A head excursion assessment is also used in both UNECE Regulation 44 and the consumer information rating programme. It addresses the risk for head and neck injuries resulting from contact to car interior.

Harness systems and shield systems interact in very different manners with the child, especially when skeletal load bearing structures are considered.

Because is it flexible, the harness adapts to the shape of the child and potentially transfers loads to the most rigid structures in contact. The five point

harness system has contacts with the clavicle, the rib cage, the abdomen and the pelvic bones. Similarly to the 3-point-belt for adults, main loads are expected to be transferred to clavicle, pelvis and rib cage. Loading of the abdomen is expected to be very limited as the contact to pelvic bone and rib cage prevent the belt from penetration into the abdomen.

Because they are rigid and stop lower than the shoulders (Figure 1), shield systems are expected to interact very differently with the child. They could mainly load ribcage and abdomen [Mizuno, 2007]. In principle it is possible to design them in way that they are also loading the pelvic bone in order to prevent abdominal loading but this does not always seem to be the case [Tanaka, 2009]. There are no geometrical requirements for shield systems defined and they are assessed based on their dynamic performance. However, the body regions that should receive special attention for shield systems (chest and abdomen) are not adequately observed. Due to the main loading to the lower rib cage and the abdomen – i.e. regions that are not very stable or able to sustain large loads – thoracic and abdominal injury risk could be expected to be higher than with harness systems.

However, despite the very different working biomechanical principles, there is only limited data supporting the use of a particular architecture or demonstrating its adverse effects.

The objective of this study is to provide an overview of evaluation procedures and past results, recent observations from the field and new testing that could be relevant for the assessment of shield systems and 5-point harnesses. While the review is not exhaustive, it is hoped that it can provide material for the discussion on the respective performances, risks and possible benefits of the two systems and highlight future research needs in this area.

METHODS

Three aspects were considered when comparing the shield and 5-pt harness systems:
1) Accident data, using the CASPER project accident database
2) Test results, using new tests and a reanalysis from previous tests provided by third parties
3) Results from misuse field studies.

Accident Data

The EC funded FP7 project CASPER involving numerous European stakeholders included specific tasks dedicated to road accident data collection. The resulting database also contained data from previous projects (CREST and CHILD) [Lesire, 2013]. Analysis of the content is possible within the limitations of the case selection criteria used. The real world accident cases are collected and reviewed for quality and level of detail in order to ensure that information on child kinematics, injury causation, injury criteria and CRS performance (including misuse where understood) are available in order to support further activities in injury criteria, dummy/model development and the understanding of misuse.

To achieve this case selection, criteria are used that generally favor more severe cases, in terms of injury and impact severity [Kirk, 2012]. To also provide a full range of data for injury criteria and an understanding across the injury severity spectrum, cases of high crash severity but low injury severity are also included. This has an implication for how the analysis should be interpreted as the database is not representative of the overall child car passenger crash population. However, the database can give an indication of which body regions are being injured in different CRS types or for different ages of children, and provides insight into restraint conditions that lead to injury.

Overall there are 1301 restrained children in the combined database, 954 in frontal impacts, 341 in lateral impacts and 6 in rear impacts. Of these restrained children, 30% have a maximum abbreviated injury score (MAIS) of 3 or above. The CASPER accident database is using AAAM Abbreviated Injury Scale (AIS98) [AAAM; 1998] for coding of injury severities of all occupants.

Comparative Test Series

In order to compare the crash protection capabilities of different CRS, 5 test series were conducted and analysed or analysed based on available data.

The first test series utilised an NPACS frontal impact test bench (also called new ECE test bench). The NPACS project defined a European protocol for the consumer oriented assessment of CRS, including a test bench design that represents the European fleet better than the ECE R44 test bench [Sandner, 2009]. The acceleration pulse was comparable with the one of a reconstructed accident (described later). In total 3 different harness systems and four different shield systems were tested with a Q1 dummy, representing the lower end of the child mass range for this installation mode. This configuration was selected because it resulted in the accident in severe child injuries at moderate crash severity level without misuse.

The second test series was similar to the first. However, a Q3 dummy representing the upper end of the child mass range for this installation mode was used. It needs to be mentioned that the test pulse was slightly less severe compared to that of series 1 as a result of a problem with the testing equipment.

In series 3, two shield systems and one harness system were tested with Q1 and Q3 in 50 km/h rigid wall tests using a super mini test car that is ECE R94 compliant. This test configuration was chosen to analyse the CRS behaviour in high pulse loading test in a modern car.

Test series 4 had its origin in the ADAC test programme using an Opel Astra body in white tested with the corresponding Euro NCAP pulse. The data was provided by ADAC for the purpose of this study. This test configuration is important for the design of CRS in Europe as the ADAC test is the most important consumer rating programme for CRS in Europe.

Table 1.
Injury criteria and corresponding load limits currently used or proposed for CRS assessment using Q1 and Q3 dummies

Criterion	Q1 limit	Q3 limit	Source
Head a_{3ms}	75 g	120 g	CASPER
Head excursion	550 mm	550 mm	ECE R44
Neck FZ	1.2 kN		CASPER
Neck FZ		1.7 kN	EEVC
Neck MY	64 Nm	96 Nm	EEVC
Chest a_{3ms}	55 g	55 g	ECE R44
Chest deflection	28 mm	25 mm	EEVC
Abdomen pressure		1.13 bar	CASPER

Test series 5 was performed by Dorel. All tests were in frontal impact, with the R44 or NPACS bench and the R44 or ADAC pulse. Four shield and three harness systems were tested. All configurations tested here represent the compulsory and the consumer requirements.

A comparison of the pulses for all test series is provided in the *Figure 2*. For the analysis within this paper, the criteria and limits according to Table 1 are used. The data sources are ECE Regulation 44, EEVC proposals [EEVC, 2008] and the CASPER project [Johannsen, 2012].

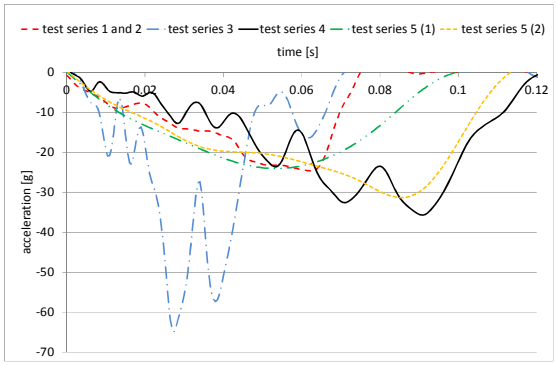


Figure 2. Pulses of all test series.

Misuse Analysis

An important real world issue in the area of child safety is the actual safety behaviour of children but also of the carer (normally parents). Most (approx. 2/3) of the children travelling in cars are not correctly restrained [Hummel, 2008, Müller, 2012]. Incorrect restraint situations are non-use of CRS, incorrect installation of CRS or incorrect restraint of children in the CRS.

To restrain children in harness systems two independent actions are required, fixing the CRS and restraining the child, while in shield systems CRS and occupant are secured by only one action. This means that the general misuse risk is lower in shield systems. However, not using the impact shield in a group I/II/III CRS is considered as severe misuse that might happen. The impact shield may be perceived uncomfortable by children and may result in resistive behaviour of the child against using the impact shield.

For analysis of the misuse risk two databases were available. The first one was the CASPER misuse field study database that contains observations from Berlin (Germany), Lyon (France) and Naples (Italy) with approx. 100 cases per location (reported more in detail by Müller et al. [Müller, 2012]). The second was the IBSR database with approx. 1500 observations from Belgium reported by Roynard et al. [Roynard, 2011]. Data collection was similar for both studies (e.g. the same form was used). Both studies did not focus on a specific CRS type and were collecting data of every child that should use a CRS based on national requirements.

RESULTS

Accident Analysis

<u>Typical injury pattern with 5-point harness</u>
For this analysis only cases collected during the

CHILD and CASPER projects are considered in order to consider mainly the most recent combinations of vehicles and CRS. There are 103 children using forward facing child restraint systems with a harness, involved in a frontal impact of which 21 are not injured and 82 are injured. The injured children have in total 228 injuries of all severity levels. Of these children 44 have AIS2+ injuries with in total 116 AIS 2+ injuries. The simple distribution of age shows that most of them are 1 year old.

Figure 3 shows how the 116 individual AIS2+ injuries for forward facing restrained children in frontal impacts are distributed across the body regions. For example, 51% of all the individual AIS2+ injuries for this sample are to the head.

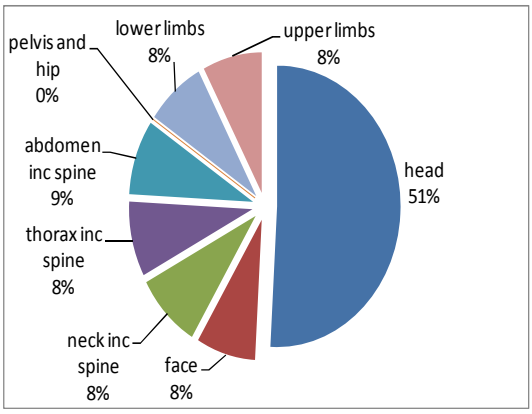


Figure 3. AIS2+ injury distribution (%) for forward facing harness CRS – frontal impacts - 116 AIS2+ injuries in total.

It is clear that the head is the most injured body region for the children in this sample. The distribution of AIS2+ injuries between remaining body regions is then very similar (except for the pelvis and hip where there are no AIS2+ injuries).

Of the casualties with AIS2+ head injuries, when a contact is identified (75% of cases), it is to the seat back in front in 48% of cases and to the B pillar in 18%. 46 of the AIS2+ head injuries are to the brain, 12 are fractures and 1 is a crush or penetrating injury. 17 children have just a brain injury, 5 just a fracture and 6 both types of injury. The injury causes to the extremities can be difficult to attribute but the seatback and the dashboard are given as possible causes.

Injuries observed in shield cases (systems from group 1 and group2) Cases with shield systems are not very numerous in the complete CASPER accident database, as their revival is recent on the European market. Nevertheless, in the global sample 32 children involved in a frontal or lateral accident are using such a system. 90% of these children were included during the CREST project (1996 to 2000) so were naturally using older CRS in older cars. It is interesting though to summarise the injuries seen in these cases, as past experiences can point towards areas to investigate currently, for both new accident case investigation and testing. 5 are not injured, 14 are slightly injured, 4 sustain injuries of MAIS2 level, and the remaining 9 suffer of injuries with a score of MAIS3+. A list of 90 injuries is available. Among them 34 are of AIS2+, and their distribution across the children's body segments is given in Figure 4.

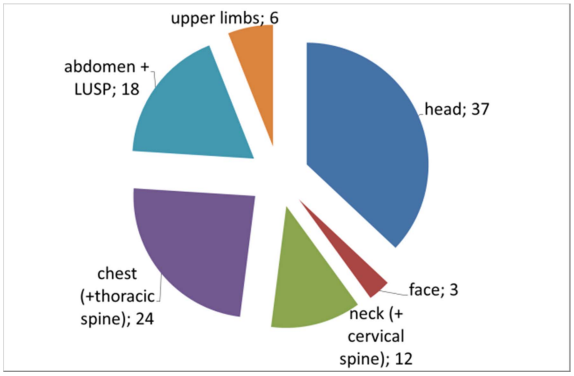


Figure 4. AIS2+ injury distribution (%) for shield CRS – frontal and lateral impacts – 34 AIS2+ injuries in total.

The head is the first body region on which moderate and severe injuries occur. It has to be noticed that in the present sample mainly brain injuries are present (12) without any fracture while in only one case a fracture occurred, without any brain damage.

The chest and the thoracic spine are the second body segment in terms of numbers of AIS2+ injuries with 24%. Injuries to soft organs are always linked with fractures of ribs except in one case that is the only side impact case. Fractures of the rib cage or of vertebrae body are also noticed without implication of soft organs.

For the abdominal area, injuries to soft organs occur both in frontal and side impacts. They are all of AIS2 level.

The neck still represents a non-negligible part of severe injuries in shield systems, their outcomes being similar to the ones observed for harness systems, it is important to consider them.

Injuries to limbs are less important than with other restraint systems. Only upper limbs fracture are recorded and in a few number.

Also the injury pattern is interesting, while global analysis of injury distribution seldom showed rib fractures for group I CRS it appears that rib fracture is a more common chest injury pattern for shield systems.

Description of a case from the CASPER accident database (including its reconstruction illustrating the situation). This accident occurred during the day on a rural road. It involved only one vehicle that went out of its lane on a wet surface due to a sudden braking. The car went on the hard shoulder located on its right hand side and finished into a ditch where it sustained a frontal collision into a little bridge that goes over the ditch. Based on the deformation of the car and after the conduction of a computer simulation, the velocity change of the car (delta-v) during the crash has been estimated to 30 km/h.

Figure 5. View of the vehicle from the accident.

The driver, a female aged of 30 years only suffered of bruises and scratches (AIS1). At the front right position a 14 month old baby weighting 11 kg was restrained in a Group I shield CRS approved according to R44/04, and correctly installed.

Figure 6. View of the CRS replaced at the seating position.

During this accident, the child suffered severe injuries that were located at the level of the lower cervical spine (C5/C6) and at the level of the upper part of the thorax (fracture of 1st to 3rd ribs right side with right lung contusion).

Although the car is was a model year 1995, the speed was quite low and only one longitudinal member was involved. The crash pulse was very similar to ECE R44 pulse, see Figure 7.

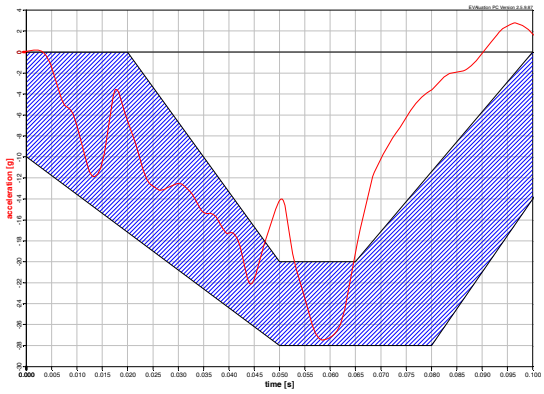


Figure 7. Comparison of accident pulse with ECE R44 pulse.

Table 2.
Summary of dummy readings from accident reconstruction

Criterion	unit	value	MAIS of corresponding body region
head a3ms	g	58	0
HIC	-	339	0
neck FZ	N	1317	5
neck MY	Nm	24	5
chest a3ms	g	31	3
chest deflection	mm	29	3

The dummy readings show in comparison to the limits according to Table 1considerably high chest deflection (29mm) that is associated with rib fractures and high neck tension force and bending moment. Head and chest accelerations are rather small compared to the used and proposed limits (see above), see Table 2.

Comparative Test Series

Test series 1 Shield system 1 is the CRS used in the accident, shield system 2 is the successor model. Both are group I CRS only. Shield system 3 and 4 are group I/II/III CRS. All tested shield systems restrain the shield directly with the car belt. The first harness CRS is an ISOFIX seat with support leg (SL) as anti-rotation device. It is expected that this CRS offers a good ride down behaviour that is comparable to the one offered by the shield systems.

Table 3.
Results of test series 1 (Q1 dummy) incl. comparison with proposed limits according to Table 1

	harness ISOFIX SL	harness belted	harness belted budget	shield 1	shield 2	shield 3	shield 4	Proposed limit
head displacement [mm]	320	370	330	250	260	270	290	550
head a_{3ms} [g]	64	51	115	69	43	62	51	75
HIC	422	224	1186	365	176	307	681	n/a
neck FZ [N]	1285	1061	1073	1520	969	928	1110	1200
neck MY [Nm]	18	19	16	26	26	19	20	64
neck NIJ*	2.1	1.8	1.7	3.1	3.2	2.6	2	n/a
chest a_{3ms} [g]	38	45	37	31	32	30	32	55
chest deflection [mm]	18	15	15	29	31	28	26	28
chest VC [m/s]	0.19	0.09	0.09	0.16	0.18	0.16	0.17	n/a

The belted harness CRS is a relatively simple seat that is fixed to the car using the car belt. There is no special pretension device for the car belt offered so a double belt slack from car belt and harness is possible. The third harness system is a budget CRS that is even more simple than the 2nd one.

The analysis of test results of test series 1 shows that shield systems have a relatively small head excursion combined with small chest acceleration but high neck loads and high chest deflection (Table 3). Except for shield system 4, chest deflection exceeds the EEVC limit, (Table 1) which is not the case for any of the tested harness system CRS. Small chest acceleration and small head excursion can be considered as an indicator for good ride down behaviour (describing the effective use of the available excursion space). For the harness system, the picture is less clear. The ISOFIX CRS shows head excursion and neck loads at comparable levels as the shield CRS. ISOFIX in combination with anti-rotation device is similar to the tested shield systems only one belt slack – for harness systems coming from the harness. The budget harness system clearly exceeds the head acceleration limit according to Table 1.

The neck injury criterion NIJ considering the parallel loading of the neck by axial force and bending moments is not yet established for Q dummies and following that it is not validated. Therefore only the comparison between the different CRS should be considered for information purposes. Normally a value of 1 is considered as NIJ load limit, which is in absence of validation not applicable here. NIJ is considerably higher for CRS with good ride down capabilities, i.e., harness system with ISOFIX and support leg and the shield systems than for the other two harness systems.

While chest compression clearly discriminates between harness systems and shield systems there is no clear trend for the viscous criterion VC. Similar to NIJ, VC has not yet been established for Q dummies.

Test Series 2 In order to assess the differences between harness systems and shield systems for the upper end of the child population that should use the CRS, size class tests with Q3 dummy were conducted. In addition at the time of performing the tests the Q3 was the only applicable dummy that could be equipped with the Abdominal Pressure Twin Sensors APTS to evaluate the abdominal injury risk.

In this test series only harness system 2 was used for the comparison with shield systems. Shield system 4 was tested twice in order to check the repeatability. The test results of series 2 are shown in Figure 8. Similar to the Q1 results head excursion is better with the shield systems

compared to the harness system. For chest deflection all tested CRS exceeded the proposed EEVC limit. However, all shield systems' chest deflection results are higher than the harness CRS deflection. In contrast to the Q1 results NIJ is smaller or similar for the shield systems compared to the harness system. Finally the abdominal pressure is much higher in the shield systems than in the harness system exceeding for shield system 1 and 2 the proposed limit. It needs to be noted that the abdominal injury criterion and injury risk curve was established for booster type CRS and direct seat belt loading. It is not yet validated for shield systems. However, there is no indication that it might be different.

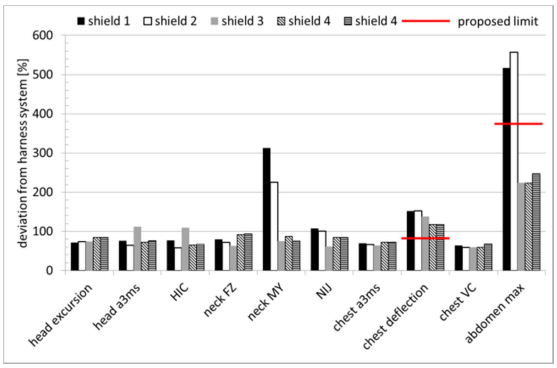


Figure 8. Test results of series 2 in comparison to harness system.

Test series 3 In test series 3, shield system 1 and shield system 4 was compared with the harness system that was already used in the other two test series in 50 km/h rigid wall full frontal tests using an ECE R94 compliant super mini. In each of the three cars a Q3 dummy was seated behind the driver's seat that was not occupied and a Q1 dummy was seated behind the front passenger's seat that was occupied by a 5th female dummy. No interaction between rear seat dummies and front seats took place. This test series should allow the assessment of the different seats in more severe conditions. As the assessment of head excursion is relatively difficult and inaccurate this important criterion was not included in the study. However, using an indicator it was possible to record that the Q3 dummy in the harness system exceeded the 550 mm limit, while in all other tests this was not the case.

The pulse in test series 3 was considerably higher than in test series 1 and 2, see *Figure* ***9***. This explains why the proposed limits were exceeded several times in test series 3, see Figure 10.

Except chest acceleration, all measurements are higher or similar in the shield systems compared to the harness systems. In contrast to the results of test series 1 and 2 that are showing smaller VC values for shield systems VC is much higher for shield systems in test series 3, see Figure 10. Analysis of the video material suggests that the higher head acceleration results from a head impact to the shield.

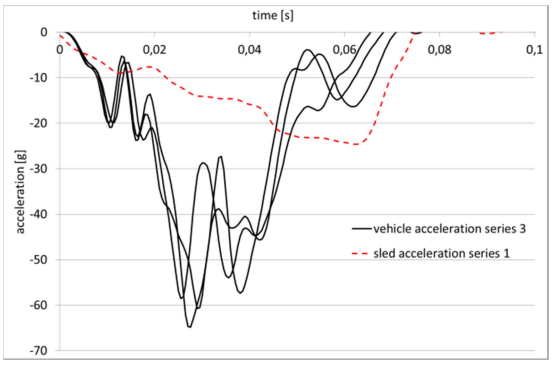


Figure 9. Comparison of vehicle acceleration in test series 3 and sled acceleration in test series 1.

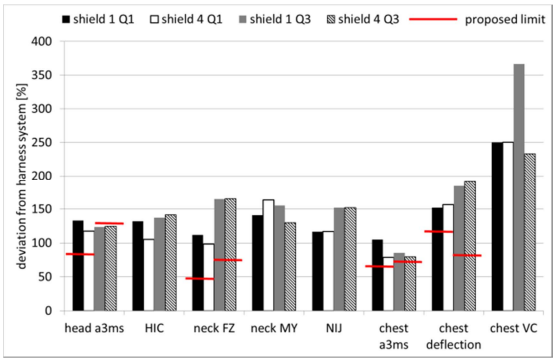


Figure 10. Test results of series 3 in comparison to harness systems.

Test Series 4 The data provided is either of the same seats as used in the previous test series or CRS with similar architecture. In total 4 different harness systems and 3 different shield systems were available for Q1 and 3 different harness systems and 2 different shield systems were available for Q3, respectively.

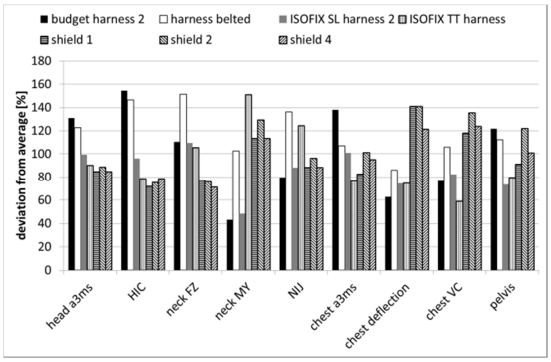


Figure 11. Test results of series 4 in comparison to the average dummy reading, Q1 dummy.

Table 4.
Summary of test series 5 results (frontal impact, Q3 equipped with APTS) incl. comparison with proposed limits according to Table 1

Test	CRS	Condition	Head Exc. mm	HIC 36	Head a3m g	Chest a3ms g	Pelvis a3ms g	Neck force res. N	Chest defl. mm	Max abdo. press. bar
Pulse R44, Bench R44, Q3 in sitting position										
4224	Shield 11	Isofix	397	481	53.6	39.9	51.5	1683	49	2.7
4225	Shield 11	without Isofix	383	447	54.3	37.7	48.1	1655	50	2.7
4226	Shield 12	Isofix	435	568	54.0	33.1	45.5	1864	40	1.8
4227	Shield 12	without Isofix	438	708	62.3	37.6	46.1	2098	44	2.1
4228	Harness 11	support leg Isofix	402	724	65.5	38.2	48.8	1962	33	0.3
4229	Harness 12	Top-Tether Isofix	412	678	57.0	33.7	46.1	2283	33	0.3
Pulse R44, Bench NPACS, lying position, no top-tether										
4329	Harness 13	Isofix	544	697	78.5	36.5	51	2535	35	0.4
Pulse ADAC, Bench NPACS, lying position										
4332	Harness 13	Top-Tether Isofix	455	1284	75.6	61.4	54	2735	28	0.4
proposed limits			550	n/a	120	55	n/a	1700	25	1,13

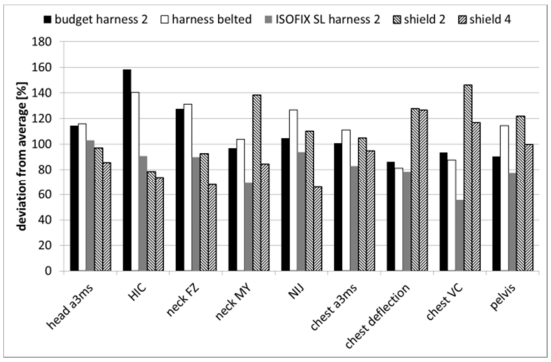


Figure 12. Test results of series 4 in comparison to the average dummy reading, Q3 dummy.

The test data of series 4 confirms the findings of the previous test series w.r.t. chest deflection. In contrast to the other test results the neck tension is considerably lower for the shield systems than for the harness systems. For the neck bending moments no clear conclusion is possible.

Test series 5 The main results from the test series 5 are summarised in Table 4. For cases without misuse and with standard posture, there was no complete separation of the shields and harness results for head excursion, HIC, chest and pelvis acceleration and neck resultant force (meaning that the worst shield result was worse than the best harness). However, shields almost always had the best scores for these criteria. For the chest deflection and abdomen, the shield results were always worse than for harnesses, even in the case of misuse, and the difference was important (7 to 19mm more for deflection, and 1.5 to 2.5 bars for pressure for the same test condition). Also shield 11 had the best results for all metrics except for the pelvis, chest deflection and abdominal pressure. Its results were the worst of the series for chest deflection and abdominal pressure.

Misuse analysis

Analysis of the CRS checking field data shows only one shield system out of 300 children composing the CASPER sample . The system was correctly used. Similarly, at first, there was only one shield CRS in the Belgium sample, but it was used without shield although the child needed to use it according to its weight. In total the number of cases is too small to draw any conclusion, except that shield CRS are seldom observed in the three CASPER study regions and Belgium.

Further analysis of the Belgium data shows that there were 14 children in group I/II/III CRS using them as group II/III although they would have needed to use group I configuration according to their weight, including the shield case. In total 60 children were travelling in group I/II/III CRS of which 8 used it correctly in group I configuration.

DISCUSSION

Head Injury Risk

Analysed test results show that the head excursion in shield systems is often smaller than in harness systems.

Differences between the two architectures could be expected in the ride down phase. For harness systems that are fixed by the vehicle's belt to the car, slack could be present in two locations (the

CRS is not perfectly fixed to the car and the child is not perfectly fixed to the CRS). This behaviour can be minimised, for example by using ISOFIX with an anti-rotation device, static belt pretensioners at the CRS etc. For shield systems only the slack in vehicle's belt is applicable as the impact shield is directly connected to it. This could contribute to reduce the head excursion leading to lower head impact risk for shield systems.

It needs to be remembered however that dummy vs. human differences may affect these observations: the dummy thoracic spine is rigid, which may lead to a different kinematics when compared with children affecting head excursion and contact point. In particular, head contact on the shield seems possible based on human model simulations [Mizuno, 2007]. The dummy head also impacted the shield in one of the test series.

Dependent on test severity, head acceleration is in most cases lower for shield systems (except the high pulse full frontal tests). There, higher dummy readings are resulting from head impact to the shield. According to Loyd et al. [Loyd, 2012] the head of the Q-dummies appears to be considerably stiffer than human heads in impact conditions to hard surfaces. This might result in an overestimation of the head acceleration in the cases with head impact to the shield.

The analysed accident data does not show any significant differences between the CRS types w.r.t. head injuries.

Neck Injury Risk

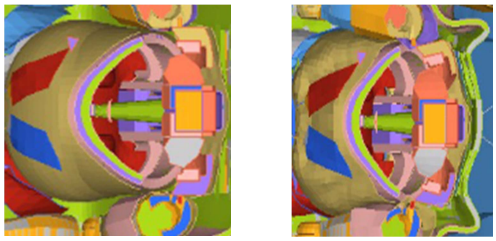
The tests analysed do not show a clear trend w.r.t. the neck injury risk. Test series 1 suggests that CRS that are offering good ride down are more dangerous for the neck than CRS with worse ride down. Good ride down behaviour is applicable for ISOFIX CRS with anti-rotation devices and shield systems. It is expected that also belted harness CRS with car belt tensioning device will show the same tendency than ISOFIX CRS but none of these products were tested in this test series. While the low severity tests show that neck loading is less of an issue for Q3 in shield systems than for Q1 dummy, it is the opposite for the higher severity tests of test series 3. The ADAC tests of test series 4 show benefits for shield systems compared to harness systems independent of the dummy size.

The few accident cases involving shield systems indicate that neck injuries that are reported for shield systems are mainly located in the lower neck [Otte, 2012]. This is completely different to children in harness type CRS. The Q1 does not offer a load cell at the lower neck, which means that the risk assessment with the Q1 dummy is not possible.

Chest Injury Risk

The occurrence of rib fractures in the 1 year old population is uncommon in the CASPER accident data base. The fracture in the reconstructed accident case therefore represents an atypical response, either due to the occupant characteristics or the rarity of the configuration (shields being uncommon in field observation). This second option could be supported by the measured chest deflection which clearly exceeds the values of the harness systems in test results. This is in full agreement with the results for Q3 in all test series, and the increased risk of chest injuries in the available accident data.

However, one may argue that chest deflection measured in harness systems is incorrect as the chest deflection measurement device is not loaded directly in these cases. Analysis of FE simulation results indicate that chest is deformed parallel to the initial shape so that only minor influence of the loading location is expected, see Figure 13.



Q3 at t0 | Q3 with maximum chest deflection

Figure 13. Deformation shape of Q3 dummy with 5-point harness system.

For the tests of the current study, there is clear need to assess both chest acceleration and chest deflection as there is no clear correlation between the two criteria. This finding is also supported by Tanaka et al [Tanaka, 2009]. While chest acceleration can be used as a global indicator for restraint system performance, it is expected that chest deflection and chest VC could reliable indicators for chest injury risks. However, no injury risk curve for Q dummies could be developed for 3-pt belt restraint due to issues of interactions between dummy and belt (sliding) [Johannsen, 2012]. It may be necessary to control both in certification tests as it is possible to design CRS that reduce chest acceleration by increasing chest deflection.

Abdomen Injury Risk

In all tests using the APTS sensors, abdominal loading – as estimated using maximum pressure values – was much higher with shield systems than with harness systems. The abdominal pressures were consistently low with harness systems; i.e. below 0.5 bars, which is lower than most values obtained in 3-point belt tests and proposed tolerance levels [Beillas, 2012a, 2012b]. It was attributed to the fact that the harness loads are transmitted to the thorax and pelvis, and largely bypass the abdomen. This was also observed with harnesses in reconstruction tests, and correlate with a relative lack of abdominal injuries with this restraint system.

For the shield systems, pressures were larger than 1.8 bars, which are levels that were only observed for injury cases for 3-point belt accident reconstructions [Beillas et al., 2012]. Caution should be exercised though as the loading surfaces are different between shield and belt and the APTS response with abdominal sensors with shields needs further investigation. FE modelling of the dummy could be used to further investigate this issue but it seems safe to indicate that the level reflects a higher loading level of the abdomen. This level seems associated with a higher risk in the accident data sample.

Geometrical issues with shield systems

Based on the current data, a combined assessment of thoracic deflection and abdominal compression seems needed to ensure that thoracic and abdominal loading are acceptable, and that the loading is not directed to a region where no instrumentation is present. However, if this approach could be sufficient to evaluate loading path in tests with Q dummies, its efficiency could be questioned for children with different geometrical shapes. Shield shape may be optimized to distribute the loads across regions in the Q dummy. Important differences between the tested shield systems exist. Section pictures of shield system 1 and shield system 4 shows that the shield shape can explain the some of the differences in the test results, see Figure 14. Shield system 4 is designed to mainly load pelvis and rib cage of Q3, while shield system 1 does not load the pelvis at all but mainly abdomen and rib cage.

Shield system 1, the pelvic bone is not engaged

Shield system 4, the lower part of the shield engaged the pelvic bone resulting in lower thoracic and abdominal loading in Q3 test

Figure 14. Comparison of shield geometries.

However, the performance may be degraded for example for obese children for which the abdomen would be more involved and the thorax less. Conversely, the thoracic load may be higher (and abdominal load lower) in underweight children. Also, while pelvis involvement would be important to reduce the loading to other regions, it is unclear if the dummy can represent the child variability in this region. Simulation studies using human models to describe the variability could help understanding this issue.

Ejection Risk

The 5-point-harness prevents ejection by coupling of the occupant to the CRS via both individual legs (due to the crotch strap) and both shoulders. With shield systems the only protection against ejection is coming from the impact shield that is coupling both legs together to the CRS. That means that the ejection risk is theoretically higher in shield systems compared to harness systems. However, the analysed accident data does not allow any conclusion w.r.t. differences in ejection risks between the two different CRS systems.

Misuse Risk

The available data is not sufficient to prove or to disprove the hypothesis of an increased risk not to use the shield. However, the analysed Belgium data suggests a higher risk for early group change in combined group I/II/III CRS. Early change from one CRS size group to the next is considered as an important injury risk [Jakobsson, 2005]. From the analysed data it appears that early change is more often observed in group I/II/III CRS than in group II/III CRS. It can be expected that the situation for shield type group I/II/III CRS will be identical.

According to Mizuno et al. [Mizuno, 2007] shield systems appear to be less sensitive to belt slack than harness systems based on testing with Hybrid

III dummies and simulation with Hybrid 3 FE dummy model and Human Model.

CONCLUSION

In the current study, accident data, test data and misuse study results were analysed to compare the performance of shield and 5-point harness systems using Q dummies. The results are somewhat limited by the relative absence of shield systems in real world observations, whether in misuse or in accident samples.

While the data is limited, nothing clearly suggests – in field study or testing – a better performance for shield systems in general. To the contrary, limited accident data suggest different neck injury patterns for shield systems that cannot be evaluated with the current Q1 dummies, and possibly higher risks for the abdomen and thorax (but the sample size is very limited and older CRS were included in the sample). Dummy readings in tests do not demonstrate a general benefit of shield systems for the neck either, but the loading to the thorax and abdomen are much more severe than with 5-point harness. This is consistent with the accident analyse results (within the limitation regarding older CRS) and the results of other studies. This suggests that additional dummy readings especially for the trunk need to be considered in the evaluations.

No conclusive data could be found in misuse studies regarding the potential benefit of shields but the sample size may have been too small to capture the limited market penetration. Studies specifically designed for that purpose may be required.

In summary, based on the data that was analysed, the consequences of the current revival of shield systems on child protection cannot be determined with certainty. No clear benefit could be established from the observations and potential risks have been identified. It is also unclear if test procedures are sufficient for the evaluation of shield systems real world protection. Caution should therefore be exercised with these systems and studies should be performed (e.g. simulation with human models, accident data analysis, comparison of performance between older CRS for which accident data is available and newer CRS) in order to understand and detect as early as possible potential real world issues.

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UK Loughborough cases, collected during the EC CREST/CHILD projects, include accident data from the United Kingdom Co-operative Crash Injury Study, collected up to 2006. CCIS was managed by TRL Ltd on behalf of the Department for Transport (Transport Technology and Standards Division) who funded the project with Autoliv, Ford Motor Company, Nissan Motor Europe and Toyota Motor Europe. The data were collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham, the Vehicle Safety Research Centre at Loughborough University, and the Vehicle & Operator Services Agency of the Department for Transport. The views expressed in this work are those of the authors and not necessarily those of the UK CCIS sponsors.

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REFERENCES

AAAM (1998) The Abbreviated Injury Scale 1990 revision - Update 1998, Des Plaines Illinois, 1998

ADAC: “Kindersitze im ADAC Test”, http://www.adac.de/infotestrat/tests/kindersicherung/kindersitz-test/default.aspx, 2012 (in German)

Beillas, P.; Alonzo, F.; Chevalier, M.C.; Lesire, P.; Leopold, F.; Trosseille, X.; Johannsen, H. 2012a “Abdominal Twin Pressure Sensors for the assessment of abdominal injuries in Q dummies: in-dummy evaluation and injury tolerance curve”, Stapp Car Crash Journal, 56:387-410.

Beillas, P., Alonzo, F., Chevalier, M.C., Johansen, H., Renaudin, F., and Lesire, P. 2012b. Abdominal Pressure Twin Sensors for the Q dummies: from Q3 to Q10. Proceedings of the ICrash Conference, Turin, July 18-20, 2012.

Hummel, Th.; Finkbeiner F.; Kühn, M.: “Misuse of Child Restraint Systems – A 2008 Observation Study in Germany”, Proceedings of 6th International Conference Protection of Children in Cars, München, 2008

Jakobsson, L.; Isaksson, I.; Lundell, B.: “Safety for the Growing Child – Experiences from Swedish

Accident Data" Proceedings of 19th ESV Conference, Washington, 2005

Johannsen, H.; Trosseille, X.; Lesire, P.; Beillas, P.: "Estimating Q-Dummy Injury Criteria Using the CASPER Project Results and Scaling Adult Reference Values", Proceedings of IRCOBI Conference, Dublin, 2012

Kirk, A., Lesire, P., Report on Accident Analysis, Deliverable 3.2.3 of the EC FP7 Project CASPER 2012

Lesire P., Johannsen H., Willinger R., Longton A., Kirk A., Beillas P. CASPER, better knowledge and better tools to improve the real protefction of children in cars, , paper n°13-0426 ESV, Seoul 2013

Loyd, A.M.; Nightingale, R.W.; Song, Y.; Luck, J.F.; Cutcliffe, H.; Myers, B.F.; Bass, C.: "Impact Properties of Adult and ATD Heads" , Proceedings of IRCOBI Conference, Dublin, 2012

Mizuno K. and Namikiri T. (2007) Analysis of Child Responses in CRS using Child Human FE Model. Paper Number 07-0145. ESV Conference.

Müller, G.; Johannsen, H.; Fiorentino, A.; Lesire, P.; Schnottale, B.;. Beillas, P.; Chevalier, M-C.: "Misuse of Child Restraint Systems – an important Problem for Child Safety." Proceedings of the ICrash Conference, Milano, 2012

Otte, D.; Müller, C.: Experiences of real world in-depth-accident investigation by single case analysis on different child restraint systems, 10th International Conference Protection of Children in Cars, Munich, 2012

Roynard, M.; Lesire, P.: "Misuse – four different Perspectives First roadside survey of child restraint system use and misuse in Belgium" Proceedings of 9th International Conference Protection of Children in Cars, Munich 2011

Sandner V., Ratzek A., Kolke R., Kraus W., Lang M. NPACS development/research/results – first step for future activities? - Paper Number 09-0298 ESV 2009

Tanaka Y., Yonezawa H., Hosokawa, N., Matsui Y., Mizuno K., Yamaguchi M., Yoshida R., (2009) Responses of Hybrid III 3YO and Q3 Dummies in Various CRSs Tested Using ECE R44 Impact Conditions. Paper Number 09-0242 ESV Conference.

TCS: "Autokindersitze 2012", Touring Club Schweiz, 2012

ANNEX 1:
COMPARISON OF SLED TEST RESULTS WITH RECONSTRUCTION TEST RESULTS

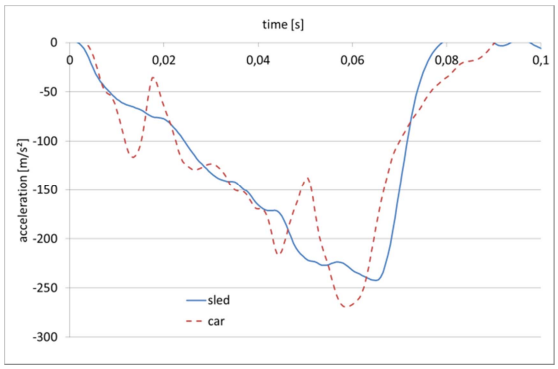

Figure 15. Comparison of sled acceleration with tunnel acceleration.

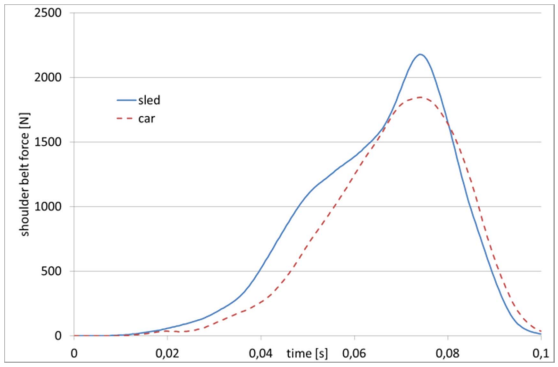

Figure 16. Comparison of shoulder belt force.

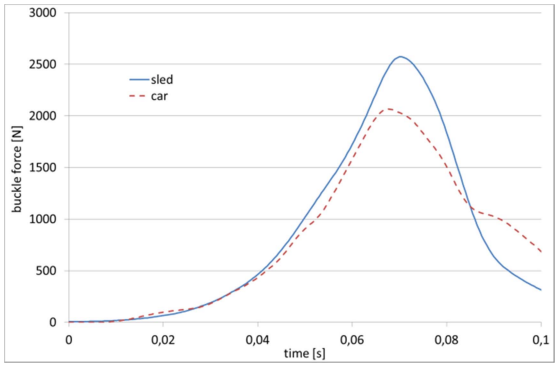

Figure 17. Comparison of buckle force.

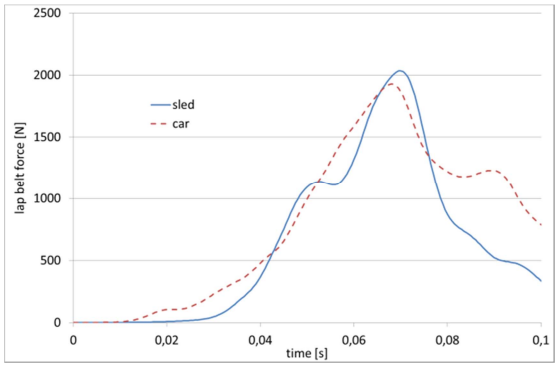

Figure 18. Comparison of lap belt force.

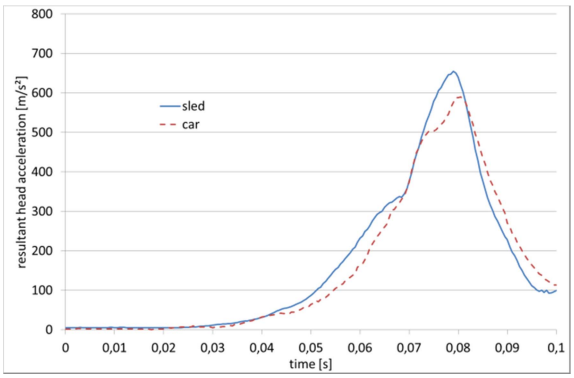

Figure 19. Comparison of head acceleration.

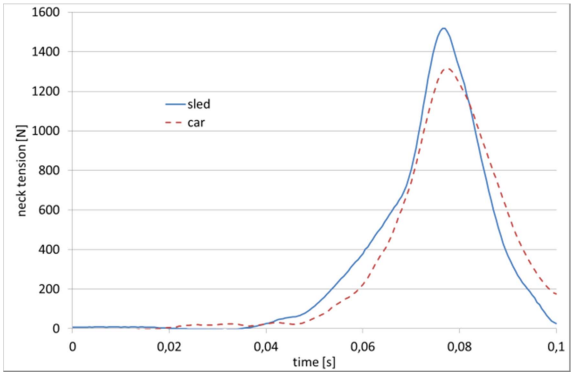

Figure 20. Comparison of neck tension forces.

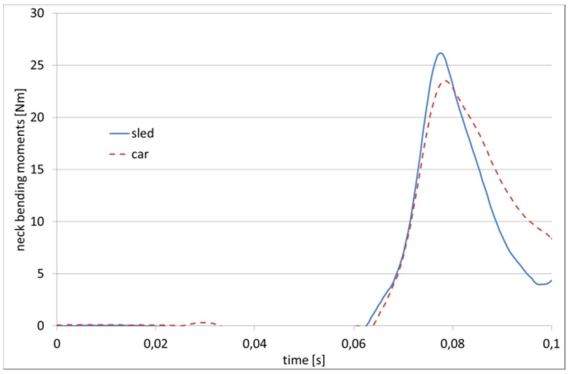

Figure 21. Comparison of neck bending moments.

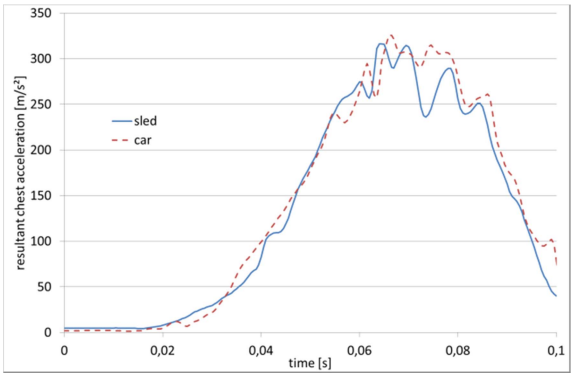

Figure 22. Comparison of chest acceleration.

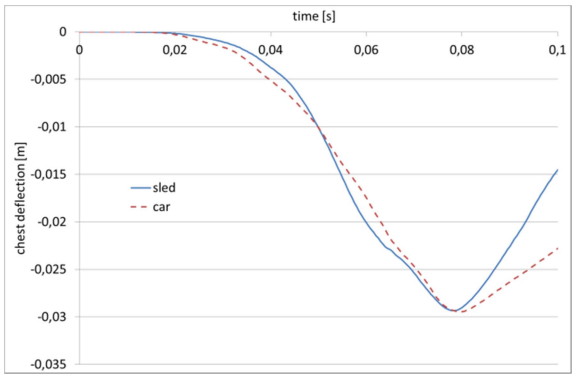

Figure 23. Comparison of chest deflection.