REAR SEAT SAFETY FOR CHILDREN AGED 4-12: IDENTIFYING THE REAL-WORLD NEEDS TOWARDS DEVELOPMENT OF COUNTERMEASURES

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ABSTRACT

This study summarizes a joint research project aiming to further enhance the safety of booster-seated children (aged 4-12) in the rear seat of passenger cars. The focus is real-world aspects of child safety, comprising the whole context of the vehicle and child restraints, and a variety of crash situations, including pre-crash events.

Real children sit in a variety of sitting postures in cars. On-road driving studies show that children take different postures due to comfort, visibility or activities. The results from three studies 18 children in a variety of restraints, showed that for only a portion of the time, they are sitting upright with contact to the seatback, i.e. similar to the standardized crash test dummy position. When using a booster with protruding head side supports the children sit forward leaning more than without, and in a large share of the time, the head is in front of the head side supports.

Approximately 40% of the crashes are preceded by evasive maneuvers. When exposing child volunteers to evasive braking they will move forward by up to 0.2m, when shoulder belt remains over the shoulder. Thirty four child volunteers were exposed to evasive braking and steering events, using different types of boosters. Depending of the size of the child and the booster used, they might slide out of the shoulder belt in steering events. In addition, existing child crash test dummies were tested and compared to the volunteer data. The volunteer data was also used to validate an active child Human Body Model, as a first step to develop a tool that can be used for evasive maneuvers.

The booster is essential for the child enabling good interaction to the seatbelt. In addition, the vehicle protection systems play an important role for the child protection. Hence, for enhancing real-world safety it is essential to replicate in-vehicle situations. Unfortunately, this is not how child restraints are certified today. This study shows that child crash test dummies benefit from side airbags and advanced seatbelt technologies, and are responsive to changes in sitting postures and crash modes. In addition to the in-crash protective systems evaluated in this study, pioneering maneuver and run-off-road tests with crash test dummies were run to evaluate the effect of an electrical reversible seatbelt retractor (pre-pretensioner) to help keep the occupant in the belt during such an event.

International multidisciplinary workshops were held and concluded that future advancements need to be data driven and incorporate multiple disciplines. Engineering advancements should strive towards less complex solutions and the shared responsibility between the child restraint and the vehicle was highlighted.

The results from this project contribute to identification and quantification of important real-world needs, as well as evaluation and development of countermeasures. It is concluded, that from a real-world perspective, the vehicle and child restraint should be designed together targeting a range of acceptable common user positions; sitting postures preferably guided by comfort and positive means. Such designs will ensure robust function of the protection systems for these young occupants, and advance the development of countermeasures that protect children in real-world crashes, also including dynamic events prior to a crash.

INTRODUCTION

Every day, more than 1,000 children and young people under the age of 25 years are killed in road traffic crashes accounting for over 30 percent of those killed and injured in road traffic crashes worldwide (WHO, 2007). Furthermore, in addition to the fatalities there are millions of injured children (WHO 2008b). The distribution of road deaths by mode of road user varies in different parts of the world. In Europe for example, where child restraint systems are mandatory and restraint usage is relatively high, 32 percent of child traffic fatalities (0-14y) involve children as passengers in cars (WHO, 2008a).

Child restraint systems (CRS) are effective in reducing fatalities and severe injuries among child passengers. For the smallest children, the safest restraint for optimal protection is rearward facing. Swedish and US data shows that children in rear facing restraints are better protected both in frontal and side impacts (Tingvall 1987, Carlsson et al. 1991, Kamrén et al. 1993, Stalnaker 1993, Tarrière 1995, Jakobsson et al. 2005, Henary et al. 2007). Rearward facing seats are used around the world for infants and are recommended in Sweden up to the age of 4-5 years.

When the child has reached 4 years of age and is sitting forward facing in the car, there are still differences in biomechanics compared to adults. The iliac spines of the pelvis, which are important for good lap belt positioning and for reducing risk of belt load into the abdomen, are not well developed until about 10 years of age (Burdi et al. 1968). The development of iliac spines, together with the fact that the upper part of the pelvis of the sitting child is lower than of an adult, are realities that must be taken into consideration, in order to give a child the same amount of protection as an adult.

Belt-positioning booster cushions were introduced in the late 1970s (Norin et al. 1979). The booster elevates the child and positions the lap part of the vehicle seatbelt over the thighs, which reduces the risk of the abdomen interacting with the belt. The booster also encourages the children to sit comfortably with their legs, helping to avoid slouching and increasing the likelihood of good seatbelt geometry (DeSantis Klinich et al. 1994). Other advantages of boosters are that the child, by sitting higher, will have the shoulder part of the seatbelt more comfortably positioned over the shoulder and will also have a better view.

Today, an increasing number of boosters have backrests (so called booster seats or highback boosters). The backrests were initially intended to provide head support in cars without head restraint, and to help route the diagonal part of the seatbelt over the child's shoulder and chest. In recent years, the designs of the backrests have evolved towards large side supports both at the height of the torso and the head. The child restraint manufacturers emphasize two reasons for this; to provide improved side impact protection and to provide comfort for children by keeping them upright when relaxed or asleep to help provide protection at all times (Bendjellal et al. 2011).

Integrated (built-in) boosters were developed in order to simplify usage and to minimize misuse (Lundell et al. 1991). This was confirmed by Osvalder and Bohman (2008) providing evidence that misuse was almost eliminated when using these types of boosters. In 2007, a second generation integrated booster was introduced providing two levels in height, adapting to the growing child (Jakobsson et al. 2007).

Belt-positioning boosters are effective tools to help protect children from injuries in frontal impacts as well as other crash directions (DeSantis Klinich et al. 1994, Isaksson-Hellman et al. 1997, Warren Bidez and Syson 2001, Jakobsson et al. 2005, Arbogast et al. 2005 and 2009). Arbogast et al. (2009) showed that seatbelt syndrome related injuries to the abdomen and spine were nearly eliminated in crashes with children using boosters compared to those restrained by seatbelts only. Children aged 4 to 8 and using booster were 45% less likely to sustain injuries than similarly aged children who were using the vehicle seatbelt only. Children in side impacts derived the largest relative protection from boosters, with a reduction in risk of 68% and 82% for near-side and far-side crashes, respectively. No difference in booster seat versus booster cushions were seen.

Several parts of the world are banning booster cushions, claiming lack of head protection in side impacts. The Australian regulation, as well as the UN ECE R129 type approval require protruding head side supports to pass the side-impact rig-test method – a method that does not include real-world vehicle protection characteristics. Recently, an amendment to UN ECE R44 was added requiring all newly approved booster cushions (without backrest) to be forbidden for children below 125cm in stature.

Over the years, an increase of booster usage is seen globally. In Sweden, the main increase in child restraint usage (including boosters) occurred during the 1980s, and was a result of increasing child restraint availability, introduction of rear seatbelt laws, and intense and unanimous public education and communication activities. (Jakobsson et al.

2005). In 2007, a child restraint usage law requiring all children of stature up to 135cm in Sweden to use an appropriate child restraint system came into effect.

The children in the rear seat also benefit from seatbelt technologies such as pretensioner and load limiters. Sled tests using a HybridIII (HIII) 6y crash test dummy showed that retractors with belt load limiting and pretensioning resulted in reduced head, neck and chest loading as well as decreases in forward displacement (Bohman et al. 2006, Forman et al. 2009). The results emphasized the need to adapt the load limiting level to the size of the occupant.

Improving safety for rear seat occupants requires enhanced knowledge in several areas involving multiple disciplines. This joint research project aims to further enhance the safety of booster-seated children (aged 4-12) in the rear seat with special focus on real-world aspects of child safety, providing state-of-art knowledge and helping set the agenda for future research and development.

METHODS

The project is a broad comprehensive research effort that combines expertise from industry and academia. The project started in 2009 and has involved research by three PhD students and additional senior researchers. The work performed up to 2011 was presented in Jakobsson et al. (2011a).

Using various methodologies of applied research, this project aims to further enhance the safety of booster-seated children in the rear seat by identifying the real-world needs, also taking restraint interaction and attitude aspects into account. The purpose is to establish guidelines for evaluation methods and protection principles, and to provide state-of-art knowledge and contribute to setting future research and development needs. The methodologies used, include **real-world crash data analysis** and **driving studies with children** in addition to **testing and simulations**, **evaluation and development of tools**, and **international coordination of knowledge** around these topics.

Real-World Crash Data

Real-world crash data was analyzed to provide insight into areas of importance for child occupant protection. Studies in the project include investigations of potential head injury mechanisms for restrained forward facing children in the rear seat (Bohman et al. 2011a) and investigations of injured children in side impacts (Bohman et al. 2009, Andersson et al. 2011). These studies are summarized in Jakobsson et al. (2011a). More recently, the project has performed four real-world crash data studies, addressing different topics which all provide input to enhance the safety of children in cars.

Child occupant fatalities in Sweden Child car occupant fatalities in Sweden were summarized over a time period of 55 years (Carlsson et al. 2013). Four different data sources were used, enabling inclusion of all crash-related fatalities among 0–14 year old car occupants during 1956–2011. The data was summarized to study the development of child safety over the years. Based on in-depth data from 1992-2011, the characteristics of the crash and the injuries were investigated, including crash direction, restraint use, crash opponent and injured body region.

Long-term consequences Insurance data was used to study injuries with long-term consequences to children aged 0-12. Data included reported car crashes from 1998 to 2010 with at least one injured child. 2619 injured children with 3704 reported medical diagnoses were included. If the child had not recovered within one year after the injury, medical specialists made an assessment of the degree of permanent medical impairment (PMI) (Bohman et al. 2014).

Pre-crash maneuver occurrence Pre-crash maneuvers and some causation factors of serious motor vehicle crashes involving child passengers were quantified by Stockman (2016). The National Motor Vehicle Crash Causation Survey (NMVCCS) conducted by the National Highway Traffic Safety Administration (NHTSA) between July 2005 and December 2007 was used. NMVCCS identified pre-crash factors via investigation of vehicles and crash scenes, and structured on-scene interviews with crash participants. The critical reason for each crash was assigned to a single driver, vehicle or environmental factor. The selected sub-samples for the study by Stockman (2016), included 841 (weighted 308,743) drivers with at least one child passenger, and as a point of reference; 5,661 (weighted 2,209,082) single drivers, and 1,544 (weighted 537,787) drivers with only passengers older than 14.

Restraint usage in Sweden Using Volvo Cars Accident database on crashes with Volvo cars in Sweden, information on restraint usage for 4-10 year old children was analyzed (Jakobsson and Lindman, 2015). The years 2000–2013 were selected enabling comparison before and after the introduction of the restraint usage law in 2007 for children up to 135cm.

Driving Studies with Children

As an important input to understand child occupant protection, studies with children riding in actual vehicles were performed. Specifically, the sitting postures, kinematics and behavior of children were monitored while riding in the rear seat, both in a **naturalistic driving study** and rigged studies **on roads** and on a test track with extensive braking and turning **maneuvers**.

Naturalistic driving study (NDS) In a joint project together with Monash University a NDS was conducted (Charlton et al. 2013). The study included 42 families and 81 child passengers aged 1-8. Each family drove the test vehicle for 2 weeks. Video recordings were made on the rear seat occupants, the driver and the surrounding traffic. For a subset of 18 families with 35 child passengers, a Kinect camera captured motion data from which head position coordinates were derived (Arbogast et al. 2016).

On-road driving studies **S**itting posture and behavior of 18 children were monitored with video recordings while riding in the rear seat using different types of child restraints. Three different studies have been performed within the project with the overall aim to increase the understanding of the natural behavior of children during a car ride. Specifically, the aim was to identify the preferred sitting postures and the seatbelt positions relative to the torso using a selection of different types of restraints, as shown in Figure 1.

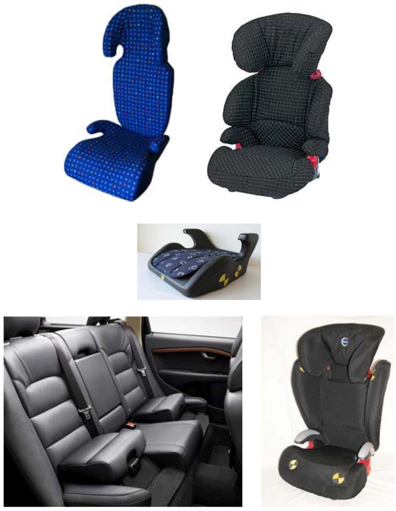

Figure 1. Child restraints used in the on-road driving studies. Top row; the two booster seats used in Andersson et al. (2010). Middle row: the booster cushion used in Jakobsson et al. (2011b). Bottom row; the IBC and the booster seat used in Osvalder et al. (2013).

A first study was conducted to investigate the effect of booster seat backrest designs on the choice of children's sitting postures (Andersson et al. 2010). Six children (3-6 years old, 90-125cm) were monitored when taken for a ride on a pre-determined trip for 40-50 minutes for each booster seat type; one with smaller head side supports (10.5cm) and no torso side supports, and the other with larger head (20cm) and torso side supports, see Figure 1.

A second driving study was performed to identify the preferred sitting posture and the seatbelt positions relative to the torso of children (8-13years old, 135-150cm) when restrained with and without a booster cushion (Jakobsson et al. 2011b, Figure 1). Six children were monitored when traveling about 40 minutes in each of the two different restraints.

The third study included six children (7-9 years old, 130-145cm), who travelled one hour on an integrated booster cushion (IBC) and one hour on a booster seat (Osvalder et al. 2013, Figure 1).

For all the studies, the children's different sitting postures were defined according to a classification system based on the position of the head and torso in the sagittal and lateral directions. The duration of each sitting posture that each child assumed for one second or longer was quantified, and their activities were documented. In addition, in the second and third study, the shoulder belt position relative to the torso was categorized and the duration the shoulder belt remained in each position was quantified. In the third study, subjective data regarding discomfort and attitudes was also collected from questionnaires and interviews.

Maneuver studies Kinematics and seatbelt position during evasive braking events and steering maneuvers were quantified for 34 children (Bohman et al. 2011b, Stockman et al. 2013a, Baker et al. 2017a and 2017b). Using the same passenger car (Volvo XC70, MY 2010), two studies comprising different types of restraint systems were performed. The studies were conducted on a closed-circuit test track. The child was restrained in the right rear seat. While traveling at a velocity of 70 km/h, the professional driver applied full braking or quickly turned the vehicle 90 degrees to the right, exposing the child to a forward or inboard motion, respectively.

In the first study, 16 children aged 4-12 years old were included (Bohman et al. 2011b, Stockman et al. 2013a). The restraint of the children varied according to their stature, each child tested two types of restraints in both braking and steering events. Children of 105-125 cm stature were using booster seat or booster cushion. Children of 135-150cm were using the booster cushion or seatbelt only.

The second study comprised 18 children aged 5-10 (Baker et al. 2017a and 2017b). The children were restrained using two different boosters; the booster cushion as in the prior study, and the vehicle's integrated booster cushion. All children were exposed to both braking and steering events using each restraint.

For the two studies, the children were monitored by video cameras, enabling quantification of the sagittal and lateral child kinematic response as well as quantification of the shoulder belt position throughout the event.

Testing and Simulations

With the aim of evaluating different restraint properties, protection principles, and capabilities of existing test tools; physical crash testing and virtual crash simulations and low-severity / maneuver tests were conducted and analyzed. In addition, a first step development of an active child Human Body Model (HBM) was conducted.

Crash testing and simulations A number of frontal and side impact tests were performed with different sizes of child crash test dummies in the project and presented previously in Jakobsson et al. (2011a). In addition, a side impact parameter study using virtual crash simulations for two sizes of occupants was presented in Jakobsson et al. (2011a) and Andersson et al. (2012). The side impact parameter study was followed by a simulation study using the SIDIIs on the struck side in the same passenger car model, including head and thorax–pelvis air bags (Andersson et al. 2013). The vehicle model was impacted laterally by a barrier in two different load cases. The crash test dummy was chosen to be representative of a young adolescent and positioned in six different sitting position representing common sitting positions for awake and asleep children.

More recently, a number of crash tests were run with the Q10, investigating its capabilities as well as evaluating the performance of restraint properties. Seven frontal sled tests simulating the EuroNCAP ODB 64 km/h (full frontal mounted mid-sized car body) and seven side impact tests simulating EuroNCAP AE-MDB tests (small vehicle, intruding door velocity of 7.5m/s), were performed (Bohman and Sunnevang, 2012). The Q10 was tested using a booster seat and booster cushion, respectively. In the frontal impact tests, the effect of seatbelt pretensioner, load limiter and various belt geometries, were evaluated. In the side impact tests, the effect of the thorax side airbag and the inflatable curtain was evaluated (Bohman and Sunnevang, 2012).

To investigate the influence on occupant excursion of a far-side positioned Q6, a sled test series were run simulating the EuroNCAP AE-MDB side impact test of a Volvo car. In four tests, the Q6 was restrained using an IBC (upper stage), with and without activation of the seatbelt pretensioner (two tests of each). In two additional tests, the Q6 was restrained using a booster seat (Britax Kidfix XP) with and without fixation (ISOFIT) to the ISOFIX anchorages.

Low-severity / maneuver tests Non-injurious frontal impact tests were performed comparing the shoulder belt and torso interaction of the Q10 to the behavior of the HybridIII (HIII) 10y and three child volunteers (Arbogast et al. 2013a). The test set-up included a seat with a three point belt on a low acceleration sled.

With the purpose of evaluating the capability of the crash test dummies to replicate kinematics and restraint interaction of real children in evasive steering and braking events, crash test dummies were exposed to the same maneuvers as the children in the maneuver studies (Stockman 2012, Stockman et al. 2013a and 2013b). The Q6, Q10, HIII 6y, and 10y were exposed to two braking events and two steering events using the same restraints as the children of their size. The Q6 and HIII 6y were compared to the kinematic response of children of stature 105–125 cm. The Q10 and HIII 10y were compared to children of stature 135-150cm. In addition, the Q3 and HIII 3y were exposed to two braking events and compared to the kinematic response of the shorter child volunteers (105–125 cm).

To evaluate potential countermeasures, steering maneuvers and run-off road events were run with Q6 and Q10 (both using IBC), and the HIII 5th female (restrained by a seat belt only), to compare the effect of activation of an electrical reversible seatbelt retractor (pre-pretensioner) (Bohman et al. 2016, Stockman et al. 2017). In the study by Bohman et al. (2016), the crash test dummies seated on the outboard rear seat position were exposed to an evasive steering maneuver when driving in 40km/h causing an inboard movement of the crash test dummy. In Stockman et al. (2017), two different types of run-off road events were simulated using a rig test with a vehicle rear seat mounted on a multi-axial robot simulating a road departure event into a side-ditch, and an in-vehicle test setup with a Volvo XC60 entering a side-ditch with a grass slope, driving inside the ditch, and returning back to the road from the ditch. The crash test dummies were positioned in the outboard rear seat position. In both studies, tests were run with different levels of pre-pretensioner forces in addition to reference tests with the pre-pretensioner inactivated. Kinematics and shoulder belt position were analyzed.

Development of tools Brolin et al. (2015) implemented postural control in the MADYMO human facet occupant model of a 6-year-old child (Cappon et al. 2007) using feedback controlled torque actuators. Control parameters were tuned and the active HBM was compared to the experimental data from braking and steering events with child volunteers. In addition, a small parameter study was run to study the influence on occupant response by the shape of the acceleration pulse in steering events.

International Coordination of Knowledge

International multidisciplinary workshops were held to identify high-priority research topics and strategizes toward their implementation. The workshops started in 2009 and have been held every second year in September, hosted by the project team at SAFER. The participants of the workshops were worldwide leaders in the fields of child occupant protection, biomechanics and auto safety. The first day of the two-day workshop included presentation of relevant topics with the focus on 'pressing issues in child and adolescent occupant protection' and reviewed progress of research priorities identified during previous workshops. Based on this, high priority areas were defined, which were discussed during the second day. An important part was to summarize and present the workshop discussions at the International Conference Protection of Children in Cars in Munich, enabling a wider dissemination and contributing to setting the agenda of future research and development. (Arbogast et al. 2011, 2013b and 2015).

RESULTS

The combination of methods provide real-world knowledge on child occupant safety in the rear seat, including input from real-world crashes, child postures and behavior in cars and insight into child kinematics in crashes and during potential pre-crash events. Efforts of evaluation and development of tools to simulate realistic child occupant situations are taken, which are essential steps to make possible evaluation and further development of protection principles for the booster seated children in the rear seat of passenger cars. Selected results from the different studies are summarized.

Real-World Crash Data Analysis

Child occupant fatalities in Sweden With the exception of initial increase during the first 10 years (mid 1950s to mid 1960s), crash-related fatalities among 0–14 years old car occupants have been declining ever since (Carlsson et al. 2013). Compared to the highest numbers of fatalities occurring in 1960s–70s, a drop of 83% was seen to 2010 with similar trend irrespective of the age of the child. This is a higher percentage decrease than the corresponding figure of 78% for the whole population, irrespective of age. In total, 24% of the fatally injured children were unrestrained and the majority of those were ejected from the vehicle. Among the restrained children, 56% were considered to be appropriately restrained for their age according to Swedish recommendations. Crash severity, complex crash situation, fire and drowning were factors that contributed to the fatal outcome, even though the restraint usage was considered to be optimal. The head was the primary injured body region.

Long-term consequences Among the injured children, 2% sustained an injury resulting in permanent medical impairment (PMI), of which 75 percent were at AIS 1 or AIS 2 level (Bohman et al. 2014). 68% of all injuries resulting in PMI were AIS 1 injuries to the cervical spine, with the majority occurring in frontal or rear-end impacts. The older children (≥6 years) had a significantly higher risk (3% versus 1%) to sustain a PMI injury to the cervical spine than the younger children. The head was the second most commonly injured body region for injuries resulting in PMI, which were predominantly of AIS≥2. In addition, mild traumatic brain injuries at AIS 1 were found to lead to PMI.

Pre-crash maneuver occurrence Of all drivers in the selected sample, 40% made an avoidance maneuver prior to crash (Stockman 2016). The most common avoidance maneuver was braking only, followed by a combination of braking and steering, and steering only. In all three sub-samples, driver error was the single most important critical reason for the event immediately preceding the crash. Of the driver errors, inadequate surveillance was the most common error in all groups followed by internal distraction. While passengers were the most common reason for internal distraction for drivers with child passengers and drivers with only passengers older than 14 sub-samples, single drivers were assigned internal distraction error, mainly due to focusing on other internal objects, retrieving objects from the floor or seat, or adjusting the radio.

Restraint usage in Sweden Jakobsson and Lindman (2015) summarized data from Volvo cars in Sweden showing that the restraint usage rate among 4-10 year old passengers (up to 135cm) increased from 63% on average during the six years before the law, to 79% on average for the six years after (2007-2013). The remaining 21% were using the seatbelt only, although they were both required by law to use a booster as well as needed it for their best protection.

Driving Studies

It is obvious that children do not always sit as crash test dummies, which are ideally positioned according to seating protocols prior the crash tests. The children's sitting postures and positions are influenced by comfort and activities (voluntary) as well as vehicle dynamics (involuntary), such as evasive maneuvers.

Naturalistic driving study (NDS) In the joint project with Monash University (Charlton et al. 2013), the ranges of head positions for child car passengers were quantified for the first time in a naturalistic setting. Head positions were analyzed for the subset of 35 children with available Kinect data (Arbogast et al. 2016). The average range of fore-aft head position changed with restraint type; increasing from forward facing child seats (218mm), to booster seat (244cm), to seatbelt only (340 mm). In general, those in the center seat position demonstrated a relatively smaller range of head positions. A shift of head position inboards the vehicle was seen, mainly due to interaction with other occupants and to view out through the front window.

On-road driving studies In the first on-road driving study (Andersson et al. 2010), the booster seat equipped with large head side supports more often resulted in a sitting posture without the head and shoulder being in contact with the booster's backrest, and consequently the head being further away from the seat backrest. This was probably due to decreased visibility as a result of the large side supports. Shoulder-to-booster backrest contact was noted during an average of 45 percent of the journey time in the seat equipped with the large head side supports, compared to 75 percent in the seat equipped with the small head side supports.

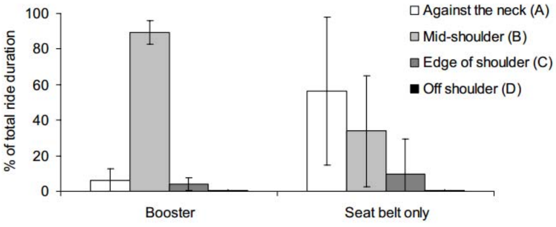

Figure 2. The distribution of shoulder belt position durations, shown as a percentage of the total ride duration. The averages (incl. standard deviations) of all children are presented by restraint type. (Jakobsson et al. 2011b).

In the second study (Jakobsson et al. 2011b), the shoulder belt was placed on the mid shoulder for a substantially longer part of the time when seated on the booster cushion, compared to using the seatbelt only, see Figure 2. Furthermore, all children were positioned in a more upright lateral posture for a greater extent of time, when using the booster cushion. When using the seatbelt only, the children changed body posture more frequently, and some children compensated for discomfort by rotating their upper body away from the shoulder belt.

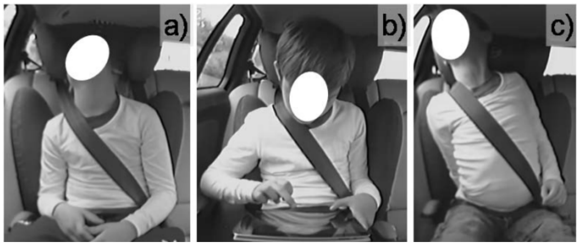

Figure 3. a) An example of sleeping posture, b) a forward leaning and slightly rotated posture while playing, c) Indication of some discomfort (Osvalder et al. 2013).

In the third study (Osvalder et al. 2013), the most frequent sitting posture when using the integrated booster was with the entire back and shoulders against the seat backrest and the head upright. When seated on the booster seat, the shoulders were seldom against the backrest. The most frequent lateral posture for both boosters was upright with the seatbelt in contact with the neck or mid-shoulder. Moderate and extreme forward and lateral postures occurred occasionally. The sitting postures and seatbelt positions were influenced by the children's activities and perceived discomfort during the ride. Some examples are shown in Figure 3.

Maneuver studies The kinematic responses and seatbelt interaction of the child volunteers were influenced by the size of the child and the restraint system used.

During the braking events, shorter children moved forward and downward with a greater flexion motion of the head compared to the taller children who had a more upright forward motion (Stockman et al. 2013a, Baker et al. 2017a). The children moved forward by up to 0.2m, when the shoulder belt remained over the shoulder. A schematic plot, representing the trajectories or the child volunteers in Stockman et al. (2013a), is shown in Figure 4. The backrest of the booster seat affected the initial position of the child relative to the vehicle and thus resulted in a more forward position at maximum displacement. For all the children, the maximum forward head position was forward the position of the booster seat's side supports.

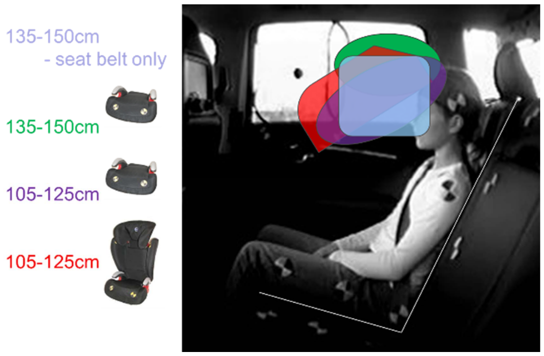

Figure 4. Schematic plot representing trajectories for forehead targets for child volunteers (Stockman et al. 2013a).

In the first test series with steering maneuvers (Bohman et al. 2011b), the seatbelt slipped off the shoulder in 20% of the maneuvers, varying by age of the child and the restraint system used. Among the shorter children, shoulder belt slip-off occurred in almost 67% of the trials when using a booster cushion while for taller children belt slip-off did not occur, irrespective of restraint type use.

In the second maneuver study (Baker et al. 2017b), initial seatbelt position on the shoulder and torso differed depending on booster and child size, which influenced how children engaged with the seatbelt during the steering. When more of the seatbelt was initially in contact with the torso, children tended to engage the seatbelt more, causing the belt path to become more curved; they moved with the shoulder belt and tended to have less inboard head displacement and less outboard motion of the seatbelt on the shoulder.

Evaluation and Development of Tools

The tests performed provide important insight into some limitations of the existing tools, and set the boundary for their use. Although existing crash test dummies were found feasible to use as loading devices during evasive maneuvers while in the restraints, developments of child occupant tools capable of simulating events when muscle activation influences the kinematics are needed. Development of an active child Human Body Model was made and showed potential as a first step approach.

Crash testing and simulations In frontal impacts, the Q10 was shown sensitive to belt pretensioning, with activation of the pretensioner reducing acceleration to the head, thorax and pelvis by 13-27%, but having a marginal effect on chest deflection (Bohman and Sunnevång, 2012). The Q10 was also shown sensitive to the combination of load limiter and pretensioner, further reducing head and thorax acceleration. Compared to a standard seatbelt, neck tension was reduced by half and chest deflection was reduced up to 37%. Among the parameters evaluated, the Q10 was most sensitive to shoulder belt geometry. Depending on starting position, various shoulder belt slippage occured. As a consequence of shoulder belt slippage, large effects on chest deflection were found. With the shoulder belt starting at a mid-shoulder position, it travelled towards the neck during the crash, resulting in low chest deflection. However, if the shoulder belt's starting position was 20mm further out on the shoulder from a mid-shoulder position, the chest deflection response increased by 50% compared to the mid-shoulder routing.

In the side impact sled tests, it was found that the Q10 was sensitive to the thorax side airbag, showing a reduction between 50-65% for chest deflection and 17-25% for pubic loading (Bohman and Sunnevång, 2012). Using the booster seat in combination with no thorax side airbag, chest injury risk reduction was not seen, although pubic loads were reduced by 18%.

Low-severity / maneuver tests In the non-injurious sled tests, it was found that for the two crash test dummies (Q10 and HIII 10y) and the child volunteers, the shoulder belt moved toward the neck during the loading (Arbogast et al. 2013a). The magnitude, as well as the rate of the shoulder belt movement, was greatest for the Q10. This may result in an underestimation of chest deflection when using Q10, due to off-loading the chest deflection sensor. Further studies with other belt geometries and crash modes should be explored to confirm these findings.

The comparison of crash test dummies to the child volunteers in the evasive steering and braking events, showed that the crash test dummies can be used in some load cases when the test setup, the time duration, and the focus of comparison with child occupants lies within their capacity (Stockman 2012 and 2016, Stockman et al. 2013a and 2013b). The capacity of the crash test dummies to replicate the kinematic responses of child occupants is limited due to the crash test dummies being too stiff and due to their obvious lack of muscle response, as illustrated in Figure 5. It was found that they can be used as a loading device for the seatbelt and booster, when the shoulder belt is on the shoulder. However, they are limited when out of the protective zone offered by the restraint. The crash test dummies were found not suitable for determining realistic child responses nor to determine the location of the head.

Figure 5. Maximum forward displacement of child volunteers (top), Q6 (bottom left) and HIII 10y (bottom right) kinematics in evasive braking maneuver of 1g.

Development of tools The active child HBM, developed based on the MADYMO human facet occupant model of a 6 year old child showed potential to study the protective properties of restraint systems in pre-crash scenarios (Brolin et al. 2015). The head and sternum displacements of the active child HBM were within one standard deviation of the experimental data, while the original HBM showed limited ability to capture the volunteer kinematics. Figure 6 shows the active child HBM compared to volunteers at start and at maximum head displacement for a 1g braking event (Stockman et al 2013a), a 0.8g steering event (Bohman et al. 2011b), and a 0.6g steering event (Baker et al. 2017b). The parameter study on steering event characteristics illustrated that the shape of the acceleration pulse highly influences the peak head displacement of child occupants.

Figure 6. The active child HBM compared to volunteers at start and at maximum head displacement for a braking event (top row), a 0.8g steering event (middle row), and a 0.6g steering event (bottom row).

Evaluation of countermeasures

It is clear that methods beyond existing regulatory and consumer information tests provide additional information needed to evaluate countermeasures addressing real-world needs. Varying sitting postures and positions in crash testing (or simulations) as well as including complex events will help guide development of protection principles.

Crash testing and simulations The side impact simulation parametric study presented by Andersson et al. (2012) concluded that the head and thorax-pelvis airbags have the potential to reduce injury measurements for the 3 and 12 year old occupant sizes evaluated. The seatbelt pretensioner was also shown effective for the near side occupants, provided that the lateral translation of the torso is managed by other features. It was also concluded that the importance of lateral movement management is greater the smaller the occupant.

The results from the side impact simulations with different sitting positions on the near-side, showed the importance of including real-world common sitting positions, beyond the nominal crash test dummy position, for improved and robust safety for child occupants (Andersson et al. 2013). The results differed for the different positions, with negative trend of protection when deviating from the nominal position.

Side impact crash tests with the Q10 positioned on the struck side, showed that the thorax side airbag reduced the chest deflection by 50-65% and the pubic loading by 17-25% (Bohman and Sunnevång, 2012).

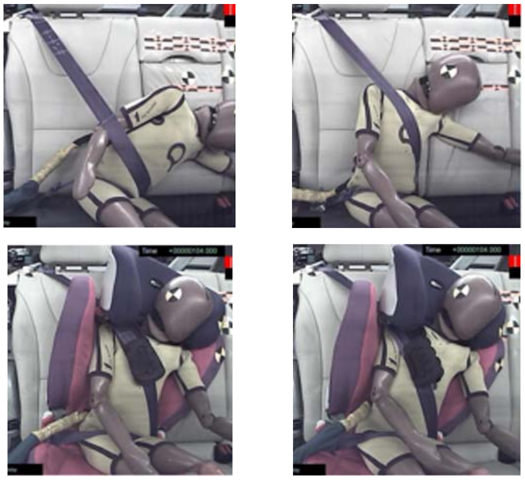

Figure 7. Maximum lateral excursion of the Q6 in side impact; top left: no pretensioner, IBC; top right: pretensioner, IBC; bottom left: pretensioner, booster seat without ISOFIT; bottom right: pretensioner, booster seat with ISOFIT.

The unpublished in-house EuroNCAP side impact sled tests with the far-side seated Q6 showed that activation of a seat belt pretensioner had a substantial effect, reducing maximal lateral head excursion by 230mm (Figure 7). No difference in extent of lateral head excursion were seen when comparing IBC and booster seat, irrespectively if attached to the ISOFIX or not. The Q6's head reached further inboard when using the booster seat, due to differences in starting positions.

Although it is not clear whether the Q10 seatbelt interaction is reflective of the real-world, the frontal impact crash tests by Bohman and Sunnevång (2012) provided insights into the overall benefits of pretensioner and load limiters for this size occupant, showing reduction to the loading of the head, neck and chest.

Low-severity / maneuver tests The effect of a seatbelt pre-pretensioner to help keep child sized crash test dummies in position in run-off road events and evasive steering maneuvers was shown in Stockman et al. (2017) and Bohman et al. (2016).

In the study with evasive steering maneuvers, the shoulder belt slipped off completely with inactive pre-pretensioner for the Q6 and the HIII 5th female, and partly slipped off for the Q10 (Bohman et al. 2016). When activating the pre-pretensioner, the shoulder belt stayed on the shoulder for all three crash test dummies and the inboard lateral excursion was reduced compared to no activation of the pre-pretensioner. Figure 8 compares the maximum inboard position for the three tests of pre-pretensioner settings; inactive, low and high level force.

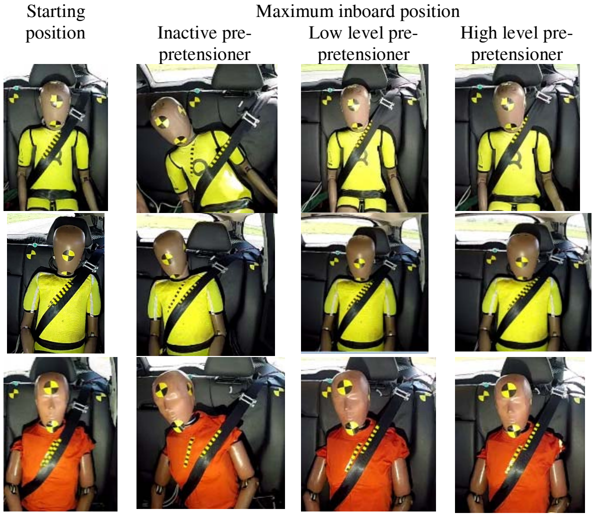

Figure 8. Q6 (top row), Q10 (middle row) and HIII 5th female (bottom row) in starting position (left column), and maximum inboard position for the three pre-pretensioner settings.

In the two simulated run-off events, the activation of the pre-pretensioner resulted in reduced lateral excursion of the crash test dummies (Stockman et al. 2017). For all three crash test dummies (Q6, Q10 and HIII 5th female), the shoulder belt remained on the shoulder and supported the side of the lower torso during the events, when the pre-pretensioner was activated, independent of force-level. In the rig test, the crash test dummy was exposed to rapid inboard lateral loads relative to the vehicle and the displacement for each crash test dummy was reduced when the pre-pretensioner was activated compared to tests with standard seatbelt. Shoulder belt slip-off occurred for the Q6 and Q10 in tests where the pre-pretensioner was inactivated. During the in-vehicle tests, the outboard rear seated crash test dummy was exposed to an inboard movement when entering the road again after driving in the ditch. The maximum inboard head displacement was reduced in tests where the pre-pretensioner was activated compared to tests with a standard seatbelt.

International coordination of knowledge

With the specific goals of the 2011 workshop to critically review the state of knowledge, and translate the 'Decade of Action' framework to child-specific priorities, high priority research topics were identified and strategies were defined toward their implementation (Arbogast et al. 2011). These included advancing the fundamental science of child occupant protection in several key disciplines and leveraging current knowledge to accelerate child occupant protection in countries where traffic safety is in its infancy. It was also emphasized that the entire field must work together to ensure that child road traffic safety is prioritized in funding decisions.

In the 2013 workshop the following eight research priorities were identified (Arbogast et al. 2013b):

1. Head injury mitigation
2. Quantify fundamental mechanics of children
3. Develop pediatric specific biomechanical research tools
4. Define realistic postures & positions of child occupants
5. Establish collaboration with rapidly motorizing countries
6. Conduct nationally or regionally representative child crash surveillance
7. Adapt AIS scale to include cost, disability and variations with age
8. Stimulate development of advanced restraints in rear rows emphasizing child occupant protection

During the 2015 workshop, the identified research priorities from 2013 were addressed and advancements were noted (Arbogast et al. 2015). With a future-oriented perspective, five important questions were identified as critical to tackle through informed and engaged dialogue from a variety of stakeholders:

1. How do we best get advanced models and biomechanics data used and accepted?
2. Child occupant protection is currently complex. How do we make typical behavior safe?
3. Our field primarily focuses on fatalities and serious injuries. Should less severe injuries be prioritized?
4. How do we ensure adequate data collection in emerging markets to address specific needs? What education or innovative technology is needed?
5. How do we ensure existing and emerging restraints are fully evaluated in diverse loading conditions for "real kids" in “real cars”?

It was concluded that future advancements need to be data driven and incorporate multiple disciplines. Engineering advancements for better child restraints should strive towards less complex solutions. The approach should be to take what families do most often and make it safe, and to highlight the shared responsibility between the CRS and the vehicle. In addition, regulation and consumer ratings programs must consider child occupants and follow fundamentals, models and biomechanics knowledge should integrate into restraint design quicker, and new markets may need new solutions.

DISCUSSION

This study addresses how to optimally protect children in a real-world perspective, acknowledging the contribution of the CRS and the vehicle. The results from this comprehensive multi-disciplinary project offer input to safety system development, standards and regulations, dummy design, test methods development as well as child restraint recommendations and future research challenges.

Although significant fatality reductions over the years are seen, there is still a need to address protection of children in cars. As concluded at the international workshops, multiple discipline competencies and actions are needed, and engineering efforts towards less complex solutions are required. Understanding the needs and behavior of occupants in real-world situations is key.

The real-world crash data analysis highlights the need to address injuries resulting in long-term consequences. Since a majority of injuries with long-term consequences are at low AIS levels, consequently these injuries may not be addressed by today’s countermeasures, which normally aim to address AIS3+ injuries. Further studies are encouraged to collect and analyze the data to investigate the specific mechanisms behind injuries causing long-term consequences.

The real-world crash data also show that in 40% of the crashes, the driver braked or steered prior to the crash. The data presented in this study is based on vehicles without automatic braking or steering technologies. There is a rapid development and implementation of collision avoidance and mitigation technologies, and they have shown great benefit in reducing numbers of collisions (Isaksson-Hellman and Lindman, 2016). Nevertheless, in future vehicles, it is likely that there will be an increase in share of crashes with preceding evasive maneuvers. Enhanced understanding of the events leading up to a crash and the influence of pre-crash factors will help drive the development of occupant protection as well as crash avoidance and mitigation technology beneficial for child car occupant safety forward.

Another finding, provided by the real-world data analysis in this study, was that even though booster seat have a long tradition, high availability and are required by law, too many children are not using boosters despite being of a size in need of such restraint. This applies specifically to the children that have reached school age. As concluded by the international workshops in this study, the approach should be to simplify use of safety technology and merge the typical behavior of CRS usage with the best practice. Furthermore, the shared responsibility between the CRS and the vehicle needs to be highlighted. Unfortunately, the development today within CRS certification is taking an opposite direction, exemplified by the side impact certification tests in UN ECE R129 evaluating the head protection for boosters without including any vehicle relevant measures in the test setup. The consequences are that the booster will become larger and less easy to bring along.

Fig. 9a. Child leaning forward for visibility (Andersson et al. 2010)

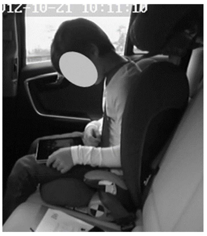

Fig. 9b. Child leaning forward using an Ipad (Osvalder et al. 2013)

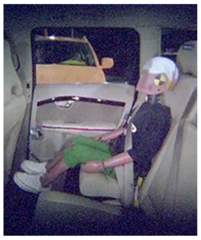

Fig. 9c. HIII 6y placed in crash test position.

When studying children during normal riding in cars it is obvious that children sit in a variety of postures. Figures 9a and 9b show examples of two forward leaning postures; for visibility and activity, respectively. Only for a limited time during the ride, the children are in the ideal posture for which the crash test dummy is positioned in testing (Figure 9c). When children are active, especially when they are engaged in tablets and smartphones, they often choose a more forward leaning posture. In case of a side impact, the head will then likely be protected by the vehicle rather than the booster's head side supports, although the latter is specifically certified for this purpose. Understanding the factors influencing the preferred sitting postures is the best way to proceed towards restricting the variability, with an ambition to derive at a range of common user positions. With this as a fundamental principle, restraints addressing the range of positions will enable robust protection for children in real-world situations. The common user positions should be guided based on comfort and positive measures in order to obtain a real effect.

Child volunteers of different sizes / ages in different restraints move forward approximately 0.15-0.20m when exposed to emergency braking of 1g, even when they are properly restrained. The difference in trajectories is influenced by the size of the child as well as the restraint system used, including initial seated posture, as illustrated in Figure 4. The areas shown in the figures are possible head impact areas in case of a subsequent side impact. This is in line with the field study by Maltese et al. (2007). As a consequence of the braking event, the head will be more forward than the coverage of most booster seat head side supports. This emphasizes the need for evaluation and development of child occupant protection that includes the vehicle and child restraint together.

Figure 10. Lateral inboard motion of a child during a steering maneuver, using booster cushion (left) and booster seat (right), (Bohman et al. 2011b)

In an evasive steering event children move laterally. The extent depends on the size of the child and the restraint used, and whether belt slip off occurred. The differences in shoulder belt slip-off between the shorter and the taller children may be explained by the fact that the stature of the taller children allowed the belt to have a grabbing effect on the shoulder while the shorter children slipped out of the belt immediately. Also, the taller children have wider shoulders. The booster backrest showed potential to maintain the shoulder belt on the shoulder during the steering maneuver (Figure 10). Whether the backrest of the booster seat will continue to keep the shoulder belt in position during a frontal impact when the booster seat and the child are in such a pre-crash position is still to be evaluated.

Based on the evasive maneuver tests, it was concluded that the crash test dummies can be used as a loading device for the seatbelt and booster, when the shoulder belt is on the shoulder. However, the utility of crash test dummies is limited when out of the protective zone offered by the restraint. The challenges include occupant kinematics to be predicted for a longer period of time and the influence of muscle activation in non-impact situations. The first step developments of the active child HBM adding postural control showed promising results to help predict child kinematics in low velocity events (Figure 6). Further developments of tools, enabling evaluation and development of countermeasures taking into account pre-crash events, are encouraged.

In the present study, some evaluations of the Q10 capabilities in frontal and side impacts were made.

The chest deflection of the Q10 was shown to be more sensitive to shoulder belt geometry than to other countermeasures such as seatbelt pretensioners and load limiters. This was followed up with the study comparing the Q10 shoulder belt slippage to child volunteer tests. These comparative tests, provided evidence that the shoulder belt slippage was faster on the Q10 as compared to the children. There is ongoing work initiated by EuroNCAP, to reduce the shoulder belt slippage on the Q10.

In side impacts, it was found that the Q10 shoulder has a potentially important load path in lateral impacts. Due to the rigid spine, the shoulder can be used to reduce loading to the thorax in an unrealistic way, which is a major drawback. Adding load measuring capabilities to the Q10 shoulder, in line with other side impact dummies (i.e. WorldSID 50th and 5th and SIDIIs) would resolve this. When these tests were conducted, a full-length arm was used. In the positioning proposal for the Q10 (same protocol for side- and frontal) the arm was positioned vertically and aligned to the thorax. It is believed that the arm interaction with the thorax has an influence on the chest deflection results by distributing the load to the thorax. After this study, a side impact kit was developed by Humanetics, including a half-arm, which is used in the side impact rating test.

The booster is essential for the child enabling good interaction to the vehicle seatbelt, however it cannot protect the child by itself. The present study exemplifies several situations where the vehicle's protection systems play an important role for the child's protection. Hence, aiming for real-world safety it is essential to replicate in-vehicle situations when developing child restraint systems, which is not how child restraints are certified today. The results from crash tests and simulations performed as part of this study show that the child crash test dummies were sensitive to and benefitted from side airbags and advanced seatbelt technologies, such as pretensioners and load limiters, in side as well as frontal impacts. In addition to the in-crash protective systems, pioneering maneuver and run-off-road tests were executed to evaluate the effect of a pre-pretensioner to be activated before crash. The tests show promising results to help keep the child in position in relation to the restraints, limiting the range of variability of postures and positions and working in line with the ambition to limit the range of user positions restricting the challenges of protection in case of a subsequent crash.

The results from this project contribute to identification and quantification of important real-world needs, as well as evaluation and development of countermeasures. It is emphasized that, from a real-world perspective, the vehicle and child restraint design should encourage a limited range of voluntary sitting postures, preferably guided by comfort. In addition, it is essential to further explore countermeasures to address the influences of dynamic events prior to a crash.

CONCLUSIONS

Real-world safety of child rear seat car passengers, involves evaluation of protection beyond crash-testing in standardized frontal and side impact conditions. This project explores a wide context of rear seat performance and emphasizes that child occupant protection is to be regarded as a multi-faceted system, combining vehicle protection and child restraint systems. Understanding how real children sit and behave in cars is essential.

Studying the children during normal riding clearly shows that the child restraint is only a part of the real-world protection. It is obvious that children interact with and benefit from the vehicle protection systems. It is also clear that the design of the child restraint influence the protection capabilities. The trend of increased head side supports will likely increase the forward leaning postures, which will expand the protection contribution needed from the vehicle. From a real-world protection perspective, it is beneficial if the vehicle and child restraint designs encourage controlled sitting postures, preferably guided by comfort, helping to restrict the variability in user positions.

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