The balance of vehicle and child seat protection for the older children in child restraints

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Introduction

Motor vehicle accidents are the leading cause of death or injury to children in several parts of the world (Subramanian, 2005) although the development of protection systems has been significant over the last decades. According to a study in NASS-CDS it was found that 2/3 of the fatally injured 0 – 12 year old children was restrained (McCray et al., 2006). In-depth accident data suggests oblique crash situations and vehicle maneuvers, prior to impact, as contributing factors for head injuries of restrained children (Bohman et al. 2011a). On-road driving studies and maneuver studies with children have illustrated that children are not positioned in a standardized crash test dummy positions in situations of potential real world crashes (Andersson et al. 2010, Charlton et al. 2010, Bohman et al. 2011b, Jakobsson et al. 2011, Stockman et al. 2012). Arbogast et al. (2011) highlighted the shared responsibility between the child seat manufacturer and the vehicle manufacturer.

The smallest children are optimally protected in a rearward facing seat, where the shell of the child restraint provides the protection of the child's vulnerable neck and head both in frontal and side impact situations, given the child and the seat are restrained (Tingvall 1987, Carlsson et al. 1991, Kamrén et al. 1993, Stalnaker 1993, Tarrière 1995, Isaksson-Hellman et al. 1997, Jakobsson et al. 2005, Henary et al 2007). Rearward facing child restraints up to 3-4 years are available in most countries and have been used as best practice in Sweden from the beginning of child restraints in the 1960:ies. Hence, the focus of the present study is on children older than 4 years old and who are forward facing. Children in the age group 4-8 years have shown great benefits from boosters in frontal impacts (Durbin et al. 2003) and they may also benefit from seat belt technologies such as load limiters and pretensioners (Bohman et al. 2006). Real world data shows that the age group 9-12 year old has higher injury risk than the younger age group (4 - 8 years) (CHOP, 2008). The older age group is not being restrained on boosters as frequently as the younger age group, but still, they are not optimally restrained on the seat only.

Protection of children in cars is the responsibility of several actors. In case of a crash the outcome is related to the interplay of the different protection systems in the car, including the child restraint. In recent years, there has been a strive to provide more pronounced protection built into the child restraint. The aim of this study is to discuss the balance of vehicle protection and child restraint protection enabling the optimal real world safety for the children of different sizes, focusing the older range of children in child restraints, from 4 years and above.

Developments of child restraints for children 4-12 years old

Belt-positioning booster cushions were introduced in the late 1970's (Norin et al. 1979). Today, there are three main belt-positioning boosters; booster cushions, booster seats (including backrests) and built-in booster cushions. The systems are used with the vehicle's seat belt which restrains both the child and the booster. The built-in booster cushions were developed in order to simplify usage and to minimize misuse (Lundell et al. 1991) as well as adjusting to the growth of the child by providing two levels in height (Jakobsson et al. 2007).

A 4-year-old child has specific car safety needs. The iliac spines of the pelvis, which are important for good lap belt positioning and to reduce the risk of belt load into the abdomen, are not well developed until a child is about 10 years old (Burdi et al. 1968). The development of iliac spines, in conjunction with the fact that the upper part of the pelvis of the seated child is lower than that of an adult, are realities that must be taken into consideration in the booster design.

The booster cushion allows the geometry of the vehicle's seat belt to function in a better way with respect to the child occupant. The booster raises the child, so that the lap part of the seat belt can be positioned over the thighs, which reduces the risk of the abdomen interacting with the belt. An important feature regarding booster cushions is the belt-positioning device (guiding horns); keeping the belt in position during a crash by restraining the booster. This feature is not necessary for built-in boosters. The booster also sets the child in a more upright position and more adaptive thigh support, so he/she will not scoot forward in the seat to find a more comfortable leg position when seated. Slouching may result in sub-optimal belt geometry (DeSantis Klinich et al. 1994). Other advantages of boosters are, by sitting higher the shoulder part of the seat belt will be more comfortably positioned over the shoulder of the child more so, the child will also have a better view.

Initially the backrest of the booster was developed to provide a head restraint for the child when seated in a vehicle seat without head restraint. The backrest was also a way of adjusting the length of the cushion to accommodate the shorter thigh length of the smallest children. When removed, the cushion length better accommodates the larger children. Also, the backrest provides belt-positioning devices for the shoulder belt with the ambition to help guide the belt into a comfortable and safe mid shoulder position (Reed et al. 2009). During the last decade the backrests of the boosters have grown in extent to provide side support for comfort as well as designed for head protection in case of a side impact (Bendjellal et al. 2011).

More recently child restraints using internal harness have been promoted for use by the older children as well. The child restraint is attached to the car using the seat belt, LATCH/ISO fix anchorages and/or top tether. The child is restrained in the child restraint by an integrated harness. This type of seat accommodating larger children is included in the Australian regulation and is also promoted in the US.

Real world safety aspects

Braking event testing with children of different sizes / ages in different restraints provided data on head excursion during an emergency braking of 1g (Stockman et al. 2012). During the braking the head of the child moved 15-20cm forward even when the child was restrained properly. Figure 1a shows the area of head trajectories of the children during the braking maneuvers. The differences in trajectories were influenced by the size of the child as well as the restraint system used, including the initial seated posture.

Stockman (2012) stated that in case of a subsequent side impact, any of the head positions in Figure 1a could be a potential position at impact. This is in line with the study by Maltese et al. (2007), who identified evidence of a variety of head impact locations for restrained children (4 – 15 years) in real world side impacts. As a consequence of the braking event, the head will be more forward than of the coverage of most booster seat head side supports. An example of head position as a result of the braking event in Stockman et al. 2012 is shown in Figure 1b. Also, in a side impact, the struck car is in many cases subject to an angled acceleration due to its initial speed, which will add to a more forward head impact point as well.

Figure. 1a. Schematic plot representing trajectories for forehead markers for child volunteers from the brake event study by Stockman et al. (2012). From darker to lighter grey, the coloured areas represent: taller children (135-150 cm) on booster cushion, taller children on vehicle seat, shorter children (107-123 cm) in booster seat with backrest and shorter children on booster cushions.

Figure 1b. Maximum forward head position of a child restrained in a booster seat during an emergency braking event (Stockman 2012).

The forward displacement due to a braking event (Figure 1a) will reduce the distance to potential head impact areas in case of a subsequent frontal impact. If the child is using a booster seat with a backrest this distance will be further reduced by the more forward initial head position. Some illustrations of initial sitting postures are provided in Figures 2 a-d, comparing children of two sizes using booster with or without backrest.

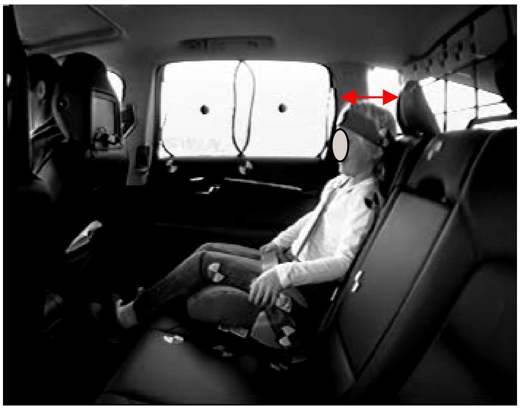

Figure 2a. Child 6 yo – 123 cm in rear seat of Volvo XC70 using booster cushion.

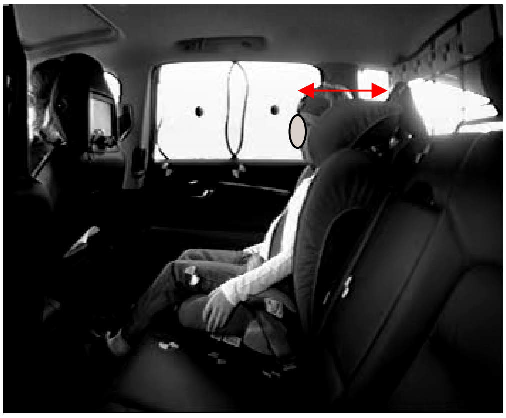

Figure 2b. Child 6 yo – 123 cm in rear seat of Volvo XC70 using booster seat with backrest.

Figure 2c. Child 7 yo – 133 cm in rear seat of Renault Grand Espace using booster cushion.

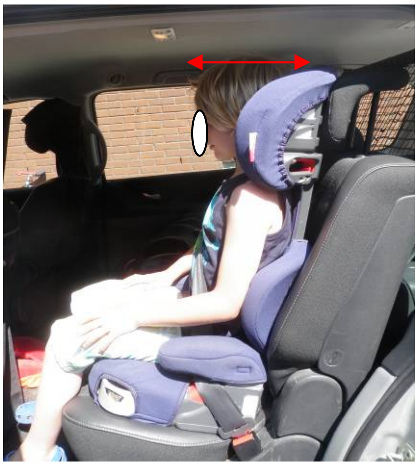

Figure 2d. Child 7 yo – 133 cm in rear seat of Renault Grand Espace using booster seat with backrest.

The design of the side supports of the booster seat influences the child's seating posture. Andersson et al. (2010) when studying children's sitting postures riding in two different types of booster seats showed that the children were more prone to lean forward when the booster seat was equipped with more protruding head side supports. For the six children (3- 6 years old) in the study it was three times more common for the children to sit with their entire back and head against the backrest when seated in the booster seat with small side head supports. Also, the children in the study were seated with the main part of the head in front of the front edge of the head side supports more than half the time, i.e. positioned forward to the standard crash test dummy position. The two most common sitting postures for the two booster seats are shown in Figures 3 a-b.

Allthough developed for protection, it is not evident that a backrest with head side supports offers lateral protection for the child in real world situations and could for the largest children even be a hazard due to unfavourable initial sitting positions increasing risk of head impacts.

Figure 3a. The most common sagital sitting posture using the booster seat with the large head side supports in the study by Andersson et al. 2010.

Figure 3b. The most common sagital sitting posture using the booster seat with the small head side supports in the study by Andersson et al. 2010.

In a swerving motion the children will move sidewise. Bohman et al. (2011b) conducted a maneuver study on a closed-circuit test track with children restrained in the rear seat of a modern passenger vehicle. Exposed for a sharp turn (lateral acceleration of approximately 0.8g) resulting in an inboard motion of the child, the kinematics were compared using different types of restraints. The children of stature 105-125cm were restrained using boosters with and without backrest. The backrest showed potential to maintaining the shoulder belt on the shoulder during the swerving maneuver (Figures 4a-b). Whether the backrest of the booster seats 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.

Figure 4a. Lateral inboard motion of a child during a swerving maneuver, using booster cushion (Bohman et al. 2011b)

Figure 4b, Lateral inboard motion of a child during a swerving maneuver, using booster seat with backrest (Bohman et al. 2011b)

Child benefits from vehicle safety systems

Children of approximately 4 years old and above can safely use the vehicle's seat belt, given that they are adjusted into good seat belt position using a belt positioning booster cushion. By using the vehicle's seat belt the child will benefit directly from the structural safety design as well as any advanced seat belt functionality (e.g. belt pretensioners and load limiters) in a frontal impact. Using a forward facing child restraint with internal harness, the child will not benefit from any advanced seat belt functionality and only benefit indirectly from the structural safety design due to introducing additional slack in the restraining of the child.

Using crash testing, Bohman et al. 2006, illustrated the benefits of seat belt pretensioners and load limiters for a child dummy in a frontal impact. In order to be effective for the child the load limiter needs to be adapted for the child. Such systems were introduced on the market in 2007 (Jakobsson et al. 2007), and have great potentials to increase in availability. The primary functionality of seat belt pretensioners is to reduce seat belt slack. The effect of seat belt pretensioners for adults in the front seat has been recognized for a long time but publications on the real world effect for children in the rear seat are more rare. However as for adults there are all reasons to believe that reducing slack is just as important and valuable for children in real world situations.

Frontal impact airbags may not be designed for children and children are thus recommended not to be exposed to frontal impact airbags. This can be achieved either by deconnecting the passenger side frontal airbag when the child is sitting in the front passenger seat or to keep the child out of the front seats. The torso side impact airbags are designed not to be harmful to the child and studies suggest that they add protection for the child as well (Andersson, 2012).

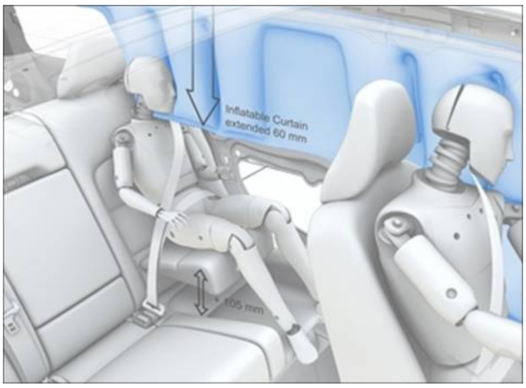

Figure 5a. Illustration of IC coverage for a child in the rear seat of a Volvo car.

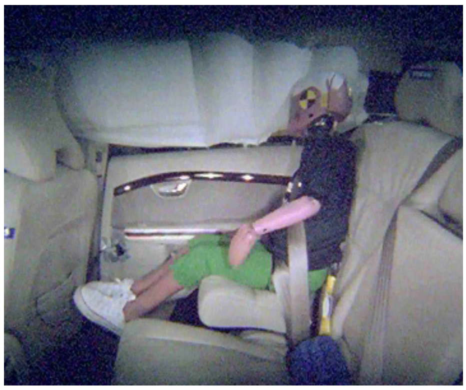

Figure 5b. Vehicle to vehicle crash test (50 km/h lateral impact speed) of Volvo V70 (model year 2008) with Hybrid III 6 yo crash test dummy, restrained using built-in booster.

The benefits of the Inflatable Curtain (IC) is the same for children as for adults when interacting with the head in a side impact or rollover events. Protection is achieved by avoiding ejection and impacts to hard surfaces of the counterpart, see examples in Figures 5a-b. IC is available in most modern vehicles and cover the window area (as required in e.g. FMVSS 226). The head protection performance of the IC is mainly evaluated by standardized side impact testing including pole impact tests with the mid size male crash test dummies and moving barrier test (IIHS) with the small female sized crash test dummy SIDIIs.

The sitting height of a small female sized crash test dummies (e.g. HIII 5%-ile, SIDIIs) is 80-90 cm. If estimated that a booster raises the child approximately 10 cm, the head position of a child with 70-80 cm sitting height would approximately correspond to the head position of the small female sized crash test dummies and would thus benefit similar head protection. This could correspond to a mid-size 8 year old child as well a large 6 year old child and equals approximately the stature of 130 cm (Steenbekkers, 1993).

Discussion

This study provides insight into modern vehicles' protection capacity in relation to the children and outlines the areas that are affected in case of an unbalance by too high ambitions on built-in protection of child restraints. In case of an emergency braking the head of the child will move 15-20cm forward even when restrained properly (Stockman et al. 2012). This will then reduce the distance to potential head impact areas in case of a subsequent frontal impact. If the child is placed in a booster with a backrest this distance will be further reduced by the more forward initial head position, examplified in Figures 2a-d. Also, in a side impact, the head will be more forward after the braking event than of the coverage of most booster head side support as shown in Figure 1b. Studies on children's sitting postures when riding in different types of protruding booster head side supports also show that the children are more prone to lean forward when the booster is equipped with large head side supports (Figure 3a). Allthough developed for protection, it is not evident that a backrest with head side supports offers protection for the child in real world situations and could for the largest children even be a hazard.

For the smaller children when restrained in booster seats with backrest, the backrest showed potential to maintaining the shoulder belt on the shoulder during a swerving maneuver, but it is not known whether the booster seat will continue to keep the shoulder belt in position during a frontal impact when booster seat and the child are in such a pre-crash position (Figure 4b).

Real world safety of rear seat occupants, especially children, involves evaluation of protection beyond standard crash testing scenarios. Modern passenger vehicles are designed to protect small adults in the rear seat. The minimum level of the lateral protection is set by the standardized tests, such as the side impact tests by IIHS using the small female sized crash test dummy in the rear seat. Some vehicles have a rear seat design with the child in focus, including built-in boosters of adjustable height, advanced seat belt functionality including belt pretensioner and child adapted progressive belt load limiter as well as child adapted side impact protetion including Inflatable Curtain coverage (Jakobsson et al. 2007 and Fig. 5). For these vehicles, the protection of the child is not depending on additional protection by a booster seat backrest and could even jepordize the functionality of the Inflatable Curtain if a too large backrest is used. A good balance is to provide add-on child restraint systems when necessary but not more than necessary. This is valid for every vehicle and child, allthough the level of add-on protection is depending on the specific combination of vehicle design and the age and size of the child.

This study focuses the size of the child by performing a first rough comparison between small adults and children. It is also to be recognized that the age of the child as well as type of travel also influences how well the child is kept in a good seat belt geometry, however this should be achieved in a way that will not add unfavourable slack in the restraint system or introduce objects that might influence vehicle safety systems negatively. As qualititative basis for all the actors in the field of child safety some basic principles are important to establish a robust direction for real world protection of children as car occupants.

It is suggested that for all modern vehicles scoring acceptable points in safety rating, the vehicle built-in protection together with a booster cushion (without backrest) will offer best protection to children of approximately 130 cm and taller. This was proposed comparing the sitting heights of small female crash test dummies and children of different sizes, taking into account that the children are raised by a booster cushion. For vehicles which are developed for protection of children even the smaller children are well protected, as illustrated in Figure 5. Thus it is important to acknowledge that different types of boosters (with as well as without backrest) need to be available and acceptable for the children to use for their optimal real world protection.

Conclusions

Except for the frontal airbags, children benefit from the vehicle safety systems, including vehicle structure, seat belts and side airbags. However, due to the anatomical development, children have specific concerns calling out for add-on protection systems for their optimal protection. Children of approximately 4 years and above can safely use the vehicle's seat belt, given that they are adjusted into good seat belt position using a belt positioning booster. By using the vehicle's seat belt the child will benefit from the structural safety design in a frontal impact as well as any advanced seat belt functionality (e.g. belt pretensioners and load limiters). By raising the child it will also benefit from structural safety design as well as available side airbags in case of a side impact. For the total safety of the child, these basic principles are needed to be emphasized in order to make a good balance.

A good balance is to provide add-on child restraint systems when necessary but not more than required related to the in-vehicle safety design as this can have an adverse effect like inducing unnecessary slack in the total restraint sequence of the child as well as giving an unfavourable initial sitting position increasing risk of head impacts. Also, too large child seats can interact unfavourably with the deployment of the Inflatable Curtain.

The study concludes that for children taller than 130 cm, a booster cushion (without backrest) together with the vehicle 3pt belt should be used as their primary restraint. By raising the children, the vehicle's built-in protection is to be used for the optimal real world protection of children of these sizes. For children shorter than this, the benefit of a backrest for the booster is depending on the vehicle used and the behaviour of the child during the specific trip. Hence, for the optimal protection of children in cars, it is essential that different types of boosters are available and accepted.

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