

REAL-WORLD PROTECTION OF BOOSTER-SEATED CHILDREN – NEEDS AND CHALLENGES IN FUTURE TRANSPORTATION

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ABSTRACT

Driven by sustainability goals, passenger cars' design and ownership setups are changing. Vehicle safety is constantly improving, yet a trend of larger belt-positioning boosters is seen. The objective is to discuss the challenges of child passenger protection in the current and future mobility context. The study focuses on children who can use the vehicle seatbelt together with a booster, typically 4 to 10-12 years.

The study is based on protection principles of booster-seated children, with a vehicle-booster-user entity focus. Studies on restraint awareness and usage today, users' perceptions on future mobility and evolutions of vehicle design and mobility trends, are summarized and reflected on. Real-world protection needs are formulated based on in-vehicle crash testing/simulations, and studies on child passenger sitting postures during drive and evasive maneuvers. This is put in the context of regulatory and booster development trends.

In a real-world crash, children are protected by the vehicle and booster in combination. Crash tests/simulations highlight the importance of the seatbelt interaction, influenced by initial beltfit and the dynamic properties of the booster. On-road driving studies show that awake child passengers spend a non-neglectable duration of the trip with a forward head position, due to visibility and activities. A forward head position could also be a result of a pre-impact braking as well as the added space by the booster seat's backrest. In case of a frontal impact, a more forward head position at time of impact will result in a more forward excursion. Real-world side-impact data shows that the booster-seated child's head is protected similar to an adult, assisted by the vehicle safety systems.

The booster serves as an adapter, not as a primary restraint for the child. Booster-seated children benefit from the vehicle safety systems, given they are raised in position for good beltfit and posture. Addressing the changing trends of passenger cars' design and ownership setups, the role of the booster should be clearly communicated. Future designs must address issues of usability, portability, and acceptance. As examples, the streamlined roof designs driven by sustainability goals, reduce the roominess in the rear-seat, whereby the booster seat backrest's width and height might require larger space than needed for an adult; and the trend from personal mobility towards increased degree of shared mobility, emphasizes the need of the booster to be portable or integrated into the vehicle.

Real-world child passenger safety involves protection aspects beyond standardized crash testing scenarios. Most importantly, the booster should be used in every trip, irrespectively of passenger car ownership setup. This study provides insight into modern vehicles' protection capacity in relation to the booster-seated children. It outlines some areas that are affected by the current booster developments, such as the increased size and complexity of booster seats, and the booster cushion ban in some parts of the world. In relation to the current and future transportation context, a booster cushion with appropriate characteristics serves as an essential complement to booster seats (of reasonable size) and will help maintain a positive child safety global trend.

THE DEVELOPMENT, EXPERIENCE AND CONTEXT OF BOOSTERS

Smaller children need infant or toddler seats with internal harness. For optimal protection they should be placed rearward facing to ensure that their neck has better chances to cope with high severity frontal impacts (Tarriere, 1995; Jakobsson, 2017). When outgrown of the toddler seats, and at approximately 4 years old, the children can benefit from the vehicle restraints, given they are raised into a good position for the vehicle seatbelt, using a belt-positioning

booster. There are three design principles of boosters; booster seat which includes a backrest, booster cushion with no backrest and integrated boosters which are built into a vehicle. Recently, several new products have been developed targeting the group of booster-seated children. Such products include, e.g., so called “inflatable cushions”, “height-less boosters” and different types of “belt straps restraints”. These products are not addressed in this study, since unless the products elevate the child in a stable manner (during ride as well as during a crash), and shorten the seat cushion length, they should not be categorized as boosters, nor should they be used as child restraints in passenger cars.

This study focuses on children who can use the vehicle restraint together with a stable boosting belt-positioning booster, typically 4 to 10-12 years old (appr. 140 cm stature).

The Development

In 1978, the world’s first booster was introduced (Norin et al., 1979). The idea of boosters for children sprung from a study initiated by the discussion of enforcing rear-seat seatbelt use, where it was questioned whether seatbelts were safe for small adults (Norin et al., 1977). The first booster was a booster cushion, shown in Figure 1a. Important features of the booster cushion are the belt-positioning guides for the lap-belt, one on each side. Their purpose is to help keep the seatbelt in position during a crash and to restrain the booster itself. Modern boosters have belt guides protruding upwards, improving accessibility, and they vary in height and design. The lap-belt guides can also serve to help position the shoulder portion of the seatbelt, by placing the shoulder belt over or under the guide on the buckle side. The same booster cushion can then help to obtain the desired mid-shoulder belt position for shorter and taller children, respectively. The booster helps to put the child in an upright position, allowing the legs to bend and providing thigh support, so the child will not slouch forward in the seat to find a more comfortable leg position. Slouching may result in sub-optimal belt geometry (DeSantis Klinich et al., 1994).



Figure 1a. World-first booster cushion 1978. The belt guides are positioned low on the side of the booster.



Figure 1b. Early version of a booster seat (1985). The belt guides are of similar design as in Figure 1a, although difficult to see in the photo.



Figure 1c. A booster seat from 1989. As the prior version (Figure 1b), it is a booster seat with removable backrest.

The backrests were initially intended to provide head support in vehicles without head restraints, as shown in the example from 1985 (Figure 1b). 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. It can include shoulder belt-positioning devices with the ambition to help guide the shoulder belt into a comfortable and safe mid-shoulder position (Reed et al., 2009). The backrest of the booster in Figure 1c allows for height adjustment, enabling the shoulder belt guide to adjust to different sizes of children. Backrests can potentially provide sleeping support and help to control the lateral position of the child’s upper body during ride.

In 1990, the world’s first integrated (built-in) booster was introduced addressing accessibility, acceptance, and reduced risk of misuse (Lundell et al., 1991), Figure 2a. A comfort cover can be used with the integrated booster (Figure 2b), providing side support when travelling, but not interfering during a potential crash. In 2007, a second-generation integrated booster was introduced providing two levels in height (Figure 2c), adapting beltfit to the growing child (Jakobsson et al., 2007). The acceptance of the integrated booster was greater, shown by the relative higher usage of

the integrated boosters, in comparison to accessory boosters, among the older children aged 8 to 10 (Jakobsson et al., 2012 and 2015). Osvalder and Bohman (2008) provided evidence that misuse was almost eliminated when using integrated boosters. A follow-up study in China, conducted with users without previous experience of integrated boosters and limited experience with boosters overall, showed similar findings of reduced risk of misuse when buckling up on an integrated booster compared to an accessory booster cushion (Bohman et al., 2016). On-road driving studies comparing integrated booster and a booster seat indicated a more positive attitude on comfort, as well as a higher degree of upright sitting posture towards the seatback for the integrated booster (Osvalder et al., 2013).

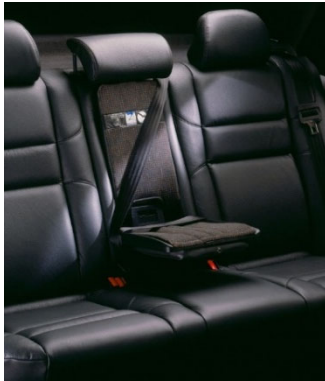


Figure 2a. World's first integrated booster, 1990.



Figure 2b. Comfort cover for an integrated booster.



Figure 2c. Two stage integrated booster; high position (left) and low position (right).

Real-World Data

Real-world safety is about real children in real vehicles. Real-world crash data provides a foundation of knowledge, which will help address future challenges as well. User studies on child sitting postures, self-selected or by evasive maneuvers, provide insight into head and seatbelt positions at start of a potential crash. These studies help interpret different crash outcomes, as well as help identify important areas of real-world safety.

Crash data studies

Real-world crash data shows that the use of boosters substantially reduces injury risk compared to seatbelt only, and that boosters are effective to help protect children in frontal impacts as well as other crashes (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; Anderson et al., 2017). In frontal impacts, seatbelt syndrome related injuries to the abdomen and spine were nearly eliminated for children using boosters (Durbin et al., 2003). Children aged 4 to 8 using boosters were 45% less likely to sustain injuries than similarly aged children using the vehicle seatbelt only (Arbogast et al., 2009). 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 side-impacts, respectively. No difference in booster seats versus booster cushions were seen (Arbogast et al., 2005 and 2009; Jermakian et al., 2007; Arbogast, 2010). No major differences in head injury patterns were seen between booster-seated children and adults, exposed to near-side side-impacts in similar passenger cars. This provides evidence of comparable mechanisms and indicates similar protection needs for both groups (Jakobsson et al., 2005).

User studies

Tests with children of different ages in different restraints provided data on head excursion during emergency braking of 1g (Stockman et al., 2013; Baker et al., 2017; Graci et al., 2019). During the braking, the head of the child moved 15-20 cm forward even when the child was restrained properly using a booster seat or a booster cushion (Stockman et al., 2013). An example of head position, as a result of the braking event, is shown in Figure 3a. Figure 3b shows the areas of head trajectories of the two child groups in the two booster types. Baker et al. (2017) showed that extent of head excursion was influenced by the degree of initial shoulder belt contact, due to differences in routing of the lower part of the shoulder belt. Using a booster cushion as compared to an integrated booster, a gap between the belt and lower torso was more frequently seen, in addition to a further outboard initial shoulder belt position on the shoulder (Baker et al. 2017).



Figure 3a. Maximum forward head position of a child restrained in a booster seat during an emergency braking event (Stockman et al., 2013).

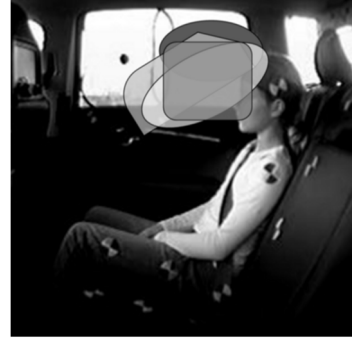


Figure 3b. Schematic plot representing trajectories of forehead markers for child volunteers from the emergency braking event study by Stockman et al. (2013).

Stockman et al. (2013) stated that in case of a subsequent side-impact, any of the head positions in Figure 3b 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 old) in real-world side-impacts. As a consequence of a braking event, the head will be more forward than the coverage of most booster seat's head side supports. Also, in a side-impact, the struck vehicle is in many cases subject to an angled acceleration due to its speed at impact, which will add to a more forward head impact point as well.

A more forward head position at time of crash may increase head excursion in frontal impacts (Bohman et al., 2018; Maheshwari et al., 2020 and 2021). The forward excursion due to a braking event (Figures 3a-b) will reduce the distance to potential head impact areas in case of a subsequent frontal impact. If the child is using a booster seat, the backrest will further reduce this distance by the more forward head position as compared to using a booster cushion, as shown in Figure 4. The backrest will position the child's head forward due to the thickness of the backrest, as well as potential fitment incompatibility with the vehicle seat.

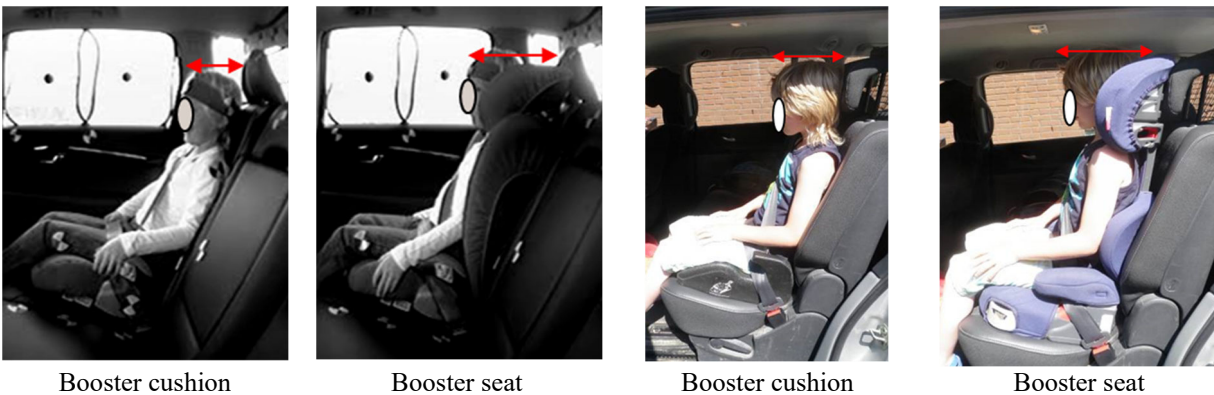


Figure 4. Illustrating influence of a booster seat's backrest on head position in relation to the vehicle. Left: 6 years old child (123 cm) in the rear-seat of a Volvo XC70. Right: 7 years old child (133 cm) in the rear-seat of a Renault Grand Espace (Jakobsson et al., 2012).

A forward head position may also be a result of a forward leaning posture due to visibility, activities or other reasons. Figure 5 shows self-selected postures due to visibility or activities. Andersson et al. (2010) showed that children were more prone to lean forward in the booster seat equipped with the more protruding head side supports, when studying children's sitting postures riding in two different types of booster seats (Figure 5a). The children 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, often due to visibility reasons. Another on-road user study identified that comfort related aspects influenced the sitting posture. Osvalder et al. (2013) found that the side supports of the booster seat's backrest restricted the children's possibilities to use their

arms when interacting with a tablet. This caused a forward leaning of the whole upper body, in addition to the head bending forward when looking at the tablet (Figure 5b).



More protruding

Less protruding

Figure 5a. The most common sagittal sitting posture for two types of booster seat head side supports (Andersson et al., 2010).



Integrated booster

Booster seat

Figure 5b. Comparing influence of backrest when interacting with a tablet (Osvalder et al., 2013).

In a swerving vehicle motion, the children will move sidewise (Bohman et al., 2011; Baker et al., 2018; Graci et al., 2019). Bohman et al. (2011) conducted a maneuver study with children restrained in the rear-seat of a passenger car. Exposed for a sharp turn (lateral acceleration of approximately 0.8g) resulting in an inboard motion of the child, the kinematics were compared when seated on a booster, with and without a backrest. The backrest showed potential to maintain the shoulder belt on the shoulder during the swerving maneuver (Figure 6a). Whether the belt guide of the booster seat's backrest 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-impact inboard tilted position is not obvious, as illustrated by Figure 6b. Figure 6b shows initial position and position at head impact from a frontal impact crash test with initial inboard tilted position of the anthropometric test device (ATD) and the booster seat.



Booster cushion

Booster seat

Figure 6a. Lateral inboard motion of a child during a swerving maneuver (Bohman et al., 2011).



Initial position

At time of head impact

Figure 6b. Frontal impact crash test with initial inboard tilted position of the ATD similar to the child in the booster seat in Figure 6a.

Protection Principles

Regardless of crash configuration, children benefit from the vehicle safety systems given they are raised in position using a booster, and the booster is supportive in retaining a good seatbelt interaction throughout the crash. As for adults, the general protection principles of balancing the torso and head movements applies. This is irrespective of crash configuration, exemplified by an even support by the vehicle interior if exposed to a rear-end or side-impact.

The specific protection principle of a seatbelt is to restrain the strong parts of the body; the pelvic bones, and across the chest and over the shoulder in a crash (Adomeit and Heger, 1975; Bohlin, 1977). The lap-belt position is crucial in helping to avoid lap-belt interaction with the abdomen in frontal impacts. The anterior superior iliac spines of the

pelvis are important for good lap-belt positioning and they are not well developed until a child is about 10 years old (Burdi et al., 1968). In addition, the size of the pelvis grows with age, having influence on the height of the anterior superior iliac spines in relation to the seat cushion. By elevating the child, the lap-belt will be routed low on the pelvis, as for adults, instead of toward the abdomen. When positioned across the chest and in a mid-shoulder position, the shoulder belt helps provide a desired head and upper body kinematics during a frontal impact (Kent and Forman, 2015). A tight and early coupling of pelvis and upper body, maximizes the use of the available space in the vehicle, used to reduce the occupant motion, often referred to as the “ride down”. Furthermore, a seatbelt performs best when routed as straight as possible. When extensively re-routed, its protective functions will be influenced due to introduction of slack, as exemplified in Figure 6b.

Figure 7 shows an animation of a frontal impact using PIPER6y which is a human body model representing a 6-year-old child. It illustrates how the lap-belt holds back the pelvis and allows the upper body to flex forward. Initially, the seatbelt pretensioner tightens the seatbelt, by reducing the belt slack, and offers an early and tight coupling of the pelvis. As can be seen, the booster elevates the child model, whereby the lap-belt is helped to interact with the pelvic bone reducing the risk of the child’s pelvis to slide under the lap-belt, referred to as submarining.

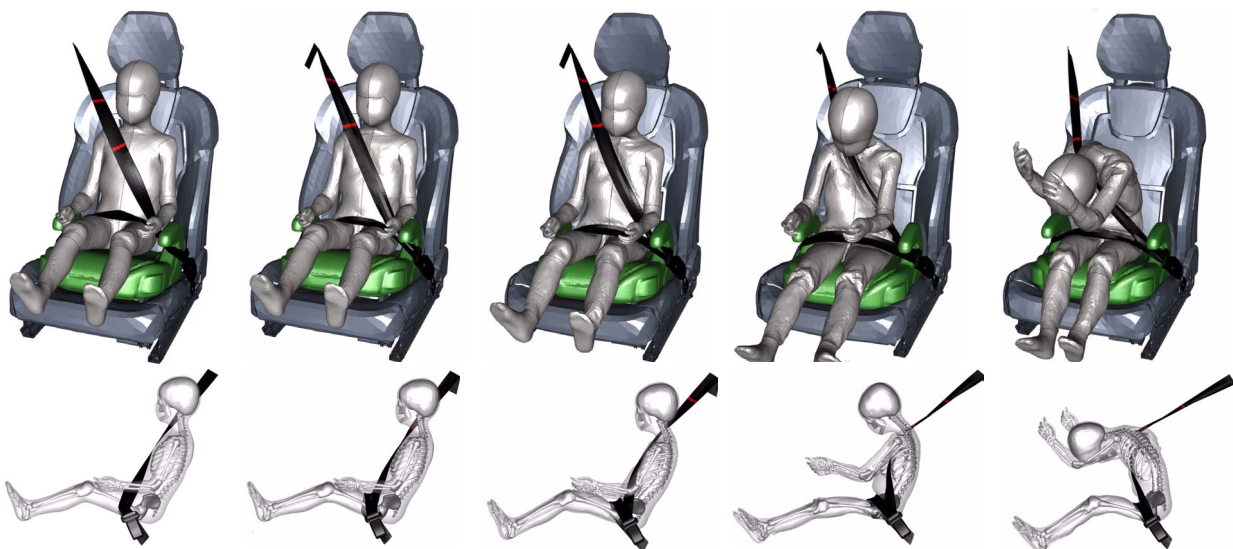


Figure 7. A frontal impact simulation with PIPER6y on a booster cushion restrained by a seatbelt with pretensioner, from start of impact to time of maximum forward head excursion. Time sequences (left to right): 0ms, 25ms, 50ms, 75ms and 110ms. Whole body in oblique frontal view (top) and skeleton in a side view (bottom). The red lines on the shoulder belt help to visualize the initial tightening of the pretensioner, occurring during the first 25ms.

The Child Passenger Protection Context

The booster is a part of a whole system, the vehicle-booster-user entity. In a real-world crash, children are protected by the vehicle and booster in combination. Crash tests and simulations highlight the importance of the seatbelt interaction with the occupant and the booster. This includes initial beltfit, the influence of belt guide design and potential re-routing due to those, in addition to the booster’s shape and stiffness. The user aspect includes the sitting posture of the child, the potential movements prior to a crash, in addition to the safety awareness and possibilities to use the booster and the seatbelt correctly when riding as a car passenger.

The vehicle

Regardless of crash configuration, booster-seated children benefit from the vehicle safety systems. In frontal impacts, the seatbelt is the main protection system, as shown in Figure 7. By using the vehicle’s seatbelt, the child will benefit directly from the vehicle’s structural safety design and collision mitigation systems, as well as any advanced seatbelt functionality (e.g., belt pretensioners and load limiters). Depending on the vehicle model, modern frontal impact

passenger airbags may add to the protection of the booster-seated child in the front passenger seat, see further in Heurlin et al. (2016).

Using crash testing, Bohman et al. (2006) and Lopez-Valdes et al. (2009) illustrated the benefits of seatbelt pretensioners and load limiters for a child ATD in a frontal impact. For the load limiter to be effective for the child, the load levels need to be adapted to the size and weight of the child. Such systems were introduced on the market in 2007 (Jakobsson et al., 2007) and have increased in availability. The primary purpose of seatbelt pretensioners is to reduce seatbelt slack. Although manually tightened on an occupant wearing tight clothes, there is still some slack to remove (see Figure 7). If wearing bulky clothes or if the seatbelt has not been tightened manually the importance of the pretensioner is even more significant, for children as well as adults. Due to the high loads in a crash, the seatbelt will always strive to take the shortest path between its anchorage points. This was exemplified in the crash test shown in Figure 6b, in which the initial position of the shoulder belt was re-routed by the belt guide of the inboard tilted booster seat's backrest. In this case, the belt guide did not manage to retain the initial routing when lap-belt forces increased up to 4 kN. When the shoulder belt was straightened it resulted in a path outside the shoulder of the ATD. Generally, re-routing of the seatbelt, although attaining an initial visually appropriate position on the body, may result in slack when the webbing is straightened, having consequences on pelvis retention and the preferred torso flexion. If no pretensioner, the addition of the initial slack will further add to the outcome.

The purpose of the inflatable curtain (IC) is to cover the open area of the side windows, in case of a side-impact, rollover crash or other crash configurations, when needed. As for an adult, the IC, in addition to the interior side structure of the vehicle, including panels and energy absorption, will also help protect a child by distribution and reducing the loads. The torso side-impact airbags are designed not to be harmful to the child and studies suggest that they may add protection for the child as well, when seated on the struck side in a side-impact crash (Andersson et al., 2012; Bohman and Sunnevang, 2012). If seated on the non-struck side, the pretensioning of the seatbelt will help to further restrain the child and limit head excursion (Tylko et al., 2015; Jakobsson et al., 2017). With the pretensioner activated, no difference in extent of lateral head excursion were seen for the ATD, comparing restrained on an integrated booster and on a booster seat, irrespectively if attached to the ISOFIX anchorages or not (Jakobsson et al., 2017).

The user

In most motorized countries there is a high awareness of the need to use boosters for children in passenger cars. In a Swedish survey in 2021, 94% of children aged 4 up to 8 report always using appropriate restraints (Bergfors et al., 2021). This observation has been stable since 2016, while an increase from 77% and 69% in 2014 and 2015, respectively. In US in 2019, 69.5 % of children aged 4-7 were using child restraints (Enriques, 2021). The usage frequency varies between countries and the age of the child, with a decreasing trend with increased age. In addition, the type of booster varies with age. For Sweden, booster cushions represent an increasing share of boosters with increased age, as well as a proportionally higher use of integrated boosters with increased age, as compared to add-on boosters (Jakobsson and Lindman, 2015). More recent Swedish data from 2021 shows that 88% use booster cushions and 23% use booster seats (multiple choice possible) among booster restrained children aged 8 to 11 (Bergfors et al., 2021). Among those aged 4 to 8, the booster cushion usage was 40%.

The reasons for non-use or part-time booster use are several: such as lack of knowledge, the child thinks it is childish or claims it to be uncomfortable and refuses, or the booster is too big (Ramsey et al., 2000; Simpson et al., 2002; Ebel et al., 2003; Bingham et al., 2006). Lack of access and inconvenience are other reasons for non-use. The boosters may not be easily available e.g., when travelling with others, or when in a hurry (Bingham et al., 2006). Compared to private vehicles, the use of child restraints is lower in taxis, which was seen attributable to the inconvenience of carrying them to and from the taxi (Keshavarz et al., 2006).

Another important safety challenge is misuse. The most frequent misuse modes for boosters relate to the belt routing; incorrect lap-belt path or non-optimal shoulder belt routing (O'Neil et al., 2009; Bohman et al., 2016). Discomfort caused by the shoulder belt being too close to the neck may be handled by placing the belt off the shoulder, away from the neck or even placing the shoulder belt under the arm or behind the back (Ebel et al., 2003; Jakobsson et al., 2011). These actions will likely increase risk of injury if exposed to a crash.

The booster

The booster is as an adapter, not a primary restraint for the child. The booster serves the purpose to adapt the child to the vehicle seat and seatbelt, addressing the protection principles for the child passenger protection. The main characteristics of a booster can be summarized as follows:

- **Boost!** – Raise the child to ensure the lap-belt is positioned low on the pelvis and the shoulder belt is positioned on a mid-shoulder position.
- Design to **position the lap-belt low on the pelvis**, ensuring contact with the boney parts of the pelvis and prevent placement too far forward on the thigh or too high on the abdomen.
- Provide **comfortable cushion length**, allowing the child to bend the legs comfortably over the seat edge.
- **Move in a controlled manner** together with the child during crash.

In addition, **lateral support** for comfort and upright lateral sitting posture, to keep the shoulder belt on the shoulder by avoiding lateral leaning, especially for the younger children and during longer trips. The lateral supports could be provided by the booster seat's backrest, but only if it does not obstruct the vehicle safety system to work. A lateral support could just as well be an add-on comfort cover, providing sleep support and restricting the lateral movement, but not influencing during a crash.

During the crash, the booster should have **stable performance**; excessive deformation of the booster has been shown to alter lap-belt positioning and increase the risk of submarining (Tylko and Bussi eres, 2012; Forman et al., 2022). Forman et al. (2022) evaluated the effect of 17 different parameters in a large-scale simulation study. They identified booster stiffness being the most influential parameter, together with sitting posture, for predicting submarining risk. In another simulation study on different booster cushion parameters, although no submarining occurred, the booster with reduced stiffness resulted in less favorable overall kinematics as the pelvis was not restrained as efficiently as for the boosters with more stable performance (Bohman et al., 2020).

Tight attachment to the vehicle (e.g., to the ISOFIX anchorages) should only be made when the vehicle-booster system is developed together, such as integrated boosters, or used only when there is a seatbelt pretensioner available to reduce belt slack. This is to ensure that the child will not slide off the booster in a frontal impact. Non-tight attachments can be used allowing the booster to move with the child forward, and still serve as a booster restraint when no child is using the booster.

CURRENT AND FUTURE MOBILITY CHALLENGES

Although there is a high awareness of the need to use boosters for children in vehicles, the usage varies between countries, and decreases with the child's age. For optimal protection, children up to approximately 140 cm should use a booster when riding in a passenger car. This is not the case in current mobility. Driven by sustainability goals, passenger cars' design and ownership setups are changing. These trends in combination with the current booster development trend pose challenges for child occupant protection. The challenges include ensuring booster usage at current levels and even more so, to increase future usage reaching the optimal situation. A summary of the three trends is provided.

Passenger Car Development Trends

Passenger cars are becoming more streamlined having implications on space between the outboard rear-seat passenger's head and the vehicle's side structure. Although an adult might fit well, as well as a child using a booster cushion, it is not as obvious for a large booster seat due to its large head and torso side supports, and thereby potential interaction with the vehicle's roof or side structure, see Figure 8. This interaction of tight fitment might even cause problems for the vehicle's safety systems to function as intended. For example, the IC is positioned within this area of interaction. In the event of a side-impact, the IC is intended to inflate and serve as a part of the protection system for both front- and rear-seat occupants. Incorrect inflation of the IC might influence protection of the child in the booster seat as well as the front-seat occupant.



Figure 8a. A mid-sized male adult in the rear-seat of a modern passenger car.



Figure 8b. A booster seat with a 6-year-old-sized ATD in the rear-seat of a modern passenger car.



Figure 8c. A booster seat with a 10-year-old-sized ATD in the rear-seat of a modern passenger car

Autobrake systems were introduced more than a decade ago and have evolved over the years, as well as increased in availability in modern passenger cars. Based on data prior to auto brake system introduction, approximately 40% of the crashes were preceded by an avoidance maneuver by the driver (Stockman, 2016). This number is likely higher when adding the maneuvers made by the vehicle, to help mitigate the severity of a crash. Hence, there will be a higher likelihood for children to be exposed to maneuvers in future crashes, having potential influence on their forward position or lateral sitting posture, including shoulder belt position at time of impact.

Mobility Trends

Passenger car ownership setups are changing. Ridesharing and car sharing (shared mobility) are increasing trends all over the world. An overview of 47 countries showed that, in October 2018, car sharing businesses included 32 million users, sharing 198 000 vehicles (Shaheen and Cohen, 2020). In 2018, online car hailing accounted for 36% of the total traffic volume in China (Sohu, 2019). Shared mobility services have also grown in popularity as a family transportation option (Ehsani et al., 2021; Koppel et al., 2021). The use of taxi services, car-pool systems, and other car sharing, such as remote activation of borrowing your friend's car on short notice, are examples of not using the same car every day. In addition, an increase of multiple transportation modes during one trip; using cars only part of the trip, becomes a consequence of city planning as well as changes in mobility trends. These changes pose challenges for child passenger protection in relation to the traditional way of car ownership/usage. For example, although child restraint usage is high in privately owned vehicles in high-income countries, child restraint usage is substantially lower in shared mobility services such as taxis, rideshare vehicles, and car sharing (Koffsky et al., 2018; McDonald et al., 2018; Prince et al., 2019; Owens et al., 2019; Koppel et al., 2021; Reed et al. 2022). Parents were most likely to report none usage of child restraint while travelling in a rideshare vehicle because: lack of child restraint in the rideshare vehicle, they did not bring a child restraint with them, or the trip was of a short distance (Owens et al., 2019; Koppel et al., 2021).

Booster Development Trends

The booster design development has been driven separately from the vehicle development, which has influenced the regulatory and consumer information tests. The test rigs lack important state-of-the-art vehicle protection characteristics, including IC, which are standard in the vast majority of current vehicles. Such test rig designs may drive optimized side structures of the booster seat.

The role of the ATD and its assessment criteria is important too. As an example, the ATD assessment in the side-impact tests are acceleration-based, which directly drives the design of the side supports in the booster's backrest. The relevant structure in the test rig is limited, whereby the backrest's side supports serve as the energy absorption, driving wider booster seats. Even more so, chest accelerations are optimally reduced by early contact, whereby thicker side

support structures are more likely rewarded with higher scores. On top of that, adjustable features such as “lateral impact devices” can further reduce contact time. Such features are typical examples of optimization for the ATD criterion in the test rig, though questionable with respect to real-world relevance. While regulatory tests provide a limit for approval, consumer information tests serve the purpose to differentiate between boosters, and therefore are motivated to include stringent targets.

Booster cushion banning

Several parts of the world are banning booster cushions, claiming lack of head protection in side-impacts. European child restraint consumer information tests disqualify booster cushions, claiming the side support of the backrest being essential for the child’s protection in side-impacts. The reasoning for this is not in line with decades of real-world experience, which shows that the vehicle protection is serving to protect the booster-seated child’s head, similar to an adult (Jakobsson et al., 2005) and no evident difference between booster seat and booster cushion is seen (Arbogast, 2010). The Australian regulation, as well as the UN Regulation No. 129 type-approval, require head side structure on the booster to pass the side-impact test. UN Reg No. 129 still includes booster cushions by allowing exception of the side-impact test. However, this is only for children 125 cm and taller. Booster height specifications, with the ambition to get the child’s head into a certain height position, make it difficult, if not impossible, to design an attractive booster cushion for the children it targets (Jakobsson et al., 2020).

Booster seat development trend

Booster seats are becoming larger and with increased complexity. This trend is beyond the ban of booster cushions, although also likely related to a lack of understanding the vehicle-booster-user entity. This trend is about adding features in the booster seat design. In combination with a created consumer belief and demand for these features, the booster seats become large, heavy, and bulky, while lacking substantial arguments on the features’ real-world safety relevance. Instead, this may have serious implications on usage for all trips, which evidently is negative for child passenger protection. The features relate to several areas, such as an extensive backrest, devices influencing the seatbelt, and attaching the booster seat to the vehicle, as exemplified in Figure 9.

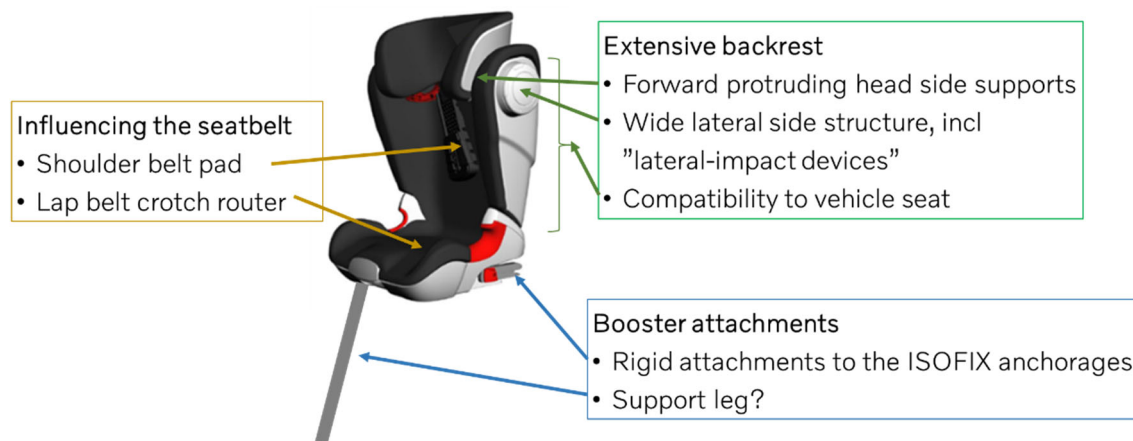


Figure 9. Examples of the booster seat design trend.

The extensive backrest

The backrest designs have evolved towards large side supports both at the torso and head area. The child restraint manufacturers emphasize two reasons for this; to provide comfort for children by keeping them upright when relaxed or asleep, and to provide improved side-impact protection (Bendjellal et al., 2011). Supporting the child to remain in lateral upright position is favorable in helping to keep the shoulder belt in a mid-position on the shoulder. This is essential for the child’s protection in case of a frontal impact or in complex crashes in general.

Although developed for crash protection, it is not evident that a backrest with forward protruding head side supports offers lateral protection for the child in all real-world situations. As exemplified in Figures 3 and 5, several reasons may influence the child’s head position at time of impact, resulting in a position more forward than of the coverage of most booster seat’s head side supports. The forward protruding head and torso side supports could even contribute

to drive a more forward sitting posture due to visibility and comfort related aspects (Figure 5). In addition, there are relatively few real-world occasions in which the child's head will interact with the head side support as in the test rig methods for which it is assessed for, when considering the variety of side-impact configurations and the forward trajectories of a child sitting in a moving vehicle when exposed to such impact.

The lateral width of the side support, as exemplified in Figures 8b-c is substantial in some booster seats. Although likely scoring well in test rig setups, it is questionable whether they are beneficial in the real-world context. Adding the adjustable "lateral-impact devices" it becomes even more questionable. In addition, the backrest as such has compatibility challenges in the vehicle seats. It is difficult to make it fit in a contoured vehicle seat back and the interaction with the vehicle head restraint may force it into a forward position, resulting in an unnecessarily upright sitting posture of the child. Although likely not a safety problem, the upright posture might be uncomfortable, whereby a better solution is to use a booster cushion together with the vehicle seat back and head restraint. Removal of the head restraint, which is often incorrectly recommended, is not a safe alternative. The vehicle's head restraint is designed and assessed for high severity rear-end impacts, while the booster seat's backrest is likely not.

Influencing the seatbelt

As previously described, the seatbelt is the primary restraint for a booster-seated child. Booster belt guides should be designed with care to secure the performance by the seatbelt at crash. This includes the lap-belt guides on the cushion part as well as the shoulder belt guides on the backrest. An example of design for good guiding is shown in Figure 10a. Some boosters guide the lap-belt too far forward on the thighs, not touching the pelvis, which may result in slouching (Jones et al., 2020), and in delayed coupling of the pelvis. Extensive shoulder belt routing might add slack and provide a sense of "false" protection expectations, as exemplified in Figure 6.



Figure 10a. A booster seat designed to guide the seatbelt without adding slack or risk for the belt to get stuck. Same design as shown in Figure 1c.



Figure 10b. A booster seat with a shoulder belt pad.



Figure 10c. A child in a booster seat with the lap-belt routed through a lap-belt crotch router strap.

Recent trends include adding pads to the shoulder belt and connecting the lap-belt to a lap-belt crotch routers, exemplified in Figure 10b and Figure 10c, respectively. The shoulder belt pad in Figure 10b was introduced to help reduce the ATD's responses in the chest and neck, by damping the head-to-torso impact. Hence, this is a device that is designed for ATDs and does not necessarily provide any benefits to real children. If used correctly, it might not harm. However, if not positioned correctly it might risk getting stuck and to hinder the seatbelt functionality, especially in a vehicle with seatbelt pretensioner. Hence, it adds an unnecessary misuse aspect, rather than protection for the child. Unfortunately, this is not understood by the users, who are told the opposite and perceives it therefore as a safety device. The lap-belt crotch router was introduced in 2015 and is now also perceived by the users as an important safety device. This lap-belt crotch router introduces slack into the lap-belt, which may reduce the overall protection effect due to delayed coupling of the pelvis. Poor lap-belt fit, due to inadequately designed belt guides, may be improved by this feature, however that aspect should be addressed by improvements to the booster design, rather than introducing an additional feature.

Attaching the booster to the vehicle

Restraining the booster seat when not used by the child will help to protect other occupants in the vehicle, in case of a crash. This can be done by the seatbelt or, as recently introduced, by attachments to the vehicle's ISOFIX anchorages. With vehicle restraints reducing potential seatbelt slack in case of a crash, this attachment might not be a problem for the child passenger in those conditions. However, it adds weight and complexity to the booster seat. In addition, crash tests in a vehicle environment have shown that with a tight attachment of the booster in combination with slack in the seatbelt, the ATD slides off the booster (Tylko et al., 2016). Hence, there might be a potential real-world protection issue, which is not detected in standardized test rig methods.

Recently, the question on allowing a support leg for the category of booster seats was raised at UNECE Working Party on Passive Safety (GRSP) (United Nations, 2022). The main argument addressed the convertible or multi-purpose type of child restraints, accommodating the use of the support leg also when in a booster seat mode. Currently, the booster seat envelope in UN Reg No. 16 does not allow for a support leg. If including the possibility of a support leg for a booster seat, there is an obvious risk that this becomes a popular feature among booster seat designs as well. Hence, it may contribute to drive the already large booster seats to become more complex, bulky and heavier. Bohman et al. (2022) showed that minor and non-consistent differences were seen when adding a support leg to a booster seat in frontal impact simulations, with two different child occupant models in a vehicle interior, when including activated seatbelt pretensioner. Although somewhat larger differences were seen in the configurations without seatbelt pretensioner activation, it was concluded that no kinematical nor response aspects provided evidence of enhanced real-world protection needs of a support leg for the booster seat (Bohman et al., 2022).

DISCUSSIONS

Children aged 4 to 10-12 are well protected if using boosters that elevate them, shorten the seat cushion length, position the lap-belt in contact with the pelvis and position the shoulder belt across the chest and shoulder. The protection is a combination of the vehicle design, the booster design and how the child is using the restraints. Integrated boosters benefit from being designed together with the vehicle restraints, optimizing their protective performance. Studies have confirmed integrated boosters to reduce the likelihood of misuse, being comfortable, and a way to attract the older children to use boosters (Osvalder and Bohman, 2008; Jakobsson et al., 2012; Osvalder et al., 2013; Bohman et al., 2016). However, integrated boosters are available in a limited number of vehicle models and never in all passenger seat positions, whereby there is a need for a non-integrated booster matching the principles of the integrated booster, while being portable and easy to use.

The Mismatch

There is a mismatch with respect to the booster trend and the challenges in current and future mobility. The current booster trend includes banning booster cushions and promoting booster seats with large designs and several features adding weight and complexity. This is also a mismatch in relation to overall real-world protection. Not allowing booster cushions causes issues as illustrated in Figure 8, showing that a booster-seated child may require more space in the vehicle seat than an adult. The potential incompatibility between a large booster seat's backrest and the vehicle interior will increase with the trend of more streamlined roof designs, as driven by sustainability goals. The reasons behind the development of the extensive side supports are partly clear. Backrests with forward protruding head side supports were introduced approximately in year 2000 and was driven by an ambition to help protect the child's head in a side-impact (Bendjellal et al., 2011). At the same time, vehicles were starting to be equipped with ICs. A decade later, the side supports of the booster seat have increased in width, mainly driven by introduction of side-impact tests using test rigs, with no vehicle-like head protection included. Likely an adult-sized ATD would be just as poorly protected in such a test rig method. Isolated from the vehicle-context, it was perceived that a booster cushion was not capable alone to protect the child without the protruding head side supports as part of the booster seat. This perception spread widely, and similar test methods were included in regulatory updates, leading to banned booster cushions in some parts of the world. Unfortunately, there was a misconception that the booster seat should serve as the main protection for the head despite real-world data that showed that the child's head was likely mainly protected by the vehicle (as for adults), prior the introduction of extensive side supports and ICs. The compatibility issues of fitment and vehicle safety systems are essential motivators for allowing use of booster cushions.

User studies show several reasons for children having a forward leaning head position at impact, such as being engaged in electronic devices or due to visibility reasons, or because of an evasive braking. Studies also show that children in boosters with forward protruding side supports were more prone to attain a forward head position, resulting in the head being out of the head side supports. In such cases, the effect of the booster's head side support will be limited. The backrest as such adds distance to the vehicle seatback and thereby positions the child more forward and closer to the structure in front, as exemplified in Figures 4 and 5b. In case of a frontal impact, a more forward initial head position, relative to the vehicle, will result in a more forward head excursion and thereby increasing the risk of head impact. Although developed for head protection using test rig methods, it is not evident that a backrest with head side supports offers head impact protection for the child in real-world situations.

More recently, shoulder belt pads and belt routing straps (Figures 10b-c), in addition to attachments of the booster to the vehicle by using the ISOFIX anchorages, have been added to serve as anticipated improvements for frontal impact protection. These features are not shown as safety enhancements in real-world situations, although there are likely situations in which they might not do any harm. Nevertheless, the seatbelt re-routing by the belt routing straps, and the tight attachment of the booster to the ISOFIX anchorages are concrete examples of a lack of understanding the booster-vehicle context and may be counterproductive. Overall, these over-engineered products drive the complexity of the boosters, likely having impact on usage.

Another mismatch is about the test rigs for booster assessment and how the results are analyzed and communicated, not acknowledging the limitations of the test rigs' real-world resemblance. Based on the simplified test setup, lacking representative vehicle and user context, safety perceptions are communicated which are not aligned with real-world safety performance. Too many consumers today are told that a booster with all the features is the safest alternative, while likely that is not the case.

A main challenge today is the increased degree of shared mobility services and to help ensure the use of a booster at every trip. The current booster offer is not aligned with this development. The trend of changing from the habit of using one vehicle from start to destination to flexible use of several different vehicles is a challenging task when addressing the needs of families. The sketch in Figure 11a illustrates some choices addressing how to make sure the whole system is in place when using the vehicle. Can they carry a booster with them; large or small? Or, could there be one available when reaching the vehicle? How can we help the users to always use a booster even in shared mobility situations? Another challenge of large booster seats is illustrated in Figure 11b, in which two mid-sized male adults are sitting together with a booster seat in a rear-seat of a modern large family car.



Figure 11a. A sketch illustrating shared mobility challenges for a family



Figure 11b. Fitting two mid-sized male adults together with a booster seat in the rear-seat of a large family car

Real-World Protection

Real-world data shows that boosters, irrespectively of backrest or not, provide protection for the child.

The fundamentals for real-world protection for the category of booster-seated children are:

- The seatbelt is the primary restraint, as for an adult.
- The booster's main purpose is to raise the child in position for good lap-belt geometry, for reduced risk of submarining in frontal impacts.
- By raising the child, the booster will also provide a more comfortable and safe mid-shoulder shoulder belt position.
- The booster shortens the cushion length, improving comfort and thereby reducing risk of slouching.
- The booster-seated child will benefit from the advanced seatbelt technologies, such as the pretensioners.
- In a side-impact, the vehicle safety systems will help protect the child, as for an adult.
- Lateral support for comfort and upright sitting posture could be provided by the booster, but only if obstruction of vehicle safety systems is avoided. It could just as well be an add-on comfort cover.

In addition, not to jeopardize real-world protection of the child these guidelines should be followed:

- Don't let the booster introduce excessive re-routing of the seatbelt. Re-routing may have negative impact on the seatbelt's performance during crash.
- Avoid extensive side supports. This may have negative impact on vehicle safety systems' function.
- The boost should maintain stable during the whole crash.
- Be careful when attaching the booster to the vehicle (by other means than the seatbelt), when the child is using it. The booster should move with the child, if needed.

Most importantly, a booster should be used at every trip.

What is Needed?

Allowing booster cushions for children from 4 years of age is essential for safe shared mobility. The consequences of banning the booster cushion could result in children not using a child restraint, due to the hassle of bringing a booster seat along to the car sharing service or limited access to boosters by the car services. The trend of decreased use of booster seats by increased age is seen already today, while the use of booster cushions is relatively greater among the older booster-seated children. Today in conventional car ownership, there is a relatively high share of seatbelt-only-restraint among the oldest children required to use boosters. If no safe and convenient alternative is available, the share of incorrectly restrained children is likely to increase when car ownership changes and multiple transport modes during one trip will increase. This will influence the protection in a crash and have negative impact on the overall traffic safety.

Banning a well-performing booster cushion based on arguments not substantiated by real-world data, is not in line with the users' needs. Instead, efforts should be focused on providing information on the importance of beltfit and sitting upright, whereby the child could fully benefit from the vehicle safety systems. This is in line with the proposed joint efforts by the vehicle, the booster and the user for the protection of the child in the vehicle. For the younger booster-seated children, they may need support for lateral restriction to ensure good shoulder belt fit throughout the ride. This need varies by individual and by the trip. Likely more support is needed during longer trips to support the child when sleeping, as compared to shorter trips. Other strategies, than a backrest with large protruding side supports, can be applied to address this, such as adding low-weight comfort support helping to stabilize the child laterally into an upright sitting posture when resting. These supports should not be rigidly attached to the booster, nor the seatbelt and they should not influence the vehicle safety systems during a crash.

As a safety community we need to ensure that parents and caregivers are educated on what a booster does. Consumer misunderstanding the role of a booster, such as considering it as a restraint and not as an adapter, may contribute to encourage the designs to be larger and have more extraneous features, that do not positively contribute to occupant safety. This is to be expected as these consumers are graduating from harness-based child restraints, which are not as

dependent of the vehicle restraint in its protective design. We need to re-orient the consumer to how a booster works, driving simple solutions that positively impact safety, as well as the other key characteristics of accessibility and affordability.

There is also a need to address the test methods for booster assessment, in addition to the interpretations and messages provided from the tests. This includes the certification tests by UN Reg No. 129 and in Australia, which today are restricting real-world safe booster cushions. It also includes the consumer information rating tests, in addition to the child seat manufactures, and their role in communicating the benefits of different features. Since the test rig has limitations in reflecting the vehicle-booster-user entity, care should be taken when communicating safety benefits of features evaluated via this method, in relation to a real-world protection context. This was also emphasized by Arbogast et al. (2022), summarizing discussions at an international workshop on child occupant protection.

The rear-seats of passenger cars are constantly improving. Therefore, there is a need to investigate how the test methods for booster assessment can be further developed, to improve the representation of modern vehicles. In addition, the child occupant's representation by the child ATDs also needs to be further addressed. In the absence of a complete understanding of the ATD limitations, the interpretation of the response can contribute to conflicting safety countermeasures (Arbogast et al., 2022). In line with the concept of a booster as an adapter, rather than a stand-alone restraint, it is important that the methods and tools for testing reflect that the booster is part of a system that includes the vehicle environment as well as the child context. To capture the full protective effect of a booster, the context should be as realistic as possible.

The Way Forward

Today there is a reluctance among families to use car sharing services, of which one of the main reasons is their concerns regarding the child restraints (Koppel et al., 2021). The journey towards increased shared mobility, being one of the enablers for a more sustainable traffic situation, is a collaborative task by all involved stakeholders. The car manufacturers, as well as the child seat manufacturers and the users, in addition to rulemaking and organizations influencing the design of the different parts, such as consumer information testing, need to work together and be aligned towards the common goal of sustainable and safe transportation.

The trend in recent booster developments is likely a result of lack of cooperative efforts between the involved stakeholders. Obviously, the booster regulation methods are done with the best intentions for the children. However, there seems to be a lack of understanding of the larger context, such as the environment in which the child will be using the booster. When used, the booster is always positioned in a passenger car seat. A car seat is designed to protect car passengers. The vehicle safety systems, e.g., the seatbelt, the vehicle interior and airbags, will help protect the booster-seated child as well. Hence the booster's main purpose is to complement with the child specific needs, i.e., being an adapter to raise the child in position for the seatbelt. From the user's perspective, different types of boosters, complementing each other, are needed to benefit overall protection of children in vehicles.

Real-world crash data includes data over many years, although not the most recent years. During these years, the basic booster designs, are included and many of the vehicles are likely without advanced seatbelt technology and ICs. Regardless of this, the real-world data clearly shows that booster-seated children are well protected. For the booster design, it is essential that we acknowledge the real-world evidence and experience and adhere to the protection principles. The protective performance of a well-designed booster cushion is proven, and there is evidence that booster cushions, as well as integrated boosters, increase usage especially among the older child age group. Adapting these to the protection needs of children aged 4 to 10-12 and making them portable, focusing size and weight still adhering the protection principles, will help keep children safe in the increased trend of shared mobility. By going back to the fundamentals and learnings from the past, we should align towards a common goal of sustainable and safe transportation for children aged 4 to 10-12.

CONCLUSIONS

There is a mismatch between booster development and assessment, and the needs for child passenger protection in current and future vehicles. Driven by sustainability goals, passenger cars' design and ownership setups are changing requiring practical solutions for child passenger protection. At the same time the boosters are becoming larger and more complex, including a ban of booster cushions. While passenger cars encompass more advanced safety systems, the boosters are assessed using test rig methods without resemblance of these characteristics, nor consideration of the large range of sitting postures in the real-world context. Real-world child passenger safety involves an understanding that the booster is an adapter and not a restraint. Most importantly, irrespectively of passenger cars' design and ownership setups, the booster should be used in every trip.

Real-world child passenger protection is achieved by the vehicle and booster together. Children benefit from the vehicle safety systems, given they are raised in a position for good beltfit: over the pelvis and across the chest and shoulder. This is exemplified by vehicle's head protection of the forward leaning child in side-impacts, and pretensioner reducing seatbelt slack when wearing bulky clothes. Hence, the design of boosters should focus the necessary elevation of the child to achieve a good initial beltfit and maintain a good seatbelt interaction during the whole crash.

This study urges all stakeholders to be aligned towards a common goal of sustainable and safe transportation for booster-seated children, typically aged 4 to 10-12. The way forward is to focus on the essential protection principles and always consider the real-world context, which includes the vehicle, the booster, and the user as an entity, and to use this as the foundation for all tests, assessments, and communication. This joint effort is an essential part to help maintain, and potentially even enhance, current real-world protection level of booster-seated children into future transportation.

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