A Safety Framework for the Evolution of Boosters: Current and Future Mobility

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INTRODUCTION

Child occupant protection research remains critical for industry, academia, government and safety advocacy organizations. While reductions in fatalities and serious injuries in high-income countries have been achieved, motor vehicle crashes remain a leading cause of death and disability for children and adolescents and as a result, represent a public health priority (Kahane, 2016). A challenge exists to achieve further reductions in crash-related fatalities and injuries for these occupants as the problems are more nuanced – beyond just getting occupants in restraints – and the solutions require multi-faceted approaches as the context of mobility continues to evolve.

There is a tremendous amount of attention on future mobility states – the business and lay press portrays a future era of autonomous driving where vehicle occupants can be engaged in a range of tasks as the vehicle drives itself. There has been little consideration for how these new mobility scenarios will affect child and adolescent occupants. Further, in the more near-term, changes are already happening as car sharing and ride sharing ('shared mobility') are increasing in most countries worldwide, meaning that children and adolescents are more often travelling in a vehicle that is not owned by the family. Specifically, 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).

As we look to the future, our field is faced with the challenge of ensuring restraint usage and optimizing protection for pediatric occupants in both shared mobility and personal mobility. Future designs must address issues of usability, portability, and acceptance. The use of taxi services, car-pool systems, and other car sharing, such as remote activation of borrowing a friend's car without planning, are examples of not using the same car every day. It is possible that restraint designs for children and adolescents may face new or different priorities when used in car/ride share or future "driverless" vehicles than in current traditional seating. These potential differences pose challenges in ensuring that these occupants are safe and that regulatory or consumer information programs adequately evaluate protection across a range of real-life scenarios.

To facilitate international coordination and sharing of knowledge around this topic, the seventh biennial workshop on Child Occupant Protection was convened in September 2022, bringing together international leaders in the fields of child occupant protection, human factors, biomechanics, and auto safety. Summaries of previous workshops were presented at earlier Protection of Children of Cars Conferences. The following describes the recommendations that emanated from the 2022 meeting.

PROCESS

A two-day workshop was held focused on the following theme:

- What strategies are necessary to further reduce the burden of motor vehicles crash deaths and injuries for children and adolescents?
- How to guide future restraint development to help protect children/adolescents in shared mobility and other future mobility scenarios while still ensuring protection in more traditional riding scenarios?

We chose to focus on children who use boosters as they present unique considerations in that their protection is derived both from an add-on restraint and the vehicle restraint system.

The second day of the workshop was dedicated to a future-oriented perspective; identifying particular challenges facing our society to continue to improve the safety of children in cars. Through the discussion on day one, we identified three critical questions for the protection of children who use boosters and stimulated discussion of potential solutions, including new areas of research, needed collaborations, and new audiences. The following questions were posed to the attendees:

- What are the test methods and assessment criteria for booster evaluation given the tools we have, that are relevant for real world conditions?
- How do we influence and inform: a) consumer information programs/regulation and b) consumers' demand for safety?
- What types of multi-disciplinary research activities are needed to advance the safety of children, youth and young adult passengers as we move into this new era?

The discussion focused on exploring these questions both for personal mobility use cases and shared mobility use cases.

This workshop included 17 individuals from diverse organizations and scientific disciplines from around the world (a complete list of attendees is contained in the Appendix):

- Behavioral scientists
- Biomechanists
- Human factors including psychology and industrial engineering
- Epidemiologists
- Government researchers
- Auto safety researchers
- Restraint suppliers
- Vehicle manufacturers
- Child restraint manufacturers
- Test centers and rating institutions

The discussion of the workshop attendees is summarized below.

DISCUSSION

In line with the United Nations' Sustainable Development Goals (SDGs) (United Nations, 2016), four characteristics emerged as priorities for future booster design to optimally protect young school age children: safe, accessible, affordable, and sustainable. These guiding principles can serve as a framework for the evolution of this restraint type.

Safety:

The key safety concept that emerged from the discussion was the need to message that a booster is an adapter not a restraint. This messaging has relevance for a range of stakeholders – from consumers/parents to vehicle and restraint manufacturers to regulatory and consumer information programs. It influences how consumers use the device and more importantly how the occupant protection environment is designed and evaluated for children of the size that use boosters.

In the vein that the booster is simply adapting the vehicle restraint system, appropriate occupant protection for those in boosters can be achieved by adhering to optimal protection principles. First, an early and tight coupling of the restraint to the pelvic bones is needed and it must be maintained throughout the whole crash event (Adomeit 1975; 1977). To facilitate this, the booster raises the child to adapt the lap belt so that it is well-positioned on the pelvis. The guiding loops of the booster provide a belt path so that the booster itself is restrained to the vehicle during the crash, but they also guide the lap belt's position to ensure contact with the boney parts of the pelvis and prevent placement too far forward on the thigh or too high on the abdomen. Further, the raised position of the occupant helps to keep the shoulder belt over the mid-clavicle. Early coupling of the pelvis is also needed to initiate torso pitch, a critical element of good restraint (Kent and Forman 2015; Adomeit 1975). Combined with the shoulder belt positioned on the clavicle, early pelvis engagement achieves a controlled forward torso and head movement. Lastly, 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 (Forman et al. 2022; Tylko et al. 2012).

By adapting the vehicle environment to better fit children, boosters offer the opportunity to improve child posture, keeping the child in a good position for the best protection in a crash. Children adopt a variety of postures when traveling in vehicles (Charlton et al. 2010; Osvalder et al. 2013) and some booster design characteristics may influence a child's posture in a manner that could negatively influence injury risk. An observational study of children traveling in vehicles found that children seated in boosters with large side wings tend to lean forward (Andersson et al. 2010); such a forward head position may increase head excursion in frontal crashes (Maheshwari et al. 2020a, Maheshwari et al. 2020b) or negate the energy absorbing benefit of the side wing design in side impact crashes if the head is positioned outside the wing. Another key characteristic of boosters is that they effectively shorten the seat cushion length, which allows children to bend their legs comfortably over the seat edge. Jones et al. (2020) observed how child volunteers position themselves in boosters in a lab setting and found a relationship between boost height and pelvis position, with lower boost heights resulting in a more forward pelvis position and a posture more indicative of slouching. Lower boost heights may not adequately shorten the effective seat cushion length, requiring a child to position their pelvis more forward to achieve a comfortable bend of the knee at the seat edge. In computational modeling studies, slouching postures in boosters have been shown to increase the likelihood of submarining (Forman et. al. 2022; Slusher et al. 2022) highlighting the importance of booster designs that promote good posture.

Critical to spurring innovation in boosters is the need to use appropriate tools and define the correct metrics to evaluate performance. There are currently two families of child ATDs used to evaluate child restraints and boosters, the Hybrid III and Q series, and each has aspects of their response that are distinctive from the other. These differences in ATD motion are particularly noticeable when the ATD is placed in a booster and installed in vehicles undergoing crash tests. Distinct from child restraints that contain an integral harness to restrain the motion of the ATD, the vehicle seatbelt restrains the ATD when it is placed in a booster. Interpretation of differences in responses in the absence of an understanding of the ATD limitations can contribute to conflicting safety countermeasures. To explore more comprehensively "reality space", sled tests used to evaluate booster performance should at a minimum include different ATDs and a range of seatbelt geometries that are representative of the rear seats in passenger vehicles. The seatbelts used in such tests should also reflect the characteristics of contemporary seatbelt technology - for example, including a realistic retractor. Furthermore, development of relevant metrics should focus on the fulfillment of basic protection principles described above. One step could be to further develop kinematic criteria. For example, it is not sufficient to evaluate pelvis restraint performance by quantifying the presence or absence of submarining, but it is also important to kinematically assess early restraint engagement and coupling of the pelvis.

Consistent with the concept of a booster as an adapter rather than a stand-alone restraint, it is important the environment for testing reflects that boosters are part of a system that includes the vehicle environment. Industry, regulatory and consumer information program stakeholders should engage in a discussion how best to accomplish this. The multi-factorial combination of numerous booster designs in a wide range of vehicles makes this a challenging concept to consider. Vehicles should not limit their assessment of booster-age child occupant protection to only the "best" boosters, and booster manufacturers cannot shoulder the burden of evaluating their product in all vehicle combinations. The current regulatory method of using a generic bench seat for booster evaluation however likely does not optimize protection as well as it should. Further, due to limitations in the current tools themselves, the real-life performance of the boosters may not always be robustly assessed in laboratories by the ATDs. One example is the limitation of current ATDs to mimic child postures. As described above, if the booster is too long or too low it may cause the child (but not the ATD) to slouch, causing the pelvis to rotate rearward and move forward to allow the knees to bend comfortably. These changes in posture may increase the risk of submarining. Virtual assessment using pediatric human body models may be able to better capture real life parameters and add information to the assessment of boosters.

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. The rear seats of vehicles are constantly improving. Therefore, there is a need to investigate how booster certification/rating test configurations can be further developed, to improve the representation of modern vehicles. The booster is just a part of the real-world protection of the child; the vehicle interior and the seat belt are just as important. To capture the full protective effect of the booster, the context should be as realistic as possible.

As we look towards future mobility, the automotive industry has imagined a range of future seating configurations that include orientations of the vehicle seat angled away from the vehicle's primary direction of motion and reclined seat backs that promote a range of occupant activities while autonomous features of the vehicle assume more of the driving responsibility. The booster "adapter" must be evaluated in the range of environments in which we envision its use. Too much of the focus of evaluating vehicle restraint performance in these new seating configurations has been on protection of adult occupants. Particularly for children in boosters who also rely on the vehicle to provide restraint, robust assessment programs of occupant safety are needed.

While most of the discussion centered around engineering evolution of boosters (e.g., advancement of designs and test methods), the workshop attendees acknowledged that it is critical to also include the user perspective on the booster as an "adapter". As a safety community, we need to ensure parents are educated on what a booster does. Consumer misunderstanding of the role of a booster – e.g., considering it as a restraint and not as an adapter – may be driving 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 – where the device itself is almost exclusively responsible for the occupant protection. We need to reorient 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 (see below).

Accessible:

We chose to focus the discussion around accessibility on the concept of shared mobility. Over the past decade, shared mobility services have grown in popularity as a family transportation option (Ehsani et al. 2021; Koppel et al. 2021). This trend has implications for child occupant safety (Owens et al. 2021). For example, although child restraint use is high in private motor vehicles in high-income countries, child restraint use is substantially lower in shared mobility services such as taxis, rideshare vehicles and carpooling (Koffsky et al. 2018; Koppel et al. 2021; McDonald et al. 2018; Owens et al. 2021; Prince et al. 2019). Indeed, Owens and colleagues (2021) recently noted that 59 percent of parents in the United States reported they restrained their children aged five years and younger 'differently' when travelling in a rideshare vehicle, including holding the child on their lap (37%) or letting their child travel without an appropriate child restraint (25%). Parents were most likely to report that they did not use a child restraint while travelling in a rideshare vehicle because: there was no restraint in the rideshare vehicle, they did not have a child restraint with them, or the trip was a 'short distance'. Similar trends have been reported in Australia (Koppel et al. 2021).

One potential explanation for the lower rates of appropriate child restraint use in shared mobility services could be related to the inconsistencies in child restraint requirements for different travel modes across states/territories. For example, in Australia, several states and one territory allow rideshare vehicles to be exempt from the national child restraint requirements, while other states and territories, for the most part, allow taxis to be exempt from these requirements (for a review, see Koppel et al. 2021). There are similar inconsistencies within the United States (IIHS, 2020). Efforts need to be undertaken to ensure these loopholes are closed.

The trend of changing from the habit of using one vehicle from start to destination, to the flexible use of several different vehicles, in addition to the potential change of transportation modes within one trip or during the day, is a challenging task when addressing the restraint needs of families. Rather than simply trying to educate parents to use a booster on every trip, regardless of shared or personal mobility, we need to consider booster design and infrastructure that makes the right booster accessible when the family needs it. This evolution forces the development of new child restraint solutions that help ensure the use of a booster on every stage of a trip. Relevant questions that should guide design are: how to ensure the whole system is in place when using the vehicle? can the booster be transported? Or, could there be one available when reaching the vehicle? Together, we need to engage in user-centered design to develop solutions (both restraints themselves and infrastructure to deliver restraints to users) that meet these needs of portability while maintaining alignment with the protection principles described above.

Affordable:

A critical partner to accessibility is affordability, particularly as booster use is considered around the world. As booster users are at that transition between an add-on harness-based restraint and use of the vehicle restraint alone (e.g., no additional cost), there is a push to move quickly or earlier than necessary through this phase. The workshop attendees discussed two main concepts around affordability that our field should prioritize.

First, providing engineeringly simple solutions by limiting features that do not drive safety will benefit consumers through ease of use and reduced misuse. When a product is over-engineered, consumers turn away from it seeking more straightforward solutions that fit their lives. In the case of boosters, over-engineering will result in children having a net negative from a public health perspective. While some may be able to afford the booster with the luxury (but not safety driving) features, overall fewer families may choose boosters for children and rely on the vehicle restraint only. These disparities in booster use have been well documented (Brixey et al. 2011; Ghetti et al. 2022; Moore et al. 2019). Efforts should be placed on ensuring that there are boosters that perform well across the price range.

Second, we discussed the role that the booster cushion plays in affordability. As a simpler restraint, the booster cushion is often quite affordable and a desired option for children at the upper end of the booster age range and in shared mobility scenarios. However, due to requirements driven by side impact testing in regulation and consumer information programs (see below), these restraints are incorrectly perceived to be less safe as their performance as part of the vehicle-booster system is not robustly evaluated. As a result, some regions are banning booster cushions and promoting boosters with several features adding weight and complexity, which may counter overall real-world protection. Due to the value booster cushions provide from an affordability and consumer choice perspective, we need to ensure that regulations and consumer testing programs do not intentionally or inadvertently drive them out of the market.

Sustainable:

Sustainability goals in city planning – and the overall "live small" movement (Kang et al. 2021) – further contribute to changes in mobility trends. Families may choose not to own vehicles or child restraints – practically resulting in an increase in the number of transportation modes during one trip; e.g. using cars for only part of the trip in concert with other public transportation modes. These changes pose challenges for occupant protection in relation to the traditional way of car ownership/usage (see discussion above regarding accessibility). However, not all families are attracted to these more sustainable modes of transportation. A study of early adopters of car sharing services in Berlin indicated that car sharing was attractive to people when not taking care of children (Kawgan-Kagan, 2015). In a travel survey, it was found that households with children, especially in low- and mid-income households, were less likely to use car sharing and ride-sourcing mobility, compared to other households (Dias et al. 2017). Hence, there is a need to further understand why the use of shared mobility is lagging for households with children and how to address their needs to promote a more sustainable transportation system. Different economic models for obtaining child restraints and boosters may be necessary as families choose a more minimalist approach.

Sustainability goals are also leading to vehicles becoming more streamlined resulting in reductions in space between the outboard rear seat passenger's head and the vehicle side. Although an adult might fit well, as well as child using a booster cushion, this might not be the case for a large booster (with a back) due to its large head side wings. In the event of a side-impact on the near side, the child on the booster cushion will benefit from protection from the Inflatable Curtain (IC), as the adult. However, the ability of the IC to function correctly may be impacted if the large head side support of the booster is in the way. The reasons behind the development of the extensive side supports are partly clear. Backrests with forward protruding head side supports were introduced around 2000 and were driven by an ambition to help protect the child's head in side impact (Bendjellal et al. 2011). During the same period, cars were starting to be equipped with IC. A decade later, the side supports of the booster have increased in width, mainly driven by introduction of booster side impact tests using test rigs, with no vehicle-like head protection included. Isolated from the vehicle-context, it was perceived that a booster cushion was not capable alone to protect the child without large side supports as part of the booster. This perception spread widely, and similar test methods were included in regulatory updates. Unfortunately, there was a misconception that the booster 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. The workshop attendees noted that the booster cushion is of importance for modern streamlined vehicles due to its size. Unfortunately, this is not what the current booster trend includes (see above discussion about affordability). Considering these ergonomic aspects of how boosters fit in smaller vehicles and the impact on restraint performance is important.

Influence and communication of this framework:
Traditionally consumer information programs and their associated websites have been a natural way of finding child safety information for the consumer. These programs play an important role in how the design of boosters are driven and how consumers perceive the benefits of these restraints for their school-age children. It is important to have a transparent assessment protocol and associated injury metrics that reflect the safety principles discussed above so improvements can be achieved by the booster manufacturers. These protocols need to be regularly evaluated and improved as knowledge is gained through research. Furthermore, the basic protection principles of a booster (e.g., that it must boost and shorten the effective seat cushion length) should be considered in a ratings program, complementing other dynamic assessment and usability assessments.

It is also important to recognize that the sources of information available to and preferred by the consumer are changing. Today influencers, who may lack knowledge in safety principles, are an influential source of information for the consumer. These may be individuals who have influence on parents/families for another reason, who due to their individual family situation at a moment in time, suddenly are interested in child occupant protection. We as a safety community need to embrace this method of dissemination and support these influencers with accurate information, recognizing that this may be the most effective channel to reach consumers. Engaging public relations professionals to develop an improved communication strategy – that is delivering accurate information – is important.

CONCLUSIONS

For boosters, it is essential that we acknowledge the real-world evidence and experience and adhere to demonstrated protection principles. When used, the booster is always positioned in a vehicle seat which has its own design principles to protect vehicle passengers. The vehicle protection, e.g., the seatbelt, the vehicle interior and airbags, will help protect the booster-seated child as well. Hence the vehicle safety technologies are essential, and the booster's main purpose is to complement them with the child specific needs, i.e., to raise the child in position for the seatbelt.

The protective performance of a well-designed booster cushion is well established, and there is evidence that booster cushions, as well as integrated boosters, increase use especially among the older child age group. Adapting these to the protection needs of booster-seated children and making them portable, focusing on size and weight while still adhering to the protection principles, will help keep children safe.

The journey towards increased safe shared mobility, being an enabler for a more sustainable and accessible traffic scenario, is a collaborative task by all involved stakeholders. Vehicle manufacturers, as well as the booster manufacturers and the users, in addition to rulemaking and organizations influencing the design, such as consumer information testing, need to work together and be aligned towards the common goal of sustainable and safe transportation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge SAFER - Vehicle and Traffic Safety Centre at Chalmers and FFI (Strategic Vehicle Research and Innovation) by VINNOVA, the Swedish Transport Administration, the Swedish Energy Agency and the industrial partners in Sweden for providing financial support for the conduct of the workshop.

WORKSHOP ATTENDEES

Specific attendees of the workshop are listed below. All contributed greatly to the discussion at the workshop and the formation of the concepts described in this manuscript.

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