Compact Child Seat – a concept designed around the users

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Introduction

Next year, child safety in cars celebrates 50 years. In 1964, Professor Bertil Aldman presented a child seat prototype, the first of its kind addressing protection of children in cars (Aldman 1964). Inspired by the way astronauts were launched in space, he designed and crash tested a rearward facing child seat prototype, Figure 1a. A few years later, the seat came into production but it took almost a decade before other child seats addressing safety in cars were designed, then forward facing for the older children (Norin et al. 1979). Some of the rearward facing child seats during early 1970's accommodated children up to 6 years old, Figure 1b. Today, the largest rearward facing seats barely accommodate a mid-size 4 year-old and even if possible to fit, a reluctance of using these large rearward facing seats exist. Although most agree that rearward facing is the safest way of travelling in cars; a necessity for the smallest children and beneficial for children up to 3-4 years of age, issues regarding ease-of-use are raised as the main concern. Over the years, child seats for this age group have become more heavy and bulky in handling as well as when mounting in cars. Going back to the initial invention by Prof. Aldman; providing a shell for distributing the loads, a rigid attachment to the car and a harness to keep the child in the shell, the design of these seats might not necessarily be as complex as the modern rearward facing seats, from a protective perspective.

Figure 1a. The first child seat prototype (child harness removed) by Prof. Bertil Aldman in 1964 (Aldman, 1964). Crash tested in a Volvo PV444.

Figure 1b. Child seat from 1972 accommodating a 6 year-old child (source Volvo).

The objective of this study is to present a child seat concept to address and illustrate the issues for ease-of-use of a large rearward facing child seat. The child seat concept is put in a context of the needs of the children and parents from a holistic ease-of-use point of view, challenging and discussing the traditional choices in child seat design and material, with an ambition to eventually derive at both safe and increasingly user-friendly rearward facing seats for children up to 3-4 years.

Rearward facing pros and cons

The smallest children are optimally protected in a rearward facing seat, where the shell of the child seat provides the protection of the child's vulnerable neck and head both in frontal and side impact situations. Rearward facing child seats 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's. This tradition has shown to influence the safety of the youngest car passenger on a national level. As an example, when looking into national child car passenger fatalities comparing Germany and Sweden, differences are seen, Figure 2. The peak of 1 year old children in Germany is not seen in the Swedish data. It is likely that this peak is influenced by the tradition in Germany of changing from rearward facing to forward facing at this age, while this move takes place later in Sweden, i.e. at an age of 2 to 4 years old (Lesire et al. 2013, Carlsson et al. 2013).

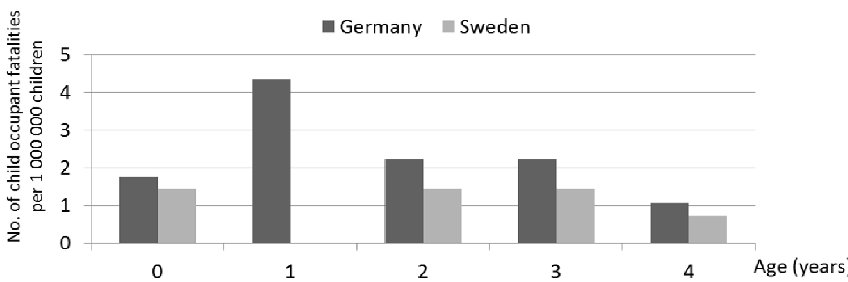

Figure 2. Normalised number of fatally injured 0–4 years old car passengers in Sweden and Germany during 2006–2011 (Lesire et al. 2013, Carlsson et al. 2013).

Evidence of the benefits of restraining children in rearward facing seats in comparison to forward-facing child restraints has been provided through crash tests as well as real world data. Tests performed in the 1970's using 3 and 6 year old sized crash test dummies showed that neck tension force was substantially reduced when rearward-facing compared to forward-facing (Turbell 1974). The risk of children (0–14 yo) being injured was shown statistically significantly lower for children in rearward-facing seats (1.3%) as compared to forward-facing child restraints (6.9%) in real world data by Tingvall (1987). A study based on data from Volvo Cars accident database in Sweden calculated an 80–90% effectiveness of rearward-facing child seats, compared to 30–60% for forward facing child restraints (Carlsson et al. 1991). Another study reviewing the same database revealed that children aged 2-4, when restrained in forward facing child restraints, were estimated to be at approximately double the risk of sustaining MAIS2+ injuries than when restrained in rearward facing seats (Jakobsson et al. 2005). In all the above studies, the forward facing child restraints were primarily of belt-positioning booster types, since forward-facing seats with an integrated child harness have not been endorsed in Sweden and are thus very rare.

In a study of children aged 0–23 months involved in crashes in 1988-2003 in the USA, it was found that children fastened in forward facing integrated child harness type seats were significantly more likely to be seriously injured in all crash types than children restrained in rearward facing seats (Henary et al. 2007). Categorised by crash type, odds ratios of 1.23 in frontal impacts and 5.53 in side impacts were seen, hence providing evidence of protection by the rearward facing seat in frontal as well as side impacts. Studies of real world cases highlight the importance of protection of the neck for the smallest children (Fuchs et al. 1989, Stalnaker 1993), recommending rearward facing seats for as long as possible, preferably until 3–4 years of age. Frontal sled test comparing rearward and forward facing child seats provided additional evidence that rearward facing seats can provide the greatest safety potential for children aged 1-3y, also highlighting the benefits of rigid ISOFIX connectors and support legs (Sherwood and Crandall 2007). The consumer information tests by Stiftung Warentest confirm this by twice or higher upper neck tension force for the toddler size dummies in forward facing seats as compared to rearward facing seats (Görlitz 2007).

To illustrate the differences, tests were run using a Q3 dummy in a vehicle sled buck simulating a severe frontal impact. Two state-of-the art child seats were selected from the EuroNCAP pick list; one forward facing seat attached using the ISOfix connectors and a top tether strap, and one rearward facing seat using the ISOfix connectors, a support leg and an anti-rotational bar towards the vehicle seat backrest, Figures 3a and 3b, respectively. It is obvious that that the forces are distributed over the back and head when rearward facing, while the head is restrained by the neck when forward facing (Figures 3a and b). When rearward facing, the upper neck tension force was below 500N, while in the forward facing it was more than six times higher, Figure 4. The upper neck shear forces and moments were of comparable relatively low magnitudes in both seats.

Figure 3a. Forward facing seat, initial position (left) and maximum forward excursion (right).

Figure 3b. Rearward facing seat, initial position (left) and maximum forward excursion (right).

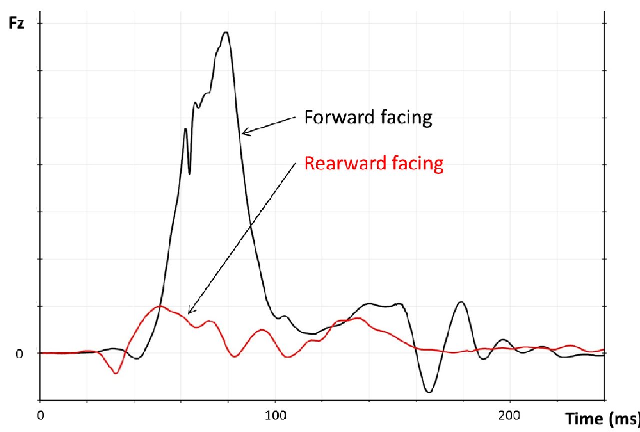

Figure 4. Upper neck tension force measured in a Q3 dummy, comparing forward facing and rearward facing seats during a severe frontal impact.

Real world data, biomechanical facts (Burdi et al. 1968, Tarriere 1994) and experience from dynamic tests clearly show that rearward facing is the safest for babies and toddlers. Over recent years, this has been more globally acknowledged, examplified by the change in US car seat recommendation for children in 2011 and the enforcements in ECE R129 resulting in no forward facing seats for children less than 15 months. Although, a reluctance of using large rearward facing seats up to 3-4 years age exists. Stiftung Warentest summarizes the main cons being that they are heavy, bulky and difficult to install (Görlitz, 2007). Also, concerns are raised that the principal advantages of travelling rearward facing is not recognized by many parents. The main stated reason for turning forward facing, even in countries like Sweden with a high awareness, is lack of space, especially for the legs. Other reasons relate to car sickness, the reduced direct contact when the child is seated in the rear seat as well as motives such as "the child wants to travel forward facing".

Hence, the main target for the child seat concept in this study was to address the cons of rearward facing, especially targeting the weight, ease of installation and roominess as well as size when not in use, to make rearward facing a desired choice even for toddlers.

The Compact Child Seat

The rearward facing child seat concept, called Compact Child Seat (CCS) is based on innovative technology offering the users improved usability and convenience without compromising safety, Figures 5a and b. The CCS accommodates children of up to approximately 100cm in stature. The design provides comfortable seating position allowing for good leg space, Figure 5c. The vehicle attachment system are optimized with respect to a safe, user friendly and compact solution, designed based on the load paths during a crash. The crash performance is evaluated in vehicle crash testing. The Compact Child Seat includes quick mounting and demounting for a compact storage whilst securing constant performance during usage. When demounted, the CCS is the size of a small sports bag and when mounted it accommodates up to a 3-4 year old child rearward facing in the car. Using this innovative technology including attachment principles and air-pump unit, the total weight of the child seat can be kept around 5kg.

Figure 5a. The Compact Child Seat (CCS).

Figure 5b. CCS mounted in a passenger car with a Q3 dummy.

Figure 5c. The leg space area for a Q3 dummy in the CCS.

Design

The child seat is an assembly of multiple air chambers, Figure 6a. Hollow plastic grommets in adjoining chambers connect to form a contiguous inflatable volume which requires only a single port for inflation and deflation. The material used is drop-stitch technology, Figure 6b. Each chamber is either an air bladder or fabricated from drop-stitch fabric which consists of two flexible non-permeable surfaces spanned by a plurality of stitches of fixed length. The stitching maintains a constant separation between the surfaces when inflated, resulting in an inflatable chamber with flat surfaces that do not curve outward.

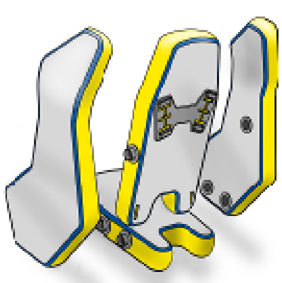

Figure 6a. Illustration of the principle design of the chambers.

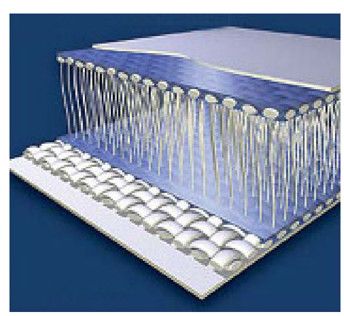

Figure 6b. Basic drop-stitch structural configuration.

The history of the drop-stitch technology began in the 1950's when NASA and US Air Force conducted considerable research to use it for aerospace applications, resulting in several inflatable aircrafts built by e.g. the Goodyear Corporation, followed by development of boats in the 1970's by e.g. the US Navy (Bagnall 2011). Examples of products using this material are fishing kayaks, stand-up paddle boats, surf boards and even rigid inflatable bottom boats (RIBB) of over 5m length.

The inflation and deflation of the seat, in this concept, is done through a built-in air-pump with pressure regulator. This unit is to be mounted under the seat cushion and requires approximately 40 seconds for inflation and somewhat less for deflation. Aiming for good size-efficiency ratio and low noise during activation, it is based on a pump from marine industry applications, using mass-production friendly solutions and material. For optimal usability, the air-pump is run with a built-in battery. The pressure guard secures that the child seat always is in the desired pressure, irrespectively of external pressure conditions. Additionally, information on the air-pump activation and/or air pressure can be transmitted into the vehicle / phone interface. Hence, the users can always be certain that the child seat status will be in accordance with specification.

Attachments

When developing the attachment principles of this concept child seat, the ambition was to find the most optimal restraint based on real world safety and usability. A series of crash tests were run evaluating different principle solutions and the most optimal was found to be mounted with straps around the child seat attached to the ISOfix anchorages for the primary restraint in frontal impacts (Figure 7a) and additional straps to the floor as the primary restraint in rear end impacts and during the rebound phase in frontal impacts, Figure 7b. As a complement for the straps to the ISOfix anchorages, support towards the front seat backrest (or dashboard if mounted in the front seat) is needed for severe frontal impacts. This support could also be achieved by a support leg, however it would then add weight, complexity in usability and size when demounted. In order to secure the forward support, an additional strap to be positioned around the front seat head restraint is included in the attachments of the concept child seat, Figure 7c.

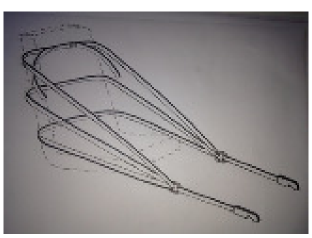

Figure 7a. Schematic restraint principles of straps around the child seat.

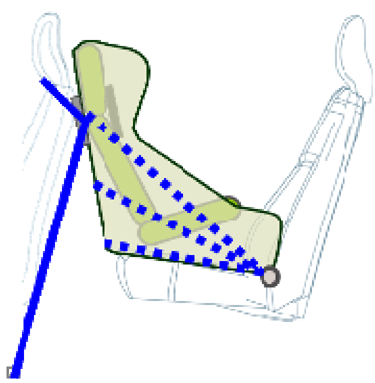

Figure 7b. Schematic restraint principles of concept CCS.

Figure 7c. Strap positioned around the front seat head restraint to secure support against the front seat.

The main principles of the CCS attachments are in line with what was first proposed by Claeson (2001), with the purpose of restraining the child seat by straps attached to the ISOfix anchorages working in tensile forces. The main benefit for the CCS is that the child seat is restrained encompassing the child, minimizing bending torques and connections to the seat structure posing potential points of failure during a crash. Since the load transfer is mainly in tension, a lightweight and optimal load transfer can be achieved. A backplate is placed on the backrest of the CCS providing attachment for the child shoulder harness and the floor straps. The child is secured by a five point harness in the child seat as shown in Figures 5a-b. The shoulder harnesses are routed through the child seat backrest around the back plate providing strength and distributed support. The lap belt portion is routed around the child seat cushion. For optimal safety, a buckle providing sound or transmitting information to the vehicle / phone interphase when unbuckled can be used.

The CCS prototype has been crash tested in a vehicle sled buck in frontal and rear end impact situations. The HIII 3yo crash test dummy was well contained and restrained during the tests and the measurements were well below injury assessment reference values. Figures 8a-b show the high severity frontal impact.

Figure 8a. Frontal impact, initial position. N.B. The seat is an early prototype with slightly different shape. The support leg is not in use in this test.

Figure 8b. Frontal impact, maximum forward excursion.

Discussion

Nowadays, most child safety experts agree that rearward facing mode is the safest alternative for infants and provide essential protection to toddlers up to 3-4 years. The arguments against rearward facing for this group are not due to safety but due to ease of use, lack of space and other comfort and ease of use usability related aspects. This study presents a child seat concept addressing some of the major complaints, such as weight, bulky to bring along, transport and store, difficult to install and comfort issues for the child.

The CCS accommodates children of up to 3-4 year of age. This is the age group of children who requires the largest and usually most complex and heavy child restraint in order to travel safely in cars. Children older than this can use the vehicle safety belt and benefit from the vehicle protection systems when using a booster cushion to raise them in position (Norin et al. 1979). Some vehicles even provide built-in boosters for children aged 4 and above (Jakobsson et al. 2007). Hence, the most important and challenging group of children are the toddlers, ranging from when they outgrow the infant seat, until they reach size suitable for using boosters. This is the reason CCS focuses this age group, providing comfort, ease of use and optimal protection.

A high spec rearward facing child seat on the market today can weigh as much as 15kg. This is a result of the material and design chosen and a continuous product development striving towards improved protection and functionality. In order to reduce weight, innovative materials, design and attachment principles are needed. An important feature of the CCS is that the crash forces are not primarily transported through the material of the child seat shell, but routed around the child and the child seat. Hence, the primary function of the child seat shell of the CCS is to contain the child and provide an even and balanced support of the child in frontal, oblique and side impacts. The homogenous material as proposed in this study is thus excellent for providing these containment properties. However other light-weight material could be used as well, if only weight is addressed.

The main benefit of the drop-stitch material is that it makes the CCS easy to adapt to the usage. When not in use, the child seat is deflated and folded together into a small size unit, easy to carry and store. When in use, the child seat is filled with air and will then serve as a full-size rearward facing child seat. The drop-stitch material has been proven durable and resistant during many years of application in different areas such as kayaks and RIBB boats design. The drop-stitch material is not to be mixed up with simple types of inflatable material such as those used in simple bath toys. The properties of parallel panels with flat surfaces enabled by the "stitching" ensure constant size and durability, which is of high importance even if the main forces are not transferred directly through the inflatable material. The functionality of inflation and deflation is positive when addressing the bulky aspects of a child seat, hence having positive effect on ease of use.

From a regulatory point of view, this concept seat stumbles on several points. Using innovative material as well as attachment principles, certification of the CCS could be difficult. This raises some interesting questions about the role of regulations when it comes to the further development of effective and usable child restraints. As an example, the ECER44 regulation specifies 'The child restraints incorporating inflatable elements shall be so designed that the conditions of use (pressure, temperature, humidity) have no influence on their ability to comply with the requirements of this'. From the general practice of regulation purpose, providing guidance on functionality and performance rather than choice of material this is stunning, since there are other possible materials being pressure, temperature and humidity sensitive that will not be affected by the wordings but still can pose the same potential hazard in a real world situation. Also, for this specific child seat concept, constant pressure is ensured by built-in technology and continuous feedback is provided to the driver comparable to integrated driver/vehicle systems such as airbag monitoring systems. Hence, improvements and change of mindset is urged for, enabling new technologies to be developed with the ambition to improve safety, which ought to be in line with the ambition of the regulation. For the prototype CCS, additional crash tests were run with the seat deflated to evaluate the performance and functionality. The dummy measurements fulfilled the requirements and the overall performances were positive in the frontal and rear-end impact situations. This was due to the attachments which restrained the child irrespectively the quality of the material of the child seat shell. However, in real world situations, the overall performance especially in oblique impact situations is likely to be reduced when deflated. This is, however, not verified in regulatory testing emphasizing the need of a critical review of the regulatory text.

The child seat attachment is another aspect where regulations set restrictions to innovative design. The CCS was developed based on optimal real world safety performance in combination with ease of use and compactness. When comparing the proposed attachment principles to existing regulations it will not easily meet any of the child seat regulations globally, since they are more design restrictive than performance focused. In relation to FMVSS213, the forward support from the front seat (or dashboard) is missing as well as the possibility of attaching the straps to the floor. The forward support is an issue also in relation to ECE R44 as well as the challenge of designing the ISOfix connectors rigid to the seat, without risking generating a load path through the child seat shell. This study contributes to question whether the regulations are based on best practice from a real world safety perspective and urges for a discussion and change in regulation adapting more towards real world vehicle situations rather than a test rig testing.

Being a major issue of rearward facing comfort, a special focus was put on addressing the area for the child's feet and legs. The design of the CCS provides comfortable seating position allowing for good leg space, enabled by the side structure of the seat being more pronounced than the seat cushion part, Figure 5c. These pronounced side structures also serve as a part of the seat retention (together with the floor straps) in a rear end impact and during the rebound phase of a frontal impact.

CCS addresses child comfort as well as adult user aspects such as weight, ease of installation and size when not in use. This covers a large portion of the perceived cons of rearward facing seats, and the anticipation is to contribute to making the safer rearward facing seat the desired choice for the users. Reasons not directly addressed by the design of the CCS are potential car sickness aspects, easy contact to driver when placed in the rear seat, as well as the cases were "the child wants to travel forward facing". Addressing the latter is a combination of helping the parent with motivations for making the safest choice in combination with providing safe entertainment alternatives for the child and providing communication devices, such as mirrors, which will also contribute to reducing distraction effects for the driver. The mirrors, which are easily available today, are the primary device addressing the child versus driver communication.

For optimal real world safety, children less than 3-4 years should be facing rearward. Taking usability and comfort aspects into account, this is not always in line with the traditional and highly regulated child seat design. This study provides arguments and solution addressing this as well as questions existing regulatory text and practice. By presenting this child seat concept, providing a light-weight, easy to carry and install, store and bring-along rearward facing child seat solution for vehicles, without compromising safety, we invite for a discussion on alternative directions of future rearward facing seats for the children up to 3-4 years. The child seat concept is put in a context of the needs of the children and parents from a holistic ease-of-use point of view, challenging and discussing the traditional choices in child seat design and material, with an ambition to eventually derive at both safe and increasingly user-friendly rearward facing seats for the children up to 3-4 years.

Conclusions

In analogy with Professor Aldman's research 50 years ago, this child seat concept, CCS, is developed based on the protection needs of children up to 3-4 years. The working method behind the child seat concept includes the needs of the users (both children and parents) from a holistic ease-of-use point of view. Some of the design aspects are not in line with the traditional and highly regulated child seat design, which this study urge to challenge. This relates both to the material used in the seat as well as the principles of design and attachments. By presenting this child seat concept, providing a light-weight, easy to carry and install, store and bring-along rearward facing child seat solution for vehicles, without compromising safety, we invite for a discussion on alternative directions of future rearward facing seats for the children up to 3-4 years.

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