ANALYSIS OF CHILD RESPONSES IN CRS USING CHILD HUMAN FE MODEL

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ABSTRACT

To investigate injuries to various body regions of a child in detail using a child restraint system (CRS), a finite element (FE) model of a 3-year-old child has been developed. Using this child FE model and Hybrid III FE model, the ECE R44 sled impact test simulations were conducted for three different types of CRS such as a 5-point harness, an impact shield and an ISOFIX CRS. For the child FE model, the whole spine flexed, whereas for the Hybrid III with stiff thorax spine, only the cervical spine and the lumbar spine flexed. As a result, in the 5-point harness CRS, the head down movement and its rotation were large for the child human FE model. The injury criteria of Hybrid III and child FE model were comparable in these CRS applications. In the impact shield CRS, the chest deflection was large. The head excursion was particularly small for the ISOFIX CRS.

The influence of belt slack of CRS on injury criteria was also examined from FE analyses. There was a relation between the ridedown efficiency and the chest acceleration. A slack seatbelt and harness in the 5-point harness CRS increased the injury risk. On the other hand, the injury criteria in the impact shield CRS with and without the seatbelt slack were comparable, which explains the low injury risks for children using the impact shield CRS in accidents.

INTRODUCTION

Accident data have demonstrated that a child restraint system (CRS) is effective for preventing injuries to children [1,2]. There are a variety of forward-facing CRS types, including those with a 5-point harness, tray shield and T-shield. Many studies have examined the differences in behavior and injury criteria of child occupants under various restraints. Melvin and Weber, for example, have shown from sled tests of CRS that the behavior of a child dummy depends on the CRS types [3]. Langwieder et al. [4,5] investigated German accident data and found that the injury risks of children were lower in an impact shield CRS than in a 4/5-point harness CRS.

In the JNCAP (Japan New Car Assessment Program), there are CRS dynamic tests, and forward facing CRS has been tested using three-year-old (3YO) Hybrid III. According to the number of units sold, CRSs are selected and subjected to a dynamic sled test using a minivan frame body [6]. In the JNCAP test, the injury criteria of Hybrid III in the 5-point harness CRS are inclined to be lower than those in the impact shield CRS with small chest deflection and low abdominal pressures. However, these results are inconsistent with the accident analysis by Langwieder et al. [4,5].

In CRS impact tests, crash dummies such as Hybrid III 3YO, TNO P3 and Q3 are widely used. Injury criteria are recorded by these dummies and CRS safety performance is evaluated. However, there are some differences in anatomical structure and mechanical properties between the human body and crash dummies. These differences can affect the responses of the child in CRS during impacts. Thus, to examine the behavior and injuries to a child by CRS types in detail, the dummy test results might be insufficient, especially for evaluating different types of CRS.

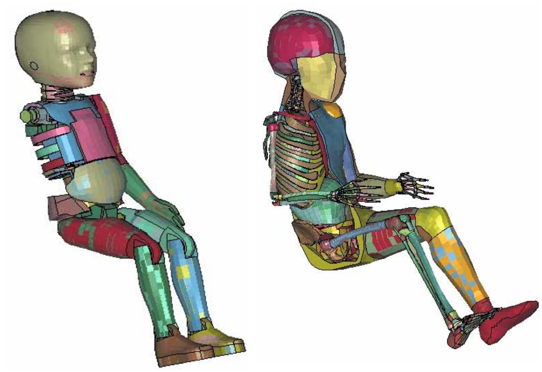
Many human finite element (FE) models of adults have been developed, and applied to the investigation of human responses in crash environments. Using these models, injury risks can be evaluated from stress and strain distributions, which cannot be measured in crash dummies. A child FE model will be useful when it is applied to evaluate the injury risk of a child using CRS. In the present research, a 3YO child FE model was used, which was developed by appropriate scaling of a THUMS (Total Human Model for Safety) AM50 (adult male 50 percentile) [7,8].

Many studies have demonstrated that the percentage of misuse is quite high in using CRS, and this misuse can limit the protective benefit of CRS [4,5,9]. There are several types of misuse in CRS. According to the CRS usage investigation by the JAF (Japan Automobile Federation) and the police in Japan, seatbelt slack (35%) and harness incorrect use (8.6%) were observed in investigated CRSs [10]. They also reported the CRS static displacement when a force of 100 N was applied in forward direction. The result was that 39.6% of CRS was relatively tight (within 30 mm), 40% was acceptable (30 to 100 mm) and 20.4% was loose (over 100 mm) installed on the car seat. An ISOFIX CRS is effective for the reduction of the frequency of incorrect attachment of CRS to the car seat. Several studies have demonstrated that the injury criteria for an occupant in the ISOFIX are smaller than or comparable with those in the conventional CRS [11,12]. In the present study, the child occupant responses in 5-point harness, the impact shield and ISOFIX CRS during impact were examined using Hybrid III and child FE model. For the 5-point harness CRS and the impact shield CRS, the influences of belt slack on the injury criteria were also examined.

METHODOLOGY

A 3YO child human finite element (FE) model has been developed by the authors for investigating injuries to children in impacts [13,14]. Taking the anthropometry and material properties of a 3YO child into account, the model was made by scaling from the adult human FE model THUMS (Total Human Model for Safety). The responses of this child human FE model were validated in various impact conditions, and they were included in the corridor of Hybrid III 3YO dummy certification tests. In the child FE model, the skull shape was modified and the pelvis model was developed with Y-cartilage to represent child anatomy [14].

A Hybrid III FE model provided by the First Technology Safety Systems (FTSS) was also used. The behavior and injury criteria were compared for various types of CRS using this child human FE model and Hybrid III 3YO FE model. Figure 1 shows the Hybrid III and child FE model.



(a) Hybrid III FE model (b) Child FE model

Figure 1. Hybrid III and child FE model.

In this study, three different types of CRS such as a 5-point harness, an impact shield and an ISOFIX CRS were analyzed. Figure 2 shows the child FE model in three types of CRS. Using the child and Hybrid III FE models, CRS sled tests based on the ECE R44 were simulated. An FE model of the ECE seat was created, and the CRS FE model was set in place on the ECE seat according to the ECE R44. The acceleration-time histories of the sled were included within the corridor of ECE R44, and the maximum acceleration was 25G with 50 km/h velocity change. Although the ECE R44 prescribes the use of a TNO P3 dummy, in the present study the Hybrid III 3YO was used because the Hybrid III 3YO has higher biofidelity.

For the 5-point harness CRS FE model, the CRS seat was modeled by shell elements, and the harness was modeled by membrane and seatbelt elements. In the impact shield CRS, the seat and shield made of styrene foam were modeled by solid elements. The material properties of these models were described in a previous study [13,14]. The ISOFIX CRS used in this study has a 5-point harness, a shell seat, a tether top and a base with two point ISOFIX attachments.

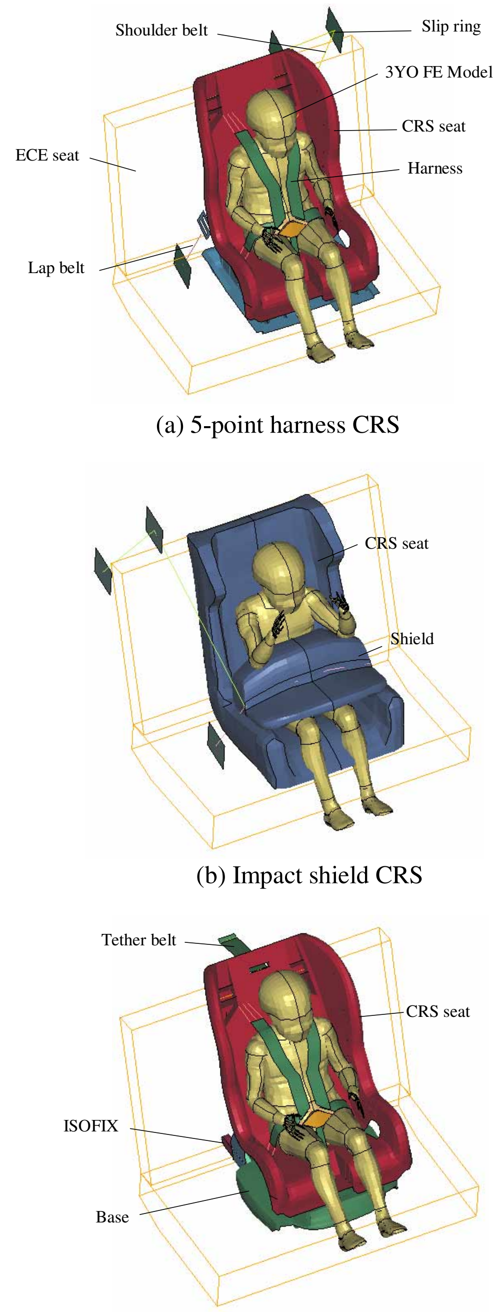
The sled tests were conducted using the Hybrid III 3YO for the 5-point harness, impact shield and ISOFIX CRS. Then, these sled tests were simulated using the Hybrid III FE model. By comparing the test and simulation results, the CRS FE models could be validated. The Hybrid III FE model also made it easier to understand the internal structural behavior of the Hybrid III model. Then, CRS sled simulations using the child FE model were conducted with validated CRS models, and the behavior was compared to that of the Hybrid III FE model. The stress distributions of the skeleton of the child FE model were also compared in three types of CRS. Injury criteria were examined for the Hybrid III and child FE model. The injury acceptance reference values (IARV) from the FMVSS 208 were used. The HIC15 is 570, the chest acceleration 539 m/s^2 and the chest deflection 34 mm. The head excursion of 550 mm was used from the ECE R44 since the ECE test setup was used.

In the FE simulation, two types of CRS misuse were examined. One was the loose installation of CRS by the vehicle seatbelt with slack. In the model, an initial seatbelt slack of 100 mm was added to a shoulder belt. The other error was the improper restraint of the child to the CRS. In this case, an initial slack of 100 mm was added to two shoulder harness straps of the CRS. Table 1 shows the matrix of the FE simulations. The seatbelt was modeled by the seatbelt elements, and the harnesses were modeled by the membrane with seatbelt elements in both ends. The initial slack was added as an option to the seatbelt elements.

During impact, occupant kinetic energy is absorbed by the restraint energy and the ridedown energy. It is known that ridedown efficiency decreases as the restraint energy increases with restraint delay due to seatbelt slack [15]. Thus, the effect of restraint slack on the injury criteria can be evaluated numerically using the ridedown efficiency. Ridedown efficiency (μ) is defined as the ratio of maximum ridedown energy to the initial occupant kinematic energy as follows:

$$\mu = \frac{\int_0^{t_1} ma\,dX}{mv_0^2/2} = \frac{2\int_0^{t_1} a\,dX}{v_0^2} \qquad (1)$$

where a is the occupant deceleration, X the vehicle displacement, m the occupant mass, v_0 the initial occupant velocity and t_1 is the time when the vehicle velocity is zero. In Eq. (1), the chest acceleration was used for the calculation.



(a) 5-point harness CRS

(b) Impact shield CRS

(c) ISOFIX CRS

Figure 2. Child human FE model with three types of CRS.

Table 1. FE simulation matrix

CRS	Model	Slack
5-point harness	Proper use	No slack
	w/ seat belt slack	Seatbelt slack 100 mm
	w/ harness slack	CRS harness slack 100 mm
Impact shield	Proper use	No slack
	w/ seat belt slack	Seatbelt slack 100 mm
ISOFIX	Proper use	No slack

RESULTS

CRS Types and Occupant Responses

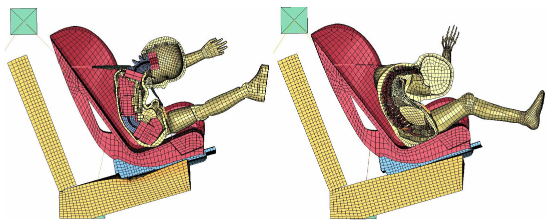
Three types of CRS, one with as the 5-point harness, the impact shield and the ISOFIX CRS, respectively, were examined based on FE simulations using the Hybrid III and child FE model under the conditions of proper use of the CRS with no belt slack.

Occupant kinematics

The behavior of the Hybrid III and child FE model in the 5-point harness CRS is compared in Figure 3. The pelvis and shoulders are restrained by the lap and shoulder harnesses. Due to head movement, the neck flexed and the chin made contact with the chest. As seen in Figure 3, whereas the thorax spine of the Hybrid III made of a steel box did not bend, the cervical and lumbar spine did. On the other hand, in the child FE model, as the whole spine flexed, the head moved downward. The accelerations of head, chest and pelvis are shown in Figure 4. In general, the acceleration tendencies of Hybrid III FE model are similar to that of the Hybrid III test. The head and pelvis accelerations of the child FE model are similar to those of the Hybrid III FE model. The chest acceleration curve of the child FE model has a plateau region when the shoulder harnesses compress the clavicles and the upper part of the rib cage. This plateau region continues after 100 ms where the inertial forces of the head, upper and lower extremities were applied to the chest.

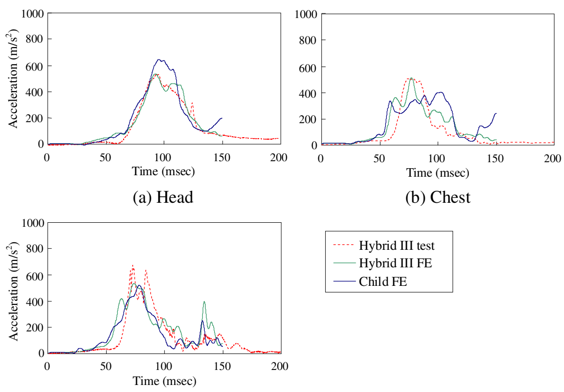
The impact shield CRS used in the present study does not have harnesses, but the shield directly supports the chest of the child during the impact (Figure 5). In the Hybrid III FE analysis, though the chest of the Hybrid III was compressed by the contact with the impact shield, the thorax spine did not flex. Instead, the torso of the Hybrid III rotated upward around the impact shield. On the contrary, in the child FE model, the torso deformed along the impact shield and the whole spine continued to flex. The inertial forces of the head, upper and lower extremities continued to transfer to the torso, and a great force was applied to the chest by the contact with the impact shield. The chest deflections of the Hybrid III and child FE models were very large. In this type of CRS, extreme neck flexion was prevented by the chin contact with the top of the shield. Figure 6 shows the acceleration-time histories of head, chest and pelvis. The accelerations of the body are comparable in the Hybrid III FE and child FE models except for the chest acceleration. For the child FE model, there are two peaks in the chest acceleration at 65 and 90 ms. The first peak is due to the chest contact with the shield, and the second peak is due to the inertia force of the head and upper extremities.

The kinematics and acceleration of the occupant in the ISOFIX CRS are shown in Figures 7 and 8, respectively. In this type of CRS, the occupant restraint starts earlier than in other types of CRS. The ISOFIX attachment and the top tether secure the CRS effectively on the car seat. Accordingly, the torso flexion angle and the head excursion were small. The head flexion angle of the child FE model was larger than that with the Hybrid III FE model. At 100 ms, the chin made contact with the sternum, which led to relatively high acceleration of the chest.



(a) Hybrid III FE model (b) Child FE model

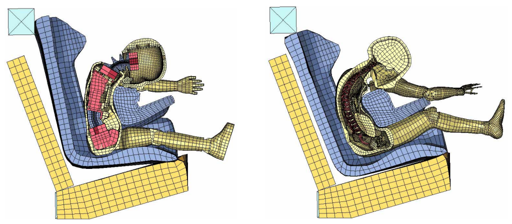
Figure 3. Occupant kinematics in 5-point harness CRS at 120 ms.



(a) Head (b) Chest

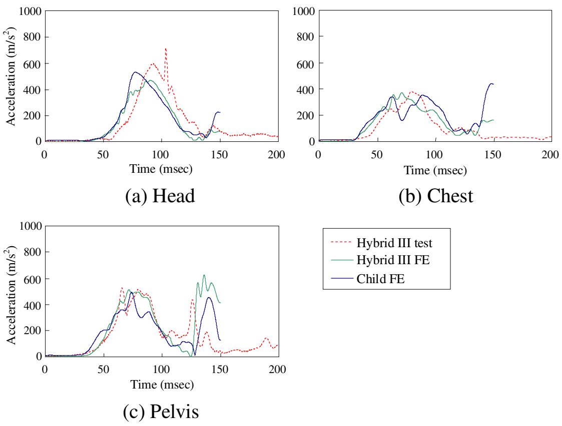
(c) Pelvis

Figure 4. Resultant acceleration of occupant in 5-point harness CRS.



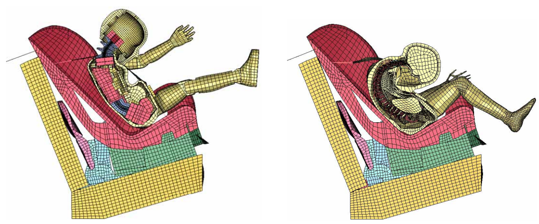
(a) Hybrid III FE model (b) Child FE model

Figure 5. Occupant kinematics in impact shield CRS at 120 ms.



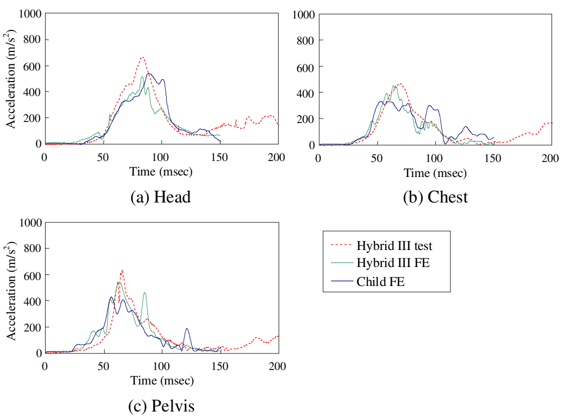
(a) Head (b) Chest (c) Pelvis

Figure 6. Resultant acceleration of occupant in impact shield CRS.



(a) Hybrid III FE model (b) Child FE model

Figure 7. Occupant kinematics in ISOFIX CRS at 120 ms.

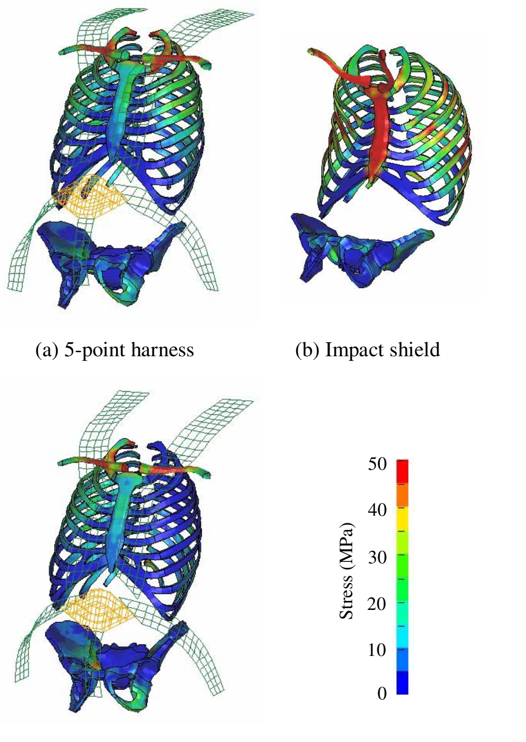


(a) Head (b) Chest (c) Pelvis

Figure 8. Resultant acceleration of occupant in ISOFIX CRS.

Stress distributions of skeleton

Von Mises stress distributions of the skeleton are presented in Figure 9. In the 5-point harness CRS, stresses are high at the clavicles and the upper part of the rib cage because great forces were applied from shoulder harnesses which control flexion of the torso. In the impact shield CRS, the middle of the rib cage deformed along the shield. Due to compression and bending of the rib cage, high stresses in the sternum and whole ribs were observed. In the ISOFIX CRS, the overall stress levels are smallest among the three types of CRSs. The stresses at the clavicle are high where the shoulder harness interacts. In general, the stress in the pelvis is small for all CRS types.

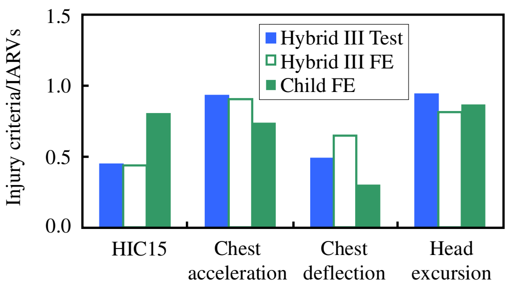


(a) 5-point harness (b) Impact shield (c) ISOFIX

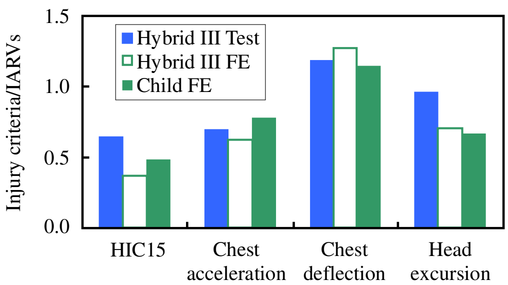
Figure 9. Von Mises stress distribution of skeleton in 5-point harness CRS (90 ms), impact shield CRS (100 ms) and ISOFIX CRS (75 ms).

Injury criteria

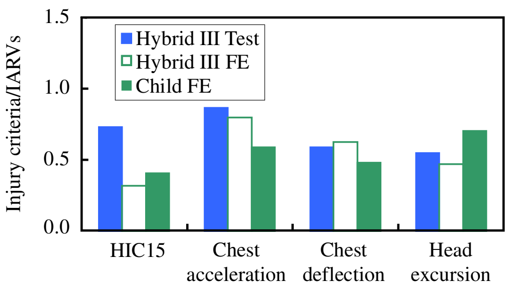
The injury criteria for the Hybrid III test, Hybrid III FE model and child FE model were examined for three types of CRS (Figure 10). Generally, the injury criteria of Hybrid III FE model and child FE model are comparable, and they are less than the IARVs except for chest deflection in the impact shield CRS. For the 5-point harness CRS, the chest acceleration and the deflection of child FE model are smaller than those of the Hybrid III FE model. The head excursion is similar between the Hybrid III FE and child FE models, because the head longitudinal direction does not change although the head of the child FE model moves downward. The chest deflection of both the Hybrid III FE and child FE model in the impact shield CRS is large as the force concentrates in the chest area. In the ISOFIX CRS, the head excursion is smallest among the three CRS types. In this CRS, the head excursion of the child FE model is larger than that of the Hybrid III FE model due to head rotation difference.



(a) 5-point harness



(b) Impact shield



(c) ISOFIX

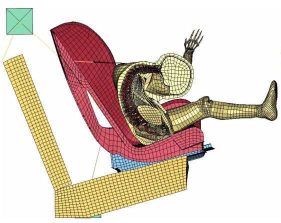
Figure 10. Ratio of injury criteria to injury assessment reference value (IARV) for three types of CRS.

Misuse of CRS

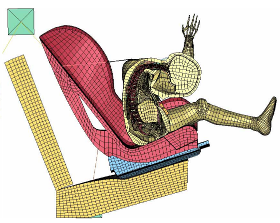
It is known that belt slack leads to delay of restraint starting time, and can result in high injury criteria. The relations between the belt slack and the occupant responses for various types of CRS were examined with respect to the occupant kinematics, injury criteria and ridedown efficiency.

Occupant kinematics

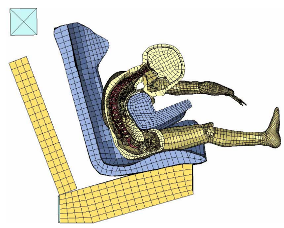
The kinematics of the child FE model with the addition of slack for various CRS types are presented in Figure 11. In the 5-point harness CRS with seatbelt slack, the CRS moved forward whereas the kinematics of the occupant is similar to the case with no slack. In the case of harness slack for the 5-point harness, because of the time delay of the restraint by the shoulder harness, the occupant torso flexed with a large head rotation angle. In the impact shield CRS with seatbelt slack, the occupant kinematics is similar to that with no slack. Accordingly, the occupant flexion behavior is affected more by the harness slack than the seatbelt slack.



(a) 5-point harness (seatbelt slack)



(b) 5-point harness (harness slack)

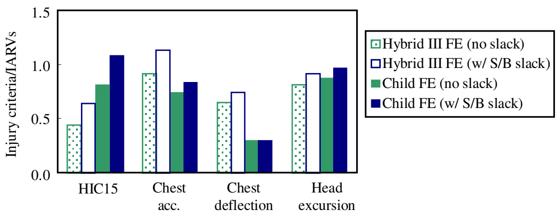


(c) Impact shield (seatbelt slack)

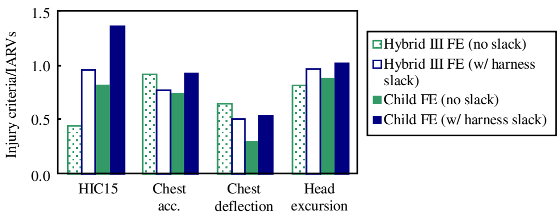
Figure 11. Occupant kinematics in various CRS with slack at 120 ms.

Injury criteria

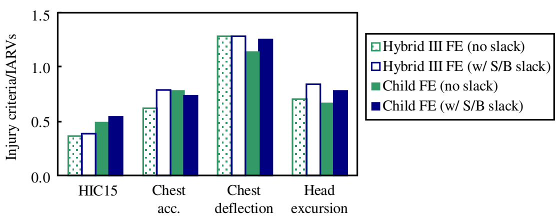
Injury criteria of Hybrid III FE and child FE models in 5-point harness and impact shield CRS for belt slack are shown in Figure 12. In all CRS types, the head excursions increase consistently due to belt slack. In the 5-point harness CRS, both the seatbelt slack and the harness slack result in high HIC or chest acceleration. Compared to 5-point harness CRS, injury criteria of the occupant in the impact shield CRS do not change so much by the seatbelt slack.



(a) 5-point harness CRSwith seatbelt slack



(b) 5-point harness CRS with harness slack

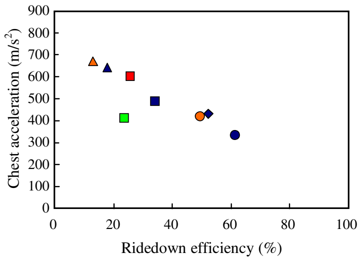


(c) Impact shield CRS with seat belt slack

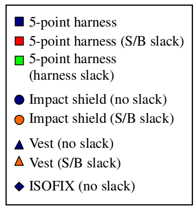
Figure 12. Injury criteria of Hybrid III and child FE model with and without belt slack.

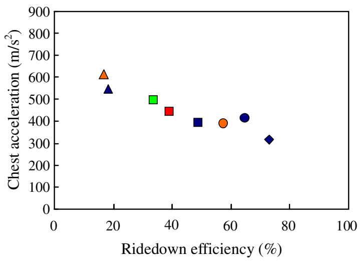
Ridedown efficiency

The ridedown efficiency was calculated by the chest acceleration and is plotted in Figure 13 for all types of CRS with and without slack. The FE analysis of the vest-type CRS [14] is also included in this Figure. The chest acceleration tends to decrease as the ridedown efficiency increases. The ridedown efficiency of the child FE model is about 18%, 48%, 65% and 72% for the vest, the 5-point harness, the impact shield and the ISOFIX CRS with no belt slack, respectively. When slack is added to the shoulder belt of the impact shield CRS, the ridedown efficiency is still high and the chest acceleration is less than the injury acceptance level.



(a) Hybrid III FE model





(b) Child FE model

Figure 13. Ridedown efficiency and chest acceleration in Hybrid III FE and child FE model.

DISCUSSION

The analysis has shown that the global flexion behavior is comparable between the Hybrid III and the child human FE models in the three types of CRS. However, there are significant differences in thorax spine flexibility. Surprisingly, the spine flexibility and anatomical structure did not significantly affect the injury criteria in the 5-point harness CRS. This is because most of the injury criteria reached the maximum value before there was any observable difference in behavior between the Hybrid III and child FE models. Furthermore, the head downward movement of the child FE model did not increase the head excursion. In the 5-point harness CRS, the harnesses apply force to the clavicle, upper ribcage and pelvis, which are relatively strong locations in the skeleton. The stresses in the pelvis were low when the forces from the lap harnesses were applied to the pelvis because this child FE model has a Y-cartilage that allows relative displacement of the ilium, pubis and ischium [14].

A local difference in chest anatomy between the Hybrid III and child FE model can also affect injury criteria. In the CRS types in which the pelvis is not restrained, e.g., the impact shield CRS, a large force was applied directly to the chest, which could lead to local deformation in the ribcage. With the child FE model, these local deformation modes and injuries can be estimated. In the impact shield CRS, the chest deformed along the shield. Therefore, the shape and energy-absorbing characteristics of the impact shield will be important to control the chest deformation during impact.

In the 5-point harness, as the chin made contact with the chest in the child FE model, deflection and stresses of the sternum were observed. This sternum deflection will not be realistic compared to the cadaver tests or real-world accidents in which sternum injuries due to chin contact are not frequently reported. In the present child FE model, the face, including the mandible, mandibular joint and teeth, has not been modeled in detail. The detailed model of face and neck of child should be included when examining the head flexion behavior which affects the chin-chest contact and neck loading. In the child FE model, the occipital condyle/C1 is not a simple kinematic joint but is modeled by bone contact and ligaments with a large deformation during impact, which makes it difficult to measure the force and moment of the neck. However, in the present study, the head accelerations of the Hybrid III FE and the child FE models were comparable, suggesting that the neck loading was similar between the two FE models. This indication might be inconsistent with the analysis by Sherwood et al. [16], who indicated that 6-year-old (6YO) Hybrid III neck loadings in the dynamic test could be overestimated due to the stiff thorax spine. It is possible that the great neck force was generated by the chin and sternum contact in the Hybrid III, and this contact interaction could change when the thorax spine became flexible. Further research is warranted to investigate the neck loadings and its injury threshold in a child with various CRS.

The seatbelt slack and harness slack can increase the injury criteria for the 5-point harness CRS. In the impact shield CRS, the influence of seatbelt slack on the injury criteria was small. In the accident analysis by Langwieder et al. [4,5], injury risks to children using the impact shield CRS were lower than using the 5-point harness CRS. In general, CRS tests are based on the proper use of CRS with tension added in the seatbelt and harness. The injury criteria of the crash dummies in the 5-point harness CRS can be smaller than those in the impact shield CRS in many tests. It is likely that the misuse of the CRS can explain the differences in the occupant injury risks observed in the accident and laboratory test. In the impact shield CRS, the chest deflections of the Hybrid III FE model and child FE model were over the IARV (34 mm). It is known that the ribcage of a child is flexible, and rib fractures are not frequent in real-world accidents. It may be still difficult to use this threshold for rib fractures of children.

The ISOFIX is effective for preventing poor installation of the CRS on a car seat. The ridedown efficiency of the ISOFIX CRS was so high, and the injury criteria of the Hybrid III and child FE model were smaller than the IARVs. In this CRS, though the head excursion of the child FE model is larger than that of the Hybrid III FE model due to head rotation difference, the head excursion was considerably less than the IARV.

CONCLUSIONS

The child responses in three types of CRS with and without belt slack were examined using Hybrid III FE model and child FE model. The conclusions are summarized as follows.

1. From the analysis of sled tests with three types of CRS, the global flexion behavior was comparable between the child FE model and Hybrid III FE model. Close examination revealed differences in behavior due to thorax spine flexibility and thorax deformation mode. Using the child FE model, injury risks to occupants using CRS can be examined in detail.
2. In the case of slack in the harness or seatbelt, the injury risks were high for the 5-point harness CRS. The impact shield CRS was robust for the injury criteria when slack was added to the seatbelt. The influence of slack of the harness and seatbelt on the chest acceleration can be summarized by the ridedown efficiency.

3. The injury criteria, especially head excursion, were small in the ISOFIX CRS for the Hybrid III and child FE model.

ACKNOWLEGEMENTS

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Q3S 3 YEAR OLD SIDE IMPACT DUMMY DEVELOPMENT

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ABSTRACT

The Q3s dummy is a three year old child crash dummy optimized for side impact crash testing. The dummy is built on the platform of the standard Q3 dummy that is part of the Q-series of child dummies developed in Europe to replace the P-series. Enhanced lateral biofidelity, durability and additional measurement channels have been designed into the Q3s dummy. The dummy features a new head that eliminates previously reported high frequency noise, an extensible neck that combines improved frontal flexion performance with the lateral and tensile performance of the Q series necks, a highly deformable shoulder with shoulder deflection measurement, a new arm with improved flesh characteristics, a laterally compliant chest and a pelvis with improved upper leg flesh, floating hip cups, and pubic load transducer. Biofidelity performance for the lateral 3 year old ATD is validated against the scaled biofidelity targets published by Irwin et al. (2002) This paper will describe the construction of the dummy and the laboratory biofidelity performance.

INTRODUCTION

According to the National Highway Traffic Safety Administration (NHTSA), about 40 percent of child fatalities to rear-seated children in the age of 0 to 8 years occur in side impact collisions. In the US, side impact crashes kill about 300 young children each year and result in more severe injuries at lower crash severities than frontal collisions.

Although side impact collisions pose a great risk to children in crashes, information about the injury cause and mechanisms is limited. Research has demonstrated the effectiveness of using age- and size- appropriate restraints in preventing injuries in this crash direction. Restraint systems for children need to account for not only the anthropometric differences of children of different ages but also the biomechanical characteristics of the child's body at different ages. In order to effectively assess the safety provided by these restraints systems, child restraints performance testing should take into account these unique characteristics of child occupants.

Except in Australia and New Zealand, there are no legal requirements in effect concerning the crash protection of restrained children in lateral collisions. The majority of test procedures used for consumer information today are based on a preliminary draft test procedure developed under the International Standards Organization (ISO), (Johannsen et al., 2003). The ISO side impact test procedure for child restraint systems is a sled based procedure that includes specifications for an intruding door member. This procedure offers the possibility to simulate the main mechanisms of lateral collisions, such as acceleration of the struck car and intrusion of the struck side structure. No appropriate side impact child test dummies and associated injury criteria, however, have been available at the present time to assess the merits of this test procedure or the potential countermeasures for side impact intrusion that such procedure would promote.

The purpose of this paper is to present the design and current biofidelity performance of the Q3s, a 3-year old dummy developed specifically for side impact testing. The Q3s dummy (Figure 1) is a modified version of the Q3 omni-directional child crash dummy that was developed and evaluated in Europe under the EC funded CREST (1997 - 2001) and CHILD (2002 - 2006) programs. The Q3s features enhanced lateral biofidelity corridors based on scaling factors applied to ISO TR9790 biofidelity corridors (Irwin et al., 2002). It also includes improved kinematics, overall test performance, durability and additional measurement channels. The paper will review the dummy's basic features, gives background to the design updates and present the test results obtained so far.

DESIGN & METHODS

The Q-series to date exists of a Q0 (infant), Q1, Q1.5, Q3 and Q6 dummies. Key design features are the anatomical representation of body regions, the relatively simple and modular design, the use of dummy-interchangeable instrumentation and easy handling properties (limited components, easy assembly and disassembly, simple calibration). As the standard Q-dummies already include some multi-directional characteristics and their design more easy to modify than traditional dummies, the Q-series was selected as a starting point for the development of a series of biofidelic side impact child dummies. The first dummy in this series, referred to as Q3s, is based on the Q3 dummy platform. The updates required for the Q3s are summarized below.

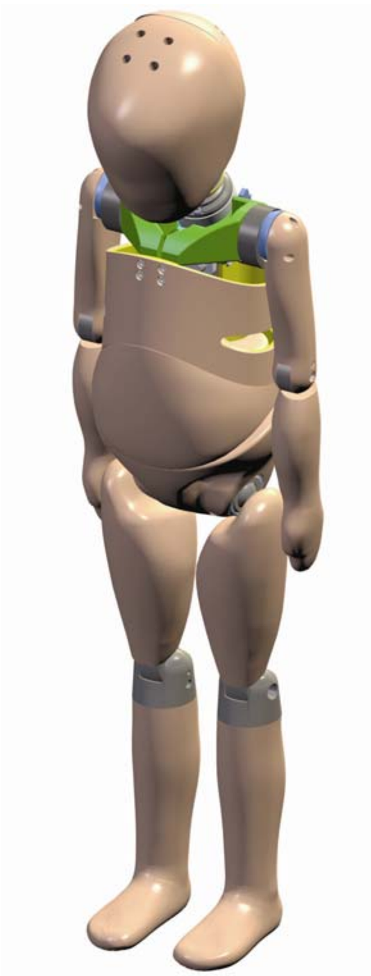

Figure 1 Q3s Dummy

The Q3s Head

Head Construction The Q3s skull material has been changed from the original design. The reason for this change is that the original Q3 urethane material exhibited a relatively low natural resonant frequency. This ringing was evident on head acceleration data especially during OOP airbag testing as noted by Berliner et al (2000). Changing the material to a higher modulus fiberglass increased the natural frequency enough for the CFC 1000 filter to attenuate the noise. The head assembly still has the flesh molded directly to the skull which insures a proper fit. The head shape and mass properties have not changed. As in the original design, an L-shaped steel bracket molded into the skull provides the mounting surfaces for the head instrumentation (linear and rotational accelerometers) and the upper neck six axis load cell.

Frequency Response To verify the Q3s head, the frequency response of the head assembly was measured. The head assembly, removed from the dummy, was suspended by strings and the skull was impacted using an Endevco model 2126 modal hammer. The impact surface was the skull material located behind the chin. The resultant vibrations were measured with 3 uniaxial accelerometers mounted on the standard Q3 head instrumentation mount at a sample rate of 25khz. Usually 1 axis of the 3 would provide a clear indication of the natural resonance frequency of the head. The frequency calculation was accomplished by timing the peak to peak period of the unfiltered data from the head accelerometers. The data were also filtered with the CFC1000 filter to show that the noise was successfully attenuated. These tests were confirmed using a complete dummy seated in front of a passenger airbag. The airbag was centered in front of the head 10" away. The airbag was fired and the head accelerations were recorded.

Head Impact Biofidelity Lateral head biofidelity is described in by Irwin et al. (2002) as a head drop on a 50mm thick steel plate from a height of 200mm. Van Ratingen et al. (1997) described a drop from 130mm for both frontal and lateral directions and FMVSS Part 572 Subpart P describes a drop from 376mm in the frontal direction. The head was suspended on cables such that during the lateral tests the impact point on the head was angled up 35 degrees from the lateral plane during the left and right side tests. In the frontal tests, the head is suspended so the impact point is 28 degrees above the frontal plane. Three (3) uniaxial accelerometers were mounted at the head center of gravity. The data were collected at 10 kHz and a CFC1000 filter was employed.

The Q3s Neck

The Q3s neck (Figure 2) is a new component and consists of 3 natural rubber segments bonded to aluminum plates with an internal cable assembly. The objective was to develop a neck that meets both frontal and side impact requirements combined with realistic elongation properties. The effective axial spring rate (130N/mm average over 11mm) of the Q series neck is controlled initially by the properties and cross-section of the neck rubber segments but then climbs rapidly once the neck cable becomes taut. This allows the neck to stretch under tensile loads but also limit the maximum elongation to protect the integrity of the neck. The segmented design distributes the bending moments over the entire length of the neck reducing the tendency to buckle at the neck midpoint. The outer shape of the neck is round and mostly symmetrical with each rubber segment having a circumferential V-groove. The head - cervical spine - thoracic spine interfaces are solid connections through 6 axis load cells on each end of the neck. .

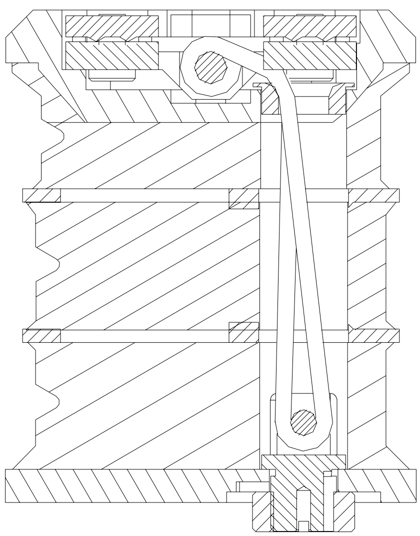

Figure 2 Q3s Neck Assembly (midsagittal cross section)

Frontal Flexion The Q3s neck is designed to meet the frontal flexion characteristics specified in the 49CFR Part 572 subpart P and the lateral flexion properties specified in the Irwin et al (2002) corridors. This was accomplished by locating the neck cable towards the back of the neck. The neck cable becomes taut during frontal flexion pulses and limits the amount of rotation of the neck while the upper neck load cell measures an associated increase in moment. The Q3s frontal flexion data was measured using a Q3s head on a standard part 572 neck pendulum at 5.5 m/s using a deceleration pulse similar to the HIII 3yo standard certification test. Head rotation was measured using rotary pots attached to the head and the pendulum filtered at CFC 180 and the moment was measured using an IF-217 6 axis load cell mounted at the upper neck location filtered at CFC 600.

Lateral Flexion Performance The Q3s neck is tested for lateral performance using a modified Q3 head on the standard Part 572 neck pendulum. The modification of the head entails a small metal rod that is threaded into the rear of the skull cap. This allows the attachment of the rotary pots for measurement of head rotation. A 6-axis load cell measures the moment about the X-axis. The data are collected at 10kHz. The rotary pot data and the moment data are plotted against corridors defined in Irwin et al. (2002)

The Q3s Shoulder

The shoulder is usually the first part of the dummy to be struck in a lateral test, therefore human-like shoulder stiffness is very important. The shoulder must be durable enough for severe impacts and also handle the forces caused by the flailing arm on the non-struck side of the dummy. The design intent was to improve the compliance and durability of the Q3s shoulder while maintaining proper anthropometry and mass distribution. A flexible rubber shoulder was developed to achieve this design goal (Figure 3). The Q3s rubber shoulder component consists of high strength aluminum parts that attach at the sternum, shoulder joint, and spine of the dummy. These parts are joined by a steel cable and the entire assembly is encased in natural rubber that forms the shape of the shoulder. The steel cable flexes with the soft rubber but limits the amount of tension that can be applied to the rubber which helps to protect it from overloading. The shape of the rubber forms the external features of the scapula and clavicle and provides a surface for the seat belt routing. Biofidelity corridors for shoulder deflection and impact response are described Irwin et al. (2002) A string pot attached to the spine is used to measure lateral shoulder deflection. The shoulder joint itself consists of a ball and socket in order to simulate the humerus scapula joint, the ball on the shoulder and the socket integral to the upper arm bone. The upper arm has urethane flesh covering the entire outer surface of the arm which helps reduce the inertial peak from a pendulum impact.

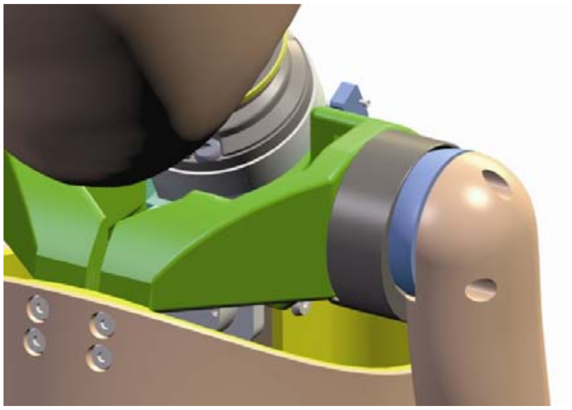

Figure 3 Shoulder Joint

Shoulder Biofidelity The shoulder was evaluated using ISO 9790 shoulder test 1, scaled as suggested by Irwin et al. (2002) The pendulum used for this test is 1.7kg. The impact angle was 90 degrees from the frontal plane at 4.5m/s centered on the shoulder joint. The dummy was seated upright with the upper arm positioned vertically down. The force data was collected using a probe mounted uniaxial accelerometer, the deflection data was collected using a string pot mounted on the front surface of the thoracic spine and connected to the bottom of the shoulder joint. The data are filtered using the CFC 180 filter.

The Q3s Thorax

Like the standard Q3, the Q3s ribcage consists of a 1 piece urethane ribcage with a bonded PVC outer skin layer. The shape, contour and thickness of the ribcage have been changed to provide improved lateral compliance. The ribcage is attached to an aluminum thoracic spine that connects the rubber lumbar spine and the shoulder-neck complex. An IRTRACC displacement sensor measures lateral displacement between the side of the ribcage and the thoracic spine.

Thorax Biofidelity To assess the biomechanical performance of the thorax, the ribcage was impacted using the 1.7kg pendulum. The impact angle was 90 degrees from the frontal plane at 4.3m/s centered on the IRTRACC rib mounting screws. The dummy was seated upright with the arm positioned vertically up. Force data was collected from a probe mounted uniaxial accelerometer, rib deflection data was collected from an IRTRACC mounted between the thoracic spine and the ribs, centered vertically on the dummy ribcage, and T1 acceleration was measured at the top of the thoracic spine. The dummy was positioned in the sitting position on 2 sheets of 2mm thick mechanical grade Teflon. The pendulum force and T1 acceleration data were filtered with the FIR 100 filter. The IRTRACC rib deflection data were filtered with the CFC180 filter. Biofidelity response is described in Irwin et al. (2002)

The Q3s Abdomen

The Q3s abdomen is the same component used on the Q3 dummy. It consists of a PVC skin filled with urethane foam. The abdomen fits neatly into a cavity formed by the ribcage on top and the pelvis assembly on the bottom.

Abdomen Biofidelity Corresponding to ISO TR9790, abdomen biofidelity is assessed using drop tests and sled tests in Irwin et al. (2002) instead of pendulum tests. These tests have not yet been conducted so far due to their complex nature. Van Ratingen et al. (1997) suggested tests using the 3.8kg probe at 4.8m/s and 6.8m/s. The impact was aimed at a spot 30 degrees forward of the lateral plane of the dummy at a point centered between the bottom of the ribcage and the top of the pelvis flesh without striking either. The dummy was positioned in the sitting position on 2 sheets of 2mm thick mechanical grade Teflon. The response data were collected from a probe mounted accelerometer at 10 kHz sample rate and filtered using the FIR 100 filter.

The Q3s Pelvis

In a lateral impact the dummy shoulder and pelvis are the first to contact the side of the child restraint; thus the kinematics of these regions of the dummy are very important. The pendulum impact response corridor described in Irwin et al. (2002) dictates that the flesh be compliant. The construction of the dummy is such that the H-point of the dummy is covered by the flesh of the upper leg. So improving the lateral impact response of the pelvis meant changing the characteristics of the upper leg. The upper leg consists of a steel reinforced urethane femur with a hollow PVC flesh shape that is filled with soft silicone rubber. The hip joint socket in the pelvis assembly is allowed to deflect inwards a maximum of 6mm. A cylindrical rubber buffer provides the spring force and preload for the hip socket. After 6mm of hip socket deflection a plastic hard stop limits further inward movement of the hip. A single channel force transducer measures force at the rubber buffer. The travel stops at both ends of the hip socket travel are plastic to prevent high frequency noise being introduced into the dummies sensor data. Biofidelity corridors for lateral pelvic pendulum impact are described in Irwin et al. (2002) The pendulum dimensions are derived from the adult 17.3kg probe described in ISO9790 yielding a diameter of 70mm, a 100mm radius on the face of the impacting surface and a mass of 2.27kg. Impact point of the pendulum is at the greater trochanter at 90 degrees from the frontal plane of the dummy. The dummy was positioned in the upright sitting position on 2 sheets of 2mm thick mechanical grade Teflon. The test is conducted at 4.5m/s as specified in Irwin et al. (2002) and at 5.2m/s as specified in van Ratingen et al. (1997). The data are filtered using the CFC 180 filter.

RESULTS

A series of tests as outlined in the previous section was performed at the FTSS Certification Lab on the Q3s prototype. Where relevant comparison data are available, this paper will report, besides the Q3s results, the results of identical tests on a standard Q3 dummy and HIII 3 year old dummy.

Head Resonance

The new fiberglass material has doubled the resonant frequency of the Q3s head assembly. At approximately 1.5 kHz, the Q3 urethane head material exhibited a frequency response that was too low to be filtered effectively by the CFC 1000 filter. The filtered data in the airbag test for that material showed a -30 to +60G trough to peak swing in the head acceleration thus complicating HIC calculation. The new fiberglass material for the skull also resonates but at frequencies at or above 3.0 kHz, high enough to be significantly suppressed by the filter.

In the airbag tests the resultant resonant frequencies were 1.5 kHz for the urethane head and 3.0 kHz for the fiberglass head. The acceleration plots filtered using the CFC 1000 filter showed pronounced high frequency noise for the Q3 head (Figure 4) and significantly suppressed noise for the new Q3s fiberglass head (Figure 5).

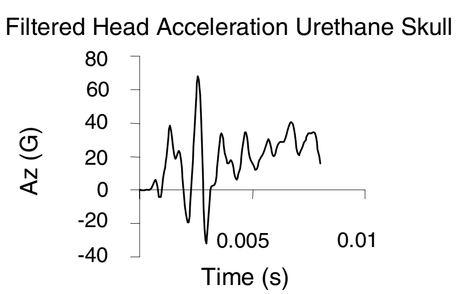

Figure 4 Head Az for the Urethane Skull

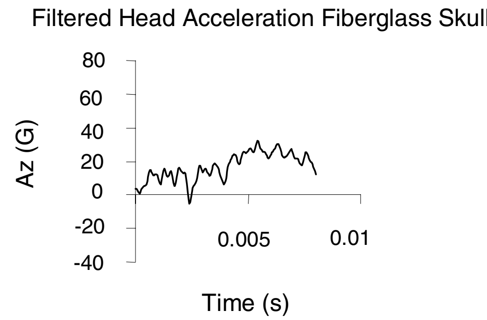

Figure 5 Head Az for the Fiberglass Skull

__Head Drop Response__ Table 1 shows the head impact response of the Q3s. While the head impact response meets all the relevant specifications for the Q3, Q3s and Hybrid III 3 year old ATDs, the current performance is at the high end of the Irwin et al (2002) corridor and at the low end of the Part 572 subpart P corridor. The data presented here was measured at the CG of the head assembly while the PMHS data collected by Hodgson and Thomas (1975) and others, that formed some of the basis for the scaled child corridors, necessarily measured accelerations on the outside of the skull where the sensors could be rigidly mounted. When the dummy head is measured in this fashion by adding angular rate sensing to the instrumentation package, the head acceleration results are about 15 - 20% higher. This is because the chosen impact point on the head does not produce a resultant force directly through the center of gravity of the head. The head both bounces and rotates after impact. In the Hodgson study, intact cadavers and decapitated heads were dropped onto a rigid plate with a 15% associated increase in measured head acceleration resulting at least partly from the fact that the neck was not restraining the rotation of the head. Since the dummy head is always intended to be used attached to the rest of the ATD the effect of the after impact rotation is ignored and the resultant acceleration at the CG is used in this paper.

Table 1 Head Impact Response

Drop Height	Q3s Resultant (G)	Reference	Specification (G)
200mm Lateral	165	Irwin et al	121-171
130mm Lateral	123	van Ratingen	93-159
130mm Frontal	123	van Ratingen	89-153
376mm Frontal	258	49CFR Part 572 Subpart P	250-280

Neck Biofidelity The Q3s neck appears to have achieved its goal of meeting both the lateral moment verses angle flexion corridors described in Irwin et al (2002) and the frontal moment verses angle flexion corridors described in FMVSS 572 Subpart P. The neck was tested at 5.5 ± 0.1 m/s using the pulse defined in the Code of Federal Regulations (CFR), 49, Part 572, Subpart P for the HIII 3YO. The results (Figure 6) show that the Q3s neck generally matches the frontal flexion corridors for the HIII 3YO neck.

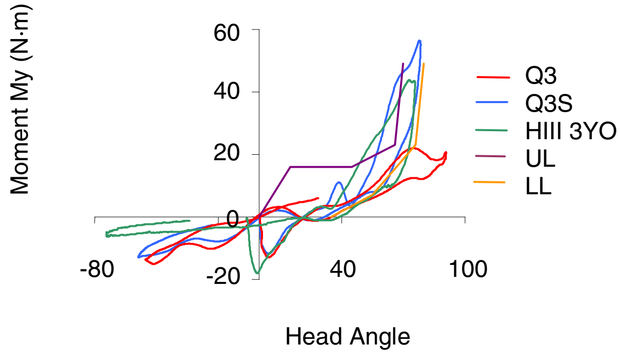

Figure 6 Neck Frontal Flexion

The lateral neck pendulum tests shown in Figure 7 resulted in a peak lateral moment Mx of 25 Nm with a peak rotation of the head of 80 degrees. The HIII 3YO neck results are not shown in the graph but due to its frontal flexion oriented design it would rotate less than 40 degrees in this lateral test.

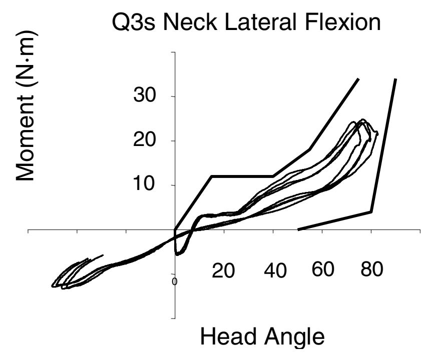

Figure 7 Q3s Neck Lateral Flexion

Tensile Stiffness

The Q3s neck, like the Q3 neck, is extensible whereas the HIII 3YO neck is not. The axial spring rate of the neck in tension has 2 modes, low rate for distractions less than 11mm and high rate above 11mm. In addition to providing overload protection to the neck, this property has the benefit of providing a distinguishable change in the Fz test data once the neck distraction has exceeded 11mm. In the quasi-static tensile test the axial spring rate of the Q3s neck began at 180N/mm decreasing to 60N/mm and averaging 130 N/mm for distractions less than 11mm. Above 11mm distraction, the axial spring rate increased gradually over the next 4mm to an approximate value of 1000N/mm. Figure 8 plots the Neck tensile load against elongation for the Q3s along with the FMVSS Part 571.208 axial tension limit for the three year old ATD.

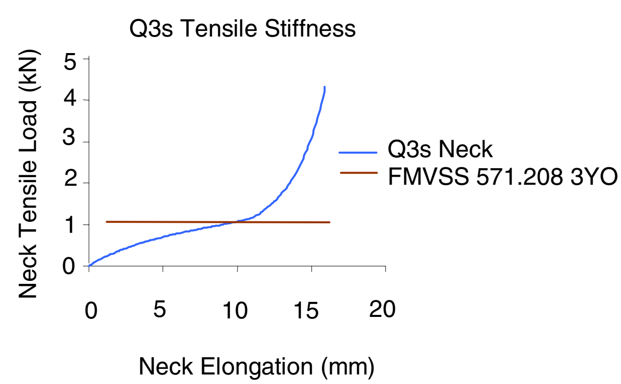

Figure 8 Q3s Tensile Stiffness

Shoulder Impact Tests

The new shoulder assembly in the Q3s shows a marked reduction in impact force over the standard

Q3 design and over the HIII 3YO. The improvement can be attributed to 2 design elements. The first is the lateral compliance of the shoulder joint and the second is the compliance of the upper arm flesh. Since the standard Q3 has a hard urethane surface at the probe impact point, it suffers from an inertial peak at impact and while the shoulder is laterally compliant its deflection is less than that of the Q3s shoulder. The HIII 3YO has a soft vinyl flesh covering the upper arm at the impact point but it has little lateral compliance in the shoulder joint.

Bolte et al. (2000) concluded that acromial – sternum deflection could be used as an injury criteria. The string pot is attached anterior, inferior and inboard of the actual shoulder joint and measures the lateral deflection of the shoulder joint but not the flesh compression of the upper arm. Shoulder rotation due to oblique impacts or swinging arm motion will have an effect on the shoulder deflection measurements either increasing or decreasing the measured deflection. The effect varies with the direction of movement of the shoulder and arm. When handling the Q3s ATD it is apparent that the shoulder allows a wide range of motion to the arm and also deflects under oblique loads. Future testing will provide data from the complete series of biofidelity tests and also should allow the characterization of the oblique impact response.

The shoulder assembly was evaluated using the ISO 9790 test as scaled in Irwin et al. (2002) Figure 9 shows the lateral impact force at the shoulder. The peak value for the new Q3s shoulder is 1.15kN, the original Q3s shoulder is 2.1kN, and for the HIII 3YO is 2.2kN. The Irwin et al (2002) corridor peak is .5kN.

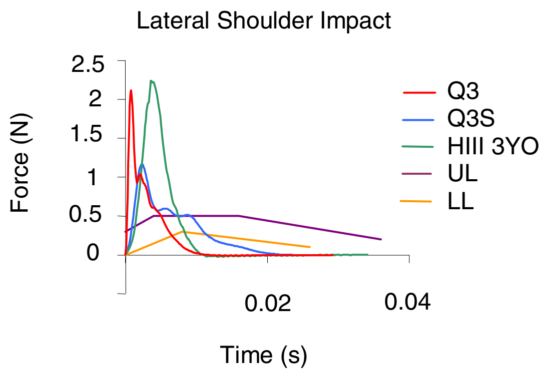

Figure 9 Lateral Shoulder Impact

Figure 10 shows the deflection measured by the string potentiometer mounted between the thoracic spine and the shoulder. Peak deflection in the Q3s was 17mm which is 4mm lower than the lower deflection limit of 21mm specified in Irwin et al. (2002) The Q3 dummy shoulder deflected 11 mm as measured by an IRTRACC that had been attached between a specially modified shoulder joint and the thoracic spine of the dummy. This measurement is not possible in the HIII 3YO.

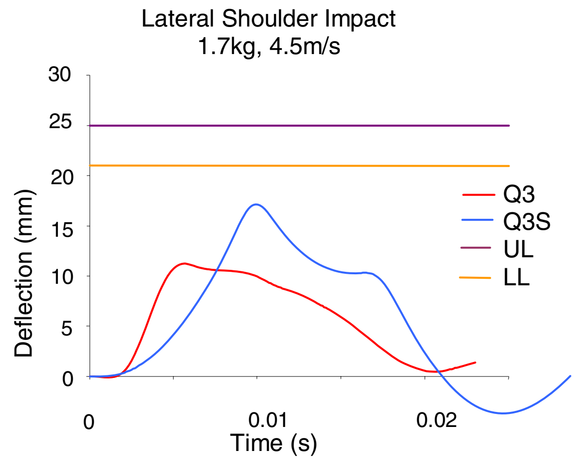

Figure 10 Lateral Shoulder Deflection for the Q3 and Q3s

Thorax Impact Response

The Q3s ribcage has good lateral compliance as evident by the pendulum force and the IRTRACC rib deflection measurements. The Q3 ribcage had been optimized for frontal impact and performed less well against the Irwin et al (2002) force corridor. The HIII 3YO ribcage does not have provision for lateral rib deflection measurements. In addition, the frontal orientation of the HIII 3YO ribcage suggests the conclusion that it is not a suitable design for lateral loading. Figure 11 shows the force time curve for the lateral thorax impact using the 1.7kg impactor. The peak force of the Q3s was .67kN and the peak deflection was 24mm. The peak force for the HIII 3YO was 1.6kN. The Irwin et al (2002) corridor peak is .66kN.

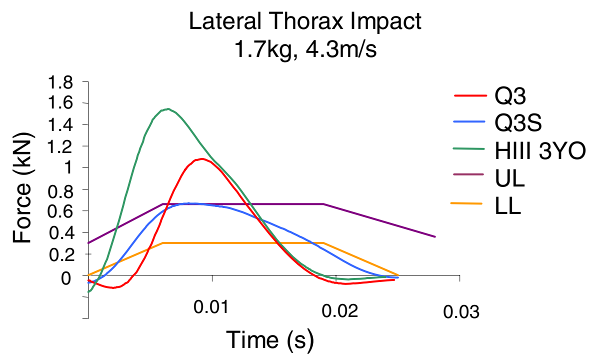

Figure 11 Lateral Thorax Impact Force for the Q3, Q3s, HIII 3YO

The HIII 3YO performed the closest to the Irwin et al (2002) corridor for T1 acceleration at 15G max with the Q3s following at 17.5G and the Q3 at 33G. The differences between the Q3s and Q3 can be explained by the greater compliance of the Q3s ribcage since the mass distribution of the 2 ATDs is similar. The better performance of the HIII 3YO cannot be explained by the differences in thorax compliance but likely due to the mass distribution in the upper thorax. Figure 12 shows the T1 acceleration results for the Q3s, Q3 and HIII 3YO. The corridor suggested by Irwin et al (2002) has peak acceleration of 15G.

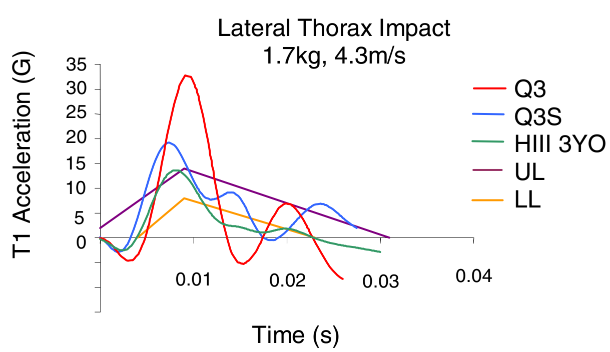

Figure 12 T1 Acceleration for the Q3, Q3s, HIII 3YO

Table 2 shows the lateral rib deflection for the Q3 and Q3s dummies. The Q3s ribcage is more cylindrically shaped than the Q3 version, while not as anthropometrically accurate to a 3 year old child, it provides more lateral compliance. The HIII 3YO is not shown because it does not have lateral rib deflection measurement capability.

Table 2 Lateral Chest Deflection for the Q3, Q3s

Dummy Type	Chest Deflection (mm)
Q3s	24.0
Q3	12.9
HIII 3YO	n/a

Abdomen Response

The Q3s abdomen performed well against the scaled corridors suggested by van Ratingen et al (1997) recommended scaled corridors for the 3 year old ATD abdomen of 1.05kN and 1.575kN maximum for impacts at 4.8m/s and 6.8m/s respectively. Future sled and drop tests must confirm the biofidelity performance of this body region. Figures 13 and 14 show the abdominal impact response of the Q3s at 4.8 and 6.8m/s using the 3.8kg impactor plotted against biofidelity curves suggested in van Ratingen et al.

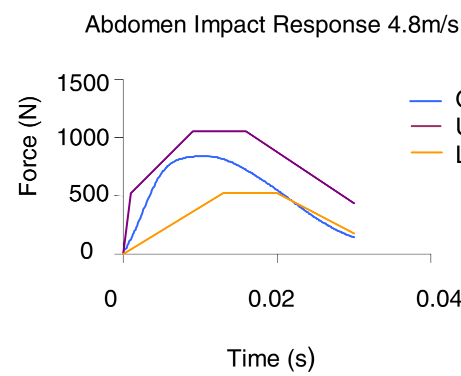

Figure 13 Q3s Lateral Abdominal Impact Response at 4.8m/s

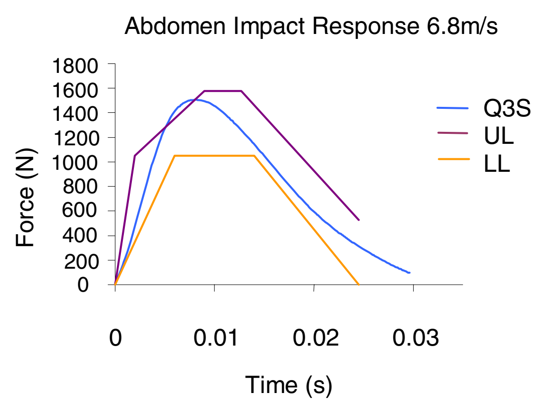

Figure 14 Q3s Lateral Abdominal Impact at 6.8m/s

Pelvis Impact Tests

The pendulum impact results are presented at two velocities, 5.2m/s and 4.5m/s. Irwin et al. (2002) suggested a velocity of 4.5m/s and provided scaled corridors for that velocity. The 5.2m/s data was included because that was the Q3 test configuration in van Ratingen et al. The existence of that data made a convenient means to provide a side by side comparison. The combination of softer upper leg flesh, floating hip cups, and the rubber buffer help the Q3s perform closer to the Irwin et al corridors in the pendulum tests. Figure 15 shows the force time curves for lateral pelvic impacts at 5.2m/s for the HIII 3YO, the standard Q3 and the Q3s dummies. The force time curve for the Q3s is also plotted against the Irwin et al (2002) corridors at 4.5m/s in Figure 16.

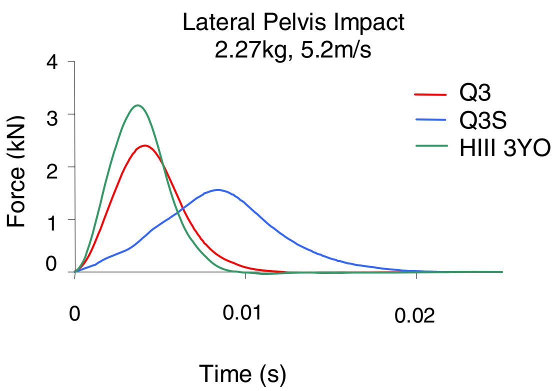

Figure 15 Lateral Pelvis Impact Force at 5.2m/s for the Q3, Q3s, HIII 3YO

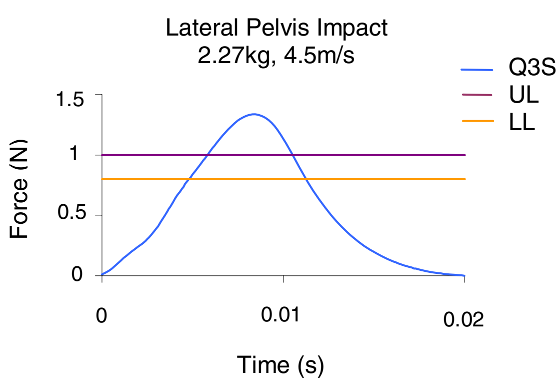

Figure 16 Q3s Lateral Pelvis Impact Force at 4.5m/s

DISCUSSION AND CONCLUSIONS

The new Q3s dummy incorporates improved lateral impact performance and enhanced instrumentation for side impact testing. Several of the original Q3 components were replaced by more compliant yet durable components. The shoulder design is a good example of this. The urethane clavicle of the Q3 was replaced with a molded rubber version. This means the shoulder joint is suspended between the thoracic spine and the sternum on a D-shaped rubber component. Lateral impacts to the shoulder cause it to collapse inward thus improving both impact response and shoulder deflection. The molded-in steel cable flexes with the shoulder joint laterally but provides protection against extreme tensile loads. In the case of the pelvis, the hip joints were allowed to compress inward. This increased the overall compliance of the pelvis assembly in the lateral direction and permitted the implementation of a pubic load cell. The dummy now has lateral force or displacement sensors at the shoulder, ribcage and pelvis which are also the primary lateral impact locations. Further study of the usefulness of these sensors and the development of injury criteria are needed. Also investigation of the oblique response characteristics of this dummy is required since many side impact events, in particular when the dummy is seated in the rear, involve an oblique component. An initial assessment against published biomechanical targets by Irwin et al. (2002) indicates that the Q3s provides an important improvement in terms of biofidelity compared to the original Q3 and the H-III 3YO dummies. Moreover, the design updates to the head and neck have been effective in addressing known head resonance issues and providing omni-directional neck biofidelity respectively.

The biofidelity assessment presented in this paper is not complete as it does not include all recommended test conditions given by Irwin et al. (2002). Specifically the Heidelberg and WSU type sled tests are an important means to assess the full-body dummy response and interaction between shoulder, thorax and pelvis regions. Furthermore, the dummy has not yet been exposed to the test conditions in which it is likely to be used in the future, i.e. lateral hinge-door sled tests following the ISO protocol and in-vehicle tests. More testing of the Q3s therefore is imperative and ongoing as part of the OSRP Q3s Task Group activities.

Finally, the design principles applied to the Q3s are currently used on the other sizes of Q-dummies, such as the Q6, in order to extend the series of side impact child dummies.

ACKNOWLEDGEMENTS

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THE EFFECT OF RESTRAINT USE AND CRASH MODE ON INJURY SEVERITY RISK FOR CHILDREN

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ABSTRACT

The safety of children in motor vehicle crashes is a major concern. Although Child Restraint Systems (CRS) are required by law for their protection, children are still exposed to the risk of injuries ranging from minor to fatal. The effect of restraint use is studied under different risk scenarios consisting of some possible contributors to injury risk: the restraint use, impact type, injury severity, and age of crash involved children. The data are analyzed at rather a micro level to estimate the relative risks associated with risk scenarios and test for possible risk factor interactions. Specifically, children of age groups: infants, 1 to 3, 4 to 8, and 9 to 12 year olds, who were either uninjured, or sustained minor to fatal injuries in frontal, side, rear-end, or rollover crashes, formed the study population. Some data concerns are also raised in course of the study.

The analysis dataset is extracted from the National Automotive Sampling System– Crashworthiness Data System (NASS-CDS). The study population is segmented, based on three injury risk factors: age group, restraint use, and impact crash mode. Clusters of data are identified in which the quantity of data are limited or contains insufficient 'information', thereby suggesting the importance of collecting more data in certain segments of the population. Injury risk factors may have an individual as well as joint influence on the outcome (injury severity) of a crash. The significance of the overall association between these factors is tested by the contingency analysis. This, however, provides only a broad picture of the phenomenon. Configural frequency analysis is used to identify the factor-based clusters of the children population that show strong to complete absence of factor association. The estimates of the relative risks associated with different clusters are obtained to compare the two groups of children: restrained and unrestrained. In general, the restrained children were found much safer against injuries.

1. INTRODUCTION

In motor vehicle crashes, the use of child restraint systems is as important a safeguard for children against crash impacts as the safety belt use is for adults. Research has shown that the proper restraint use can considerably reduce the injury risk to a child (1986, 1996.) The recognition of this fact led to mandatory requirement of restraint use. Nevertheless, children are still injured in crashes. The question, therefore, arises as to why they are injured and what saves them from being injured. This could be merely 'due to chance' or attributable to certain risk factors, such as age, impact, and restraint use. This study conducts an in-depth analysis of the crash data to identify those sectors of the data in which the injury severity can be attributed to some general risk factors. In the course, some other issues, such as sample size etc. are also discussed.

Statistical analysis based on ten years of data brings out some interesting facts about restraint use and its effectiveness in protecting children in crashes. This can provide guidelines for further improvement in restraint use and give some ideas about further research in this area. The study starts with the rationale of segmenting the data into clusters based on some potential risk factors, such as age, restraint use, impact etc. This is done in Section 2 as a preparation of the analysis data. In Section 3, it is established whether or not there is an overall dependence among these risk factors. To compare restrained and unrestrained children of different age groups with respect to the risk factors, relative risk is estimated for all data clusters in Section 4. The cell sample sizes are assessed for sufficiency in Section 5. The analysis continues in Section 6, where the strength of association among risk factors is tested for clusters of the data. Section 7 summarizes the findings of this study.

2. DATA

The present study is focused on injury severity risk to children 12 years and under. Both experimental and field data are available on child safety restraint use. The experimental data, however, is based on a limited number of conditions used under a controlled experimental environment. The data thus generated can reflect only a part of what happened in real life conditions and lack capability of generalizing the results to the entire population of children. The field data, on the other hand, has inherent in them the characteristics of a probabilistic phenomenon under which crashes occurred and the crash-involved children sustained injuries due to different types of crash impacts. Ten years of NASS-CDS field data (1994 through 1996 and 1998 through 2004) are used in the study. Studying the effectiveness of restraint systems in mitigating children's injury severity is of concern. Many factors are likely to play a role, individually or jointly. The effects of these factors, if present, can bring variation into the data. In order to explain if the variation is actually due to these factors or is merely due to chance, it is important to take them into account in the analysis. This was done by segmenting the data at several layers.

It is recommended that for best possible protection children use age appropriate child restraints in the back seat. In this study, age is used as one of the criteria for data segmentation. This was done based on the following guidelines recommended by NHTSA: Infants (less than a year) – Rear-facing infant seat, $1 \leq$ Age <4 (forward facing seat), $4 \leq$ Age < 8 (booster seat), and $8 \leq$ Age < 13 (adult seat belt). Specifically, the data were segmented in four age groups: 0 to <1 year, 1 to 3 (<4) years, 4 to 8 (<9) years and 9 to 12 (<13) years old children. Each of these age groups, characterized by the presence or absence of restraint use, forms a population in itself. In the subsequent analysis and discussion, the data pertaining to these age groups are treated as independent (with respect to restraint use) populations.

The next layer of data segmentation consisted of classifying the children in each age category, based on the restraint use status, i.e., whether the child was restrained or unrestrained. To account for the child injury severity, the data in each of these categories were segmented into three sub-categories, depending on the maximum injury severity on the Abbreviated Injury Scale (MAIS). Three levels of injury severity were considered: MAIS=0 (no injury), MAIS=1 (minor injury), and MAIS=2^+ (moderate to severe or fatal injury). Research shows that a child's (restrained or unrestrained) injury severity also depends on the type of impact. To account for this variation in the data, four types of impacts: Frontal, Side, Rear-end, and Rollover were considered as another layer of segmentation. This sets up the analysis data for this study.

3. ANALYSIS: INDEPENDENCE OF RISK FACTORS: RESTRAINT, MAIS, IMPACT

Based on three classification criteria, restraint use at 2 levels, MAIS at three levels, and impact at 4 levels, the segmented data were arranged in a 2x3x4 contingency table of 24 cells. Each cell in this table can be identified by a combination of the levels of these factors, to be referred to as a 'crash scenario' or 'configuration'. In the subsequent discussion, these terms will be used alternatively.

The analysis data as explained above can be thought of as a sample from a multivariate population with various probabilities and partitions of the categories subject to restrictions, in addition to those of the multinomial distribution. In studying the effectiveness of restraint use, the data were first analyzed to confirm if there were actually an interaction effect of the three factors, i.e., testing the hypothesis of dependence of the three classifications.

Consider the events, defining the incidences related to Restraint, MAIS, and Impact.

Restraint = 1, if the child was restrained,
= 2, if the child was unrestrained;

MAIS = 1, if child suffered no injury (MAIS=0)
= 2, if child suffered minor injury (MAIS=1)
= 3, if child suffered moderate to fatal or serious injury (MAIS=2^+)

Impact = 1, if the crash impact was Frontal,
= 2, if the crash impact was Side,
= 3, if the crash impact was Rear-end,
= 4, if the crash impact was Rollover.

Also, define the joint and marginal probabilities of these events.

$$p_{ijk} = \Pr ob\{\text{Re stra int} = i, \text{MAIS} = j, \text{Im pact} = k\},$$
$$i = 1,2;\ j = 1,2,3;\ k = 1,2,3,4$$

$p_{i..} = \text{Prob}\{\text{Restraint}=i\}, i = 1, 2$
$p_{.j.} = \text{Prob}\{\text{Mais}= j\}, j = 1,2,3$
$p_{..k} = \text{Prob}\{\text{Impact} = k\}, k = 1,2,3,4.$

Using these definitions, the hypotheses of dependence among risk factors can be expressed as

$$H_0 : p_{ijk} \neq p_{i..}\, p_{.j.}\, p_{..k}, \text{ for at least one } i, j, k,$$
$$\sum\sum\sum p_{ijk} = 1, \; i = 1,2 \text{ (Restraint)}, \; j = 1, 2, 3 \text{ (MAIS)}, \quad (1)$$
$$\text{and } k = 1, 2, 3, 4 \text{ (Impact)}.$$

Alternatively, the hypothesis of independence can be expressed as

$$H_1 : p_{ijk} = p_{i..}\, p_{.j.}\, p_{..k}, \; i = 1, 2 \text{ (restraint)}, \; j = 1, 2, 3 \text{ (MAIS levels)}, \text{ and } k = 1, 2, 3, 4 \text{ (impact type)}$$
(2)

The hypothesis H_0 was tested against H_1 using the information measure

$$I(1:2) = N_{...} \sum_i \sum_j \sum_k p_{ijk} * \log\left(\frac{p_{ijk}}{p_{i..}\, p_{.j.}\, p_{..k}}\right) \quad (3)$$

where

$$p_{ijk} = \frac{N_{ijk}}{N...}, \text{ with } N_{...} = \sum_{i=1}^{2} \sum_{j=1}^{3} \sum_{k=1}^{4} N_{ijk}, \text{ and}$$

$$p_{i..} = \frac{\sum_{j=1}^{3}\sum_{k=1}^{4} N_{ijk}}{N_{...}}, \; p_{.j.} = \frac{\sum_{i=1}^{2}\sum_{k=1}^{4} N_{ijk}}{N_{...}}, \; p_{..k..} = \frac{\sum_{i=1}^{2}\sum_{j=1}^{3} N_{ijk}}{N...} \quad (4)$$

The information measure in (3) is, basically, a measure of the joint relation among row-, column-, and depth categories [3]. If row, column, and depth classifications are independent, the quantity $2I(1:2)$ is asymptotically distributed as χ^2 with 17 degrees of freedom . Based on the analysis data, the information, $2I(1:2)$ = 2981.9 (Infants), 4983 (1 to 3 year-olds), 2612 (4 to 8 year-olds), and 6532 (9 to 12 year-olds) is highly significant at 95% confidence level, in favor of H_0. This shows a strong evidence of overall interrelationship among three factors for all age groups.

Having inferred the interrelationship among three classifications, it is of further interest to identify those clusters of the data where this relationship is more significant as compared with other sectors of the data. A micro level categorical analysis can reveal this and in turn can highlight those risk scenarios where the use of restraint systems can be more or less effective.

4. RELATIVE RISK COMPARISON OF RESTRAINED VS. UNRESTRAINED CHILDREN

The relative risk (RR), in general, is a measure of how much a particular risk factor influences the risk of a specified outcome (say, injury sustained by a child due to being unrestrained and having been involved in a frontal impact). For example, a relative risk of 2 associated with this risk factor means that children with that risk factor (unrestrained in a frontal impact) have a 2 fold increased risk of having been injured to the level associated with the configuration as compared to children without that risk factor. Similarly, a relative risk of 0.5 means that the children with the risk factor have half the risk as compared to the children without the risk factor.

<u>Estimation of Relative risk</u>:
In the present context, the risk factor is the combination of Restraint use (i = 1, 2), Injury level (k=1, 2, 3), and Impact type (j=1, 2, 3, 4). As an example, R_{111} is the relative risk associated with infants, for instance, who were restrained, uninjured and involved in frontal impact. The relative risk associated with the ijk-th configuration is given by

$$R_{ijk} = \frac{N_{ijk}}{E_{ijk}} \quad (5)$$

where N_{ijk} and E_{ijk} are, respectively, the observed and expected frequencies corresponding to Restraint = i, MIAS= j, and Impact = k [4]. In terms of the probabilities defined in (2), the relative risk R_{ijk} can be alternatively expressed as

$$R_{ijk} = \frac{p_{ijk}}{p_{i..}\, p_{.j.}\, p_{..k}}, \; i = 1,2, \; j = 1,2,3, \; k = 1,2,3,4 \quad (6)$$

<u>Interpretation of results</u>:
The purpose of the analysis in this section is to compare groups of restrained children (with selected injury levels and impact types) to the unrestrained children with the same injury levels and impact types to see if the risk factors have contributed to the level of injury sustained by a child under different risk scenarios. Table 1 through Table 4 show risk factors and the associated relative risks. As an aid for comparison of injury risk for the two groups: restrained and unrestrained, the relative risks are shown as bars on a logarithmic scale in Figure 1 through Figure 4. While interpreting the results presented in these tables

and figures, it is important to remember that $R_{ijk} > 1$ shows that more cases were observed than were expected under the assumption of no factor interaction in the ijk-th risk factor combination, also referred to as configuration. On a logarithmic scale in these figures, this case emerges as an upward bar. Similarly, $R_{ijk} < 1$, shows that less than expected cases were observed for the ijk-th risk factor combination. The bars in the figures for such scenarios show as dropping bars. Obviously, in case of no injury (MAIS=0), evidence goes in favor of the restraint use if more than expected children were observed uninjured, i.e., $R_{ijk} > 1$ or if R_{ijk} (restrained) > R_{ijk}(unrestrained). However, in case of minor or serious injury, evidence goes in favor of restraint use if less than expected children were observed injured, i.e., $R_{ijk} < 1$ or if R_{ijk} (restrained) < R_{ijk}(unrestrained) .

4.1 Relative Risk Comparison of Restrained and Unrestrained Children Under 1

Table 1 shows risk factors and the corresponding relative risk for the restrained and unrestrained infants. Correspondingly, the results are also presented in Figure 1. The values of RR for MAIS=0 being greater than 1 (relative risk bars in Figure 1 rising above 1) shows that the restrained infants were protected against any type of injury in frontal, side, and rear-end crashes. Although in rollover crashes, the relative risk for the restrained group is slightly less than 1, it is much greater than the unrestrained group, thereby showing that being unrestrained is much more riskier in rollover crashes.

Similarly, the values of RR being less than 1(relative risk bars in Figure 1 dropping below 1,) the restrained infants have low risk of having minor injury in frontal, side, and rear-end crashes. The relative risk of 9.9 of minor injury in rollover crashes for the unrestrained and 1.4 for the restrained group shows that an unrestrained infant is much more susceptible (about 10 times) to minor injuries as compared with restrained group in rollover crashes.

The third segment in Figure 1 shows that restraint use did provide protection to infants against moderate to serious injuries in frontal and rear-end crashes. The relative risk of 29.1 for the unrestrained and 1.6 for the restrained group in rollover crashes shows that an unrestrained infant is much more at risk (about 18 times) of sustaining moderate to serious injuries as compared with a restrained infant.

Table 1. Risk factors and the associated Relative risks for restrained and unrestrained infants.

RISK FACTOR		RELATIVE RISK (RR)	
MAIS	IMPACT	RESTRAINED	UNRESTRAINED
0	Frontal	1.0109	0.5365
0	Side	1.0782	0.7705
0	Rear-end	1.1062	0.5666
0	Rollover	0.8709	0.0444
1	Frontal	0.8726	4.631
1	Side	0.7438	0.0452
1	Rear-end	0.6186	0
1	Rollover	1.3997	9.0908
2+	Frontal	0.9157	4.3601
2+	Side	0.3087	0.4559
2+	Rear-end	0.3866	2.7414
2+	Rollover	1.6161	29.0755

Data source: NASS-CDS, NHTSA

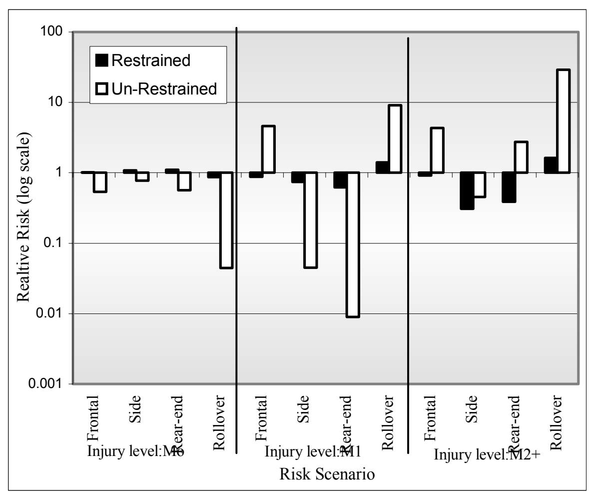

Figure 1. Risk scenarios and the associated Relative risks presented as bars for Restrained and Unrestrained Infants.

4.2 Relative risk comparison of Restrained and Unrestrained children of ages 1 to 3 years

Table 2 shows risk factors and the corresponding relative risk for restrained and unrestrained children of ages 1 to 3 years. Correspondingly, the results are also presented in Figure 2. The relative risks 0.303, 0.349, and 0.76 for MAIS=0 in frontal, side and rollover crashes, respectively, show that there are low chances of protection against injuries for these children when they are unrestrained. In a rollover crash, the relative risk 1.74 of being uninjured for an unrestrained child is higher than 1.09 for a restrained child.

In the case of minor injury, the relative risks 0.88, 0.79, 0.51, respectively, in frontal, side, and rear-end crashes are indicative of low risk of minor injury to 1 to 3 year olds in these types of crash modes. In rollover crashes, the relative risk 10.33 of minor injury to an unrestrained child is about 7 times higher than the relative risk 1.42 to a restrained child.

Table 2. Risk factors and the associated Relative risks for restrained and unrestrained children of ages 1 to 3 years.

RISK FACTOR		RELATIVE RISK (RR)	
MAIS	IMPACT	RESTRAINED	UNRESTRAINED
0	Frontal	1.0882	0.3032
0	Side	1.058	0.3459
0	Rear-end	1.0904	1.74
0	Rollover	0.6188	0.7599
1	Frontal	0.8854	1.5969
1	Side	0.7958	3.2671
1	Rear-end	0.5112	0.1483
1	Rollover	1.4225	10.3345
2+	Frontal	0.7167	1.6512
2+	Side	0.9222	2.2707
2+	Rear-end	0.8828	1.9386
2+	Rollover	1.4773	10.4377

Data source: NASS-CDS, NHTSA

The third segment of Figure 5 shows a comparison of the two groups with respect to moderate to serious injuries. The situation for this injury level is somewhat the same as for other levels of injury. The results for this case in Table 5 and Figure 5 again show that the restrained children have low relative risks of serious injury; being 0.71, 0.92, and 0.88, respectively, for frontal, side, and rear-end crashes. The risk (10.44) to an unrestrained child in rollover crashes is about 10 times higher than the relative risk (1.48) to a restrained child.

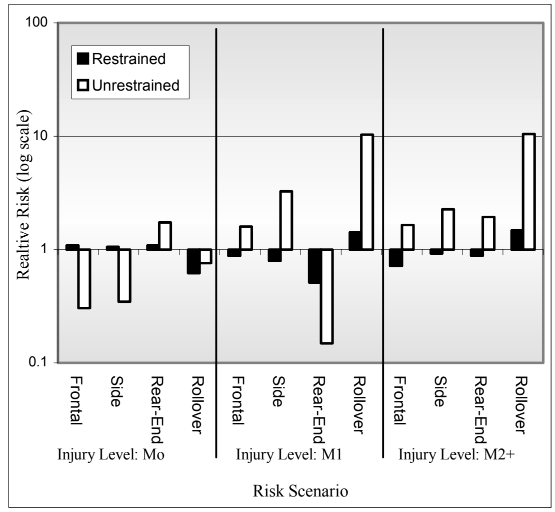

Figure 2. Risk scenarios and the associated Relative risks presented as bars for Restrained and Unrestrained children of ages 1 to 3 years.

4.3 Relative risk comparison of Restrained and Unrestrained children of ages 4 to 8 years

Table 3 and Figure 3 show risk factors and the corresponding relative risks for restrained and unrestrained 4 to 8 year olds. Comparison of relative risks for the two groups: restrained and unrestrained in Table 3 or the corresponding Figure 3 shows that in side, rear-end, and rollover crashes, these children have greater chance (RR>1) of being uninjured when they are restrained. The relative risk 0.95 of no injury for the restrained group and 0.47 for the unrestrained in frontal crashes show that there are lower chances of an unrestrained child being uninjured as compared with a restrained child. In the case of minor injury, the restrained children showed a low risk in side, rear-end, and rollover crashes. These children have a higher risk 1.6 of sustaining minor injury in frontal crashes when they are unrestrained as compared with restrained children who have a relative risk of 1.15. Also, the restrained children of this age group have much lower relative risks of moderate to serious injuries: 0.47 in frontal, 0.80 in side, 0.15 in rear-end, and 0.24 in rollover crashes. In fact, correspondingly, the relative risks for the unrestrained group were, respectively, 7.7, 7.6, 13.3, and 23.6 times higher than the restrained children.

Table 3. Risk factors and the associated Relative risks for restrained and unrestrained children of ages 4 to 8 years.

RISK FACTOR		RELATIVE RISK (RR)	
MAIS	IMPACT	RESTRAINED	UNRESTRAINED
0	Frontal	0.9534	0.4716
0	Side	1.25284	0.52181
0	Rear-end	1.42773	0.3928
0	Rollover	1.03627	0.98064
1	Frontal	1.15827	1.59928
1	Side	0.63271	0.84333
1	Rear-end	0.48905	0.55191
1	Rollover	0.64491	3.00161
2+	Frontal	0.47209	3.62583
2+	Side	0.80188	6.1002
2+	Rear-end	0.15117	2.00729
2+	Rollover	0.24525	5.79946

Data source: NASS-CDS, NHTSA

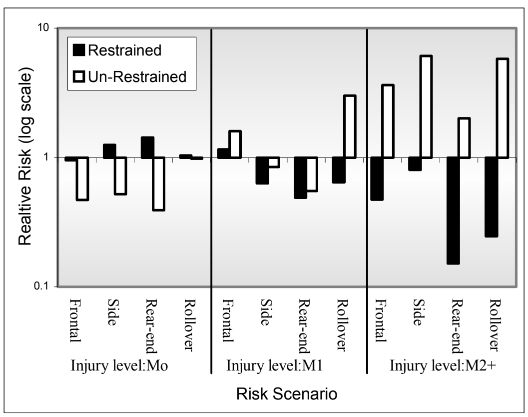

Figure 3. Risk scenarios and the associated Relative risks presented as bars for Restrained and Unrestrained children of ages 4 to 8 years.

4.4 Relative risk comparison of Restrained and Unrestrained 9 to 12 years old children

Table 4 shows risk factors and the corresponding relative risks for restrained and unrestrained children of ages 9 to 12 years old. These results are also presented in Figure 4. The relative risks (>1) of no injury: 1.07 in frontal, 1.13 in rear-end, and 1.45 in rollover crashes for the restrained group show that the restraint use provided protection against injuries to these children in frontal, rear-end, and rollover crashes. Also, the relative risk of sustaining injuries for these children in side impacts was higher for the unrestrained children.

The relative risks of minor injury in the case of frontal, side, and rollover crashes being smaller than 1, the restraint use was beneficial in these types of impacts. The relative risks of serious to moderate injuries: 0.81 in frontal, 0.87 in side, 0.68 in rear-end, and 0.79 in rollover crashes for the restrained group show that the restraint was protective for 9 to 12 years old children against moderate to serious injuries in these types of crashes

Table 4. Risk factors and the associated Relative risks for restrained and unrestrained children of ages 9 to 12 years.

RISK FACTOR		RELATIVE RISK (RR)	
MAIS	MAIS	RESTRAINED	UNRESTRAINED
0	Frontal	1.07126	0.67079
0	Side	0.88159	0.68854
0	Rear-end	1.12815	0.86815
0	Rollover	1.45299	0.27941
1	Frontal	0.98574	1.17309
1	Side	0.89873	2.6549
1	Rear-end	1.00757	0.53779
1	Rollover	0.51268	0.8082
2+	Frontal	0.81206	1.16263
2+	Side	0.87419	1.76099
2+	Rear-end	0.67774	0.75465
2+	Rollover	0.78829	5.36293

Data source: NASS-CDS, NHTSA

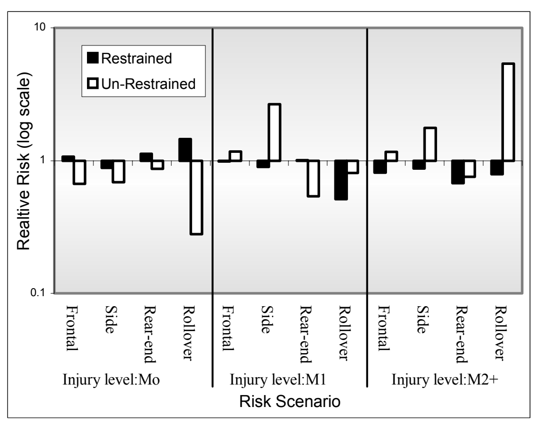

Figure 4. Risk scenarios and the associated Relative risks presented as bars for Restrained and Unrestrained children of ages 9 to 12 years.

5. IDENTIFICATION OF CLUSTERS WITH LIMITED DATA

Sample sizes in some of the 24 cells appeared to be small. However, whether a cell sample size is actually small depends on the purpose for which it is used. In the present context, the end objective is to compare injury risk to a restrained and unrestrained child under different risk scenarios. This was done by comparing the relative risks associated with the risk scenarios considered in this study. It is, therefore, important to precisely estimate RR. An important concept embodied in the confidence limits of an estimate is the precision of estimation. The wider the confidence interval, the less is its precision. This concept was exploited to assess the precision of RR for different configurations, using the width of the confidence limits as a yardstick for comparison. Using the normal approximation for the probability distribution of RR, defined in (5), the 95% confidence limits were computed for each of the four age groups. Figure 5 shows the lower and upper limits of RR associated with each configuration for the four age groups.

The results (width of the confidence interval) show that the sample sizes in segments: 11, 15, 18, 20, 22, 23, and 24 for age group $0 \leq Age < 1$; 15, 19, 22, 23, and 24 for age group $1 \leq Age \leq 3$; 11, 15, and 23 for age group $4 \leq Age \leq 8$; and 11, 15, 19, and 24 for age group $9 \leq Age \leq 12$ were not sufficiently large to precisely estimate RR. Therefore, care must be taken to interpret results for these scenarios.

6. CONFIGURAL FREQUENCYANALYSIS: STRNGTH OF FACTOR ASSOCIATION FOR EACH RISK SCENARIO

The multivariate analysis technique, Configural Frequency Analysis (CFA) was used to examine every configuration, i.e., risk scenario (e.g., an unrestrained child who suffered severe injury in frontal impact crash) to determine how close the observed frequencies are to the expected frequencies. A first order CFA model was used, meaning that the variables (factors) are totally independent of each other, i.e., they are assumed to be not associated in pairs or triplets in every configuration. However, main effects are assumed to exist. For this analysis, alpha, the significance level α, was set to 0.05, which after the

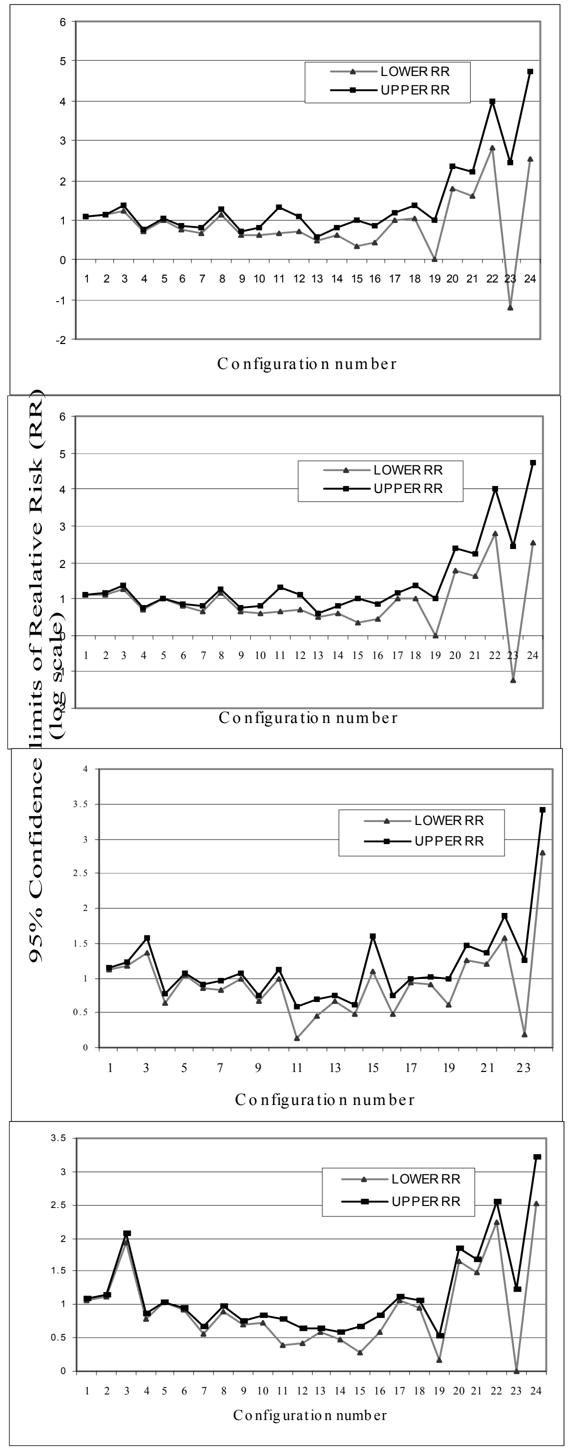

Figure 5. 95% confidence limits for 24 configurations in four age groups: infants, 1 to 3, 4 to 8, and 9 to 12 year olds.

Bonferroni adjustment reduces to $\alpha^* = 0.0021$, where $\alpha / \text{Number of configurations}$. Z-test (Standard normal test) was applied to determine if the deviation of an observed (N) frequency from an expected (E)

frequency is significantly large to conclude the presence of factor interaction for a risk scenario. Assuming $H_0 : N_{ijk} = E_{ijk}$ is true, the statistic

$$Z = \frac{N_{ijk} - E_{ijk}}{\sqrt{E_{ijk}}}, i = 1, 2, j = 1, 2, 3, k = 1, 2, 3, 4, \quad (7)$$

is distributed as standard normal. This test statistic will be used to test the hypothesis H_0 against the alternative H_A: $N_{ijk} \neq E_{ijk}$ meaning the presence of factor interaction for the ijk-th configuration. The results for four age groups of crash-involved children are presented in Table 5 through Table 8 that show risk scenarios and the corresponding Z- and p-values.

A positive or negative significant Z-value (with p-value smaller than $\alpha^* = 0.0021$) corresponding to a risk scenario is indicative of the presence of factor interaction in the corresponding cluster of children in an age group.

6.1 Risk factor association for Infants

Table 5 shows risk scenarios and the corresponding Z- and p-values for infant population. Comparison of p-values with the adjusted level of significance $\alpha^* = 0.0021$ shows that for all but one configuration, '111', the deviations are significant.

However, the configurations 111, 133, 134 in the restrained category and 213, 214, 222, 223, 224, 232, 233, and 234 in the unrestrained cases will be omitted from discussion of results due to insufficiency of their sample sizes, as assessed in the previous section. Significant positive values of Z for configurations 112 and 113 and significant negative Z-values for the configurations 121, 122, 131, and 132, show strong evidence in favor of the hypothesis $H_A : N_{ijk} \neq E_{ijk}$. This in turn means that in clusters of infant population as defined by these configurations, in addition to main effects, there is an evidence of significant interaction of the factors: restraint use, injury level, and crash impact mode.

Table. 5 95% Significance of difference between observed and expected frequencies of configurations and relative risk for infants

CONFIGU-RATION	RESTRAINT STATUS	MAIS	IMPACT	Z-VALUE	p-VALUE
111	Restrained	0	Frontal	2.8076	0.002
112	Restrained	0	Side	14.3067	0
113	Restrained	0	Rear-end	10.0471	0
114	Restrained	0	Rollover	-11.7849	0
121	Restrained	1	Frontal	-12.818	0
122	Restrained	1	Side	-18.3208	0
123	Restrained	1	Rear-end	-14.1039	0
124	Restrained	1	Rollover	14.2687	0
131	Restrained	2+	Frontal	-3.1204	0.0009
132	Restrained	2+	Side	-18.188	0
133	Restrained	2+	Rear-end	-8.3477	0
134	Restrained	2+	Rollover	8.0932	2.2E-16
211	Unrestrained	0	Frontal	-30.1682	0
212	Unrestrained	0	Side	-10.6158	0
213	Unrestrained	0	Rear-end	-10.3713	0
214	Unrestrained	0	Rollover	-22.0752	0
221	Unrestrained	1	Frontal	92.399	0
222	Unrestrained	1	Side	-17.2721	0
223	Unrestrained	1	Rear-end	-9.3571	0
224	Unrestrained	1	Rollover	73.0809	0
231	Unrestrained	2+	Frontal	31.4632	0
232	Unrestrained	2+	Side	-3.6221	0.0001
233	Unrestrained	2+	Rear-end	5.9959	1E-09
234	Unrestrained	2+	Rollover	93.315	0

Data source: NASS-CDS, NHTSA

6.2 Risk factor association for 1 to 3 year old children

Table 6 shows risk scenarios and the corresponding Z- and p-values for children in the age group: 1 to 3 years. Comparison of p-values with the adjusted level of significance $\alpha^* = 0.0021$ shows that the Z-values (positive or negative) for all configurations are significant. However, this inference for configurations 133, 213, 214, 223, 233, 234 is not based on sufficient sample size as shown in an earlier section. These configurations will therefore be excluded in the following discussion.

Following the same argument as for infants, significant positive Z-values for 111, 112, 113, 124 and significant negative value of Z for configurations 114, 121, 123

131, and 132 show strong evidence for significant factor interaction in clusters of 1 to 3 year olds population, as defined by these configurations.

Table. 6 95% Significance of difference between observed and expected frequencies of configurations and relative risk for 1 to 3 Years Old Children

CONFIGU-RATION	RESTRAINT STATUS	MAIS	IMPACT	Z-VALUE	p-VALUE
111	Restrained	0	Frontal	42.218	0
112	Restrained	0	Side	22.69	0
113	Restrained	0	Rear-end	21.45	0
114	Restrained	0	Rollover	-69.03	0
121	Restrained	1	Frontal	-29.098	0
122	Restrained	1	Side	-42.434	0
123	Restrained	1	Rear-end	-61.553	0
124	Restrained	1	Rollover	40.615	0
131	Restrained	2+	Frontal	-20.931	0
132	Restrained	2+	Side	-4.707	1.2E-06
133	Restrained	2+	Rear-end	-4.293	8.8E-06
134	Restrained	2+	Rollover	13.349	0
211	Unrestrained	0	Frontal	-103.239	0
212	Unrestrained	0	Side	-79.302	0
213	Unrestrained	0	Rear-end	54.368	0
214	Unrestrained	0	Rollover	-13.467	0
221	Unrestrained	1	Frontal	46.946	0
222	Unrestrained	1	Side	145.889	0
223	Unrestrained	1	Rear-end	-33.215	0
224	Unrestrained	1	Rollover	277.861	0
231	Unrestrained	2+	Frontal	14.901	0
232	Unrestrained	2+	Side	23.793	0
233	Unrestrained	2+	Rear-end	10.65	0
234	Unrestrained	2+	Rollover	81.742	0

Data source: NASS-CDS, NHTSA

6.3 Risk factor association for 4 to 8 years old children

Table 7 shows risk scenarios and the corresponding Z- and p-values for 4 to 8 year olds. Comparison of p-values with the adjusted level of significance $\alpha^* = 0.0021$ shows that only for configuration 214 the z-value is not significant. Of the remaining clusters, sample sizes for configurations 133, 213, and 233 are not large enough as established earlier. The results for all other risk scenarios in Table 7 show significant factor interaction in clusters of 4 to 8 year olds population.

Table 7. 95% Significance of difference between observed and expected frequencies of configurations and relative risk for 4 to 8 Years Old Children

CONFIGU-RATION	RESTRAINT STATUS	MAIS	IMPACT	Z - VALUE	p-VALUE
111	Restrained	0	Frontal	-25.665	0
112	Restrained	0	Side	90.224	0
113	Restrained	0	Rear-end	80.71	0
114	Restrained	0	Rollover	10.142	0
121	Restrained	1	Frontal	63.506	0
122	Restrained	1	Side	-95.484	0
123	Restrained	1	Rear-end	-70.239	0
124	Restrained	1	Rollover	-72.327	0
131	Restrained	2+	Frontal	-61.778	0
132	Restrained	2+	Side	-15.021	0
133	Restrained	2+	Rear-end	-34.032	0
134	Restrained	2+	Rollover	-44.836	0
211	Unrestrained	0	Frontal	-111.908	0
212	Unrestrained	0	Side	-65.616	0
213	Unrestrained	0	Rear-end	-44.058	0
214	Unrestrained	0	Rollover	-2.082	0.018
221	Unrestrained	1	Frontal	92.465	0
222	Unrestrained	1	Side	-15.661	0
223	Unrestrained	1	Rear-end	-23.687	0
224	Unrestrained	1	Rollover	156.776	0
231	Unrestrained	2+	Frontal	118.162	0
232	Unrestrained	2+	Side	148.697	0
233	Unrestrained	2+	Rear-end	15.529	0
234	Unrestrained	2+	Rollover	109.636	0

Data source: NASS-CDS, NHTSA

6.4 Risk factor association for 9 to 12 years old children

Table 8 shows risk scenarios and the corresponding Z- and p-values for crash involved children of ages 9 to 12 years. Comparison of p-values with the adjusted level of significance $\alpha^* = 0.0021$ shows that except configuration 123, the z-values for all configurations are significant. However, of the remaining clusters, clusters defined by configurations 133, 213, 223, and 234 have insufficient sample sizes. Thus, except for these clusters and the one corresponding to configuration 123, the factor interaction is significant.

Table 8. 95% Significance of the difference between observed and expected frequencies of configurations and relative risk for 9 to 12 Years Old Children

CONFIGU-RATION	RESTRAINT STATUS	MAIS	IMPACT	Z-VALUE	p-VALUE
111	Restrained	0	Frontal	28.41	0
112	Restrained	0	Side	-33.392	0
113	Restrained	0	Rear-end	24.125	0
114	Restrained	0	Rollover	93.482	0
121	Restrained	1	Frontal	-4.649	0
122	Restrained	1	Side	-23.353	0
123	Restrained	1	Rear-end	1.165	0.12208
124	Restrained	1	Rollover	-82.231	0
131	Restrained	2+	Frontal	-21.884	0
132	Restrained	2+	Side	-10.363	0
133	Restrained	2+	Rear-end	-17.72	0
134	Restrained	2+	Rollover	-12.761	0
211	Unrestrained	0	Frontal	-62.795	0
212	Unrestrained	0	Side	-42.024	0
213	Unrestrained	0	Rear-end	-11.876	0
214	Unrestrained	0	Rollover	-71.147	0
221	Unrestrained	1	Frontal	26.997	0
222	Unrestrained	1	Side	182.581	0
223	Unrestrained	1	Rear-end	-34.042	0
224	Unrestrained	1	Rollover	-15.485	0
231	Unrestrained	2+	Frontal	9.061	0
232	Unrestrained	2+	Side	29.99	0
233	Unrestrained	2+	Rear-end	-6.455	0
234	Unrestrained	2+	Rollover	125.82	0

Data source: NASS-CDS, NHTSA

7. DISCUSSION OF RESULTS

It is generally believed that an age appropriate restraint system, if used properly according to NHTSA's guidelines, 'Child Passenger Safety- A Parents primer' http://www.boosterseat.gov/CPSpostcard.pdf can provide protection to a child against different types of crash modes. Based on ten years of field data, this study statistically investigated how restrained and unrestrained children were injured in different crash modes. Preliminary statistical screening of the segmented data (based on age, restraint, injury, and impact mode) revealed that sample sizes in some sectors of the data were not large enough to statistically validate the findings. The reason for limited or insufficient data could either be the rare occurrence of certain risk factor combinations or the result of insufficient attention in collecting the pertinent data. This shows the necessity of collecting more data in such sectors of the data so that valid conclusions could be drawn about restraint systems effectiveness. The question, however, remains as to how much and how these sample sizes should be increased. The research on this issue is underway at NHTSA.

As regards the effectiveness of restraint use, it was found, in general, that for both infants and 1 to 3 year olds, restraint use was effective in all crash modes. For 4 to 8 year olds, being restrained was beneficial in side as well as rear-end impacts. The relative risk of injury to these children in frontal and rollover crashes was greater when they were unrestrained. The restrained 9 to 12 years old children were found safer against injuries in frontal, rear-end, and rollover crashes and had higher risk of injuries in side impacts. The results show the overall effectiveness of restraint use in protecting the children from different crash impacts. As minor injuries typically result from things, such as flying glass, interior surfaces, etc., a considerably large number of cases falling in the category of MAIS=1 shows success of CRS in protecting children.

The level of injury to a child may further depend on whether the frontal impact was full, offset, or center and side impact was near-side or far-side. Although accounting for these details was considered important while conducting this study, due to the resulting smaller cell sample sizes, the results could not be statistically validated. In addition, factors, such as impact speed and vehicle incompatibility are some of the vehicle related parameters that can be considered in the model.

8. REFERENCES

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THE FEASIBILITY OF AGE-BASED CRITERIA FOR CHILD RESTRAINT SELECTION

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ABSTRACT

Surveys of automotive child restraint use in various countries have repeatedly shown that many parents do not select the correct type of restraint for the child and lack knowledge about correct restraint selection. Advice to parents is based on the dimensions of the child, usually weight, but such prescriptions may be difficult for parents to remember, and parents often do not know the weight of their children. The child's age might be preferable for promotion and regulation because parents know it. Using a dataset of the distribution of children's weights at one-month intervals of age, and assuming that all children change from one restraint device to another at a particular age, we demonstrate the trade-off between the number of children too large for the smaller device and the number too small for the larger device. This is used to suggest an optimum transition age. The regulatory jurisdictions of Australasia, Europe and the United States of America are compared. The analysis shows that in Australasia, where there are currently significant overlaps in the weight ranges of each type of restraint, recommendations to make restraint transitions at 6 months and 4 years of age would mean that about 10% of all children under the age of 8 would be in a restraint unsuited to their weight. Corresponding figures for the European and United States Standards are 6% and 16%. Instead of battling to get parents to use child's weight as the criterion for restraint selection, it might be better to promote exact ages as the transition criteria, and to write the Standards for child restraints on the basis that this will happen.

INTRODUCTION

Surveys of automotive child restraint use show that children often graduate from one type of restraint to the next at too young an age. This is so whether we are referring to different types of child restraints, to belt-positioning booster seats, or to adult belts (Apsler et al., 2003; Brown et al., 2005; Durbin et al., 2001; Ebel et al., 2003a; Simpson et al., 2002).

Interventions to increase correct restraint use often contain an education element designed to increase knowledge about criteria for restraint selection and use (e.g. Apsler et al., 2003), and the Association for the Advancement of Automotive Medicine sees education as an integral part of a strategy to improve the safety of children in automotive crashes (Durbin et al., 2003). Efforts to instil knowledge in parents can lead to increased rates of correct restraint use (Ebel et al., 2003b). However, in the present paper, we take an alternative approach. We will accept that parents often do not know either the weight of their child, or the weight range for which a given restraint is suitable. But they do know the age of their child. Therefore we ask how serious it would be – in terms of the number of children inappropriately restrained – if restraint selection were based on child's age, not weight.

There are two kinds of error that may occur in the restraint selection process: a child in restraint type A when they have outgrown it, or one who has progressed to restraint type B while still too small. For a given specification of the restraint in terms of the child's weight, an age-based transition will involve a trade-off between these two types of error.

The next Section will give some further introduction to the Standards for child restraints and to the strategies for promoting their use that have been adopted by various jurisdictions. Then a methods Section will describe the calculation of the numbers of children who would fall outside the weight ranges of the Standards, were graduation from one restraint to another to occur at a particular age. This calculation is based upon published data on the weights of children of different ages. Then come results, discussion and conclusions Sections.

RESTRAINT STANDARDS AND ADVICE TO PARENTS

Whether or not a selection error has occurred is determined by a combination of the child's size (usually weight) and the standard under which the restraint was designed and manufactured. All child restraint standards are written to require restraints of a certain class to adequately protect children of a certain size range. Table 1 shows the classification of major restraint types in several standards used in the USA, the EU and Australia/New Zealand. FMVSS 213 is does not explicitly categorise restraints in the way that UN ECE R44 and AS/NZS 1754 do. However, the weight categories listed in Table 1 reflect the most straightforward interpretation of FMVSS 213.

Notable in the various standards is the fact that restraint requirements are defined in terms of weight, and sometimes height (not listed in Table 1), rather than age. The logic of this is seemingly obvious given that the requirements of a design standard are engineering ones, and that manufacturers must ensure that their products can adequately protect children of the relevant sizes. But while the objective of any design standard on child restraints is to ensure adequate levels of protection offered by a compliant restraint, the objective of promotion and education is rather different: it is to assist in maximising the rate of correct restraint selection and use.

Restraint promotion aims to improve compliance. Practices vary from country to country. For example, the (U.S.) website BoosterSeat.gov suggests promoting children from infant carriers after they are 12 months of age, from a forward facing child restraint at 40 pounds weight and from a booster at 8 years. Recent practice in Australia has been to promote use on the basis of the child's weight, in a way that clearly represents the criteria contained within the applicable Australian Standard. In Australia, age-based recommendations on child restraint transition have fallen out of favour, and the most important factor was the perception that age is too crude a proxy for the dimensions of a child that really matter in relation to appropriate restraint fit.

However, AS/NZS 1754 specifies overlaps in weight between restraint types. The intent of this might have been to allow all children to graduate to a restraint at a similar age, with the lower and upper ends of the weight range chosen to cater for the smallest and largest children graduating to that restraint at the specified transition age. (And if that was not the intent, at least it is a coherent strategy.) If so, the consequence of promoting restraint use on the basis of age, in conjunction with a well-coordinated design standard, should be that relatively few children beyond the low or high end of each weight range should be using any particular class of restraint. Promoting the weight ranges themselves may in fact be inconsistent with one of the purposes of such design standards, given the pressure from children themselves to graduate from something that is more babyish to something that is more adult.

Some aspects of the promotion of restraint selection based on the child's weight are advantageous: the advice is a straight rendering of the relevant design standard, and variation in children's sizes by age becomes irrelevant.

However, there are also disadvantages to weight-based promotion and advantages to age-based promotion.

Firstly, where overlapping weight ranges exist and are promoted, advice is ambiguous and might be confusing: where within the transitional weight range should the transition to the next restraint be made? It is possible that such advice might, because of its ambiguity, encourage transition at too early a stage – as children typically want! And there is empirical evidence that the advice is not memorable. A recent survey in Adelaide, Australia, found that the large majority of respondents could not cite the weight criteria (Edwards et al., 2006).

Secondly, surveys of restraint use have found that

Table 1.
Weight ranges by restraint categories in child restraint Standards

Restraint type	FMVSS 213[1]	UN ECE R44.04	AS/NZS 1754:2004
Infant restraint	0-10 kg	0-10 or 13 kg[2]	0-9 kg
Forward facing child restraint	10-18 kg	9-18 kg	8-18 kg
Larger restraint/booster seat	18-29.5 kg	15-36 kg[3]	14-26 kg

[1] FMVSS 213 does not strictly categorise seat types except for infant-only restraints. Rather, weight specifications for individual seat models determine what dummies should be used for compliance testing. And concerning the upper weight limit of the booster seat, this has been inferred from the requirement of the seat to accommodate a weighted 6-year-old dummy in a dynamic test (NHTSA, 2006). (Models of seat rated to well beyond the limit are available in the US market, and hence 29.5 kg represents a conservative upper limit for booster seat use in the USA.)
[2] Two types specified: Group 0 and Group 0+
[3] Seats fitting into Group 2 and Group 3

many parents do not know even the approximate weightes of their children (Apsler et al., 2003; Edwards et al., 2006). Quite low skill of parents in estimating the weight of their children is also documented in the context of deciding upon an appropriate dosage of medication (Leffler and Hayes, 1997; Goldman et al., 1999; Harris et al., 1999). An average figure from that literature is that parents are in error by more than 10 per cent in 27 per cent of cases. In a similar vein, child restraint surveys also find that many drivers are unable to suggest the height of the children they are transporting (Edwards et al., 2006; Ebel et al., 2003a). To follow weight and height guidelines, parents would need to regularly monitor the weight and height of their children (which in turn necessitates having the tools at their disposal to do so).

Thirdly, it may be easier for the parent to get the child to accept waiting until a concrete figure such as 4 years, rather than the ill-defined moment implicit at the present. (With the present concern over childhood obesity, it is obviously unacceptable for the concrete figure to take the form of a weight.)

Criteria for restraint transition should be simple, definite, and memorable (e.g. 12 months, 4 years and 8 years). This would make promotion of child restraints and the specification and enforcement of legislation easier than at present.

However, there would be some negative consequences of using age-based recommendations, and these should be quantified. It is unlikely that every child would be catered for and the smallest and the largest children might be misclassified by such an approach. The level of misclassification depends upon the relevant design standard, the age chosen for transition from one restraint type to another and the distribution of weights (and other dimensions) at various ages. The following analysis quantifies the misclassification with respect to weight that would arise using age-based advice.

METHODS

Anthropometric data

A convenient source of data on the distribution of children's weights is provided by the U.S. Centers for Disease Control and Prevention (Ogden et al., 2002), which is based on the US National Health and Nutrition Examination Survey (http://www.cdc.gov/nchs/nhanes.htm). This source is easy to use because it summarises the weights of each one-month age cohort using three parameters.. Although the dataset describes children in the USA, it is also used in Australia as a reference for normal growth patterns in children (Department of Human Services, State Government of Victoria, 2006). It could be replaced by data from other jurisdictions if required.

Summary of each weight distribution is by the LMS method (Cole, 1990). For each one-month age cohort of surveyed children, Ogden et al. (2002) calculated three parameters: the coefficient of the Box-Cox transformation (L), which transforms the data to a nearly normal distribution, the median (M) and the generalised coefficient of variation (S). For a given weight u, the proportion of children of a certain age, weighing more or less than u, can be obtained by determining the z-score corresponding to the age cohort i. Given L, M and S, the z-score is given by

$$z = [(u/M)^L - 1]/LS \qquad (2)$$

After calculating z, it is straightforward to find the proportions that lie either side of u, using statistical tables or a computer package. These proportions are the functions $F_i(u)$ and $1 - F_i(u)$.

The growth data from the CDC is tabulated separately for boys and for girls, and so proportions are calculated for girls and boys, then averaged.

Trade-off analysis

We envisage a sharp age transition between restraint types, not a band of ages (because, children being what they are, this will degenerate to the youngest age in the band). We will examine the numbers of children who would be in the wrong restraint for their weight. To do this, we use a dataset giving the distribution of weight amongst the population of male and female children at each month of life. For each potential transition age, we calculate the number of children that would be in the wrong restraint (misclassified) according to their weight: those under the transition age but too large for the pre-transition restraint, and those over the transition age but too small for the post-transition restraint. Any choice of a transition age will entail a trade-off between the two classes of misclassification, but an age can be chosen that minimises their sum. We shall examine these numbers in relation to the three design standards given in Table 1: FMVSS 213, UN ECE R44.04 and AS/NZS 1743:2004.

Consider the following situation.

- A child progresses from one restraint (device A) to a larger restraint (device B) at some well-defined and precise age y.
- The relevant design standard is written to ensure that A is satisfactory for children

who have a dimensional value (e.g. weight) of $u = a$ or less.

- Similarly, B is satisfactory for a child with a dimensional value of $u = b$ or greater.

Note that b may be less than a, providing some transitional overlap. However, the overlap may be non-existent ($a = b$) or even negative ($a < b$).

Our notation will be that the proportion of children with a dimensional value less than u within the age cohort i is $F_i(u)$. The convention we shall adopt is that a child in their ith month of life is in the one-month cohort i. The transition between restraint types occurs at the end of month y. (For example, a transition at 6 months of age occurs at the end of a child's 6th month of life.)

If all children progress from the first restraint to the second at age y, the number of children in an "incorrect" restraint, P, is given by

$$P = \sum_{i=0}^{y} 1 - F_i(a) + \sum_{i=y+1}^{\infty} F_i(b) \qquad (1)$$

The total number of children misclassified (in units of the number of children in a month cohort) is the sum of children that are aged less than y that are too large for A, and those that are aged more than y that are too small for B. Hence, P in Equation 1 describes the total misclassification, while the two sums refer to the number of children using A who are too large and the number of children using B who are too small. These quantities are illustrated in Figure 1.

It is possible to determine P and its two components for different choices of the transition age y. The two sums, representing the number of children too large for A and the number of children too small for B, represent the trade-off that must be made if restraint transition is to be made at a certain age. Plotting one sum against the other shows how the trade-off is affected by the choice of transition age and indicates the age at which the total P is minimised. The trade-off graph is illustrated in Figure 2.

We assume that for children of weight less than a, restraint A is satisfactory. Further, that for children of weight greater than a, restraint A is unsatisfactory. And we assume a sharp change for B also. This is unrealistic; it is likely that "satisfactory" is correct and "unsatisfactory" is an exaggeration, and thus our results will overstate the true number of inappropriately restrained children. However, it is not the aim here to examine actual rates of so-called appropriate restraint use that might ensue from age-based transitions, but to examine how children's weights would comply with restraint specifications.

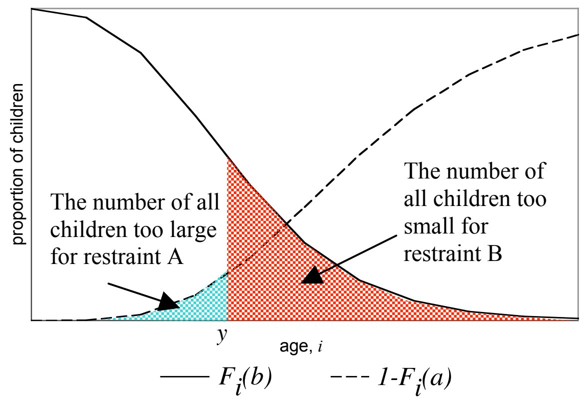

Figure 1. The shaded area is the total number of children that would be misclassified (according to their size) into restraints A and B, if all children were to move from restraint A to restraint B at age *y*.

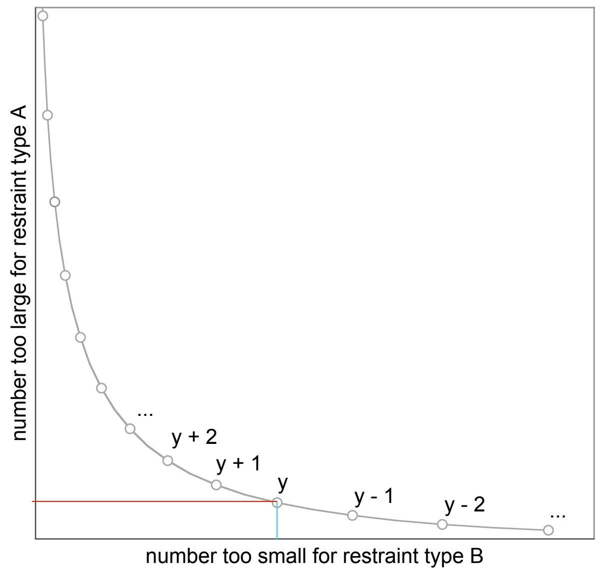

Figure 2. The trade-off graph showing the two proportions shaded in Figure 1 plotted against one another for different values of the transition age *y* (in months).

Incidentally, it not necessary that a and b describe the same dimension: one may describe weight, and the other seated height or any other relevant measurement. All that is required is knowledge of the distribution of the dimension at different ages.

An extended interpretation of Equation 1

When considering the effects of misclassification, the following two assumptions make a natural starting point.

- There is a sharp change from a restraint being satisfactory to being unsatisfactory if the child is fractionally too small or too large was assumed.
- Being too big for device A and being too small for device B are equally serious.

We will express our results above in terms of the numbers of children of an age range who fall outside the specification of a restraint, and thus are misclassified by age to an inappropriate restraint type. The above assumptions will thus be by-passed. Nevertheless, let us sketch how they may be relaxed, so that the effects of misclassification could be studied. This may be done by introducing the idea of a misfit penalty function.

For device A, let the penalty from misfit be a non-decreasing function of child's dimension u, $M_A(u)$, for $u > a$ and 0 for $u < a$. And for device B, it is a non-increasing function of u, $M_B(u)$, for $u < b$ and 0 for $u > b$. Earlier, in writing Equation 1, $M_A(u)$ and $M_B(u)$ were in effect both taken as 1. The total misfit for children younger than y but bigger than a is the sum over all weights bigger than a and all ages younger than y of the product $f_i(u)M_A(u)$, where $f_i(u)$ is the proportion of children of age i who are of weight u. Similarly, the total misfit for children older than y but smaller than b is the sum over all weights less than b and all ages older than y of the product $f_i(u)M_B(u)$. A trade-off graph similar to Figure 2 could be obtained by making several different choices of y.

Ideally, M_A and M_B would reflect the increase in risk associated with being too small or too big for the restraint, but this probably goes beyond what current data can support.

RESULTS

Transition from infant restraints to forward facing child restraints

AS/NZS 1754:2004 requires infant restraints to satisfactorily restrain children from birth to 9 kg in weight. It requires forward facing child restraints to satisfactorily restrain children whose weight lies in the range of 8 to 18 kg. Therefore, to examine the transition from infant restraints to forward facing child restraints we calculate P by setting $a = 9$ kg and $b = 8$ kg.

UN ECE R44,04 differs from AS/NZS 1754 in that infant restraints built under those standards are required to accommodate children to 10 kg, and forward facing child restraints from 9 kg. For this standard, P will be calculated by setting $a = 10$ kg and $b = 9$ kg.

FMVSS 213 is less prescriptive about restraint classes. However, we believe the usual interpretation is that infants should be transported in rear facing infant restraints to 22 pounds and in forward facing car child restraints from 22 pounds to 40 pounds.

Note that both AS/NZS 1754 and UN ECE R44.04 nominate a one-kilogram overlap weight range, while U.S. practice provides an exact transition weight and no range.

The results of the trade-off analysis are shown in Figure 3. It shows the number of children less than b kg ($F_i(b)$) plotted against those greater than a kg ($1 - F_i(a)$), for various transition ages. The three lines correspond to AS/NZS 1754, UN ECE R44.04 and FMVSS 213.

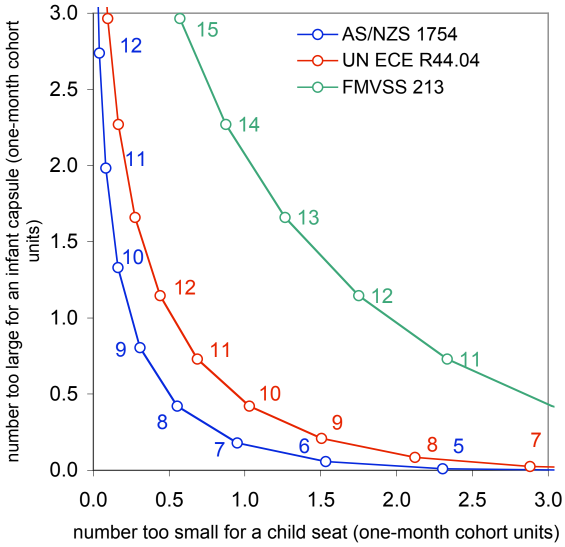

Figure 3. Trade-off graph for age-based transitions from an infant carrier to forward facing child restraint. The data points are labelled with the transition age (months). The three lines refer to (from bottom to top) Australia (*b* = 8 kg, *a* = 9 kg), the EU (*b* = 10 kg, *a* = 9 kg) and the US (*a* = *b* = 10 kg).

To illustrate the utility of this Figure, consider a recommendation under AS/NZS 1754 to move children from an infant restraint to a forward facing child restraint at 6 months of age. Figure 3 shows that a very small number will have exceeded the upper weight limit of the infant carrier at this stage; it is a number equivalent to 0.06 of a one-month cohort of children. On the other hand, a larger number of children do not satisfy the minimum weight specified for a forward facing child restraint: a number equivalent to 1.5 one-month cohorts of children are not yet heavy enough. It might also be seen from Figure 3 that about one-third of these children will not reach the minimum weight after a further 2 months, but very few are still too light at 11 months of age.

If the calculations could be performed for transition ages of fractional months, each line in Figure 3 would be a smooth curve and the optimum would be where its slope equals –1. For AS/NZS 1754, this is evidently at about 8 months of age. Changing the transition age from 6 months to 8 months would theoretically reduce the number of children in forward facing child restraints who are too light by two-thirds. The trade-off would be an increase in the number of children in infant restraints that exceed the upper weight limit. The total misclassification (the number in the wrong restraint for their weight) for a transition at 8 months of age would be equivalent to a single one-month cohort. For 6 months it is 1.5 one-month cohorts.

Now consider the range 9-10 kg specified by UN ECE R44.04. It may be noted that:

- The optimum transition age given the specifications in UN ECE R44.04 is 11 months, rather than 8 months under AS/NZS 1754.
- The total number of children in the incorrect restraint, *P*, is equivalent to 1.4 one-month cohorts. Transition ages of 10 months and 12 months produce similar numbers for *P* (1.5 and 1.6).
- Overall, the trade-off line for UN ECE R44.04 lies to the right of, and above, the trade-off line for AS/NZS 1754, despite both Standards specifying a one-kilogram overlap of weights. This is because the variance of the weights of a cohort of children increases as they get older. Hence a greater overlap of weights is required for a higher transition age, *y*.

Age transition at 12 months under UN ECE R44.04 would mean that 1.15 one-month cohorts would be too large for their restraint. Of children in forward facing child restraints, 0.44 one-month cohorts would be under 9 kg, but the majority of these children would become 9 kg or greater within two months.

Finally, in the line in Figure 3 representing FMVSS 213, we can see the effect of providing no weight overlap. Because FMVSS 213 and UN ECE R44.04 specify the same upper weight limit (10 kg) the ordinate value for each transition age is the same under each Standard. However the abscissa values of the transitions ages are different. For example, given a transition age of 12 months under FMVSS 213, the number of children occupying forward facing child seat that are too light for the seat is three times the number under UN ECE R44.04.

- The optimum transition age given the specifications in FMVSS 213 is 12 months.
- The total number of children in the incorrect restraint, *P*, is equivalent to 2.9 one-month cohorts.

Transition from forward facing child restraints to booster seats

As mentioned above, as a cohort of children age, the variance in their weights increases and so we should expect an age-based transition from the forward facing child restraint to a booster seat to require a larger overlap than the transition from an infant carrier to a forward facing child restraint. Overlap of specifications for a forward facing child restraint and a booster seat differs from one standard to another: 14-18 kg in AS 1754, 15-18 kg in UN ECE R44 and no overlap with FMVSS 213. Figure 4 shows the number of children less than *b* kg ($F_i(b)$) plotted against those greater than *a* kg ($1 - F_i(a)$), for various transition ages. The three lines correspond to AS/NZS 1754 ($b = 14$, $a = 18$ kg) UN ECE R44.04 ($b = 15$ kg, $a = 18$ kg) and FMVSS 213 ($a = b = 18$ kg).

The optimum age transitions, where *P* is minimised, are close to 4 years (48 months) for AS 1754 and UN ECE R44.04. For FMVSS 213, the optimum is close to 5 years of age (60 months), and it is clear that *P* is much larger for FMVSS 213 specifications than for the other two Standards. About five times as many children would be misclassified for an age based transition under FMVSS 213 as under AS/NZS 1754. Note also that advice mentioning the use of forward facing child seats to 4 years of age (e.g. NHTSA, 2005) is not consistent with FMVSS 213, as many more children are below 18 kg than over 18 kg at this age. The value of *P* under each Standard is as follows:

FMVSS 213 $P_{y=60}$ = 10.4 one-month cohorts
UN ECE R44.04 $P_{y=48}$ = 3.4 one-month cohorts
AS/NZS 1754 $P_{y=48}$ = 1.9 one-month cohorts

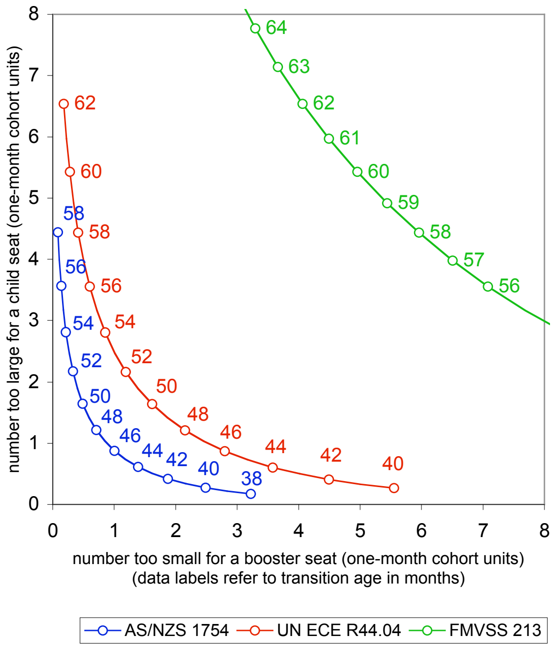

Figure 4. Trade-off graph for age-based transitions from a forward facing child restraint to a booster seat. The data points are labelled with the transition age (months). The three lines refer to (from bottom to top) Australia (b = 14 kg, a = 18 kg), the EU (b = 15, a = 18 kg) and the US (a = b = 18 kg).

Transition from booster seat to adult seat belt

The transition from use of a booster seat to use of an adult seat belt is a subject that may have been given less attention than it deserves, with Standards for child and adult restraints not being fully coordinated with one another. However, we have not conducted a trade-off analysis for this as the design and specification of the adult seat belt is outside the scope of the three child restraint Standards considered in this paper.

Summarising the effect of aged based transitions

Having estimated separately the errors resulting from age-based transitions between infant carriers and forward facing child restraints, and between forward facing child restraints and booster seats, we now summarise the effect and examine the temporal course of misclassification errors. The stage at which a child should cease use of a booster seat is unclear, and may depend of the geometry of the adult restraint specific to the vehicle, but 8 years of age is often used as a guideline. Hence we will examine the error up to that age.

It is straightforward to estimate the proportion of children at each age that exceed the upper weight specification of the booster seat under each Standard by just considering the sum 1 - $F_i(a)$. The value of a (the upper weight specification) for booster seats is 26 kg under AS/NZS 1754 (currently under review) and 32 kg under UN ECE R44.04. The application of FMVSS 213 extends to children weighing 65 pounds or 29.5 kg (some models of restraints may accommodate children of a higher weight).

Figure 5 shows the error for each month cohort, when child restraint selection is made on the basis of the ages indicated. Included in this Figure are those children under 8 years of age who are heavier than the upper weight specification of the booster seat.

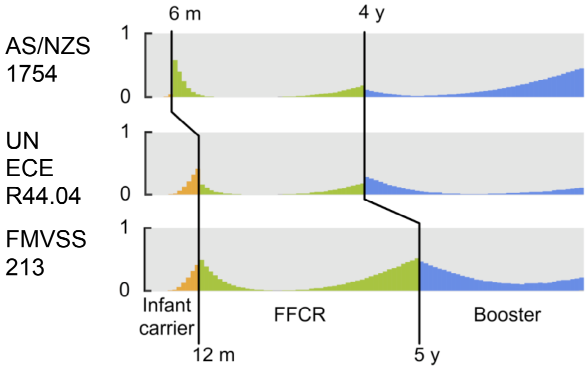

Figure 5. Proportion of each one-month cohort misclassified (too heavy or too light) under the three Standards AS/NZS 1754, UN ECE R44.04, and FMVSS 213, for restraint transitions at the ages indicated (months of life), for all children aged 0-8 years.

In interpreting Figure 5, note that the population to 8 years of age is represented by the area of the shaded boxes, and the coloured areas represent the proportion of the population incorrectly classified to the restraint type. The numbers of children represented by the coloured areas in Figure 5 are given in Table 2, while the proportion of children correctly restrained (represented by the remaining grey area in Figure 5) is given in Table 3.

Table 2.
Number of children (in one-month cohorts) misclassified to child restraint types according to their weight, when transitions are made on the basis of age

Standard	Transition ages	Number misclassified							Percentage of children under 8
		Infant carrier		Child seat		Booster seat		Total	
		Type of misclassification							
		Too light	Too heavy	Too light	Too heavy	Too light	Too heavy		
AS/NZS 1754	6 m, 4 y, 8y	-	0.06	1.53	1.21	0.71	6.28	9.79	10.2%
UN ECE R44	12 m, 4 y, 8 y	-	1.15	0.44	1.21	2.15	1.13	6.08	6.3%
FMVSS 213	12 m, 5 y, 8 y	-	1.15	1.75	5.43	4.96	2.32	15.61	16.3%

Table 3.
Proportion of children in each restraint type who are in the correct mass range, when transitions are made on the basis of ages

Standard	Transition ages	Proportions correctly classified by restraint type			Proportion of children under 8
		Infant carrier	Child seat	Booster seat	
AS/NZS 1754	6 m, 4 y, 8 y	99.0%	93.5%	85.4%	89.8%
UN ECE R44	12 m, 4 y, 8 y	90.4%	95.4%	93.2%	93.7%
FMVSS 213	12 m, 5 y, 8 y	90.4%	85.0%	84.8%	83.7%

DISCUSSION

The ability of age-based transitions to classify children into the correct restraint differs across the three design standards considered in this analysis. The average error ranges from 6.3% of the relevant population (UN ECE R44.04) to 16.3% (FMVSS 213), though the latter estimate is somewhat pessimistic as many models of booster are rated to beyond 29.5 kg. The average errors are not high, although the peaks in the temporal error, occurring around the transition ages can be much higher – up to 50% of a one-month cohort in the case of FMVSS 213 where there is no overlap of weight range between restraint types. It has not been the purpose of this analysis to make conclusions on the increase in risk this error would represent. Rather, we are examining how the compliance of children with seat weight specifications would be affected by recommending a transition on the basis of their age. That is, our purpose has been to explore the consequences of age-based transitions, rather than to positively advocate them. Many children incorrectly classified to restraint types are within 1 or 2 kg of the limit of the weight specification, and it is unlikely that these children are unprotected by their restraints. Noting the transient nature of the error (children growing into the restraint, or graduating to a more advanced restraint), it is unlikely that the increase in risk over the first eight years of life would be substantial.

The differences in the error between restraint types mean that advice to use or refrain from using age in restraint advice is not necessarily transferable between jurisdictions. For example, if a recommendation were to be made to parents to move their children to a booster seat at age 4 in Australia, the consequence for correct restraint selection would be rather different from a similar piece of advice recommending restraint transition at 5 years of age in the United States.

To balance, and perhaps outweigh, the error that age-based transitions produce, two further factors should be considered.

- First, children who obviously outgrow their restraints before the transition age may be graduated to the next restraint by their parents earlier, thus limiting the extent of the problem.

- Second, and more central to this analysis, is the current high rate of incorrect restraint selection that is reported in nearly all surveys of restraint use. Even in Australia where age-based promotion is discouraged, parents consistently and naturally want to nominate an age to identify the stage at which to make the transition from one restraint to the next. And many of those who know weight and height are important are unable to report the size of the relevant dimensions contained in recommendations.

The transition ages we have chosen to examine in this analysis were 6 months, 12 months, 4 years and 5 years. In some cases these do not exactly align with the optimum age for the weight specifications of each kind of seat. However, if age advice is to be given, it seems reasonable to choose ages that are simple to remember. Any improvements that might be gained by recommending a less memorable transition age would probably be negated by a lower rate of compliance.

Weight is not the sole determinant of correct restraint fit, but the analysis here may be repeated with other anthropometric dimensions to guide all aspects of restraint design. For example, if the distribution of seated shoulder height were known as a function of age in the population, a trade-off analysis could be performed to examine the minimum and maximum slot heights for the shoulder belt harness.

The analysis has taken the Standard as given, and has examined the effect of age-based transitions. A further step would be to take an aged-based transition as given (e.g. at 4 years), and quantify the effect of different overlaps in the Standards. This would remove some of the factors that make it difficult for parents to comply with restraint guidelines, and shift the task to the engineer who is designing the seat. We propose that it should therefore be possible to decide on a simple message for parents – transition on the basis of age – and to then create a design standard to accommodate the large majority of children who complied with the recommendation.

We should also note that a similar method of analysing trade-offs between two types of error could conceivably be applied outside of the child restraint context – to child-proof gates for swimming pools (given the distributions of heights of children and adults), or to child-proof caps for medicine bottles (given the distributions of strengths of children and adults).

CONCLUSIONS

- The consequences for recommending transition on the basis of age are different depending on which standard applies.
- In all cases, the average error is low – 16.3% of children under 8 years of age would be incorrectly specified to their restraint type under FMVSS 213. Lower error rates are produced by specifications AS/NZS 1754 and UN ECE R44.04.
- Even small increases in the overlap of weight ranges specified for restraint types can drastically reduce the error.
- It is possible to use age as the transition criterion if the Standard is designed to support it.
- Overlap of weight ranges optimised for a given age transition can mean that age based transitions can be used with confidence, opening up possibilities for improved promotion, compliance, regulation and enforcement.
- The trade-off analysis presented here may be applied to other anthropometric measures.

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REAR SEAT FRONTAL IMPACT PROTECTION FOR CHILDREN SEATED ON BOOSTER CUSHIONS – AN ATTITUDE, HANDLING AND SAFETY APPROACH

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ABSTRACT

Real-life data has shown that booster cushions are highly beneficial to belted children, but misuse and non-use problems remain. Furthermore, the rear seat belt system may be optimized for both children and adults.

The aim of this study was to evaluate protection concepts offering benefits in from of attitudes, handling and safety perspectives, for children seated on booster cushions.

Focus groups, observations and sled tests were performed. Initially, focus groups consisting of 16 children aged 7-8 years discussed the use of booster cushions. Seven children and their parents were then observed buckling up in a car using an integrated booster cushion and an aftermarket booster cushion. Lastly, sled tests were conducted with a Hybrid III 6 year old dummy seated on different booster cushions and restrained by various seat belt systems, including belt load limiting and pretensioning.

It was found that children wanted to use booster cushions for safety and comfort, but perceived the use of booster cushions as childish. Parents motivated non-use due to inconvenience.

The handling study showed that adults felt secure when handling the integrated booster cushion because it could only be unfolded in one way. Integration facilitated buckling up. Furthermore, it was stable when entering or leaving the car. Misuse was detected for most children when using the aftermarket booster cushion as opposed to only one case of minor misuse with the integrated version.

The sled tests with retractors with belt load limiting and pretensioning resulted in reduced head, neck and chest loading as well as forward displacement.

By using an attitude, handling and safety approach, the combination of integrated booster cushion, belt pretensioning and load limiting would increase appropriate usage of restraints, decrease dummy injury values and keep forward displacement, thereby saving rear seat occupant lives.

INTRODUCTION

Occupants of all ages and sizes can be seated in the rear seat. Due to the presence of frontal airbags in the front seat, the rear seat might be the only available space for children in the car. Cuerden et al. (1997) found that children, females and older occupants sat oftener in the rear seat compared to the front seat. Smith et al. (2004) found in NASS-CDS data that 62% of all rear seat occupants were less than 15 years of age. Swedish data showed that 50% of all rear seat occupants were children (Krafft, 1989).

Although children have a lower risk of injury or death compared to adults (PCPS, 2006), motor vehicle accidents were the leading cause of death in children over three years of age in the US (Subramanian, 2005). There is a need for continuous improvement of the safety for rear seat occupants. The challenge is to design a restraint system for the rear seat suited to the wide range of occupants.

Booster cushions – use, misuse and non-use

At approximately 4 years of age, children should stop using child safety seats (forward or rearward seats with internal harnesses) and begin using booster cushions or booster seats (a booster cushion with back). It is recommended to continue using a booster cushion until approximately 10-12 years of age (NHTSA, Swedish Road Administration). The European Union has decided that by 2006 all concerned countries in Europe should have introduced a new law enforcing children shorter than 135 cm to be restrained with additional protective equipment such as infant seats, child safety seats or booster seats/cushions (European Directive, 2003). A child of 133 cm corresponds to a 50th percentile of 9 year olds (Pheasant, 2001).

Durbin et al. (2003) showed that the injury risk for children aged 4-8 years was reduced by 59% when seated on a booster cushion compared to a seat belt only. In the same study, seat belt syndrome related injuries to abdomen and spine were nearly completely eliminated in accidents with children seated on booster cushions/seats compared to only seat belts.

It could be assumed that parents perceive the booster cushion as much easier to use and handle compared to forward/rearward facing child safety seats, since the seat and the child are buckled up simultaneously by the seat belt in one handling sequence. Observation studies confirmed a higher misuse rate (80%) with child safety seats compared to booster seats (39%) (NHTSA, 2004). Still, there remain problems with non-use and misuse of booster cushions.

In a study by NHTSA (2004), critical child restraint system (CRS) misuse was identified by a number of experts. The parameters applicable to booster cushions were: Age and weight inappropriateness of CRS, placement of CRS in relation to airbag, installation and secureness of CRS to the vehicle seat (tight seat belt), fit of vehicle seat belts across child in belt-positioning booster seat, and defective or broken CRS elements. The same study showed that the most common misuse of booster cushions were improper fit of shoulder belt (21%), loose seat belt (16%), improper fit of lap belt (10%), and age/fit inappropriateness (9%). A study by the European CHILD project (Willis et al., 2006) showed a misuse rate of 67% among booster cushions, where belt routing problems over the guiding loops was the main problem (25%), followed by belt twisting (20%) and belt behind the back (16%), using French data.

Recently, Partners for Child Passenger Safety (2006) showed how restraint use by age group 4-8 has increased from 15% in 1999 to 54% in 2005 in the USA. Although, there has been considerable improvement, a large proportion of children 4-8 and 9-12 years old are still inappropriately restrained by seat belt alone.

Several studies have been carried out to determine the reasons for using or not using booster cushions. Bingham et al. (2005) performed a survey with 350 parents of 4 to 8 year-olds. The majority (93%) understood that booster cushions reduced the risk of injury, but 37% of parents said they would not use the booster cushion for short trips. Reasons for using booster cushions were safety, comfort, control of the child and enabling the child to see out of the car. The most common reasons for part-time non-usage were that the child rode with others, was in a hurry, and was too big or just refused to use the booster cushion. For the question “What would make booster seat use easier?” several test subjects answered; “built-in seat”, “required by law”, “everyone using it” and “the child likes it”.

Similar findings were observed by Charlton et al. (2006) in their Australian questionnaire study to parents of children aged 4-11 years. The most frequent reasons for non-usage were that the child was too big, followed by the child disliked the booster cushions or were more comfortable in a seat belt only and that they were too “grown-up”.

Most studies of booster-use attitudes have been directed towards adults, thus giving limited knowledge of children’s attitudes towards the use of booster cushions and how they handle the booster cushions.

Crash safety

Over time, vehicle structures have become stiffer (Swanson et al. 2003) resulting in less intrusion and decreased injury values. In addition, front seat protection nowadays normally includes pretensioners, load limiters and airbags. In the rear seat functions such as pretensioner and load limiters are rarely included.

Until now, real-life data has shown rear seats to be safer than front seats (Braver, 1998). However, Kuppa et al. (2005) showed in a double paired comparison of FARS data that occupants older than 50 were significantly more effectively restrained in the front seat than in rear seat. A new analysis of the same data by Kuppa (2006) showed a new trend that the rear seat was less safe than the front seat in newer car models (year model 1999-2005) compared to older car models (year model 1991-1998) This new trend was also recognized in British data by Welsh et al. (2006) in a study comparing older car models with younger car models (1998 and later).

Aim of the study

The aim of this study was to evaluate protection concepts offering benefits, in form of attitudes, handling and safety perspectives, for children seated in booster cushions.

The study was limited to occupants aged 6 to 8 years. This age group should be directly restrained by the seat belt seated on a booster seat/cushion.

METHODS

The study was divided into three parts: attitude, handling and safety. The bulk of the safety study (sled tests) were published previously (Bohman et al., 2006).

In the attitude and handling studies children of 7 to 8 years were participating. This is a critical age when children stop using booster cushions (PCPS, 2006), despite a continued need for them.

Attitude study

The attitudes towards usage of booster cushions were studied by using three focus groups with a total 16 children at 7-8 years of age. Each group discussion lasted for about one hour. Reasons for use and non-use were identified. The study took place at the children’s primary school.

Handling study

In a handling study, 7 children (7-8 years) together with a parent were observed when buckling up in a real car in a laboratory environment. Two different booster cushions were used: an integrated booster cushion (IBC) with one elevated height (Volvo V70, year model 2005) and an aftermarket booster cushion (BC1) (Kid, Britax) (figure 1). This particular booster cushion offered better comfort with thicker padding compared to many aftermarket booster cushions. It also has a well defined belt routing path with red markings under the guiding loops. It also has an adjustable width, but was set to the maximum width in the tests.

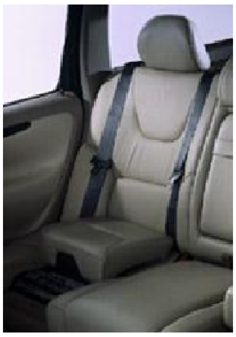


Figure 1. The IBC and the BC1 used in the handling tests.

The children in the study still used booster cushions and considered themselves as consistent users. They were also used to aftermarket booster cushions.

Participants were observed by 4 video cameras and a voice recorder. The children were asked to position the booster cushion, sit on the booster cushion, buckle up, unbuckle, leave the car, and remove the booster cushion. The parent was then asked to position the booster cushion, buckle up the child, unbuckle and then remove the booster cushion. adults. Information on attitudes towards booster cushions was also collected in the handling study.

In addition to the observations, interviews and surveys were conducted with both children and

Sled tests

Frontal sled tests were performed with a reinforced car body, front and rear seat included. A Hybrid III 6 year old child dummy (HIII 6y dummy) was positioned on the left outboard position in the rear seat. Three different 3-point belt retractors were used: a standard configuration, a retractor with pretensioner and a retractor with both pretensioner and load limiter. Hereafter the systems will be referred to as STD, STD+P and STD+P+LL. The belt force limit was 3,3 kN. The retractor was directly mounted on a shelf behind the seat back with direct belt outlet eliminating the need for an additional pillar loop.

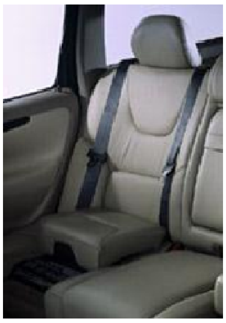
Four booster cushions were used, two aftermarket booster cushions with backrest (BCb1, Volvo Booster seat and BCb2, Maxi-Cosy Rodi XP), one aftermarket booster cushion without backrest (BC2, Volvo booster cushion) and one integrated booster cushion (IBC, Volvo V70), which was designed with the vehicle seat (figure 2). The aftermarket booster cushions had belt guidance (guiding loops) for the lap belt. The BCb1 had a weight of 2.6 kg. BCb2 had shoulder belt guidance as well (pillar loop type) with a weight of 4.8 kg. The BC2 had a weight of 1.2 kg. All booster cushions were tested with the three different seat belt restraints, except for the BCb2, not tested with the STD+P.

The crash pulse used in the tests was based on a mean of 5 real-life frontal crashes in which AIS2+ injuries were found in belted rear seat occupants (figure 3). The pulse data was provided by Folksam Insurance Company, Sweden, which has installed crash pulse recorders in a range of cars. The Δv was 55 km/h, peak acceleration 27g at 25ms and a mean acceleration of 12.1g. Some additional tests were run with a USNCAP test pulse for a large family car

BCb1

BCb2

BC2



IBC

Figure 2. Booster cushions for sled tests.

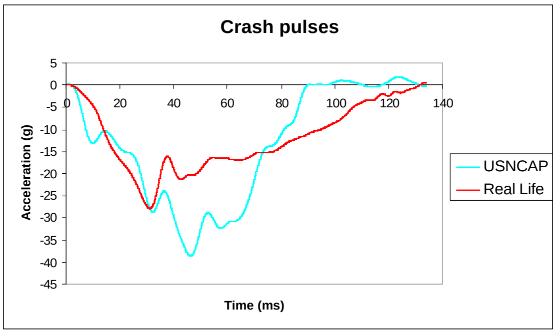


Figure 3. Crash pulses for the sled tests.

with a Δv of 56 km/h, peak acceleration of 38.6g and a mean acceleration of 19.3g.

RESULTS

Attitude

From the child's perspective, the most common reasons for using a booster cushion were: easier to see out, better seat belt comfort (particularly for the shoulder belt), safety and "parents told them to".

From the child's perspective, the most common reasons for not using a booster cushion were: the booster cushion was perceived as being childish, crowded with 3 (or more) in the rear seat, friends not using the booster cushion and if the family had only one booster cushion, the youngest child used it.

The most common reasons for using a booster cushion according to the adults were: safety and comfort, including both proper belt fit and the ability see out of the car.

From the adult perspective, the most common reasons for not using a booster cushion were: inconvenience with storage and transportation, lack of space with 3 in the rear seat and the child negatively influenced by friends.

For the question to adults "Why did children prematurely stop using the booster cushion?", the answer was mostly related to inconvenience in combination with poor knowledge about child crash safety. Adults often expressed thoughts that the children wanted to feel older. Not using a booster cushion seemed to be a sign of getting older.

When the children talked about their own booster cushions they usually described them in means of color, pattern and if the sitting surface was hard or soft.

Handling

Timing of the handling sequence - The average time to perform each action in the handling sequences for the two booster cushions is shown in the figures 4 and 5.

For the children, there was a marked difference between the two booster cushions for the time to fold up the IBC/put in BC1 and time to fold back the IBC/take out the BC1 respectively. It was the first time the children used an IBC and the average fold up time was 19 seconds the first time. They were asked to repeat the handling sequence a second time, and the time was reduced to 7 seconds. The time to unfold the IBC was reduced from 13 seconds to 4 seconds when repeated a second time.

The adults reduced the folding up time of the IBC from 6 to 3 seconds, when repeating the handling sequence a second time. There was no difference in time between the first and the second time the adults unfolded the IBC.

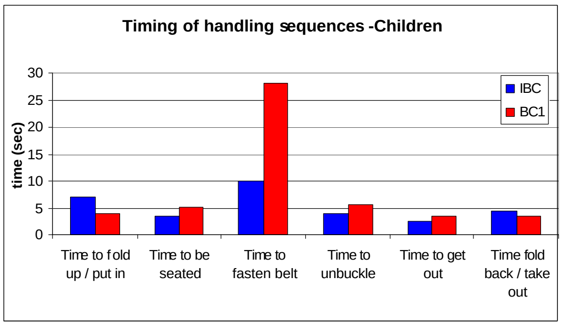


Figure 4. Average time for each action in the child's handling sequence.

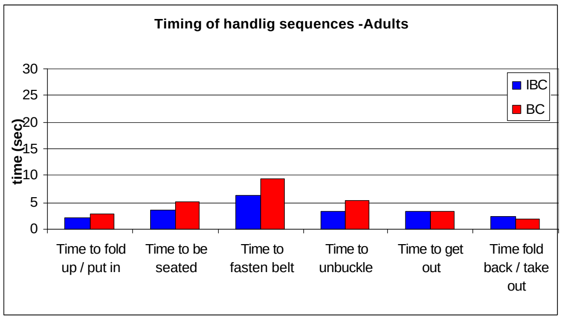


Figure 5. Average time for each action in the adult's handling sequence.

Parents felt secure when unfolding the IBC whereby it could only be done in one way.

Both booster cushions were perceived as being easy to leave and enter. However, the IBC was easier since it lacked guiding loops. The IBC was also more stable while the BC1 was unstable and moved around, especially during the entering phase.

Buckle up - It was easier and faster to buckle up the child on the IBC since no belt routing around guiding loops were necessary. The IBC also allowed easy access to the buckle. The BC1 required the adult and child to lean further forward in order to be able to see and access the buckle, whereby it was partly hidden by the guiding loops.

The parents appreciated the small risk of incorrect belt routing when seated on the IBC, due to the lack of guiding loops.

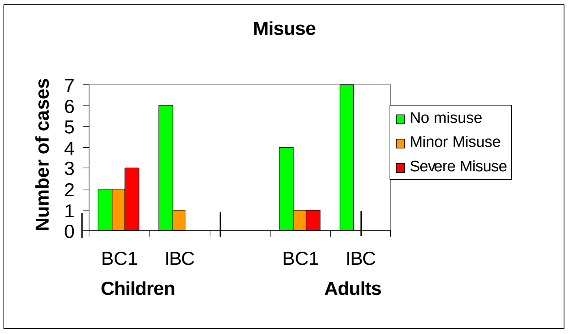


Figure 6. Misuse in the handling study of the BC1 and IBC.

Misuse was detected for 5 of 7 children when buckling up on the BC1 (figure 6). Two of the children failed to guide the lap belt under the guiding loops and one child had excessive slack. These three cases of misuse were graded as severe, according to the misuse study by NHTSA (2004). The other two children had the shoulder belt positioned over the guiding loops, graded as minor misuse. Severe misuse was detected for 1 of 7 adults when buckling up seated on the BC1, where the parent had failed to guide the lap belt around the outboard guiding loop. Two parents failed to put the shoulder belt under the guiding loop. One case was regarded as minor misuse, since the shoulder belt was too close to the neck, while the other case was not regarded as misuse, since the child was tall (140 cm) and the belt did not come too close to the neck.

One case of misuse was detected for the IBC, where the child had twisted the diagonal belt. It was graded as minor misuse. No misuse occurred when the parents buckled up the children on the IBC.

Sled tests

In figures 7 and 8, the effect of pretensioning and load limiting is expressed by the load with

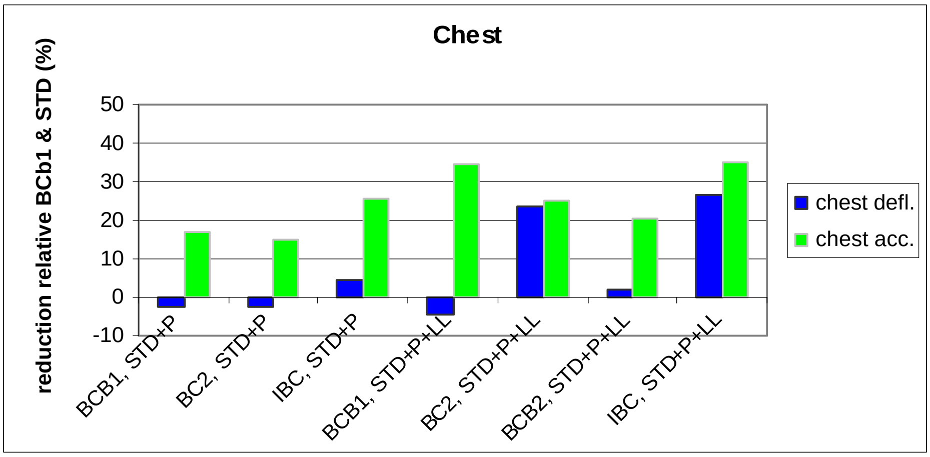


Figure 7. Reduction of chest loading for various retractor systems and booster cushions relative loading for configurations BCb1 with STD.

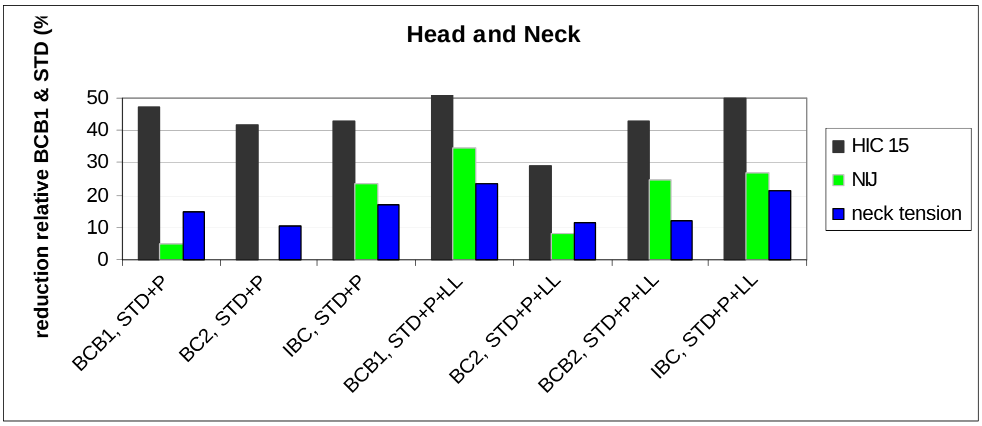


Figure 8. Reduction of head and neck loading for various retractor systems and booster cushion relative loadings for configuration BCb1 with STD.

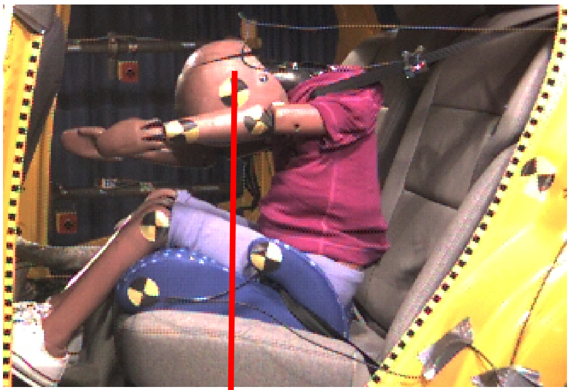
booster cushion with back and seat belt with a standard retractor (BCb1+STD). Adding a pretensioner to the standard retractor reduced the chest acceleration from 16-25%, HIC15 42-47%, NIJ 0-24% and neck tension by 10-17%, but had only a limited effect on chest deflection. When adding a load limiter to the pretensioner, chest acceleration and neck loadings were further reduced. Additionally, the effect of load limiting reduced chest deflection by 23% and 27% compared to a standard retractor for the BC2 and the IBC respectively. The average shoulder belt force was 4.2 kN with the STD and 3.3 kN for the STD+P+LL.

No head impacts with the interior occurred for any belt configuration.

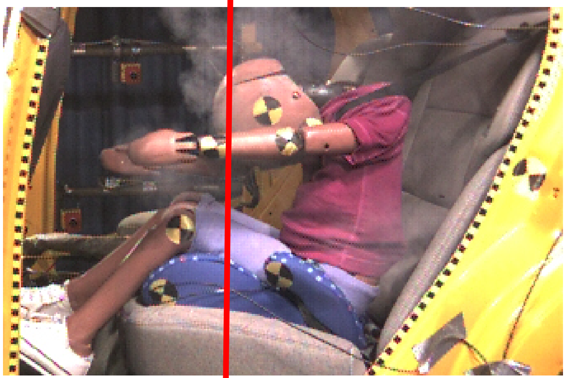
In four tests, BCb1+STD, BCb2+STD, BCb2+STD+P+LL, BC2+STD+P+LL, the shoulder belt slid off during the loading phase and fastened in the gap between shoulder and arm.

Some additional tests were run with the more severe USNCAP pulse with the HIII 6y dummy restrained on the BCb1 with the STD and STD+P+LL. In these tests, all the dummy loadings were higher compared to tests using the real-life pulse. When the pretensioner and load limiter were added to the system, all dummy loadings were reduced. Chest acceleration was decreased by 35% but chest deflection was less affected (5%). Neck loadings were decreased from 11-16%. Shoulder belt force reached 6.4 kN with the STD and 3.7 kN with the STD+P+LL. The shoulder belt slid off the shoulder during loading phase when the dummy was restrained by the standard belt.

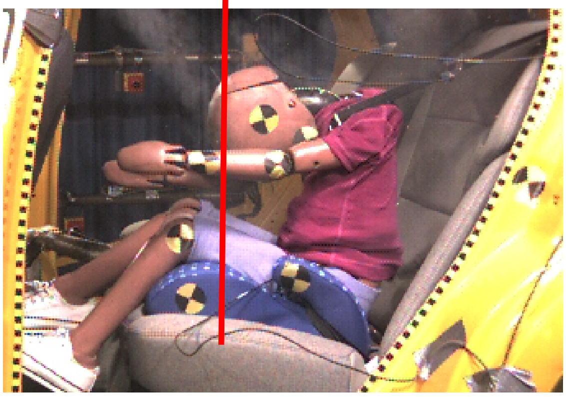
Head forward displacement - The displacement of the head was within legal requirements (ECE R44) for all four types of booster seats and for all seat belt configurations. The longest forward displacement of the head was found when the dummy was seated on an aftermarket booster cushion restrained with a STD belt. When the pretensioner was added the forward head displacement was reduced by 23 to 74 mm for the various booster cushions. When the load limiter was added to the retractor (LL+P) displacement was increased compared to retractor with pretensioner, but was still a shorter displacement compared to STD configurations (figure 9). The shortest forward head displacement was found with the IBC for all seat belt configurations.



9a) No pretensioner



9b) With pretensioner



9c) With pretensioner and load limiter

Figure 9. a,b,c Forward displacement of the HIII 6y dummy seated on the BC2.

Not only the retractor function influenced head forward displacement, but the initial position of the head was also important. The initial position of the head was up to 130 mm forward with a booster with back compared to a booster without back (figure 10).

10a) Initial position – BCb2

10b) Initial position –IBC

Figure 10. a,b Initial position of the HIII 6y dummy in two different booster cushions.

There was a tighter coupling to the integrated booster cushion and the rear seat, preventing the IBC to move forward during the crash compared to the various aftermarket booster cushions, even when a pretensioner was added and thereby restricting forward displacement of the aftermarket booster cushion (figure 11).

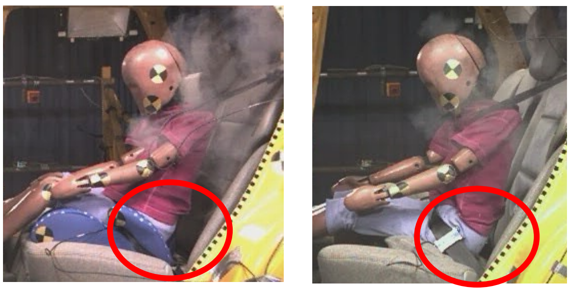


Figure 11. The HIII 6y dummy restrained by BC2 (left) and IBC (right) at 60 ms. The belt include both pretensioner and load limiter. Note the difference in forward displacement of the BC compared to IBC.

DISCUSSION

Attitude and handling

Adult's attitudes in this study were similar to findings in the study by Bingham et al (2005), showing that inconvenience was a major issue in the non-use of booster cushions. Availability and ease of handling could reduce inconvenience-related causes of non-use.

Another important attitude issue identified was the importance of the child feeling more grown up. A study by Edwards et al. (2006) confirmed the findings that children were concerned because "booster seats were for babies" and they saw adult belts as a more "grown-up" choice. The fact that Jakobsson et al. (2007) showed continued use of the integrated booster cushion in children up to 11 years of age indicated the importance of offering an appealing, "grown-up" restraint system.

Several studies (NHTSA, 2001, Winston et al. 2000) showed the problem of premature transition to seat belts in the age group intended for booster cushions. Children aged 9-15 have a greater injury risk than lower age groups (PCPS, 2006). Furthermore, a study (Kuppa, 2005) showed an increase in abdominal injuries in children older than 8 years, which could be a consequence of decreased booster cushion use.

Huang and Reed (2006) measured the seat cushion length of 56 late-model vehicles and found that only 13% of the children taller than 145 cm had a proper seating position without slouching using an average seat cushion. Using a booster cushion shortens the seat cushion length allowing the child to bend the knees without slouching resulting in a more comfortable and safer position. NHTSA recommends continued booster cushion use up to 145 cm, corresponding to a 50th percentile for an 11 year-old child. In conclusion, it is important, however possible, to continue to encourage children to use booster cushions until the age of 10-12 years.

It was unexpected in this study that 5 of 7 children had misuse problems with the BC1. These children were used to this type of booster cushion and considered themselves as "consistent users" normally putting on their seat belts themselves. Furthermore, they were aware of being observed and thus should have been more cautious when buckling up. Still, misuse occurred.

Two children and two parents placed the shoulder belt above the inboard guiding loop of the BC1, although this may not have been a severe misuse problem. But if poor fitting of the shoulder belt caused discomfort by rubbing the neck it may have lead to placing the belt under the arm or behind the back when trying to avoid discomfort resulting in severe misuse.

One child twisted the shoulder belt one turn when buckling up with the IBC. It was considered a minor misuse. In this case, the twist did not affect belt geometry and it was also considered to have a limited effect on the pretensioning of the seat belt.

The misuse occurring with the BC1 due to the belt routing problems around the guiding loops could not occur on the IBC. The integrated booster cushion can be designed without guiding loops since it is fixed attached to the vehicle and the anchorage points of the belt is possible to design to maintain a good belt geometry of both booster seated children as well as adults.

It was observed that only 5 of 14 tightened the belt after buckling up on the IBC and the corresponding figures for the BC1 were 4 of 14. It was the same two children and two adults who tightened the belt for the two booster cushions. This is an indication that neither children nor parents regularly tightened the belt after buckling up on the booster cushion. Belt slackening could easily occur, especially for the lap belt part, when buckling up on a booster cushion with guiding loops. A belt pretensioner eliminates slack in the belt system in the initial phase of a frontal crash.

Information to parents on booster cushion use will always be needed, but this study showed moreover that improving the design of the booster cushion could encourage booster cushion use as well as decreasing misuse.

In an ongoing study by the authors, 150 children aged 4 to 12 children were observed when buckling up in two different designs of booster cushions. Misuse, such as bad belt routing and belt slack, are some of the parameters to be analyzed.

Sled test

Mechanical and mathematical simulations with the HIII 50th percentile and HIII 5th percentile for the rear seat exposed to frontal impact at 48 km/h were conducted in parallel to the current study. Various load limiting levels and pretensioners were evaluated.

The HIII 50th percentile dummy had a belt force of 7.3 kN (pretensioner included, no load limiting) and when the load limiting of 5 kN was added the chest deflection was reduced by 12%.

The HIII 5th had a belt force of roughly 6 kN when only a pretensioner was added to the belt system. When a load limiter level of 5 kN was added, chest deflection was reduced by 10%. With a further reduction of the belt force to 3 kN chest deflection was reduced by 31% compared to the case without load limiter. The head did not impact the front seat back.

Chest, head and neck loading of the HIII 6y dummy was reduced when belt force was reduced from 4.2 kN to 3 kN. Results showed the need of adapting the load limiting level to the size of the occupant.

Tylko et al. (2005) conducted full frontal rigid tests with late model vehicles (2003 to 2005) in range of 40 to 56 km/h with a HIII 6y dummy in the rear seat. Belt force loads of more than 6 kN were measured for the HIII 6y dummy seated in the rear seat, resulting in high chest loading for deflection and acceleration. Although real-life data has not indicated that chest injuries were a problem to booster-seated children (Kuppa et al. 2005), Tylko et al. (2005 found chest deflection as high as 52 mm in their tests. High chest deflections were also associated with belt sliding off the shoulder.

Accident data has shown that the head was the most frequently injured body region among children (PCPS, 2006). Sled tests in this study showed that by introducing a pretensioner, head forward displacement could be reduced, even when a load limiter was introduced. Adding a load limiter in combination with a pretensioner, did not increase the risk of head impact with the interior.

The HIII 6y dummy was sensitive to belt geometry, whereby the belt slide off the shoulder for some configurations thereby increasing the risk of impacting the interior. This emphasizes the importance of maintaining good control of belt geometry for the child, which could be achieved by designing the booster cushion together with the seat belt.

Some additional misuse sled tests were performed with incorrect belt routing over the guiding horn of the BC2. This could only occur when using the booster cushion (with or without backrest) and not with the IBC, since there is no guiding horn for that design. When the lap belt was above both guiding horns, the dummy slid off the booster cushion, whereby the cushion was not restrained. The dummy submarined, but due to lack of instrumentation, the severity of injury to the abdomen or lumbar spine could not be estimated.

CONCLUSIONS

To motivate parents to use a booster cushion for the children it is essential to eliminate inconvenience by offering a booster cushion easily accessible and easy to handle.

To encourage continued use of booster cushion up to the ages of 10-12 years, the design must be appealing while reducing feeling of being childishness.

An integrated booster cushion offers fast and easy handling, with a reduced risk of possible misuse.

A load limiter of about 3 kN reduced loadings to HIII 6y. When adding a pretensionern to the retractor it was possible to reduce head forward displacement and while adding a load limiter it was still possible to keep the head forward displacement shorter than with a standard retractor.

By applying an attitude, handling and safety approach the combination of integrated booster cushion, belt pretensioning and load limiting would increase appropriate usage of restraints, decrease dummy injury values and keep forward displacements thereby saving rear seat occupant lives.

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INVESTIGATION OF LOWER ANCHORAGE SYSTEMS FOR CHILD RESTRAINTS IN AUSTRALIA

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Australian Government Department of Transport and Regional Services
Paper No. 07-0298

ABSTRACT

Australia is considering allowing the use of lower anchorage systems for child restraints in motor vehicles. However, care needs to be taken to ensure that the mix of existing Australian child restraint systems and any proposed lower anchorage system does not pose safety risks for children. In addition, it is desirable to avoid unique requirements for an Australian lower anchorage system and hence an assessment of UNECE ISOFIX and US FMVSS LATCH requirements was undertaken.

A series of 28 frontal impact sled tests were conducted based on the Australian Standard AS/NZS 3629 child restraint dynamic test method. A further series of 15 tests were conducted in a vehicle body mounted on an impact sled with an acceleration-time history representative of a 56 km/h full frontal rigid barrier crash. Three different models of forward-facing child restraint were tested, with varying anchorage configurations including rigid ISOFIX, flexible LATCH strap and 3-point seatbelt. Top tethers were evaluated with anchorages directly behind the child restraint (0°) and offset at an angle of 20°. P3 and Hybrid III 3 year old dummies were used. Anchorage loads and safety performance of the restraint system were assessed. In tests in the vehicle body, maximum dynamic top tether loads were in the range of 7-8 kN and maximum dynamic lower anchorage loads are estimated to be in the range 13-14 kN. Tests using rigid ISOFIX anchorages generally produced lower head acceleration and forward excursion than other tested anchorage types. However, this was accompanied by increased chest deflections and neck flexion moments. These data suggest that lower anchorage systems may be acceptable in Australia, but that modifications to the UNECE and LATCH requirements may be required to ensure compatibility with existing Australian child restraint systems without a degradation of child safety.

INTRODUCTION

In Australia, the use of child restraints and top tethers has been mandatory since the 1970s. Typically, Australian passenger vehicles have been equipped with a top tether anchorage in each of three second row seating positions. When used in conjunction with a seatbelt, the top tether plays an important role in overall restraint performance by acting as an anti-rotation device.

The safety and performance of child restraint systems in Australia is regulated via requirements for the child restraint under Australian Standard AS/NZS 1754 (a mandatory consumer product safety standard under the *Trade Practices Act, 1974*) and requirements for the anchorages in the vehicle under Australian Design Rule ADR 34/01 (a legislative instrument under the *Motor Vehicle Standards Act, 1989*).

The Australian Standard AS/NZS 1754 currently requires all child restraints supplied to the Australian market to be designed to be attached to the vehicle using an adult seatbelt and top tether. This standard does not address connectors for lower anchorage systems and child restraints with ISOFIX or LATCH lower anchorage systems are currently unable to gain approval under this standard.

The Australian Design Rule ADR 34/01 currently requires each top tether anchorage to be designed to withstand a 3.4 kN static load for a period of at least 1 second. A dynamic anchorage strength test requirement may be satisfied as an alternative to this static requirement. There are currently no lower anchorage requirements in ADR 34/01.

Australia is currently considering allowing the use of child restraints equipped with lower anchorage systems. However, it is particularly important that the adoption of any proposed harmonised child restraint anchorage requirement for vehicles (including vehicle top tether anchorage strength and anchorage location requirements) does not adversely impact on the ongoing use and performance of existing Australian child restraint systems.

In this study, dynamic top tether and lower anchorage load measurements are used to assess UNECE ISOFIX (Regulation 14) and FMVSS LATCH (FMVSS 225) anchorage strength requirements, and dummy sensor measurements and head excursion results are used to evaluate the restraint performance for ISOFIX, flexible LATCH, and 3-point seatbelt child restraint systems.

METHOD

Two separate series of frontal impact sled tests were conducted using 3 different forward facing child restraint models and an instrumented 3 year old frontal impact dummy. Top tether loads, lap/sash belt loads, lower anchorage loads, head excursion, and dummy sensor output were measured and analysed for the purpose of evaluating the performance and anchorage loads of ISOFIX, flexible LATCH strap, and 3-point seatbelt child restraint systems.

One of the three tested child restraint models (Model A) was a UNECE Reg. 44 approved restraint equipped with an ISOFIX lower anchorage system. This child restraint model (Model A) is also able to be restrained using a 3-point seatbelt or a flexible LATCH strap fitted using the seatbelt mounting in the back of the restraint. The other two tested restraint models (Model B & Model C) are/were popular in the Australian market and are considered to be representative of existing (3-point seatbelt + top tether) Australian child restraint systems. Model B is able to be restrained by either a 3-point seatbelt or flexible LATCH strap using the seatbelt mounting provided at the rear of the restraint. Restraint model C is also able to be used in conjunction with either a flexible LATCH strap or 3-point seatbelt, however, for this restraint, the flexible LATCH strap / lap belt is fitted around the front base of the restraint. Restraint models A and B are both fitted with a floating or Y-shaped top tether. Model C is fitted with a single top tether strap.

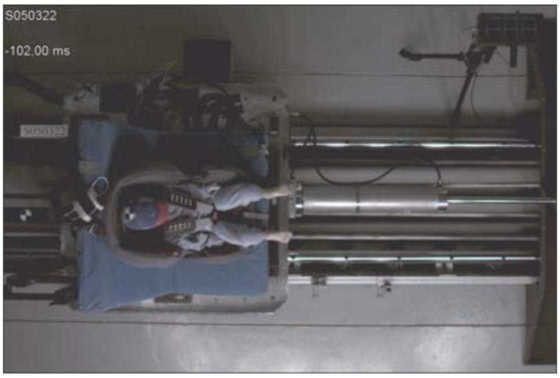

Figure 1. Sled setup (with pneumatic spring) used to certify child restraints under Australian Standard AS/NZS 1754.

The first series of 28 frontal sled tests were conducted on a sled used to certify child restraints under the existing Australian Standard AS/NZS 1754 (Child Restraint Systems for Use in Motor Vehicles) as shown in Figure 1. This sled utilises a pneumatic spring to simulate a frontal impact, and when calibrated according to the dynamic test rig requirements of the Australian Standard AS/NZS 3629.1 (Methods of Testing Child Restraints), produces a velocity change of approximately 49 km/h. Each of these sled tests were conducted using a P3 dummy fitted with tri-axial head and chest accelerometers. Load cells placed between the sled and lower anchorages were used to measure flexible LATCH and rigid ISOFIX lower anchorage loads. Top tether and seatbelt loads were measured using load cells designed to be fitted to belt webbing. The tests conducted in this series are listed in Table 1.

Table 1.
Test Matrix (Series 1)

Number of Tests	Restraint Model	Dummy	Top Tether Angle	Anchorage Method
3	A	P3	0	ISOFIX / Top Tether
3	A	P3	0	Flexible LATCH / Top Tether
3	A	P3	0	3 Pt Belt / Top Tether
2	B	P3	0	Flexible LATCH / Top Tether
2	B	P3	0	3 Pt Belt / Top Tether
2	C	P3	0	Flexible LATCH / Top Tether
2	C	P3	0	3 Pt Belt / Top Tether
1	A	P3	20	ISOFIX / Top Tether
1	A	P3	20	Flexible LATCH / Top Tether
1	A	P3	20	3 Pt Belt / Top Tether
1	B	P3	20	Flexible LATCH / Top Tether
1	B	P3	20	3 Pt Belt / Top Tether
1	C	P3	20	Flexible LATCH / Top Tether
1	C	P3	20	3 Pt Belt / Top Tether
2	A	P3	0	3 Pt Belt / Top Tether*
2	A	P3	n/a	ISOFIX / No Top Tether

* top tether failure

A further 15 restraint tests were conducted using the same three child restraint models and a vehicle buck constructed from a previously crash tested vehicle body (see Figure 2 and Figure 3). The vehicle model used was equipped with factory fitted lower anchorages in each outboard rear seating position. The front row seats were removed from the vehicle and two transparent polycarbonate sheets were used to simulate the front seat back location in the mid track fore/aft position (with front seat back angle set to give an adult torso angle of 25º). The second/rear row bench seat was reinforced to allow multiple tests to be conducted. A sled and bending bar brake were then used in conjunction with this vehicle buck to simulate a 56 km/h full frontal rigid barrier crash pulse for this vehicle (see Figure 4). A P3 or HIII 3 year old dummy was used for each of the tests in this series. The P3 dummy was fitted with the same instrumentation used for the first test series. The HIII 3 year old dummy was fitted with head, chest, upper spine, lower spine, and pelvis tri-axial accelerometers, as well as an upper neck load cell, and a chest deflection rotary potentiometer. Lower anchorage loads were not measured. Webbing load cells were used to measure top tether, 3-point seatbelt, and flexible LATCH strap loads. The tests conducted in this series are listed in Table 2.

Table 2.
Test Matrix (Series 2)

Number of Tests	Restraint Model	Dummy	Top Tether Angle	Anchorage Method
1	A	P3	0	ISOFIX / Top Tether
1	A	P3	0	3 Pt Belt / Top Tether
1	A	P3	0	3 Pt Belt (P) / Top Tether
1	B	P3	0	Flexible LATCH / Top Tether
1	B	P3	0	3 Pt Belt / Top Tether
1	B	P3	0	3 Pt Belt (P) / Top Tether
1	C	P3	0	3 Pt Belt / Top Tether
1	A	P3	20	ISOFIX / Top Tether
1	A	P3	20	3 Pt Belt / Top Tether
1	A	P3	20	3 Pt Belt (P) / Top Tether
1	B	P3	20	Flexible LATCH / Top Tether
1	B	P3	20	3 Pt Belt (P) / Top Tether
1	A	HIII 3 y.o.	0	ISOFIX / Top Tether
1	A	HIII 3 y.o.	0	3 Pt Belt / Top Tether
1	A	HIII 3 y.o.	0	3 Pt Belt (P) / Top Tether

(P) – pre-tensioned

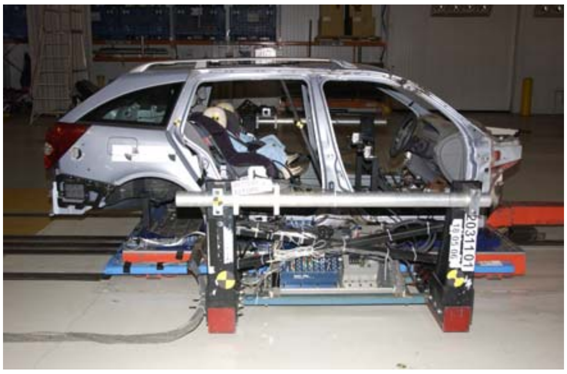

Figure 2. Vehicle body shell / buck mounted on crash sled (Series 2).

Figure 3. Test setup used in vehicle body / buck test series (Series 2).

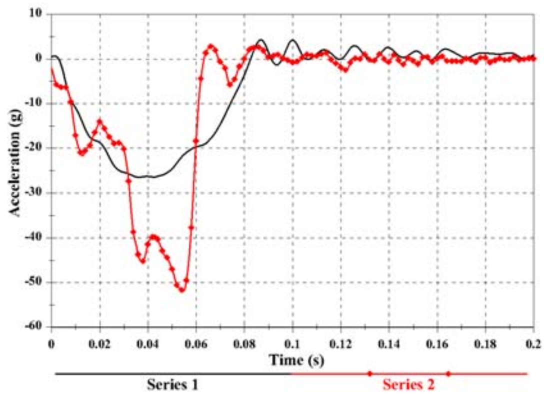

Figure 4. Typical acceleration-time history / crash pulse for each series of child restraint frontal impact tests.

Each child restraint test was conducted using, no top tether anchorage (2 sled tests only), a 0º tether anchorage, or a 20º tether anchorage (see test matrices). For the first series of tests, each 0º top tether was anchored to the sled on the seating reference plane, approximately 230 mm behind the shoulder reference point. For the vehicle buck sled test series, each 0º tether test was conducted with the top tether attached to a child restraint anchorage located on the seating reference plane at the base of the seat back. All 20º tether tests (both series) were conducted with the tether anchored approximately 1 metre behind the shoulder reference point and 20º inboard from the seating reference plane.

For each individual test (see Table 1 and Table 2), each child restraint was tested using ISOFIX, flexible LATCH strap, or 3-point seatbelt anchorage. In the case of flexible LATCH, tests were conducted by fitting the flexible LATCH strap through/around the available seatbelt mounting. For the second test series (vehicle buck), the safety and performance of seatbelt pyrotechnic retractor pre-tensioning was also investigated.

All dummy sensor and load cell channel data were collected at a 20 kHz sampling frequency. Each data channel was then filtered using the channel frequency classes (CFC) specified in Table 3. All data plots presented in this paper are in accordance with the sign conventions specified by SAE J211-1 (Dec 2003).

High speed video images and motion analysis software were used to calculate dummy forward and lateral head excursion relative to the intersection of the seat back / bight. For the first series of tests, an off-board overhead camera view was used to calculate both forward and lateral head excursion. For the second test series, an off-board overhead camera view was used to calculate lateral head excursion, and onboard side camera views were used to calculate forward head excursion.

Table 3.
Channel Frequency Class

Data Measurement Channel	CFC (Hz)
Head acceleration x, y, and z	1000
Upper neck force x, y, and z	1000
Upper neck moment x, y, and z	600
Chest acceleration x, y, and z	180
Chest deflection x	600
Pelvis acceleration x, y, and z	1000
All top tether, seatbelt and lower anchorage loads	60

RESULTS

Dynamic Lower Anchorage Loads

Figure 5 shows the maximum lower anchorage loads obtained from the frontal sled test series conducted using the existing AS/NZS 3629.1 pulse (Series 1). For this series of tests, multiple (repeat) tests (2-3) were conducted for each 0º tether test configuration (i.e. for each unique combination of restraint model and lower anchorage method). For multiple tests, the maximum anchorage load from any one test is plotted in Figure 5 (see Appendix for all results).

The maximum total (left + right) lower anchorage load recorded during the first test series was 7.2 kN (restraint model A with ISOFIX lower anchorage and 20º top tether anchorage). In some cases, most notably the tests conducted with a 20º tether angle, the lower anchorage load was not uniformly distributed between each of the two lower anchorages. Excluding tests conducted without a top tether, the maximum dynamic load on any one anchorage (i.e. left or right anchorage) was 4 kN. For the tests conducted with a 0º top tether anchorage, the maximum total lower anchorage load was 6.3 kN. Two additional tests (not shown in Figure 5) were also conducted using restraint model A with rigid ISOFIX anchorage only (i.e. no top tether anchorage). For these additional tests, the maximum total lower anchorage load was 11 kN.

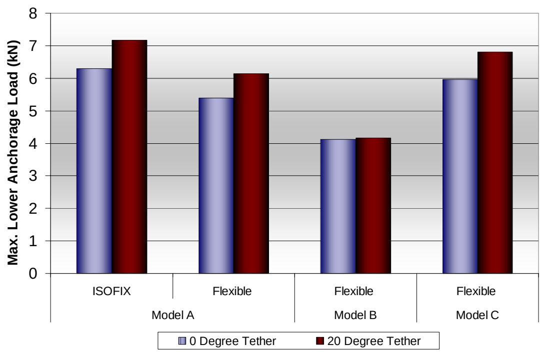

Figure 5. Maximum total lower anchorage loads (Series 1).

Rigid lower anchorage loads were not measured during the series of tests conducted using the vehicle body / buck (Series 2). For this test series, it was not physically possible or practical to use load cells (or other means) to measure lower anchorage loads. However, it is possible to use lap belt loads obtained from both series of tests, and lower anchorage loads recorded during the first test series, to estimate likely lower anchorage loads based on the proportionality of loads.

The maximum outer lap belt load (see Appendix) recorded during the vehicle buck sled test series was 5.93 kN (restraint model A with 0º tether and 3-point seatbelt mounting). For this restraint model and tether angle, the maximum outer lap belt load and maximum lower anchorage load recorded during the first series of sled tests were 2.8 kN (excluding tests conducted with top tether modification or failure) and 6.3 kN respectively. Therefore, for the initial sled test series, the maximum total rigid lower anchorage load was approximately 2.25 times the maximum outer lap belt load (for restraint model A). Assuming a similar maximum load ratio for the vehicle buck sled test series, maximum dynamic rigid lower anchorage load is approximately 13.3 kN (i.e. 2.25 × 5.93 kN).

Dynamic Tether Anchorage Loads

Figure 6 shows the maximum top tether anchorage loads recorded during the first series of frontal sled tests. Similarly to lower anchorage loads, where multiple tether anchorage loads are available for a given test configuration, the maximum recorded anchorage load from any test is plotted (see Appendix for all results). The maximum top tether anchorage load for this series of tests was 9.4 kN (restraint model A with 3-point seatbelt and 0º top tether anchorage). In this series, 20º tether anchorage loads were generally 15-40 percent lower than the corresponding 0º tether anchorage loads. The maximum tether anchorage load recorded for the 20º tether angle was 6.5 kN.

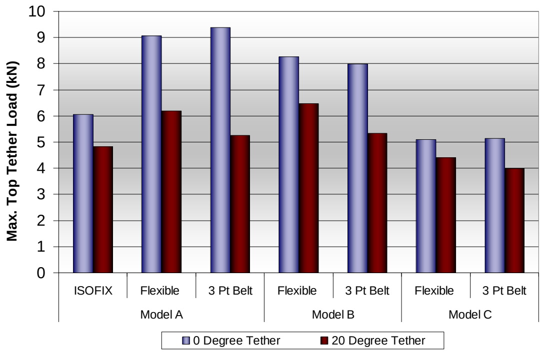

Figure 6. Maximum top tether anchorage loads (Series 1).

Figure 7 shows the maximum top tether anchorage loads recorded for each vehicle buck sled test (Series 2) conducted using a P3 dummy (see Appendix for tether anchorage loads obtained from tests conducted using HIII 3 year old dummy). The maximum top tether anchorage load measured during this test series was 7.7 kN (restraint model B with pre-tensioned 3-point seatbelt mounting and 0º tether anchorage). For the tests conducted with a 20º tether angle, the maximum top tether anchorage load was 6.9 kN.

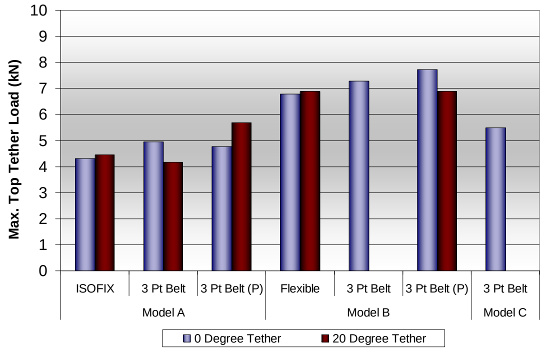

Figure 7. Maximum top tether anchorage loads (Series 2).

Head Excursion

High speed video images and motion analysis software were used to estimate forward and lateral head excursions. To enable evaluation of results, motion analysis techniques were consistently applied to each test conducted in each test series. However, it should be noted that different fixed camera angles / positions were used for series 1 and 2. Head excursion results obtained for series 1 and 2 are therefore unable to be directly compared (i.e. results not comparable across series), but do provide a good indication of the relative performance of each restraint model / restraint anchorage method (i.e. results can be compared within each series).

Figure 8 shows dummy forward head excursion relative to the seat back / bight intersection for the first series of sled tests. Where multiple tests were conducted for the same test configuration, average head excursions are plotted, with the full range of recorded test results indicated by vertical bars (see Appendix for all results). For restraint model A, rigid ISOFIX anchorage produced the lowest forward head excursion, and flexible LATCH anchorage produced the highest forward head excursion. For restraint models B and C, flexible LATCH and 3-point seatbelt anchorage systems produced similar forward head excursion. For this test series, multiple test results indicate good repeatability for forward head excursion. For the additional tests conducted using restraint model A, rigid lower anchorage, and no top tether anchorage (see Appendix for results), removal of the top tether increased forward head excursion by an average of approximately 130 mm (relative to restraint model A with 0º tether anchorage).

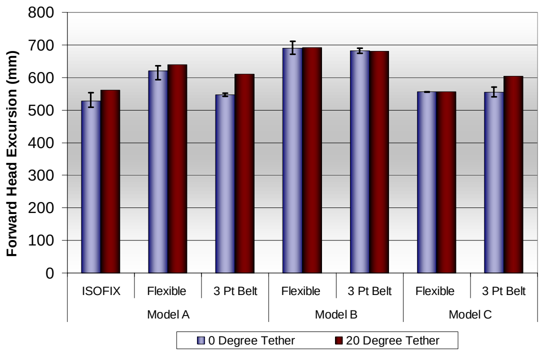

Figure 8. Forward head (centre of gravity) excursion (Series 1).

Figure 9 shows dummy forward head excursion relative to the seat back / bight intersection for each vehicle body / buck sled test conducted using a P3 dummy (see Appendix for forward head excursion results obtained from tests conducted using HIII 3 year old dummy). During some of these tests, the dummy head collided with the polycarbonate sheet / seat back (see HIC 36 results for further details). This polycarbonate sheet was used to simulate the front row seat back location for the mid track for/aft position and an adult torso angle of 25º. Therefore the seat back places an upper limit on forward head excursion. For the tests in which the dummy head collided with the seat back, this forward head excursion limit is determined by the trajectory of motion of the head / position (i.e. height) of impact. Due to the inclined angle of the polycarbonate, greater forward head excursion is possible for trajectories of motion in which the head impacts the polycarbonate closer to the base of the front seat. As a rough guide, forward head excursions of approximately 450mm resulted in head contact to the polycarbonate sheet. In this series, rigid ISOFIX anchorage produced substantially less forward head excursion than 3-point seatbelt mounting. Seatbelt pre-tensioning produced a small reduction in forward head excursion compared to no pre-tensioning.

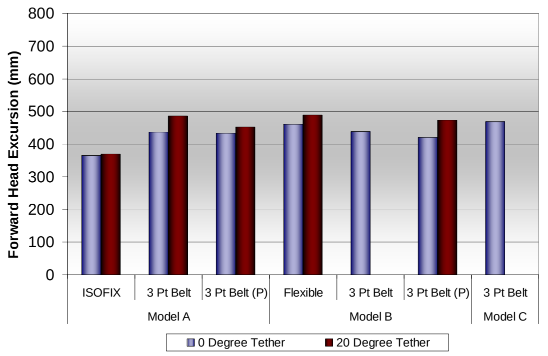

Figure 9. Forward head (centre of gravity) excursion (Series 2).

Figure 10 shows dummy lateral head excursion for the first series of sled tests. Similarly to forward head excursion, average lateral head excursions are plotted, with vertical bars used to indicate the range of results obtained from multiple / repeat tests (see Appendix for all results). Lateral head excursions were influenced more by top tether configuration, than by lower anchorage method. For each restraint model / lower anchorage method, lateral head excursions were greatest for the test conducted with a 20º tether angle. The lateral head excursion estimates obtained from this series of tests do not exhibit the repeatability observed for forward head excursion (i.e. lateral head excursion results appear to be less repeatable / subject to greater variability).

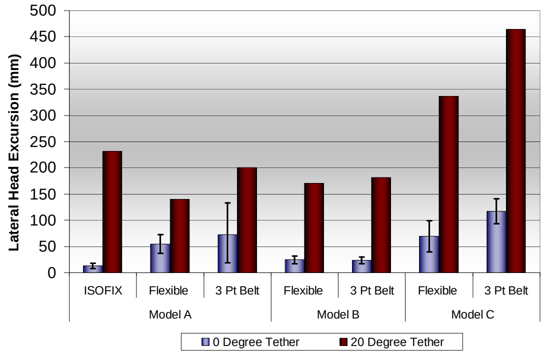

Figure 10. Lateral head (centre of gravity) excursion (Series 1).

Figure 11 shows dummy lateral head excursion for each vehicle body / buck sled test conducted using a P3 dummy (see Appendix for HIII 3 year old lateral head excursion results). Like the first test series, lateral head excursions were influenced more by tether angle, than by lower anchorage method. With the exception of restraint model A with ISOFIX lower anchorage, lateral head excursions were substantially greater for tests conducted with a 20º tether anchorage.

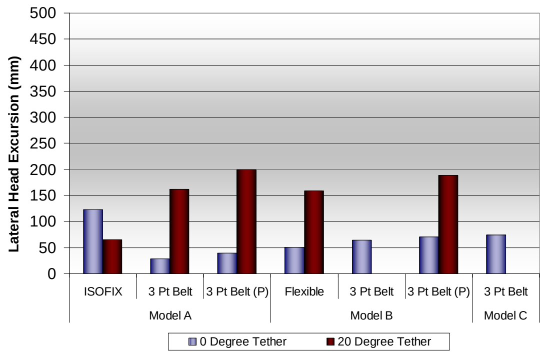

Figure 11. Lateral head (centre of gravity) excursion (Series 2).

P3 Dummy Sensor Data

A P3 dummy was used for each test conducted in Series 1, and for all but three of the tests conducted in Series 2. In this section, where multiple tests have been conducted for a single test configuration, averages are plotted and vertical bars are again used to indicate the range of recorded results.

During the first test series, dummy head to knee / buckle collisions were observed for some tests (see Appendix for test specific details). These collisions were not necessarily repeatable for multiple tests (i.e. each 0º tether configuration). Furthermore, during the second test series, the presence of a front row seat back was observed to greatly diminish the likelihood of head to knee / buckle collisions. Therefore, for some test configurations, the occurrence of head collisions is likely to have artificially increased both the average and range of 3 ms head acceleration / HIC 36 results.

Figure 12 and Figure 13 show 3 ms head acceleration and HIC 36 for the first series of sled tests. The 3 ms head acceleration and HIC 36 results obtained for restraint model A, indicate similar levels of head injury risk for rigid ISOFIX and 3-point seatbelt anchorage methods. In most cases, results obtained for flexible LATCH anchorage indicate a head injury risk approximately equal to or greater than that of 3-point seatbelt mounting. There were however, some test configurations for which flexible LATCH anchorage exhibited HIC 36 results superior to 3-point seatbelt mounting (restraint models B and C with 20º tether anchorage). Head acceleration and HIC 36 results obtained from two additional tests conducted with rigid lower anchorage only (see Appendix for results); indicate an increased head injury risk for no top tether anchorage compared to tests conducted using top tethers.

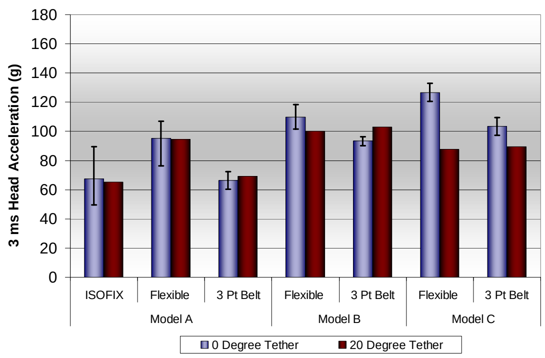

Figure 12. 3 ms head acceleration (Series 1).

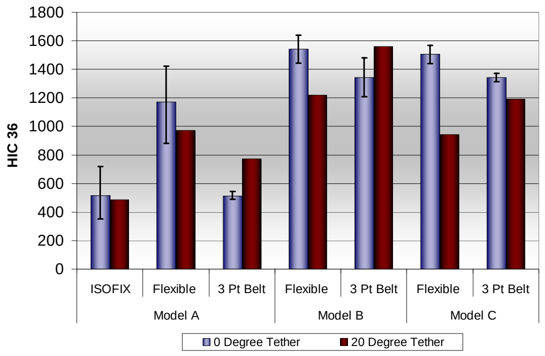

Figure 13. HIC 36 (Series 1).

During the vehicle buck sled test series, all but one of the HIC results greater than 2500 occurred as a consequence of the head striking the polycarbonate front row seat back simulation. It is important to note that the energy absorbing properties of an upholstered seat back are quite different to a transparent polycarbonate sheet. Consequently, the 3 ms head acceleration and HIC 36 results obtained from tests involving head to polycarbonate collisions provide an indicative rather than truly representative measure of head injury risk.

Figure 14 and Figure 15 show 3 ms head acceleration and HIC 36 for each vehicle buck sled test conducted using a P3 dummy. The 3 ms head acceleration and HIC 36 results obtained for restraint model A, indicate a lower head injury risk for rigid ISOFIX anchorage than for either form of 3-point seatbelt mounting. In this series, flexible LATCH anchorage was only tested using restraint model B. For this restraint model and 0º tether anchorage, flexible LATCH anchorage produced slightly lower 3 ms head acceleration and HIC 36 than 3-point seatbelt mounting. For some restraint test configurations, seatbelt pre-tensioning was effective in reducing forward head excursion by just enough to prevent the dummy head from colliding with the polycarbonate sheet / front row seat back (eg. restraint model A with 20º top tether anchorage). For these test configurations, seatbelt pre-tensioning produced a substantial reduction in both 3 ms head acceleration and HIC 36. However, for restraint model A with 0º top tether anchorage, there were no head collisions with the polycarbonate seat back, and 3 ms head acceleration and HIC 36 were similar for 3-point seatbelt mounting with and without pre-tensioning. The effect of seatbelt pre-tensioning is most pronounced when the reduction in forward head excursion due to pre-tensioning is such that head contact to the polycarbonate sheet that would otherwise occur is prevented.

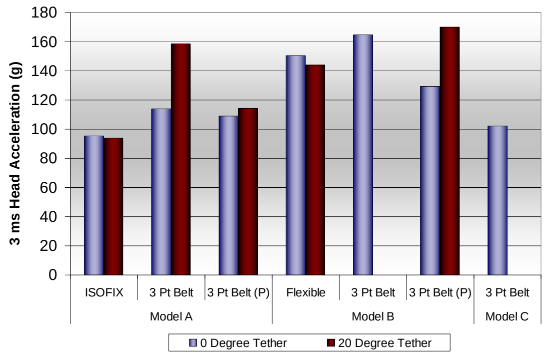

Figure 14. 3 ms head acceleration (Series 2).

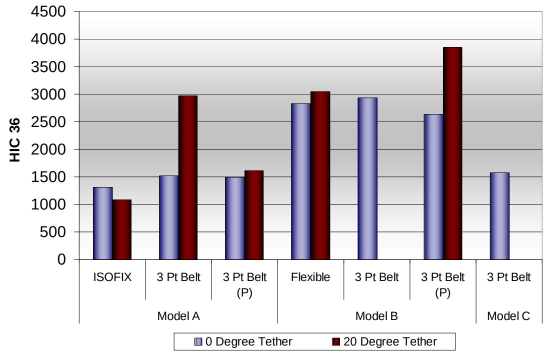

Figure 15. HIC 36 (Series 2).

Figure 16 shows maximum resultant chest acceleration for the first sled test series. For each child restraint model tested; rigid ISOFIX, flexible lower anchorage, and 3-point seatbelt mounting all produced similar maximum resultant chest accelerations.

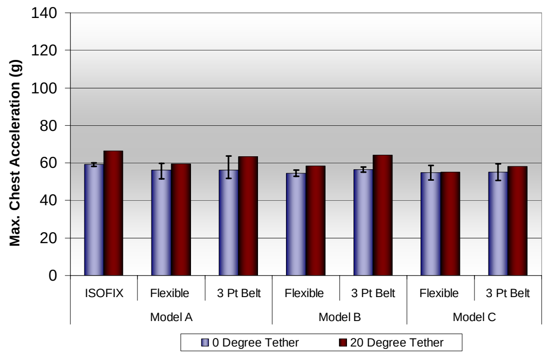

Figure 16. Maximum chest acceleration (Series 1).

Figure 17 shows maximum resultant chest acceleration for each vehicle buck sled test conducted with a P3 dummy. For this series of tests, there was no clearly identifiable and consistent correlation between maximum resultant chest acceleration and lower anchorage method. Peak resultant chest accelerations varied depending on a range of factors, including the restraint design and the top tether anchorage location / angle. The lowest maximum chest acceleration occurred for restraint model A with rigid ISOFIX lower anchorage and 20º top tether anchorage.

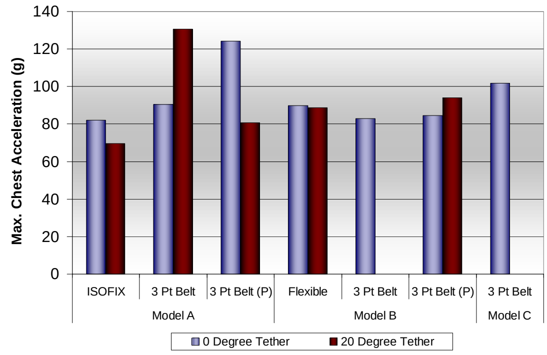

Figure 17. Maximum chest acceleration (Series 2).

HIII 3 Year Old Sensor Data

The current Australian Standard AS/NZS 3629.1 (Methods of Testing Child Restraints) specifies P series dummies for the dynamic testing of child restraints. Each child restraint must retain the appropriate P series dummy without any separation of load carrying parts. Vehicle anchorage strength requirements should ensure that vehicle top tether anchorages are able to withstand loads at least equal to those to which child restraints are certified. For this reason, a P3 dummy was used for each frontal sled test conducted using the AS/NZS 3629.1 pulse.

To enable comparison of test results, a P3 dummy was also used in the majority of tests conducted in the vehicle buck sled test series. However, a major limitation of the P series dummies is their lack of instrumentation – the P3 dummy is equipped with head and chest accelerometers only. In contrast, the HIII 3 year old dummy is equipped with head, neck, chest, upper spine, lower spine, and pelvis instrumentation. Consequently, the HIII 3 year old dummy is able to be used to identify potential injury risks not measured by the P3 dummy. For this reason, three restraint tests were conducted using restraint model A and an instrumented HIII 3 year old dummy. Each of these HIII 3 year old tests was conducted with a 0º tether anchorage and rigid ISOFIX, 3-point seatbelt, or pre-tensioned 3-point seatbelt mounting.

Figures 18 to 25 show dummy sensor output for each restraint test conducted using a HIII 3 year old dummy. Table 4 lists 3 ms head acceleration, HIC 36, and head excursion results for each test. Each restraint anchorage method produced similar resultant chest acceleration (values slightly higher for ISOFIX), neck tension, and neck shear results. In contrast, head excursion, head acceleration / HIC 36, upper neck moment, chest deflection, and pelvis acceleration results were substantially affected by restraint anchorage method.

Similarly to the vehicle buck sled tests conducted with a P3 dummy, rigid ISOFIX anchorage produced substantially less forward head excursion than either form of 3-point seatbelt mounting. When 3-point seatbelt mounting was used the dummy head collided with the polycarbonate sheet / front row seat back, producing a local head acceleration maximum (see Figure 18, t ≈ 0.079 seconds). For this restraint model and tether angle, seatbelt pre-tensioning reduced forward head excursion by enough to prevent the dummy head from colliding with the polycarbonate sheet.

Table 4.
Summary of Head Injury Predictors
(HIII 3 year old)

Anchorage Method	3 ms Head Accel. (g)	HIC 36	Max. Forward Head Excursion (mm)	Max. Lateral Head Excursion (mm)
ISOFIX / Top Tether	103.40	1578	376	33
3 Pt Belt / Top Tether	132.90	1853	467	150
3 Pt Belt (P) / Top Tether	95.32	1673	431	73

(P) – pre-tensioned

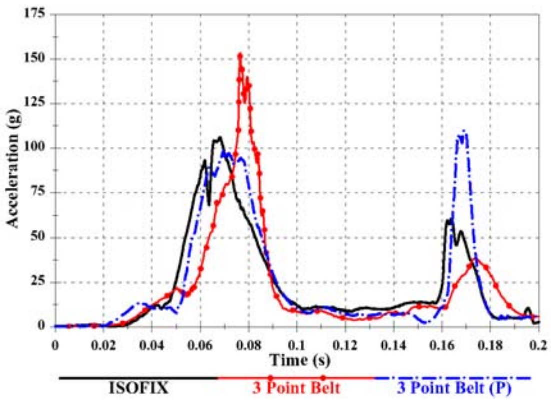

Figure 18. Resultant head acceleration (HIII 3 year old – Series 2).

Each restraint anchorage method produced similar peak upper neck tension and peak upper neck shear load results. Rigid ISOFIX and pre-tensioned 3-point seatbelt anchorage methods both produced significantly longer upper neck tensile load duration (above 1 kN) than 3-point seatbelt mounting.

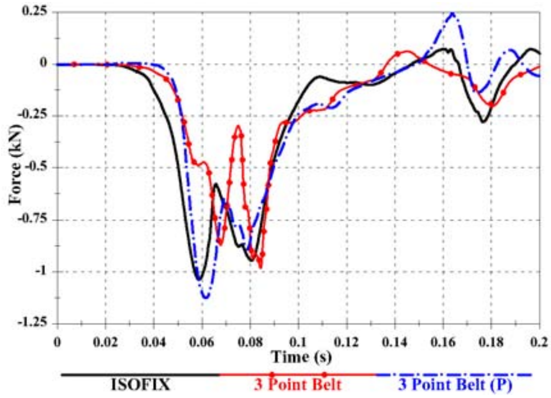

Figure 19. Upper neck shear load (Fx) (HIII 3 year old – Series 2).

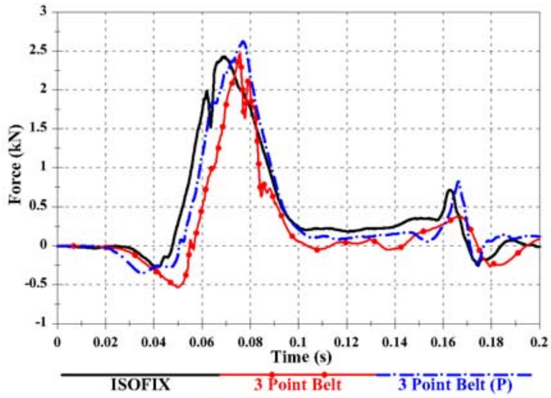

Figure 20. Upper neck tension (Fz) (HIII 3 year old – Series 2).

Peak upper neck moments about the x-axis in the dummy coordinate system (Mx) varied depending on the restraint anchorage method used. The largest of these peak upper neck moments (19.5 Nm – see Figure 21) was produced by 3-point seatbelt mounting. For rigid ISOFIX anchorage, the peak upper neck moment about the x-axis was 6.1 Nm. As a result, 3-point seatbelt mounting exhibited more visible head rotation about the x-axis (ear tilts towards shoulder), than rigid ISOFIX anchorage.

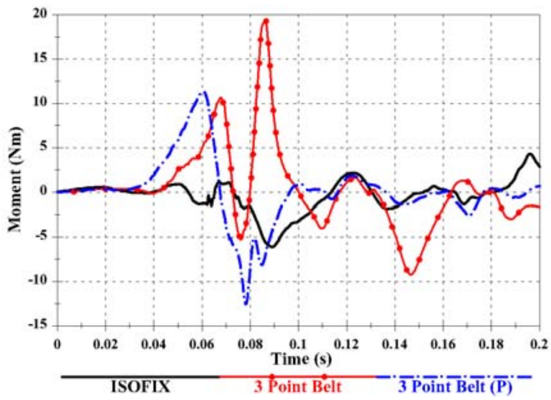

Figure 21. Upper neck moment (Mx) (HIII 3 year old – Series 2).

Rigid ISOFIX and pre-tensioned 3-point seatbelt anchorage methods produced substantially higher neck flexion / extension moments than 3-point seatbelt mounting. For rigid ISOFIX, 3-point seatbelt, and pre-tensioned 3-point seatbelt anchorage, the peak upper neck flexion moments were 29.8 Nm, 13.8 Nm, and 35.5 Nm respectively. For each of these anchorage methods, the corresponding peak upper neck extension moments were 24.8 Nm, 9.3 Nm, and 20.4 Nm (see Figure 22).

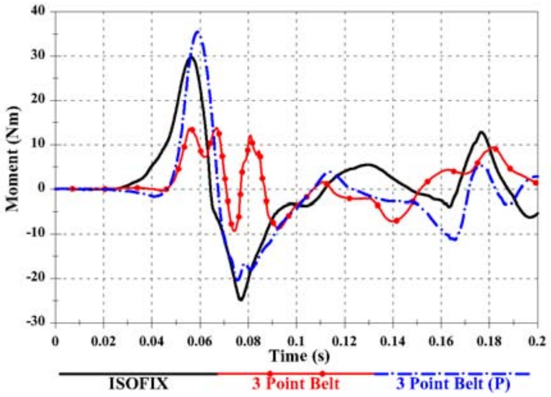

Figure 22. Upper neck moment (My) (HIII 3 year old – Series 2).

Maximum resultant chest acceleration was similar for each 3-point seatbelt anchorage method tested. Rigid ISOFIX anchorage produced slightly higher maximum resultant chest acceleration. There were also differences in the relative timing of maximum chest acceleration. For the rigid ISOFIX and pre-tensioned 3-point seatbelt anchorage modes, maximum chest acceleration occurred approximately 15-20 ms before maximum head acceleration. For 3-point seatbelt mounting, maximum head and chest acceleration occurred at approximately the same time.

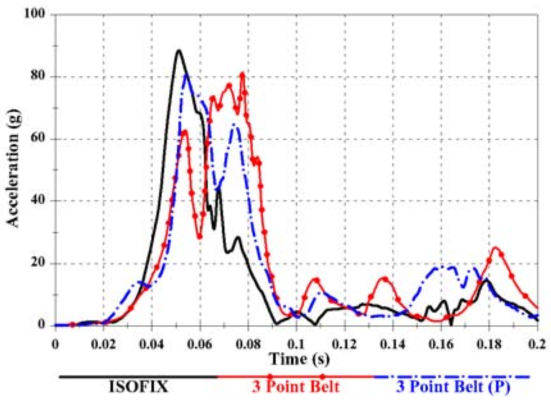

Figure 23. Resultant chest acceleration (HIII 3 year old – Series 2).

The onset, duration, and magnitude of chest deflection varied depending on the restraint anchorage method used. Rigid ISOFIX and pre-tensioned 3-point seatbelt mounting both produced substantially more chest deflection than 3-point seatbelt mounting. For rigid ISOFIX, 3-point seatbelt, and pre-tensioned 3-point seatbelt anchorage, the peak chest deflections were 17.5 mm, 16 mm, and 8.2 mm respectively. For rigid ISOFIX anchorage, the chest deflection response also indicated an earlier onset and longer duration of chest loading (see Figure 24).

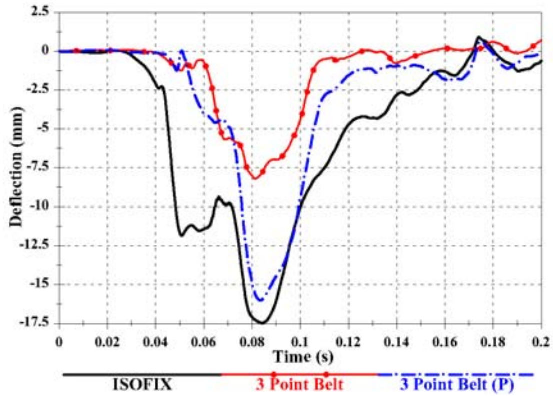

Figure 24. Chest deflection (HIII 3 year old – Series 2).

Peak resultant pelvis accelerations were substantially greater for 3-point seatbelt mounting, than for rigid ISOFIX anchorage (see Figure 25). Pelvis acceleration values were not obtained for the test using pre-tensioned 3-point seatbelt attachment. When 3-point seatbelt mounting was used, the base of the child restraint moved forward before the lap portion of the 3-point seatbelt began to carry substantial load. This delay in the onset of lap belt load, led to a higher and later occurrence of peak resultant pelvis acceleration (relative to rigid ISOFIX anchorage).

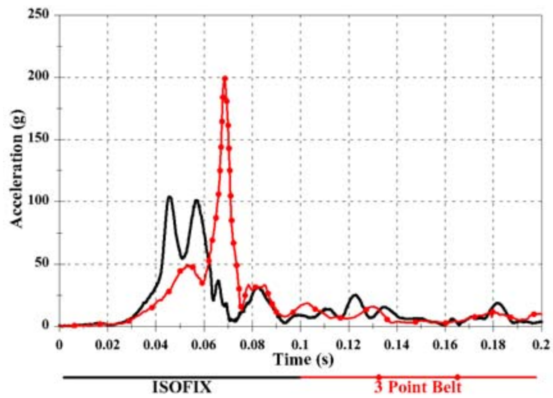

Figure 25. Resultant pelvis acceleration (HIII 3 year old – Series 2).

DISCUSSION

Australian Design Rule (ADR) 34/01 currently requires each child restraint top tether anchorage to be able to withstand a minimum static test load of 3.4 kN. The Department of Transport and Regional Services is not aware of any cases of failure in the field of top tether anchorages complying with ADR 34/01.

The results presented in this paper show a maximum dynamic top tether load of 9.4 kN for a restraint attached using 3-point seatbelt and subjected to the AS/NZS 3629.1 test pulse. Tests of restraints mounted in the vehicle body shell using 3-point seatbelt recorded a maximum dynamic top tether load of 7.7 kN. Maximum dynamic top tether loads for restraints mounted using rigid ISOFIX were around 6 kN. These results indicate that the use of lower anchorage systems to mount child restraints does not impose increased loading on top tether anchorages compared with the loads imposed by the mounting of child restraints using 3-point seatbelts.

The application of static or dynamic load imposes different stress states on anchorages. A static load of the same magnitude as a peak dynamic load is a more severe load condition than the transient dynamic load. Due to the longer duration of loading, a static load may cause greater deformation than a transient load of greater magnitude acting only for short duration. This would suggest that in order to withstand a 9.4 kN dynamic load, a top tether anchorage may need to withstand a static load somewhat less than this value. The 3.4 kN static load requirement of ADR 34/01 is significantly lower than the 9.4 kN maximum recorded dynamic load and there is a risk that an anchorage designed to withstand the 3.4 kN static load may not be able to withstand the 9.4 kN dynamic load. However, there is no field data to suggest that the ADR requirement is inadequate. This may be because the AS/NZS 3629.1 test is a more severe condition than observed in the field. This contention is supported by top tether loads recorded in the vehicle body shell that were lower than those in the AS/NZS 3629.1 tests. It is also important to note that the 3.4 kN static test load is a minimum load that must be withstood. Vehicle manufacturers are likely to design top tether anchorages to pass this requirement by a significant margin, such that the static failure load is significantly higher than 3.4 kN.

The maximum dynamic load on the lower anchorages recorded during tests of child restraints with a top tether connected and subjected to the AS/NZS 3629.1 pulse was 7.2 kN. Tests conducted using rigid ISOFIX without a top tether connected recorded a maximum dynamic lower anchorage load of 11 kN. For tests conducted in the vehicle body shell, maximum dynamic lower anchorage loads have been estimated to be 13.3 kN.
Both UNECE Regulation 14 and US Federal Motor Vehicle Safety Standard (FMVSS) 225 specify the testing of child restraint anchorages by application of static force through a fixture loading only the lower anchorages. UNECE Reg 14 requires an 8 kN static test load; FMVSS 225 requires 11 kN static test load. In addition, there is a requirement to use a fixture to test the strength of the lower anchorages and top tether anchorage simultaneously – UNECE Reg 14 requires an 8 kN static test load; FMVSS 225 requires 15 kN.

The maximum dynamic load on the lower anchorages in the tests reported in this paper has been estimated to be 13.3 kN. It is not straightforward to determine the static test load that would need to be used to ensure that anchorages are capable of withstanding this peak dynamic load. One possible approach could be to use the experience gained from existing ADR 34/01 requirements to find a ratio of static to dynamic loads that may be appropriate. This approach would suggest that either the UNECE static load requirement (8kN) or the FMVSS static load requirement (11 kN) may be sufficient to address the 13.3 kN maximum dynamic load. However, one further step of research will be required to confirm the static load requirements for lower anchorages.

The geometry of the UNECE and FMVSS fixture used to simultaneously load the lower anchorages and top tether anchorage is such that roughly half of the applied load is distributed to the top tether anchorage. A static force of 8 kN applied to the fixture would result in approximately 4 kN static load applied to the top tether anchorage. This compares favourably with the 3.4 kN requirement currently in ADR 34/01. There is however, a difference in the duration of the UNECE Reg 14 and ADR 34/01 static test loads. UNECE Reg 14 requires the load to be sustained for at least 0.2 seconds, whereas ADR 34/01 specifies 1 second.

In terms of restraint performance and dummy injury measures from the tests reported in this paper, flexible LATCH strap does not seem to offer any significant benefits when compared with 3-point seatbelts. Indeed, it could be argued that some of the injury measures for restraints mounted using flexible LATCH straps indicate a higher risk of injury than for 3-point seatbelts. However, the LATCH strap routing path was the same as that used for 3-point seatbelt and was not optimised for a flexible strap to be attached to the lower anchorages. Such optimisation may improve the performance of restraints attached using the flexible LATCH strap.

Attachment of restraints using rigid ISOFIX shows a reduced risk of injury for many of the dummy injury assessment measures, but with a relative increase in risk for neck injury and chest deflection when using a Hybrid III 3 year old dummy. However, these relative increases in injury risk for rigid ISOFIX attachment were similar to those observed for attachment using 3-point seatbelt with pyrotechnic retractor pre-tensioning. Hence, it could be argued that rigid ISOFIX attachment would not present any increased safety risk compared with systems that would currently be allowed in the Australian market.

The current Australian Standard AS/NZS 1754 for child restraints for use in motor vehicles does not specify injury assessment reference values for dummies when testing forward facing child restraints.

Appropriate injury criteria and injury assessment reference values for children are the subject of ongoing international research and debate. Scaling techniques have been applied to adult injury risk functions in an attempt to estimate injury risk to children. However, consensus has not always been reached on which adult injury risk functions should be used as the starting point and the proposed scaling techniques and scaling factors vary widely. This paper is not intended to appraise, select or recommend particular scaling techniques or child injury assessment reference values, but it is informative to refer to some of these as they provide a context in which the data from the tests reported in this paper can be considered.

The Recommended Procedures for Evaluating Occupant Injury Risk from Deploying Side Airbags (Side Airbag Out-of-Position Injury Technical Working Group) provided a set of injury reference values and additionally a set of injury research values which specify injury limits for the Hybrid III 3 year old dummy. Some of these are reported in Table 5. Scaling techniques reported in the US National Highway Traffic Safety Administration (NHTSA) report entitled “Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems II” can also be applied to adult injury reference values from UNECE Regulation 94 to determine equivalent injury limits for the Hybrid III 3 year old dummy. Some values determined in this way are also reported in Table 5.

For tests using the Hybrid III 3 year old dummy, some of the injury measures recorded during the tests exceed the injury limits contained in Table 5. This suggests that these tests are relatively severe and represent a condition that may cause injury to a child and hence may serve as a useful comparison in assessing the anchorage loads anticipated during such a crash, as well as providing some basis for comparison of the performance of child restraints attached to the vehicle by various methods.

Table 5.
Injury Limits for Hybrid III 3-year-old Dummy

Injury Measure	Limit Value
15 ms HIC	570*
36 ms HIC	900**
3 ms Head Acceleration	80 g***
Upper Neck Tension	1.13 kN*
Upper Neck Flexion	68 Nm*
Upper Neck Extension	34 Nm*
Upper Neck Shear	0.9 kN**
Thorax Deflection	36 mm*
Thoracic Spine Acceleration	55 g*

* Side Airbag Out-Of Position Technical Working Group Recommended Procedures for Evaluating Occupant Injury Risk from Deploying Side Airbags.

** UNECE Regulation 94 adult injury limit scaled using techniques described in NHTSA report entitled “Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems II”.

*** UNECE R94 adult injury limit.

The results using rigid ISOFIX connection with a Hybrid III 3-year old dummy show a reduced risk of head injury, but a slightly increased risk of extension injury to the upper neck and chest injury (thorax deflection and thoracic spine acceleration) when compared to other mounting systems. The results for neck extension moment and chest deflection are below the limit values in the above table. The peak thoracic spine 3 ms acceleration for rigid ISOFIX was around 85 g compared with 75 g for the other mounting systems. All of these values exceed the proposed 55 g limit.

CONCLUSION

The use of lower anchorage systems for mounting of child restraints does not provide increased loading on top tether anchorages when compared to mounting child restraints using the adult 3-point seatbelt. On the basis that the current ADR 34/01 requirement for a 3.4 kN top tether static test load is adequate, static test loads at or above this level would be sufficient to ensure structural integrity of top tether anchorages.

The maximum dynamic lower anchorage loads determined during child restraints tests according to AS/NZS 3629.1 and in a vehicle body under simulated 56 km/h full frontal barrier test conditions are less than or equal to 13.3 kN.

Mounting of child restraints using flexible LATCH straps does not seem to offer any safety improvement over the use of the adult 3-point seatbelt and may reduce the level of safety in some instances.

Mounting of child restraints using rigid ISOFIX anchorages offers some safety benefits over the use of the adult 3-point seatbelt, but may increase the risk of neck and chest injury compared to some child restraint systems currently in use in Australia. However, the neck and chest injury results for the rigid ISOFIX system evaluated in this test series do not indicate an increased injury risk when compared to some child restraint systems that would currently be permitted.

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[4] United Nations Economic Commission for Europe (UNECE) Regulation 14.

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APPENDIX

Table A1.
Summary of Test Results

Sled Test / ID		Restraint	Mounting	Dummy	Top Tether Angle	Sled dV (km/h)	Sled g	Max. Tether Anchorage Load (kN)	Max. Lower Anchorage Load (kN)	Resultant 3 ms Head Accel. (g)	Max. Resultant Chest Accel. (g)	HIC 36	Max. Forward Head Excursion (mm)	Max. Lateral Head Excursion (mm)
SERIES 1														
Calibration		n/a	n/a	n/a	n/a	49.5	26.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a
1	S050308	Model A	Rigid ISOFIX	P3	0	48.8	26.4	6.06	6.01	49.41	59.54	350	509	18
2	S050309	Model B	Flexible LATCH	P3	0	48.1	26.9	8.27	4.11	101.60	56.11	1446	670	32
3	S050310	Model B	3-point Seatbelt	P3	0	48.5	27	7.78	n/a	90.20	55.05	1207	691	30
4	S050311	Model B	3-point Seatbelt	P3	0	48.2	27	7.98	n/a	96.25	57.82	1482	675	17
5	S050312	Model B	3-point Seatbelt	P3	20	47.9	26.9	5.33	n/a	102.90	64.14	1559	681	181
6	S050313	Model A	3-point Seatbelt	P3	0	48.2	26.9	6.31	n/a	68.63	65.53	446	570	105
7	S050314	Model A	3-point Seatbelt	P3	0	48.1	27	3.85	n/a	66.33	51.66	496	552	133
8	S050315	Model A	3-point Seatbelt	P3	0	49.2	26.9	9.38	n/a	60.35	53.49	491	543	19
9	S050316	Model A	3-point Seatbelt	P3	0	47.9	26.7	6.33	n/a	66.70	62.36	451	574	104
10	S050317	Model A	3-point Seatbelt	P3	0	48.1	27	5.11	n/a	72.40	63.75	543	546	67
11	S050318	Model C	3-point Seatbelt	P3	0	48.4	27	5.13	n/a	109.40	50.73	1372	541	93
12	S050319	Model C	3-point Seatbelt	P3	0	48.2	26.8	4.83	n/a	97.26	59.54	1315	570	141
13	S050320	Model A	3-point Seatbelt	P3	20	48.3	27.2	5.26	n/a	69.19	63.43	775	610	200
14	S050321	Model C	3-point Seatbelt	P3	20	48.2	27	3.98	n/a	89.37	58.22	1190	604	464
15	S050322	Model A	Rigid ISOFIX	P3	0	48.8	26.5	5.78	6.18	63.27	58.22	480	522	13
16	S050323	Model A	Rigid ISOFIX	P3	0	49	26.7	5.66	6.30	89.56	60.17	717	553	8
17	S050324	Model A	Rigid ISOFIX	P3	20	48.9	26.8	4.82	7.17	65.16	66.34	486	561	231
18	S050325	Model A	Flexible LATCH	P3	0	48.2	26.8	8.28	5.39	106.80	59.77	1421	636	56
19	S050326	Model A	Flexible LATCH	P3	0	48.7	26.8	9.06	4.92	76.15	51.33	882	593	37
20	S050327	Model A	Flexible LATCH	P3	0	47.9	26.8	8.39	5.19	102.20	57.03	1212	631	72
21	S050328	Model A	Flexible LATCH	P3	20	47.4	26.9	6.19	6.14	94.30	59.53	972	639	140
22	S050329	Model B	Flexible LATCH	P3	0	47.9	27.1	8.10	4.03	118.20	52.94	1641	711	17
23	S050330	Model B	Flexible LATCH	P3	20	47.7	27	6.48	4.17	100.20	58.26	1219	692	170
24	S050331	Model C	Flexible LATCH	P3	0	47.9	26.8	5.08	5.97	120.30	58.73	1568	555	40
25	S050332	Model C	Flexible LATCH	P3	0	48.4	26.9	5.10	5.88	132.80	51.00	1442	557	99
26	S050333	Model C	Flexible LATCH	P3	20	48.2	27	4.39	6.81	87.51	55.14	945	557	336
27	S050334	Model A	Rigid ISOFIX	P3	n/a	48.1	26.7	n/a	10.63	89.40	56.29	749	647	39
28	S050335	Model A	Rigid ISOFIX	P3	n/a	48.2	26.8	n/a	11.04	79.92	54.59	717	668	8
SERIES 2														
1	20310-01L	Model A	Rigid ISOFIX	P3	0	63.2	51.4	1.86	-	109.30	70.51	1541	411	48
	20310-01R	Model B	Flexible LATCH	P3	0	63.2	50.4	5.02	7.87	138.50	99.54	2545	470	96
2	20310-02L	Model A	Rigid ISOFIX	P3	0	62.7	52.3	4.31	-	95.40	82.16	1308	365	123
	20310-02R	Model B	Flexible LATCH	P3	0	62.7	48.7	6.79	6.29	150.40	89.94	2835	460	51
3	20310-03L	Model A	3-point Seatbelt (P)	P3	20	63.1	50.5	5.68	n/a	114.20	80.58	1617	453	200
	20310-03R	Model A	3-point Seatbelt (P)	P3	0	63.1	48.2	4.76	n/a	108.90	124.13	1488	433	40
4	20310-04L	Model B	3-point Seatbelt	P3	0	63.1	52.7	6.12	n/a	214.50	114.23	4896	493	220
	20310-04R	Model B	3-point Seatbelt (P)	P3	0	63.1	50.7	7.73	n/a	129.30	84.61	2632	420	71
5	20310-05L	Model B	Flexible LATCH	P3	20	62.7	47.8	6.88	6.68	143.90	88.72	3045	489	159
	20310-05R	Model B	3-point Seatbelt	P3	0	62.7	50.5	7.28	n/a	164.50	82.77	2930	439	65
6	20310-06L	Model A	Rigid ISOFIX	P3	20	62.2	46.2	4.45	-	93.79	69.47	1087	370	66
	20310-06R	Model A	3-point Seatbelt (P)	HIII 3 y.o.	0	62.2	47.4	4.56	n/a	95.32	81.16	1673	431	73
7	20310-07L	Model A	Rigid ISOFIX	HIII 3 y.o.	0	62.9	49.9	4.39	-	103.40	88.46	1578	376	33
	20310-07R	Model A	3-point Seatbelt	P3	0	62.9	46.9	4.95	n/a	114.10	90.47	1517	437	29
8	20310-08L	Model A	3-point Seatbelt	P3	20	62.5	51.9	4.16	n/a	158.60	130.57	2972	486	162
	20310-08R	Model A	3-point Seatbelt	HIII 3 y.o.	0	62.5	48.2	4.79	n/a	132.90	81.45	1853	467	150
9	20310-09L	Model B	3-point Seatbelt (P)	P3	20	62.8	48.2	6.88	n/a	170.00	94.11	3851	473	189
	20310-09R	Model C	3-point Seatbelt	P3	0	62.8	52	5.49	n/a	102.10	101.63	1579	468	75

Table A2.
Seatbelt Webbing Load Cell Measurements

Sled Test / ID	Restraint	Mounting	Dummy	Top Tether Angle	Outer Lap Belt Load (kN)	Inner Lap Belt Load (kN)	Inner Sash Belt Load (kN)	Outer Sash Belt Load (kN)
SERIES 1								
S050310	Model B	3-point Seatbelt	P3	0	2.06	1.47	-	0.34
S050311	Model B	3-point Seatbelt	P3	0	2.07	1.71	-	0.39
S050312	Model B	3-point Seatbelt	P3	20	2.1	1.64	-	0.96
S050313	Model A	3-point Seatbelt	P3	0	4.56	3.27	-	1.92
S050314	Model A	3-point Seatbelt	P3	0	3.46	2.58	-	1.77
S050315	Model A	3-point Seatbelt	P3	0	2.79	1.92	-	0.68
S050316	Model A	3-point Seatbelt	P3	0	4.3	3.42	-	2.91
S050317	Model A	3-point Seatbelt	P3	0	3.56	2.61	-	1.57
S050318	Model C	3-point Seatbelt	P3	0	2.98	1.68	-	0.58
S050319	Model C	3-point Seatbelt	P3	0	2.65	1.49	-	0.47
S050320	Model A	3-point Seatbelt	P3	20	3.18	2.45	-	1.42
S050321	Model C	3-point Seatbelt	P3	20	3.54	1.72	-	1.01
SERIES 2								
20310-03L	Model A	3-point Seatbelt (P)	P3	20	5.31	5.09	4.21	6.24
20310-03R	Model A	3-point Seatbelt (P)	P3	0	5.62	4.44	-	6.58
20310-04L	Model B	3-point Seatbelt	P3	0	4.36	3.88	3.27	4.15
20310-04R	Model B	3-point Seatbelt (P)	P3	0	3.65	3.13	3.39	4.38
20310-05R	Model B	3-point Seatbelt	P3	0	3.49	2.8	1.66	2.48
20310-06R	Model A	3-point Seatbelt (P)	HIII 3 y.o.	0	5.33	4.26	4.69	6.11
20310-07R	Model A	3-point Seatbelt	P3	0	5.93	4.15	4.56	5.71
20310-08L	Model A	3-point Seatbelt	P3	20	5.85	5.35	5.27	6.43
20310-08R	Model A	3-point Seatbelt	HIII 3 y.o.	0	5.18	5.1	3.98	6.57
20310-09L	Model B	3-point Seatbelt (P)	P3	20	4.06	5.82	-	-
20310-09R	Model C	3-point Seatbelt	P3	0	5.24	4.98	3.89	3.11

Notes:

S050313, S050316: The restraint top tether failed due to fracture of the plastic shell at the left side top tether slot. This allowed the tether webbing end plate to pull through the back of the restraint. The restraints used for these tests were not originally fitted with top tether straps. The initial method of attaching tether straps was found to be inadequate.

S050314, S050317: Re-test of the previous failed restraint (with tether modification)

S050310, S050320, S050322, S050334, S050335: Chalk paint evidence of possible head contact with harness buckle assembly.

20310-01L, 20310-01R: Vehicle rear seat back deformation occurred. Seats were then supported with an additional cross member along their upper edge for the remainder of the test series. Results provided, but not used for analysis purposes.

20310-04L: The top tether webbing cut on an exposed bolt head which was part of the additional seat back strengthening cross member. Results provided, but not used for analysis purposes.

Rebound was ignored for the calculation of maximum values (eg. 3 ms head acceleration).

20310-02R, 20310-05L, 20310-05R, 20310-08L, 20310-08R, 20310-09L: Dummy head collided with polycarbonate sheet.

REAR SEAT SAFETY FOR THE GROWING CHILD – A NEW 2-STAGE INTEGRATED BOOSTER CUSHION

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ABSTRACT

The overall protection of the growing child in the car is a question of designing child safety systems specifically for the needs of the child, such as age, stature and weight. Safety benefits are seen if children use booster cushions up to the ages of 10 to 12 years. The aim of this study is to present and to evaluate the safety potential of a new rear seat design for the growing child, including 2-stage booster cushions together with progressive load-limiters.

The 2-stage booster cushion is an evolution of the first generation integrated booster cushions which were launched in 1990. The 2-stage booster cushion was designed to help provide an even better fit for an even broader range of sizes of forward facing children. In its high position, the seat belt fit for the smaller children is in focus. In its low position it offers a more adapted thigh support (reducing likelihood of slouching) for the larger children, as compared to when using the adult seat position. The progressive load-limiter is adapted to the child.

Referring to accident experiences of children in rear seats of prior Volvo cars and published data on booster usage, misuse, performance and functionality, the safety potential is estimated and discussed.

This study presents a new rear seat safety concept for enhanced overall protection for children aged approximately 4 to 12 years old. The 2-stage booster cushion and the progressive load limiter working as a system has potential for increased safety by attracting increased usage by a larger span of child occupant sizes together with a more adapted crash performance.

INTRODUCTION

The development of child restraint systems for cars began in the early 1960's. During the past 40 years, different child restraint systems have been developed to improve protection for children of different sizes and ages. Isaksson-Hellman et al. (1997) and Jakobsson et al. (2005) showed a clear upward trend of steadily increased safety for children in cars during this time period in Sweden. This was due to the increased frequency in the use of restraints, and the development of effective child restraint systems.

Belt-positioning boosters

Belt-positioning booster cushions were introduced in the late 1970's (Norin et al. 1979). Today, there are three main belt-positioning boosters; booster cushions, booster seats (including seat backs) and integrated (built-in) booster cushions. The systems are used with the adult seat belt which restrains both the child and the booster. The integrated boosters were developed in order to simplify usage and to minimize misuse (Lundell et al. 1991). They can be found in the rear seats of Volvo cars from 1991 onwards, in the mid-seat or outboard position (depending on car model) and always with 3-point seat belts.

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

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

Rear seat safety development

Safety standards for passenger cars have been steadily improving for several decades, even in the rear seat. Three-point belts in the outer seating positions in the rear seat were introduced in the late 1960's. Three-point retractor belts were introduced on some markets in 1972 and in 1975 became standard for Volvo cars in all markets. A further improvement to the rear seat was the anti-submarining floor ridge introduced in 1982 in the Volvo 760 model (Lundell et al. 1981). In the rear centre seat the lap-belt was the only belt available for several years. However, improvements to the rear centre belt began in 1986, with the introduction of a three-point belt and head restraint for the centre seat as an accessory on the Volvo 700 saloon model (Karlbring and Mellander 1987). This became standard equipment for the rear centre seat starting with the Volvo 900 saloon in 1990 (Lundell et al. 1991) and estates in 1992 (Lundell et al. 1994). All new Volvo models are fitted with them still. Height-adjustable head restraints were introduced with the three-point belts in the rear centre seat. These were necessary prerequisites for the integrated booster cushions offered as an optional feature (Lundell et al. 1991 and 1994). The present study takes us to the next generation of rear seats for children, enhancing protection further.

The aim of this study is to present and evaluate the safety potential of a new rear seat design, including 2-stage booster cushions together with progressive load-limiters.

OUTLINE

A new rear seat safety design for the growing child, including 2-stage integrated booster cushions with progressive load-limiters will be presented. Referring to accident experiences of rear seated children in prior Volvo cars and published data on booster usage, misuse, performance and functionality, the safety potential is estimated and discussed.

FIELD DATA

Subset

A dataset of children in Volvo Cars' statistical accident database is analyzed. Crashes involving Volvo cars in Sweden where the repair costs exceed a specified level (currently SEK 45 000) are identified by the insurance company Volvia (If P&C Insurance). Photos and technical details of the cars (e.g. damage) are sent to Volvo Cars' traffic accident research team. The owner of the car completes a questionnaire (shortly after the crash) to provide detailed information about the crash and the occupants. Injury data is gathered from medical records and analyzed by a physician within Volvo Cars' traffic accident research team. Injuries are coded according to the Abbreviated Injury Scale (AIS, AAAM 1985). This forms the basis of the database.

Rear seat child occupants aged 3 to 12 years old, who have been involved in a crash occurring within the years of 1987 and 2006 have been selected for this study; a total of 2179 occupants, 48% girls and 52% boys. The distribution of restraint type is shown in Table 1. Among the 874 children using boosters, 47 were restrained in integrated boosters, the majority in mid-rear seat position. The somewhat low proportion of integrated boosters available is due to the dataset, covering also car models prior to the availability of integrated boosters.

Table 1.
Number of forward facing child occupants 3-12 years old in the rear seat with respect to restraint type.

Restraint type	*Total*
unknown	*49*
unrestrained	*85*
rearward facing seats	*30*
seat belt	*1141*
boosters	*874*
Total	*2179*

Boosters are belt-positioning booster seats or booster cushions, of accessory as well as integrated types. In all of these, the child together with the booster is restrained by the adult seat belt. Unfortunately, information regarding how the seatbelt is placed (potential misuse) is not available in the material.

Restraint type versus age

The distribution of restraint type in the rear seat versus age is shown in Figure 1.

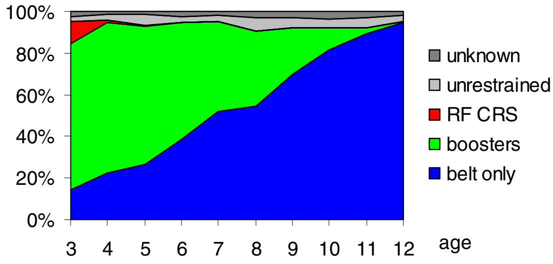

Figure 1. Distribution of restraint type for children aged 3-12 in rear seat.

As can be seen in Figure 1, the overall restraint use is high, less than 10% of the children are unrestrained. In the data, over half of the children use seat belts only with a rather linear increase from 14% at the age of 3 to more than 90% use at the age of 12. Only approximately 40% of the rear seat child occupants at the age of 7 use boosters, and approximately 15% of the children above 7 years old and above use boosters.

Integrated boosters are used across the whole age span. Compared to accessory boosters a trend of higher usage rate with increased age is seen for the integrated boosters, Figure 2.

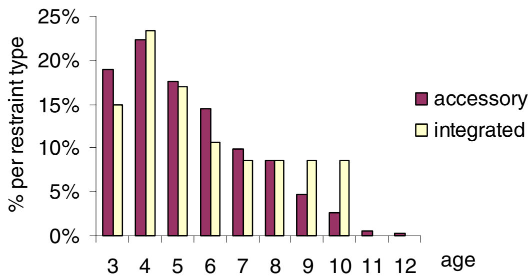

Figure 2. Distribution of booster type over age.

For the sample of occupants selected, the overall injury reducing effect (MAIS 2+) for boosters is 75% (with the confidence limits 42% and 89%) as compared to unrestrained children. The injury reducing effect of boosters as compared to belted-only children is calculated as 31%, however not statistical significant. The method for calculating the injury reducing effect was presented in Isaksson-Hellman et al. 1997.

Abdominal injuries in frontal impacts

The distribution of abdominal injuries can be seen in Figures 3a and 3b for children in frontal impacts, belted-only and in boosters, respectively. The 23 (out of 28) occupants with integrated boosters in a frontal impact with known impact severity are indicated in Figure 3b.

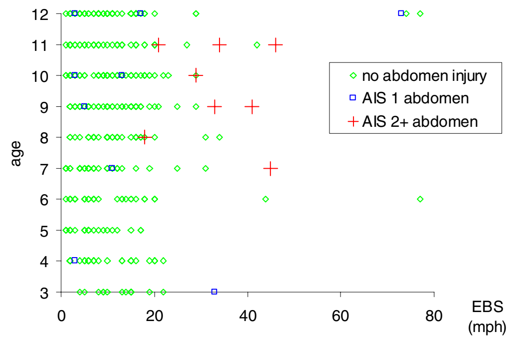

Figure 3a. Distribution of abdominal injury AIS for children in a rear seat restrained by <u>belt only</u> in frontal impacts, Equivalent Barrier Speed (EBS) versus age.

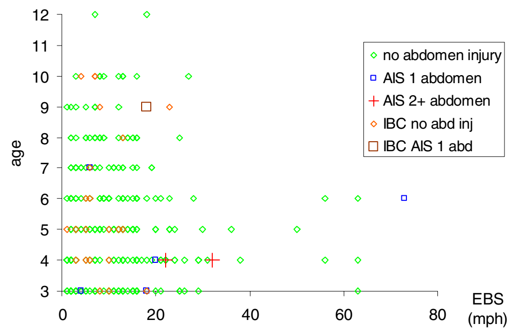

Figure 3b. Distribution of abdominal injury AIS for children in a rear seat restrained by <u>boosters</u> in frontal impacts, EBS versus age. 23 cases of integrated boosters (IBC) are indicated.

The abdominal AIS 2+ injury rate is less for children restrained in boosters (0.8%) as compared to belt-only restrained (1.5%). Only one injury to the abdomen (level AIS 1) was seen for the occupants using integrated boosters. Among the children using booster, only two children sustained AIS 2+ abdominal injuries. The two injured four-year-olds were both seated on booster seats (of accessory type) with very poor guidance of the lap belt. During the crash, the pelvis slid under the belt and the loads were transferred into the soft tissues in the abdomen, resulting in fatal abdominal injuries for one of them and internal abdominal injuries, AIS 2, for the other.

NEW 2-STAGE INTEGRATED BOOSTER CUSHION WITH PROGRESSIVE LOAD LIMITERS

The 2-stage booster cushion, Figure 4, has evolved from the first generation integrated booster cushions as introduced in 1990. The 2-stage booster cushion was designed to provide an even better fit for an even broader range of sizes of forward facing children. In its high position, the seat belt fit, ride comfort and visual aspects are taken into consideration. In its low position it offers a more adapted thigh support (reducing likelihood of slouching) for the larger children, as compared to when using the adult seat position. Recommended use of the cushions is for children aged from 4 years to 10-12 years old.

Figure 4. The new 2-stage integrated booster cushion, low and high position, respectively

Technical description of booster

Figures 5a and 5b show sketches of the integrated booster in its low and high position, respectively.

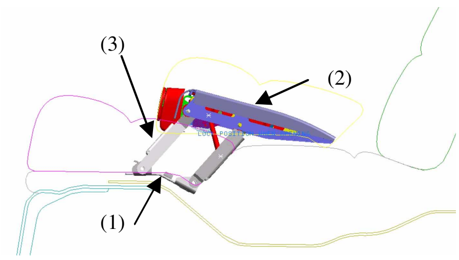

Figure 5a. Sketch of the integrated booster at its low position.

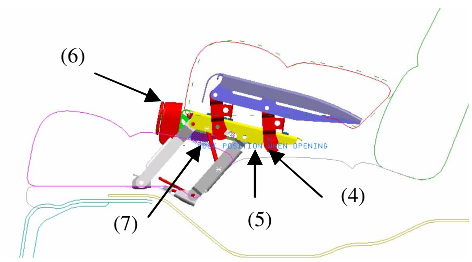

Figure 5b. Sketch of the integrated booster at its high position.

The booster cushion is attached to the rear seat wire frame by a screw-fixed base plate (1). The trim and foam, on which the occupants sit, are attached to the seat plate (2) via foam and trim carrier. The base plate and the seat plate are attached to each other by dual link arms. There are two sets of link arms, one for the lower first stage (3) and one for the higher second stage (4). Between the two sets of link arms there is a sub frame (5). Most of the locking mechanism, including the handle (6) is attached to the sub frame. During a frontal impact, the deformation element (7) helps enables enhanced crash performance by deforming.

The locking mechanism allows the booster cushion to be fixed in its three positions; folded down adult seat position, first stage low position and second stage high position. A number of springs in the system ensures that the booster is self-presented when released from a lower to a higher position.

Functionality and handling of booster

In its low position, the integrated booster is designed for larger children, fitting children 115-140 cm / 22-36 kg. In its high position, the booster fits children 95-120 cm / 15-25 kg.

Figure 6 illustrates the belt fit for two children of different sizes using their most adaptable stage of sitting.

Figure 6. Photo of two children using the 2-stage integrated boosters.

At both stages, the child will perceive stable seating, due to the dual link arms. This is especially important in the second stage, where the child has a high seating position.

Figures 7a and 7b illustrate the 2-stage up-folding functions. When adjusting from the folded down adult seat position to first stage low position, handling is similar to that of the first generation integrated booster cushions (Lundell et al. 1991), i.e. pulling the handle outwards. The booster is then locked in position by pushing the booster backwards. Adjustment from first stage low position to second stage high position is facilitated by pushing the button above the handle inwards. As in the low position, the booster is then locked by pushing the booster backwards.

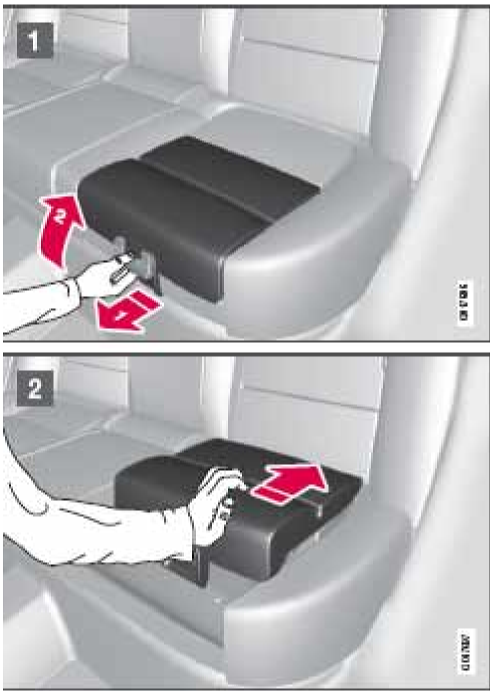

Figure 7a. Folding function from folded down adult seat position to low position.

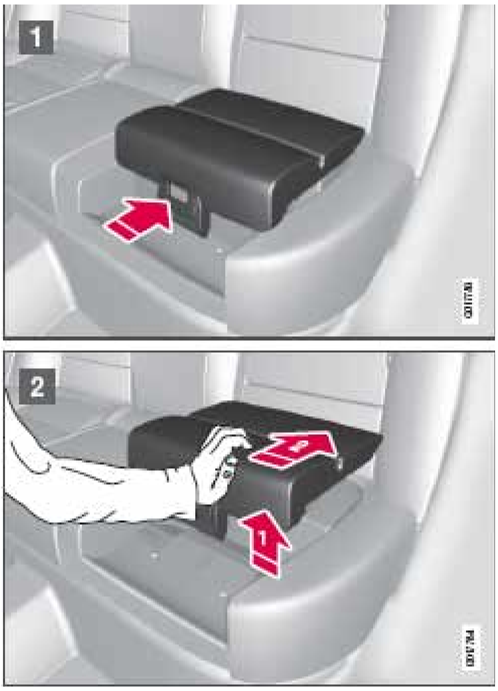

Figure 7b. Folding function from low to high position.

The booster is folded down from either the first stage or the second stage by pulling the handle outwards and pushing the booster downwards. It is not possible to operate the booster from its second stage to its first stage without first folding it down into the adult seat cushion.

The thickness of the foam has been chosen to give adults sitting on the booster in its folded down adult position as good comfort as possible. Adults, being heavier than children, require thicker foam to be comfortably seated. A lot of care has been taken not to jeopardize adult comfort. Therefore, the booster cushion has been designed to the lowest possible height so that the comfort foam can be as thick as possible and that the step between the rear seat foam and the booster foam is not perceived. The packaging size of the 2-stage booster is equal to the first generation of booster, providing an equal level of adult comfort.

An attitude and handling focus group session was performed using 17 children aged 7 years old and their parents testing both accessory and integrated boosters (Bohman et al. 2007). The integrated booster was rated good with respect to ease of use, fast to buckle up, the user feeling secure when handling, no lap-belt misuse and stability when entering/leaving the car. The new 2-stage integrated booster offers these benefits and adds further benefits for adapting the seat to both smaller and older children.

One of the main functionalities of the booster is to offer the child a more adapted thigh support. Anthropometry data of children's thigh length (from the buttock to the inside of the knee) is shown in Figure 8. As can be seen, almost no children aged 12 years or under have a thigh length that allows them to sit comfortably in the adult seat. Thus, slouching is a very probable effect of attaining comfort for many children if using an adult seat. The booster, which is shorter than the adult seat, will allow the child's knees to bend comfortably at the edge of the booster and encourage a more upright and safe sitting posture.

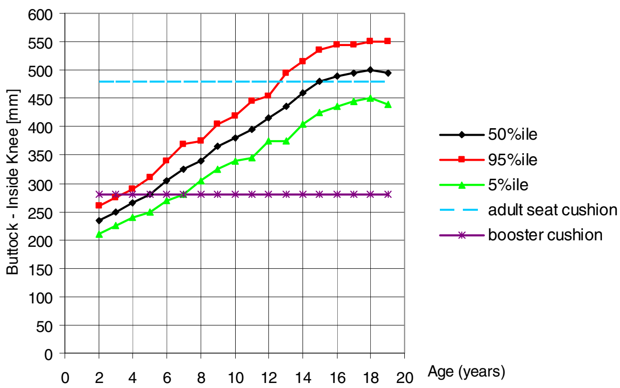

Figure 8. Buttock to inside knee length for children and young adults (ref Pheasant 1986). Upper horizontal line is the adult seat cushion depth. The lower horizontal line is the booster cushion length.

Another functionality is the raising effect of the booster and this aspect in side impacts. The average eye heights for children of different ages when seated are plotted in Figure 9, showing the three different positions; adult seat, stage 1 and stage 2 respectively. In this Figure, the lower coverage level of the inflatable curtain (IC) is indicated. Due to initial seating posture and kinematics during a crash, this level is approximate and serves only as an indication. As can be seen, the gain in height using the booster as compared to the height of the adult seat will offer children better adaptability of the safety systems of the car.

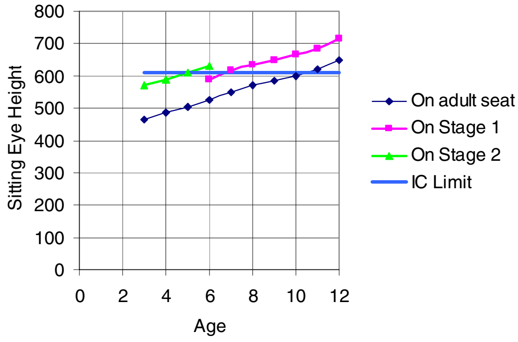

Figure 9. Eye height for children when seated (50%-ile boys, ref Pheasant 1986). Horizontal line is the approximate level of the Inflatable Curtain (IC).

There are also well-being advantages with using boosters such as in the higher positioned boosters even the younger children can look out through the side window and thereby enjoy the ride more. It not only calms the child but can induce feelings of harmony and happiness. As a result they are less likely to 'distract' the driver. In a large questionnaire based survey conducted in Australia, 71% of the children traveling in boosters reported that they liked being elevated so they could look out of the window better (Charlton et al. 2006).

Progressive load limiter

Together with the 2-stage integrated booster, the seat belt is equipped with a pretensioner and load limiter to further enhance the crash performance.

The pretensioner is pyrotechnical with increased pretensioning effect compared to the existing V70 introduced 1999. Increased pretensioning effect is introduced to further remove initial slack in the belt system at the early phase of the crash.

The load limiter is progressive in two stages by a torsion bar, as seen in Figure 10.

Figure 10. Torsion bar of the seat belt load limiter.

The first stage with low load limiting (narrow diameter) is initially active when the seat belt is loaded during impact. After a certain turning angle of the seat belt's bobbin, the first stage is locked by a mechanical sleeve and the higher load limiting level (thicker diameter) is active for the rest of the impact.

Progressive load limiting allows the occupant to experience improved crash performance depending on weight of the occupant and crash severity.

Performance

The setting of the progressive load limiter and the design of the integrated booster cushion is based on extensive frontal impact testing using different dummy sizes and impact severities. The aim was to achieve a robust performance for the variety of occupant sizes and severities, especially focusing on children, who represent almost 50% of all rear seat occupants. Although designed for children aged approximately 4 to 12, the child dummy sizes used in the testing are the existing 3, 6 and 10--year-old child dummies.

Extensive testing confirms the ambition of robustness by comparable results for different occupant sizes in same impact situation. The difference in injury values for a 3-year-old and a 10-year-old in a 35 mph impact is less than 20% for relevant dummy readings. The introduction of the load limiter enabled the possibility to enhance performance of the smaller occupants due to the progressive two step load limiter characteristics.

SAFETY POTENTIAL PREDICTION

The importance of a belt-positioning booster for forward-facing children, to avoid abdominal injuries caused by the abdomen slipping under the belt, has been shown in several studies (DeSantis Klinich et al. 1994, Isaksson-Hellman et al. 1997, Hummel et al. 1997, Warren Bidez and Syson 2001, Durbin et al. 2003). The field data presented in this study supports these findings and emphasizes the importance of boosters, and that the booster is designed to hold the belt firmly against the pelvis or thighs during a frontal impact. The overall effectiveness (MAIS 2+) of boosters is estimated as 31% as compared to using seat belt only and as high as 75% as compared to no restraint at all. Getting all children of appropriate age and size to use boosters offers a potentially significant safety benefit.

Booster usage varies greatly for different countries. Less than half of the children aged 4 to 12 in Volvo cars in Sweden use boosters as indicated in Figure 1. For those above 7 only 15% use a booster. In a questionnaire based survey in Australia (Charlton et al. 2006), which covered 700 parents with children 4 to 11 years old, 42% of the children included in the survey were appropriately restrained based on the height criteria (<140cm should use boosters). Data from the US shows a significant increase in booster usage in the 4 to 8 year age group from 4% in 1999 increasing to 27% in 2004 (Arbogast and Winston 2006). Although the trend is positive, the overall booster use rate in the US is low and the booster seat use of children above 8 years of age also needs to be addressed (as illustrated in Figure 8). In a study conducted in Spain only 9% of children aged 6 to 12 used child restraints (unspecified type) (Tejera 2006).

Even though small sample size, Figure 2 indicates that the acceptance of integrated boosters seems to be higher for older children as compared to accessory boosters. It can then be speculated that by offering an integrated booster, usage will increase along with the overall potential safety benefit.

For the children using boosters, different types of misuse affects the performance. The frequency of misuse varies depending on which study is analyzed, but the share is significant. According to a study carried out in the US by NHTSA (2004), 39.5% of the 664 children inspected in belt-positioning boosters were considered as critical misuse. The most commonly occurring cases of misuse were improper fit of shoulder belt followed by loose belt, improper fit of lap belt and inappropriate age/fit. Morris et al. (2000) studied 164 children in belt-positioning boosters in the US and identified misuse in 20% of the cases. The most common misuse was incorrect positioning of shoulder belt, followed by child inappropriate in size, inappropriate seat belt for booster and seat belt routed incorrectly. In Germany, the misuse rate for booster cushions was reported to be 46.8% according to a study by Fastenmeier and Lehnig (2006). A Spanish study carried out as a part of the EU-project CHILD, identified that nearly 50% of the children, aged 6 to 12 restrained with a child restraint (unspecified type), had some type of misuse (Tejera 2006). The most common misuse was having the seat belt placed behind the back of the child. Data from France in the same study indicates figures of booster misuse as approximately 65%. The most commonly occurring cases of misuses were lap belt over belt guiding, twisted seat belt and seat belt behind the back.

In an attitude and handling focus group study, all children questioned (7 years old) managed to handle the seat belt correctly in the integrated booster, while 5 out of 7 had incorrectly handled (misused) the belt with the accessory boosters (Bohman et al. 2007). Using a Hybrid III 6-year-old dummy with incorrect belt routing over the guiding horn of the accessory booster in a frontal impact test, it was shown that when the lap belt was above both guiding horns, the dummy slid off the booster causing the dummy to submarine with potential abdominal injuries as a result (Bohman et al. 2006). Integrated boosters have an advantage with respect to this type of misuse, since no such guiding horns are needed. With regard to incorrect belt routing of the shoulder belt because of discomfort, the integrated booster has been designed in conjunction with the seat belt geometry which could potentially reduce this type of misuse. A 2-stage booster increases this potential by further adapting the seat belt geometry to different sizes of children, as illustrated in Figure 6.

A questionnaire based study on 4 to 11-year-old children in Australia (Charlton et al. 2006) reported that one of the reasons for moving the child from booster to adult seat belt only (69%) was primarily that the child was too big for the booster. Other major reasons were that the child disliked sitting in a booster, the child had reached the upper weight limit recommended, the child would be more comfortable using a seat belt only and that the child thought they were too 'grown-up' for a booster. The study concludes that the design of boosters should have the capacity to seat bigger children as well as being more appealing to children. Children do not grow in distinct steps and they naturally strive to be seen as 'grown-up'. This is important and not always in line with using the same child safety system from the ages of 4 to 10-12. By offering a two-stage concept, integrated in the car, it is believed that the level of acceptance will increase and thus enhance overall protection.

One reason for abdominal injuries for children using a seat belt only is the phenomena of slouching (DeSantis Klinich et al. 1994). If thigh length is shorter than the seat cushion, slouching is natural to increase comfort. As shown in Figure 8, not many of the children below 12 will sit upright with knees bent comfortably when using the adult seat only. The low stage of the new booster is for children 6 years and above. It is designed to be comfortable for this group and should reduce the likelihood of slouching, thus increasing safety.

The performance of belt pretensioners and load limiters for child protection was illustrated by Bohman et al. 2006 and van Rooij et al. (2003). Using a Madymo HybridIII 6-year-old dummy, van Rooij et al. showed that the combination of a belt pretensioner (to tie the child to the vehicle deceleration at an earlier phase) and a force limiter (to limit peak chest loading) was very beneficial. Head, neck and chest values were significantly reduced when compared to the reference; a reduction of 15% to 70%. Bohman et al. (2006) used a Hybrid III 6-year-old dummy and four different types of boosters (one integrated), comparing the effect of a pretensioner and a load limiter. Adding a pretensioner to the standard retractor reduced the chest acceleration from 16-25%, HIC_{15} 42-47%,

N_{IJ} 0-24% and neck tension 10-17%, having a limited effect on the chest deflection. Adding a load limiter to the pretensioner, the chest acceleration and neck loadings were further reduced. Additionally the effect of load limiting reduced the chest deflection by 23% and 27% compared to a standard retractor for the accessory boosters and the integrated booster, respectively. The HIII 6-year-old dummy was best protected using an integrated booster and seat belt with pretensioner and load limiter (reductions from 21 to 50% compared to worst condition). The 2-stage integrated booster with the progressive load limiter will, as a system, enhance performance across a wide range of occupant sizes and impact severity, thus increasing overall protection.

When introducing the world's first integrated booster (Lundell et al. 1991) tests were presented showing the differences in performance between integrated boosters and accessory boosters. Bohman et al. (2006) found that when comparing an integrated booster and an accessory booster, the integrated booster offers a more direct coupling to the seat belt system, without slack introduced by a loose cushion. In addition, the lap belt force with an integrated booster was lower than the lap belt force with an accessory booster. Most types of boosters offer good protection if used correctly. But knowing that correct usage is not always the case, the robustness for misuse is an important aspect of the safety of a booster.

Jakobsson et al. (2005) showed that head injuries were the most frequent injuries to children in side impacts and the head injuries sustained by children were of similar types and mechanisms as for adults. Using the integrated booster, children will gain height (Figure 9) and thereby enhance adaption to the safety systems in the car in a side impact as compared to sitting on the adult seat. Integrated systems designed to perform with the rest of the car safety systems will increase overall protection.

The total safety prediction of the new 2-stage integrated booster with progressive load limiter cannot be calculated in absolute numbers at present. However, overall protection is expected to increase as usage increases, by increased acceptance and comfort, together with the safety performance of a robust and adapted system.

DISCUSSIONS

The protection of the growing child in the car is a question of designing child-restraint systems specifically for the needs of the child. A child's age, size, and even feelings are important aspects with regard to the specific needs. For the children in the age group of 4 to 10-12, restraints need to compensate for the development and size of the pelvis to accommodate belt geometry for good protection during a crash. This study presents an appealing way of pleasing the needs of the growing child.

In order to avoid abdominal injuries by the abdomen slipping under the belt during a frontal impact it is advisable for children up to the age of around 10 to 12 years old to use belt-positioning boosters. Data from different places in the world shows that, at present not many children above 7 use boosters, even though thigh length and pelvis size and development is not compatible with an adult seat. Safety potential is significant if booster usage is increased worldwide and by offering an integrated 2-stage booster in the car, the availability, functionality and acceptance is anticipated to result in an increase, although it is difficult to state this in absolute numbers.

For those using boosters, the misuse factor is significant. Worldwide, the most common booster misuse factor is incorrect routing of the seat belt. Studies have shown that integrated boosters are found to be easier to use for lap belt positioning. The 2-stage system is believed to further adapt to the different sizes of children for shoulder belt comfort and placement.

This study presents a 2-stage integrated booster with progressive load limiter. This is a result of many years research in child safety and safety of the rear seat occupants and a natural step in rear seat safety development at Volvo Cars. In a study in 1997 (Isaksson-Hellman et al.), it was concluded that the safety systems available offered good protection and that the areas of concern were; not using the restraints or not using the appropriate restraint for the child's age and size. The importance of adapting the child safety system to the growing child, when considering both acceptance and performance, is anticipated to make a positive impact on better overall safety.

CONCLUSIONS

The study presents a new rear seat safety concept for enhanced overall protection for children aged 4 to 10-12. The 2-stage booster and the progressive load limiter working as a system has the potential to increase safety by encouraging increased usage by a large cross-section of child occupant sizes together with a more adapted crash performance for the children.

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ABDOMINAL INJURY RISK FOR CHILDREN SEATED IN BELT POSITIONING BOOSTER SEATS

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ABSTRACT

Previous studies have demonstrated that booster seats reduce the risk of seat belt syndrome, in particular the occurrence of abdominal organ injuries, by improving the fit of the seat belt on young children and encouraging better posture and compatibility with the vehicle seat itself. However, other researchers have shown that abdominal injuries are still prevalent even with the use of booster seats. In the US, as booster seat use increases and more data become available, particularly on older children in booster seats, the abdominal injury risk to these children should be revisited. Therefore the objective of this study was to quantify the time trend increase in appropriate restraint for rear row(s) seated children age 4 to 7 years old and define the prevalence of abdominal injuries in those restrained by belt-positioning booster seats. A probability sample of 4,517 crashes involving 5,259 children, weighted to represent 89,588 children in 77,153 crashes was collected from an on-going child specific crash surveillance system between December 1, 1998, and December 31, 2005. Appropriate restraint, including the use of belt positioning boosters, increased from 17% to 67% among 4 to 7 year olds during the time period of data collection. In frontal impacts, abdominal injuries occurred among 0.25% of all 4- to 7-year-olds, including 0.32% of those in seat belts and 0.04% of those in belt-positioning booster seats. Among children restrained in belt positioning booster seats, we were not able to detect a difference in the risk of abdominal injuries between the age groups This study, conducted on a dataset with increased booster use by 6 and 7 year olds, confirms previous analyses that point to a reduced abdominal injury risk for children in belt-positioning booster seats. Abdominal injuries still occurred in some booster-seated children, however, suggesting the need for further in-depth study into the circumstances surrounding these injuries.

INTRODUCTION

Abdominal injuries are the second to head and face injuries in young children using adult seat belts. [1] Reported injuries to this region focus on "seat-belt syndrome", which consists of belt-induced abdominal injuries and lumbar spine fractures. [2-6] While all children are at risk of developing seat belt syndrome, the poor fit of the belt in younger children likely places them at higher risk than older children. In a study of abdominal injuries in belted children, the scenarios resulting in injury involved several vehicle and child factors such as seat belt geometry not ideal for children (e.g. a shallow lap belt angle), position of the shoulder belt behind the back or slouched posture to position the knees over the edge of the seat. [7]

The use of a belt positioning booster seat (BPB) improves these factors by improving the fit of the seat belt on young children and encouraging better posture and compatibility with the vehicle seat itself. They are the recommended restraint for 4 to 8 year old children according the American Academy of Pediatrics and National Highway Traffic Safety Administration. Booster seats are designed to improve lap and shoulder belt fit on children, minimizing the factors that result in abdominal injury. Our previous research has confirmed this in real world crashes by showing booster seats reduce the risk of injury to children age 4-7 years old by 59% compared to similar age children in adult seat belts. This reduction in injury risk was particularly evident in the abdomen, resulting in 0 injuries per 1,000 booster seat restrained children in crashes versus 4.4 per 1,000 for children in belts. [1] This analysis conducted on data from 1998 to 2002 was based primarily on children age 4 and 5 years of age due to the usage practices during that time period. In the time since this research was published, however child restraint use including booster seats among children age 4 to 8 years of age has improved by 54% [8] and, as more children, in particular older children, are appropriately restrained in booster seats, continued monitoring of their real world experience is paramount.

Recently, other researchers have questioned the issue of abdominal injury prevention by booster seats. Several studies have reported the occurrence of these injuries in other field studies. In France, a study of 1629 children under 10 years old involved in crashes during 1992 and 1993 revealed that abdominal and pelvic injuries represented 13% of AIS 2 and greater injuries sustained by booster-seated children. [9] Using data from this study, Trosseille reported on the abdominal injuries sustained by nine booster-seated children but reported few crash or restraint use details such as impact type, severity, booster seat type or presence of misuse. [9] More recently, Johannsen used data from the European CHILD (CHild Injury Led Design) project to reconstruct real world crash events in an effort to validate newly designed abdominal sensors for the Q family of ATDs. In his study, he reconstructed and reported on four cases of frontal impacts involving abdominal injury in booster-seated children. [10] In a recent study of booster-seated children in Australia, Brown reported on 2 children who sustained abdominal injuries, one as the result of a frontal impact and one as the result of a side impact. [11]

Due to the changing nature of the booster use landscape and these case series reports of abdominal injuries in booster seat restrained children, this issue deserves further investigation. Therefore the objective of this study was to quantify the time trend increase in appropriate restraint for rear row(s) seated children aged 4 to 7 years old and define the prevalence of abdominal injuries in those restrained by belt-positioning booster seats.

METHODS

Study Population and Data Collection

Data collected from December 1, 1998 to December 31, 2005 as part of Partners for Child Passenger Safety (PCPS) were used in this analysis. Detailed descriptions of the study population and methods involved in data collection and analysis have been previously published. [12] PCPS consists of a large scale, population based, child-specific crash surveillance system in which insurance claims from State Farm Insurance Co. (Bloomington, IL) function as the source of subjects. Crashes qualifying for inclusion were those involving at least one child occupant < 15 years of age riding in a model year 1990 or newer State Farm-insured vehicle. Qualifying crashes were limited to those that occurred in fifteen states and the District of Columbia, representing three large regions of the United States (East: NY, NJ [until 11/01], PA, DE, MD, VA, WV, NC, DC; Midwest: OH, MI, IN, IL; West: CA, NV, AZ, TX [starting 6/03]). On a daily basis, data from qualifying and consenting claims were transferred electronically from all involved State Farm field offices to researchers at The Children's Hospital of Philadelphia and University of Pennsylvania. Data in this initial transfer included contact information for the insured, the ages and genders of all child occupants, and a coded variable describing the medical treatment received by all child occupants. Data in this initial transfer included contact information for the insured, the ages and genders of all child occupants, and a coded variable describing the level of medical treatment received by all child occupants as reported by the policyholder (no treatment, physician's office or emergency department only, admitted to the hospital, or death).

A stratified cluster sample was designed in order to select vehicles (the unit of sampling) for the conduct of a telephone survey with the driver. Vehicles containing children who received medical treatment following the crash were over-sampled so that the majority of injured children would be selected while maintaining the representativeness of the overall population. If a vehicle was sampled, all child occupants in that vehicle were included in the survey. Drivers of sampled vehicles were contacted by phone and, if medical treatment had been received by a passenger, screened via an abbreviated survey to verify the presence of at least one child occupant with an injury. All vehicles with at least one child who screened positive for injury and a 10% random sample of vehicles in which all child occupants who were reported to receive medical treatment but screened negative for injury were selected for a full interview; a 2.5% sample of crashes where no medical treatment was received were also selected. The full interview involved a 30-minute telephone survey with the driver of the vehicle and parent(s) of the involved children. Only adult drivers and parents were interviewed. The median length of time between the date of the crash and the completion of the interview was six days, with 95% of interviews completed within 47 days of the crash.

Variable Definitions

Restraint status of children was determined from the telephone survey. Children were classified as unrestrained or restrained, with the restraint type further classified as seat belt, belt-positioning booster (BPB), or child safety seat (CRS). Among the 169 children aged 4-7 for whom paired information on restraint use was available from both the telephone survey and crash investigations, agreement (child restraint vs. no child restraint / unrestrained) was 96% between the driver report and the crash investigator (kappa value for agreement beyond chance=0.86, p<0.001). Seating location of each child was determined from the telephone survey. Among the 170 children for whom paired information on seating position (front versus rear) was available from both the telephone survey and crash investigations, agreement was 99% between the driver report and the crash investigator (kappa value for agreement beyond chance=0.99, p<0.001).

Survey questions regarding injuries to children were designed to provide responses that were classified by body region and severity based on the Abbreviated Injury Scale (AIS) score, and have been previously validated for their ability to distinguish AIS 2+ from less severe injuries. [13] For the purposes of this study, children were classified as injured if a parent/driver reported a clinically significant injury: any injury with an AIS score of 2 or greater (concussions and more serious brain injuries, all internal organ injuries, spinal cord injuries, and extremity fractures).

Separate verbal consent was obtained from eligible participants for the transfer of claim information from State Farm to CHOP/Penn, for the conduct of the telephone survey, and for the conduct of the crash investigation. The study protocol was reviewed and approved by the Institutional Review Boards of both The Children's Hospital of Philadelphia and The University of Pennsylvania School of Medicine.

Data Analysis

The primary purpose of these analyses was to compute the increase in appropriate restraint for children 4 to 7 years of age over the time period of study and the relative risk of abdominal injury for those restrained in belt positioning booster seats compared with seat belts. Chi-square tests of association were used to compute p-values under the null hypothesis of no association between restraint type and risk of injury. Logistic regression modeling was used to compute the odds ratio (OR) of injury for those seated in belt-positioning booster seats versus seat belts, both unadjusted and adjusted for several potential confounders including differences in driver age (< 25 years vs. 25 and older), seating position (front vs. rear), crash severity (intrusion, towaway/no intrusion, non-towaway), and vehicle type.

Because sampling was based on the likelihood of an injury, subjects least likely to be injured were underrepresented in the study sample in a manner potentially associated with the predictors of interest. [14] To account for this potential bias, and to adjust inference to account for the stratification of subjects by medical treatment and clustering of subjects by vehicle, robust chi-square tests of association and Taylor Series linearization estimates of the logistic regression parameter variances were calculated using SAS-callable SUDAAN: Software for the Statistical Analysis of Correlated Data, Version 9.0 (Research Triangle Institute, Research Triangle Park, NC, 2006). Results of logistic regression modeling are expressed as unadjusted and adjusted odds ratios (OR) with corresponding 95% confidence intervals (CI).

RESULTS

This analysis includes 5,259 restrained 4 to 7 year old children in 4,517 crashes, weighted to represent 89,588 children in 77,153 crashes. Overall, 41% of children were appropriately restrained in child restraints or belt positioning booster seats during the time period of data collection. Eighteen percent were restrained by harness-based child restraint systems (CRS), 23% by belt positioning booster seats (BPB), and 59% by the vehicle seat belts. The overall risk of AIS 2 or greater injuries to all body regions was 1.13% for all restrained children, and 0.70% and 1.43% for appropriately and inappropriately restrained children, respectively.

Table 1 shows the distribution of the study sample in terms of the child’s seat position, driver characteristics, crash severity and vehicle type. Appropriately restrained children were more likely to be seated in the outboard positions and be driven by a parent at the time of the crash. Inappropriately restrained children were more likely to be in crashes resulting in intrusion or vehicles towed from the scene.

Trends in Appropriate Restraint Use

During the time period of data collection, appropriate restraint increased from 17% to 67% for 4 to 7 year old children, a three-fold increase during the seven-year period. For the older children, 6 to 7 years of age, appropriate restraint increased from 3% in 1999 to 50% in 2005. For the younger children, 4 to 5 years of age, appropriate restraint increased from 30% to 82% in the same time period. Figure 1 shows the time trend increase in appropriate restraint for 4 to 5 year old and 6 to 7 year old children, stratified by CRS, high back BPB and low back BPB use.

Table 1.
Characteristics of Crashes Involving Children Aged 4 to 7 Years by Appropriate and Inappropriate Restraint Use*

Characteristics	Appropriate Restraint (%) (unweighted n=1613)	Inappropriate Restraint (%) (unweighted n=3646)	P Value
Seat position			
Left rear	46.2	38.9	<0.001
Center rear	9.7	18.4	
Right rear	44.1	42.7	
Driver			
Aged <25 yrs	5.4	5.3	0.90
Parent of child	87.1	79.5	<0.001
Crash severity			
Intrusion	7.1	8.4	0.011
Towaway, no intrusion	23.6	28.1	
Not towaway, no intrusion	69.2	63.5	
Vehicle type			
Passenger car	42.9	44.1	0.66
SUV	24.3	22.2	
Minivan	26.8	27.4	
Large van	1.6	2.3	
Pickup truck	4.4	4.0	

*Data presented as weighted percentages

In 1999, 65% of appropriately restrained 4 to 5 year old children were using a harness-based CRS, 28% in a high back BPB, and the remaining 8% in a low back BPB. By 2005, a larger proportion of 4 to 5 year olds were in booster seats, with 41% and 24% in high and low back BPB, respectively. Thirty-five percent remained in CRS. For 6 to 7 year old children, few children were appropriately restrained in 1999 (3%), 80% of which were in a harness-based CRS. By 2005, the appropriately restrained 6 to 7 year old children (50%) were primarily in booster seats, 42% and 39% in high and low back BPB, respectively. The remaining 19% were in CRS.

Abdominal Injury Risk

In order to examine abdominal injury risk of those restrained in belt positioning booster seats, the analysis was further restricted to the subset of children in frontal impacts, who were restrained by BPB (high back or low back) or seat belts at the time of the crash. This resulted in 2,102 children in 1,789 crashes, weighted to represent 34,301 children in 29,061 crashes. The overall abdominal injury risk was 0.25% for all 4 to 7 year olds, including 0.30% for 4 to 5 year old children and 0.20% for 6 to 7 year old children. Table 2 shows the abdominal injury risk by age group for children restrained by BPB and vehicle seat belts.

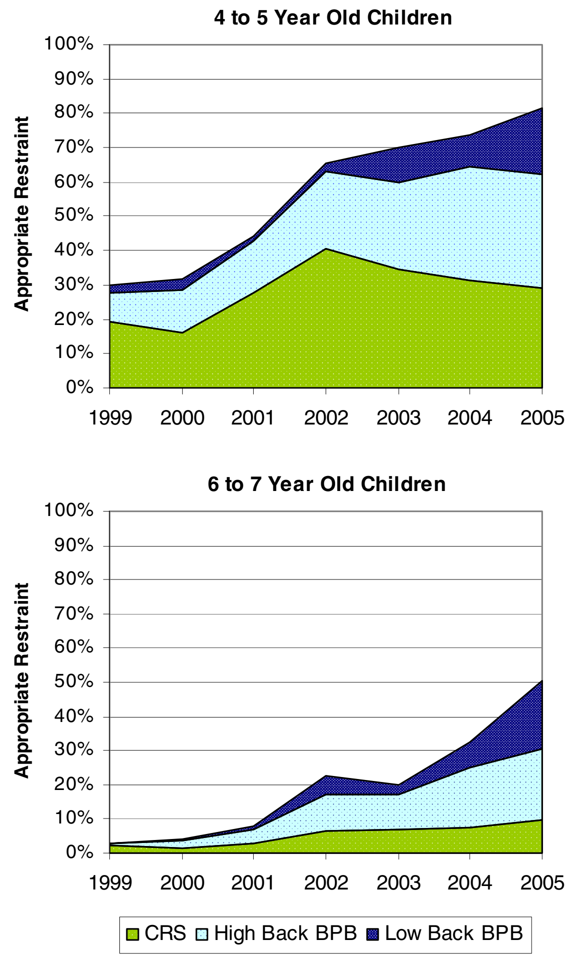

Figure 1. Time trend increase in appropriate restraint for 4 to 5 year old and 6 to 7 year old children.

Children aged 4 to 7 using the vehicle seat belt were more likely to sustain abdominal injuries than similarly aged children using belt positioning booster seats (OR 9.22, 95% CI, 2.01-42.36). The younger age group, children 4 to 5 years of age, showed a significant increase in abdominal injury risk when using seat belts (OR 13.99, 95% CI, 1.66-117.8). The older age group, children 6 to 7 years of age, also showed an increased abdominal injury risk when using seat belts but this finding did not reach statistical significance (OR 5.61, 95% CI, 0.65-48.2). Among children restrained in belt positioning booster seats, we were not able to detect a difference in the risk of abdominal injuries between the age groups (OR 0.82, 95% CI, 0.07-9.23). When stratified by seat belt type, the results were similar with a reduction in abdominal injury risk for booster seated 4 to 7 year olds over both lap belted children (OR 5.16, 95% CI, 1.37-19.42) and lap/shoulder belted children (OR 10.20, 95% CI, 2.05-19.42).

Table 2.
Abdominal Injury Risk for 4 to 7 Year Old Children by BPB and Seat Belt Use

Age Group (yrs)	BPB (%) (unweighted n=388)	Seat belt (%) (unweighted n=1,714)	P Value
All 4 to 7	0.04	0.32	0.004
4 to 5	0.03	0.46	0.015
6 to 7	0.04	0.23	0.116

*Data presented as weighted percentages

Table 3 shows the abdominal organ injured by restraint type. The table shows a count of injured organs, therefore it may sum to greater than the number of children injured. . Injuries to children in seat belts occurred more commonly to the stomach and intestines than the solid organs such as liver and spleen. Only three children in BPB were injured in this study sample, resulting in one injury to the liver, stomach/intestines and other organ.

Table 3.
Distribution of Injured Abdominal Organ by Restraint Type

Organ of Injury	BPB (n=3)	Lap Belt Only (n=9)	Lap and Shoulder Belt (n=22)
Liver	1	1	2
Spleen	0	2	3
Stomach/Intestines	1	5	9
Other Organ	1	1	4
Unknown	0	0	4

DISCUSSION AND CONCLUSIONS

Our research findings confirm those of previously published studies indicating an increase in appropriate restraint among children aged 4 to 7 years old. [15, 16] This percentage continues to increase over time; however in 2005, 20% of 4 and 5 year old children and 50% of 6 and 7 year old children continued to be inappropriately restrained in vehicle seat belts. This points to the need to continue education and legislative efforts toward appropriate restraint in this age range. . Recent research has shown that, in the United States, appropriate restraint increases in states that amended child restraint laws to mandate booster seat use up through age 7 years. [15]

Appropriately restrained children were using a combination of CRS, high back and low back booster seats. CRS and high back BPB are the most common restraints for the younger age group but the proportion of low back BPB continues to increase. Most appropriately restrained children in the older age group are in belt positioning booster seats, also demonstrating a rise in the proportion of low back boosters. While all booster seats have guides to position the lap portion of the belt low and flat across a child's upper thighs, high back boosters also provide head support and upper belt guides to optimize the position of the shoulder portion of the belt. As low back booster use increases, research to better understand the experience of children in these restraints should continue.

This study extends previous reports that belt-positioning booster seats reduce the risk of abdominal injury in children 4 to 7 years of age by studying a greater percentage of 6 and 7 year olds. [1] While children in BPB are at significantly decreased risk of these injuries, some abdominal injuries still occurred. These included injuries to both the solid and hollow organs, including some injuries that may be associated with seat belt syndrome. Abdominal injuries in booster-seated children continue to be rare events but deserve more detailed examination through review of in-depth investigations.

Limitations

This research is conducted on crashes involving State Farm Insurance Co. policyholders only. State Farm is the largest insurer of automobiles in the United States, with over 38 million vehicles covered; therefore, its policyholders are likely representative of the insured public in this country. The surveillance system is limited to children occupying model year 1990 and newer vehicles insured in 15 states and the District of Columbia. Our study sample represents the entire spectrum of crashes reported to an insurance company including property damage only, as well as bodily injury crashes. While our sample included a significant number of vehicles with intrusion into the occupant compartment, it is possible that the PCPS study does not have a representative sample of the most severe crashes. Nearly all of the data for this study were obtained via telephone interview with the driver/parent of the child and is, therefore, subject to potential misclassification. On-going comparison of driver-reported child restraint use and seating position to evidence from crash investigations has demonstrated a high degree of agreement. Some misclassification of seat type may occur due to the changing market of child restraints such that many are combination seats that may be used with a harness or a lap and shoulder belt. In addition, misuse of the booster seat and the lap and shoulder belt may not be fully accounted for in these analyses.

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SPINAL INJURIES IN REAR SEATED CHILD OCCUPANTS AGED 8 – 16 YEARS

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ABSTRACT

While spinal injury in child occupants is relatively rare, the significance of these injuries is high. For children too big for booster seats the best available protection is adult belts in the rear seat. This paper presents a case series of 27 rear seated restrained child occupants aged between 8 and 16 years diagnosed with a injury to the spinal region, and discusses the current lack of regulatory or consumer assessment of injury risk to child occupants too big for booster seats.

Data was collected from retrospective medical record review of all children treated at two major children's hospitals over a five year period. Cases were collected using spinal trauma related ICD 10 codes and all restrained child occupants between the ages of 8 and 16 years (inclusive) were extracted. All types and severities of spinal injuries were included. Restraint, seating position and crash details were taken from ambulance reports.

Most children sustained minor injuries (56%), however 13 of the 27 sustained moderate to severe spinal injuries. These include spinal cord injuries, vertebral fractures and dislocations and major ligamentous damage. Most minor injury occurred in the cervical region, and most serious injury occurred in the lumbar region. Almost all children were using the available lap sash seat belt (23/27).

There was more serious spinal injury among those children aged 8 – 12 (9/18) than there was among the older children aged 13-16 (3/9), and more than half of those younger children with serious injury (5 of 9) had associated abdominal injuries, while associated abdominal injury was not a feature among the older children.

International booster seat use legislation, the lack of regulatory and consumer assessment of injury potential to older rear seated children and the need for more widespread evaluation of rear safety for older child occupants is discussed.

INTRODUCTION

Spinal trauma in children is rare but the significance both in terms of financial and community cost is high. The most common cause in children is motor vehicle crashes [1-5]. For child occupants younger than approximately 8 years there are a number of different restraints that have been designed for the anatomical and anthropometric immaturity of children. Other authors have investigated spinal injury in children using dedicated child restraints [6-11], and in children using adult belts who should have been using dedicated child restraints [12-13]. However few have looked at this issue in older children for whom the adult lap sash seat belt is the best available restraint.

There are anatomical differences in the maturing spine compared to that of an adult, and while changes continue well into adulthood, most literature suggests much is complete by about 8 years. Anatomically then there is no reason to suspect any inherent difference in spinal injury risk in children from this age up. However, the overall growth of children continues until somewhere between 16 and 18 years, and since adult occupant restraint systems are designed for adult anthropometry there is likely to be some consequence for smaller occupants using these restraint systems.

Adult seat belts are effective in providing crash protection for child occupants compared to no restraint at all [14-16], but for children up to age 8, the overall level of protection has been found to be much better in restraints specifically designed for the smaller anthropometry of these children [17-18].

There are particular injury types associated with seat belt use, and this includes some forms of spinal injury. The 'seat belt syndrome' is a well established pattern of injuries involving the lumbar spine and and/or abdomen in occupants using adult belts and is attributed to a mechanism involving hyperflexion of the upper torso around a poorly positioned lap belt. While this syndrome was originally described in adult occupants using lap only belts [19-20], it has also been frequently discussed in terms of child occupants [18, 21].

The primary measure introduced to counter the seat belt syndrome has been the replacement of 2 point lap only belts with 3 point lap sash belts. However in many cases, these types of injuries have been described in association with both lap only belt use and lap sash belt use [21-23]. Similarly cervical injury has also been associated with seat belt use [6, 24].

In 1994, Lane [21] noted that improvements to seat belt and seat design were required to further reduce these types of injuries in 3 point lap sash belts.

This paper presents a sample of child occupants aged 8-16 years diagnosed with a spinal injury following involvement in a crash, illustrating the significance of seat belt like syndrome injuries in these children.

METHODS

Medical records for all children aged 0-16 years treated at the Children's Hospital Westmead and the Sydney Children's Hospital from 1999 to 2004 with ICD 10 codes for all types and severities of spinal trauma were retrospectively reviewed. The ICD codes included all those for cord injuries, vertebral fractures and dislocations, ligamentous injury and internal and external soft tissue injuries. All cases where the child had been injured as a passenger in a motor vehicle were then selected for inclusion in the overall data set. A case series of rear seated restrained children aged 8 – 16 years was then constructed from this data set.

Information related to the child's age, gender, height, weight and detailed injury descriptions were then extracted. Detailed information related to the crash, seating position and restraint type and quality was also extracted. The ambulance report was used for this purpose wherever possible, and where conflicting information was recorded in the ambulance report and the medical record, details from the ambulance report was used. Crash data in the ambulance report includes a description of the crash, details of the extent and location of damage to the vehicle, and an estimation of impact severity as low, medium or high, based on the extent of damage. This was used to compile case descriptions.

Quality of restraint use was classified incorrect if ambulance officers noted misuse of the restraint. All other cases were classified as correct.

Spinal injuries were coded according to the Abbreviated Injury Scale (AIS:90), and classified as minor or serious. Minor injuries consisted of external and soft tissue injuries analogous to AIS 1 injuries. Major spinal injuries were those injuries that posed some risk to the integrity of the spinal column or cord and included cord injuries, bony fractures and dislocations, and rupture of spinal ligaments. Associated injuries were also recorded.

Age in months was estimated using date of birth and date of hospital attendance, and then rounded to the nearest whole year.

The study methodology was approved by the Human Ethics Committees at the Children's Hospital at Westmead and the Southeastern Area Health Service, and ratified by the University of NSW, Human Research Ethics Committee.

CASE SERIES OVERVIEW

Overall, data was collected for 81 child occupants aged between 2 and 16 years, (with a mean age of 8.5 years) who had been diagnosed with an injury to the spinal region. There were 40 restrained children aged between 8 and 16 years, 27 rear seated, 12 front seated and one child whose seating position could not be determined. The median age of front and rear seated children was 12 and 11 years respectively. This case series contains details for all those known to be rear seated. Each case is summarised in Table 1.

Almost two thirds of the case series were female, and all but one child (Table 1 #11) was using an adult belt. This child was using a booster seat in combination with an adult lap sash belt. Of the 26 using adult belts, 3 were using lap only belts (Table 1 #9,10 & 27). The remaining 23 were using lap sash belts however incorrect use of the sash portion of the belt was identified in 2 cases (Table 1 #3 & 13).

Twenty of the 26 children occupied outboard seating positions (11 in the left rear and 9 in the right rear) and 5 occupied the centre rear position (Table 1 #9, 10, 13, 18 &27). The exact seating position of two rear seated children could not be determined (Table 1 #14 & 24).

The most frequent crash type was frontal (12 cases). There were 2 side impacts, 7 rear impacts, 3 roll overs; and 2 cases where impact direction was unknown. All cases involving roll over involved either an impact with a fixed object or another vehicle prior to or after rolling. More than half of the cases (17/27) were classified as high severity. There were 7 cases involving single vehicles, and all of these involved impacts with fixed road side objects such as trees or poles.

Of the children, approximately half had minor AIS 1 external injuries and 13/27 sustained significant spinal trauma. No child with external AIS 1 spinal injury sustained any significant injury to other body regions while most (10/13) with more serious spinal trauma did. These associated injuries primarily involved abdominal and head regions. Overall, the cervical level was most frequently involved (17/27) followed by the lumbar region (7/27). There were 3 children with thoracic spinal injury. However almost all injury to the cervical region involved external AIS 1 injuries (14/17) whereas almost all lumbar injury (6/7) and all thoracic injury involved serious spinal trauma.

Proportionally more serious injury occurred in high severity impacts (73%) compared to other severities (10%); single vehicle impacts (80%) compared to multiple vehicle impacts (40%); and impacts with fixed objects (83%) compared to impacts with other vehicles (37%). There was less difference in outcome by seating position (50% serious in outboard positions compared to 60% in the centre position) and restraint type (45% of lap sash users with serious injury compared to 33% of lap only users). All children identified to be using their restraint incorrectly sustained the more serious types of injuries. There was a fairly even split of minor and serious injury in frontal and side impacts. All cases involving rollover involved serious injury, while no cases involving rear impact involved serious injury.

There was more serious injury among those children aged 8-12 (50%) than among the older children (33%). However, there was little difference in the proportion of younger and older children in single vehicle crashes and impacts with fixed roadside objects. Older children were more often in high severity crashes (67% compared with 50%).

While there was a greater frequency of younger children seated in centre rear positions, the proportions of younger and older children using lap only belts was similar. In other words most of the younger children seated in centre rear positions were using lap sash seat belts.

Serious spinal injury among the younger children also often involved an associated abdominal injury, and this involved serious abdominal (AIS3+) injury in 44% of cases. There was no serious abdominal injury among the older children.

DETAILED DESCRIPTIONS OF CASES WITH SERIOUS SPINAL TRAUMA

As described above, there were 13 children who sustained significant spinal trauma. This included 1 child using a booster seat, 1 child using a lap only belt, and 10 children using lap sash belts. Incorrect use of the sash belt was definitively identified in 2 cases.

Booster Seat

This case (Table 1, #11) involved a 9 year old male in the right rear of an SUV using a lap sash belt with the booster. The vehicle rolled over an embankment at high speed, and then hit a tree on the right side. Both the child and the booster were reported to have been ejected out of the right window. The child sustained an atlanto-occipital dislocation and extradural hematoma in the cervical region. There was also degloving of the skin over the left scalp and diffuse axonal injury within the child's brain.

Lap Only

One of the three children using lap only belts sustained serious spinal injury. This (Table 1, #10) was a 9 year old female seated in the centre rear of a vehicle that hit a power pole side on (angle unknown) at high speed, breaking the pole. The child sustained a wedge fracture of L1with no ongoing neural deficits and abdominal abrasion with internal abdominal injury, and a forehead abrasion.

Incorrect Lap Sash Use

Incorrect use of the sash in children using lap sash belts was reported in two cases and both involved serious injury. In the first (Table 1, #3), an 8 year old female was seated in the right rear of a vehicle involved in a high severity frontal impact. The child sustained an L2 chance fracture with ligament rupture and intradural haemorrhage causing displacement at the cauda equina nerve roots. There was also grazing of the left upper abdomen, bruises to the right lower abdomen and internal abdominal organ contusions.

The second case (Table 1, #13) involved a 10 year old male seated in the centre rear of a vehicle fitted with a lap sash belt in this position. This child also failed to use the sash part of the belt and also sustained an L2 chance fracture with external contusions, this time in a high severity single vehicle impact with a tree. The orientation of this impact was not reported.

Correct Lap Sash

Five of the nine children with serious spinal injury correctly using lap sash belts also sustained lumbar and or thoraco-lumbar junction fractures.

No	AGE	Crash Details	Seat & Restraint	Quality	Spine Injury	Other injuries
1	Female, 8 yrs	Low severity multiple vehicle side impact o/s	Left rear, Lap sash	Correct use	Minor sorft tissue	abdominal contusion, pain
2	Female, 8 yrs	High severity single vehicle frontal impact with fixed object	Left rear, Lap sash	Correct use	small graze left side of neck anteriorly. Lumbar soft tissue hematoma (L1)	belt abrasions bilaterally
3*	Female, 8 yrs	High severity multiple vehicle frontal impact	Right rear, Lap sash	Incorrect use, sash not used correctly	Chance fracture L2 with ligament ruptue and intradural haemorrhage causing anterior displacement at the cauda equina nerve roots. Soft tissue oedema posterior to the entire spine and in the interspinous reqion of C1/2	grazing left upper abdomen; bruises right lower abdomen; pancreatic contusion; mesenteric contusion
4	Male, 8 yrs	Medium severity single vehicle frontal impact with fixed object	Left rear, Lap sash	Correct use	bruise neck	nasal fracture
5	Male, 8 yrs	Unknown severity multiple vehicle frontal impact	Right rear, Lap sash	Correct use	graze right side of neck	contusion behind left ear
6	Female, 9 yrs	Low severity multiple vehicle rear impact	Right rear, Lap sash	Correct use	minor soft tissue only	nil
7*	Female, 9 yrs	High severity multiple vehicle frontal impact	Right rear, Lap sash	Correct use	lateral chance type injury at T12/L1 and weakness/parathesis left leg	rupture left kidney with retroperitoneal haematoma; associated rib fractures left side 10-11; large left side pulmonary contusion with pleural effusion
8*	Female, 9 yrs	High severity single vehicle frontal impact with fixed object	Left rear, lap sash belt	Correct use	Chance fracture L1 with anterior wedging, fracture through pedicles, paraspinal hematoma	Significant small bowel injury, retorperitoneal heamatoma; bilary tree perforation, transverse bruise across abdomen at level of umbilicus; fracture lateral aspect of right 10th rib
9	Female, 9 yrs	Medium severity multiple vehicle rear impact	Centre rear, Lap only	Correct use	transient right arm numbness, called neck sprain	nil
10*	Female, 9 yrs	High severity single vehicle frontal impact with fixed object	Centre rear, Lap only	Correct use	wedge fracture L1 spinous process with extension through the superior articular facets of L2 vertebral bilaterally and subluxation of L1-2 facet joints	abdominal abrasion; oedema and fluid in root of the mesentry, paracolic gutter and pelvis; abrasion forehead
11	Male, 9 yrs	High severity single vehicle roll over then side impact with fixed object	Right rear, Booster, lap sash	Ejected out window	atlanto occipital dislocation with extra dural hematoma extending anteriorly to C1 and in a prevertebral distribution to the level of C4, and associated ligament damage	DAI left frontal lobe, left temporal lobe, basal ganglia and right internal capsule regions; deglove injury left scalp and eye region; fracture right clavicle; fracture right pubic ramus
12	Female, 10 yrs	High severity, multiple vehicle impact, unknown	Left rear, lap sash	Correct use	fracture pedicle of C2 and lamina on left. Distraction of fragments on right. Anterior slip of C2 on C3	Liver laceration associated with a subscapular hematoma

Table 1. Case series of spinal injuries in rear seated child occupants

No	AGE	Crash Details	Seat & Restraint	Quality	Spine Injury	Other injuries
13*	Male, 10 yrs	High severity, single vehicle impact with fixed object	Centre rear, lap sash	Incorrect Use	L2 chance fracture, chance fracture L2 and anterior wedging of L1	hematoma left side of back; anterior abdominal and right chest bruising; wrist contusion
14	Female, 12 yrs	Medium sevrity, Multiple vehicle rear impact	unknown rear, lap sash	Correct use	minor soft tissue only	nil
15	Female, 12 yrs	Medium severity, Multiple vehicle frontal impact	Left rear, lap sash	Correct use	minor soft tissue only	nil
16	Female, 12 yrs	High severity impact details unknown	Left rear, lap sash	Correct use	Ligamentous injury and fracture superior body T2 with transient neurological deficiet	Left adrenal hematoma, pulmonary contusion, liver contusion
17	Female, 12 yrs	High severity side impact o/s and impact with fixed object	Left rear, lap sash	Correct use	Crush fractures T4 - T9. MRI; Extensive soft tissue oedema posteriorly and ligamentous injury.	open fracture mandible; minor facial & neck abrasions; fracture right scapular, small pleural effusions
18*	Female, 12 yrs	High severity, Multiple vehicle frontal impact	centre rear, lap sash	Correct use	Wedge fracture L1/2.	abdominal abrasion,; abrasion r forehead
19*	Female, 13 yrs	High severity, Multiple vehicle frontal impact and then roll over	Left rear, lap sash	Correct use	Wedge compression fracture T12 and L1 vertebral bodies, with ligamentous injury	fracture right humerus
20	Male, 13 yrs	Medium severity, Multiple vehicle rear impact	Right rear, lap sash	Correct use	soft tissue injury, intial parasthesia right hand that resolved	nil
21*	Male, 13 yrs	High severity frontal impact with fixed object	Right rear, lap sash	Correct use	wedge compression of L3, Chance fracture L1/2 with sensoral changes scaral region	seat belt mark across abdomen
22	Female, 14 yrs	High severity, Multiple vehicle rear impact	Right rear, lap sash	Correct use	minor soft tissue only	nil
23	Female, 14 yrs	High severity near side impact and then roll over	Left rear, lap sash	Correct use	Lateral mass C1 fracture, crush fracture T8	Long deep lacerations to right cheek and ear, glass in left eye
24	Male, 14 yrs	Medium severity, frontal impact	Rear unknown, lap/sash	Correct use	Neck sprain	Abrasions and contusion knees
25	Male, 14 yrs	High severity, Multiple vehicle frontal impact	Left rear, lap sash	Correct use	soft tissue neck injury	abrasion left to right over neck; abrasion lumbar area
26	Female, 14 yrs	Medium severity, Multiple vehicle rear impact	Right rear, lap sash	Correct use	lateral neck contusion, neck pain	nil
27	Male, 15 yrs	High severity, Multiple vehicle rear impact	Centre rear, lap only	Correct use	transient tingling in arms, neck pain	abdominal pain

Table 1. Case series of spinal injuries in rear seated child occupants (continued)

In case #7 (Table 1), a 9 year old female sustained a lateral chance type injury at T12/L1 with residual neural deficits, together with a ruptured left kidney and retroperitoneal haematoma, left side rib fractures left side 10-11 and a large left side pulmonary contusion with pleural effusion. This child was seated in the right rear of a vehicle involved in a high severity head on collision with another vehicle. A similar pattern of injuries was observed in case #8, (Table 1), where another 9 year old female using a lap sash belt, this time in the left rear, sustained significant abdominal injuries, rib fracture and a chance fracture of L1. This child was in a vehicle that was clipped by another vehicle before running off road and impacting a pole head on.

A male aged 13 years (Table 1, #21) sustained a wedge compression fracture of L3, and a chance fracture of L1/2 with sensoral changes in the sacral region. There was also a seat belt mark across the abdomen. He was seated in the right rear of a vehicle that was involved in a high severity frontal offset collision with a power pole. A female aged 12 years also sustained a wedge fracture of L1/2 (Table 1, #18) and abdominal abrasions. This child also sustained a forehead contusion and was seated in the centre rear of vehicle involved in a high severity multiple vehicle frontal impact. A 13 year old female (Table 1, #19) sustained a wedge compression fracture of T12 and L1 vertebral bodies, with associated ligamentous injury and fractured right humerus in a vehicle that was involved in a high severity frontal impact before rolling over. She was seated in the left rear.

Two children sustained different types of fractures in the thoracic region. One child, a 12 year old female sustained crush fractures of T4-T9 (Table 1, #17) while seated in the left rear of a vehicle that was t-boned by a heavy vehicle and then impacted a power pole on the off side of the vehicle. The child also sustained facial and scapular fractures and a small pleural effusion. The other, (Table 1, #24) also a 12 year old female, sustained a fracture to the superior body of T2 together with ligamentous injury, transient neurological deficit, a left adrenal hematoma and pulmonary and liver contusions.

There were also two of the nine children using lap sash belts who sustained cervical fractures. The first, a 10 year old female (Table 1, #12) sustained a fracture of the pedicle of C2 and a liver injury. This child was seated in the left rear of vehicle involved in a high severity multiple vehicle impact. The second was involved in a high severity near side impact with another vehicle before rolling over (Table 1, #23). This child, a 14 year old female, was seated in the left rear and sustained a lateral mass fracture of C1, and a crush fracture of T8. She also sustained a long deep laceration over the right cheek and scalp.

DISCUSSION & CONCLUSIONS

This case series presents details of 27 rear seated children aged 8-16 years with spinal injury who presented to the two major children's hospitals in Sydney over a five year period. These children, together with the 13 front seated children who were not included in this series, represent all child occupants within this age range who were diagnosed with spinal trauma throughout this time. While these relatively small numbers, and even smaller numbers of serious injury, reiterate the relative rarity of spinal trauma in child occupants, the problem should not be underestimated. Involvement in a motor vehicle crash as an occupant is one of the most common causes of spinal injuries in children of this age [1-5]. A recent five year estimate of the costs to the New South Wales Compulsory Third Party Scheme for children 16 years and under with spinal trauma was approximately $AUS68 million. Lifetime cost for a single child with a catastrophic spinal injury is estimated to be in the order of $AUS4.5 million (personal communication J Edwards NSW Motor Accidents Authority, August 2006).

Furthermore, from a road safety perspective, these small numbers might mean that spinal injury among child occupants may have historically merited a lower priority than more frequently occurring injuries. However as more and more vehicle safety improvements have been introduced (with concomitant reductions in casualties) the need for identifying the further scope for reducing casualties increases.

Unlike injuries to other body regions, spinal injuries are often mechanistically associated with restraint interaction. In this sample there are at least 8 such cases (indicated in Table 1), and all would fit the classic "seat belt syndrome".

The seat belt syndrome is a well established pattern of injuries that links trauma to the lumbar spine and thoraco-lumbar junction with restraint factors [18-21]. Originally the term referred to a pattern of injury seen in adults using poorly positioned lap only belts, but over the last few decades it has often been reported in children in both lap only and lap-sash belts. However, there has been little investigation of the mechanism of this injury in lap sash belts.

Notably in the 8 'seat belt syndrome' cases in this series, 7 children were using lap sash belts, although incorrect use of the sash was reported in 2 of the cases. A lap only belt was being used by only one child. All cases involved frontal impacts.

Gotschall et al [24] compared the risk and pattern of injury among children using lap sash and lap only belts and reported observing abdominal injuries in the same frequencies in the two types of belt system but not lumbar fractures. They concluded that lap sash belts appear to be protective for lumbar fracture. This does not appear to be the case in this series. Gotschall et al did however discuss possible mechanisms of belt induced abdominal injury in lap sash belts suggesting that it is difficult to obtain good sash belt fit in small children and that a loose fitting sash belt might result in the crash loads being applied predominately to the lap portion of the belt. This might also explain the mechanism involved in lumbar fracture, if the lumbar part of the belt is positioned above the bony pelvis.

There are primarily two ways, acting together or alone, that the lap part of a correctly tightened belt might be positioned improperly. There may be improper positioning initially i.e. from poor fit and/or poor lap belt anchorage geometry, or the belt might move upwards if the buttocks slide forwards during the impact (i.e. submarining).

"Submarining" of the pelvis was also proposed as a possible mechanism of lumbar (and lower thoracic) fracture in lap sash belts by Huelke et al [25]. These authors suggested that there were several mechanisms that might on their own, or in combination, be responsible. They believe that if the occupant (regardless of age) is in a pre- crash slumped position, the thoraco-lumbar spine is in already in a flexed or 'pre-flexed' position. Any rotation of the pelvis under the lap belt (or submarining) further flexes these areas of the spine.

Poor initial positioning of the belt and poor pre-impact positioning is not unexpected in small children hence the need for dedicated child restraints and booster seats. However this sample includes only children 8-16 years, and all of the lumbar injury was among children aged 8-13 years. For most of these, the adult belt is likely to have been the only restraint available. While the most commonly cited guideline for achieving good adult belt fit is a height of 145cm [26], the timing of the transition from a booster seat to an adult belt is defined differently in different jurisdictions. In some places the transition is advised through recommended practices and elsewhere specific height or weight limits are legislated (see Appendix 1). Based on these recommendations and regulations, transition times will vary between 6 and 12 years depending on the jurisdiction. However, booster seats and booster cushions design mass limits effectively (based on mass alone) limit booster seat use to children from approximately age 8. Currently the upper most mass limit for boosters is in the vicinity of 36 kg, based on anthropometric data [27] would mean that 11% of 8 year olds, 22% of 9 year olds, and more than half of children over age 10 would be above the design mass limit (personal communication M Paine, Vehicle Design & Research, 2006). Therefore, for most children between the ages of 8 and 16 years, the lap sash belt is the only available restraint, and using this in the rear seat is the best option for good crash protection.

A vital ingredient to good initial lap belt positioning is a seat cushion length that discourages a slouched seating posture [26]. Recent Australian work [Bilston unpublished data, 2006] suggests that based on thigh length (buttock to popliteal measurements), children are unlikely to achieve good lap belt fit until approximately 13 years of age. Huang & Reed [28] in a similar study, reported that the median seat cushion length in a sample of North American vehicles are too long for most people using the rear seat, and the posture needed to encourage good lap belt fit would be a problem for 83% of children aged between 4 and 17 years, and 24% of adults.

In 2005, Tylko & Dalmotas [29] reported results obtained from rear seated small adult and child dummies included in full frontal compliance testing and offset frontal research testing. In these the 5^{th} percentile female (anthropometrically equivalent to a 12 year old child); the 10 year old and six year old child hybrid III dummies were restrained in lap sash belts in different vehicles. This work demonstrated variations between vehicle models in lap belt motion during the test, with a number of examples of 'abdominal penetration' occurring. With the 5^{th} percentile female, the authors noted variations in the distribution of loads between the sash and lap parts of the belt that appeared to correlate with the upward motion of the belt, the lumbar response measured in the dummy and an associated forward pivoting motion of the torso. The authors also reported undesirable behavior of the sash portion of the belt. With the Hybrid III 10 year old, the sash portion of the belt was seen to slip off the shoulder (when the dummy was in a booster seat), and translate up the neck (when the dummy used the belt alone). They concluded that the motion of the upper torso was controlled almost exclusively by the geometry of the sash anchorage.

These sorts of observations from the laboratory together with clear evidence of a seat belt syndrome like mechanisms occurring in the real world suggest further work is required to understand the role seat properties and belt geometry might play in preventing lumbar fracture.

Good sash belt geometry requires the sash to pass over the centre of the shoulder and maintain this position during impact. Failure to achieve this sort of fit might lead to the types of sash behavior reported by Tylko et al. [29] where the shoulder comes free and the torso can flex over the lap belt resulting in the lumbar injuries described above. Sash belts that sit too high across the neck, or move into this position during the impact can lead to cervical injuries. Bilston (unpublished data, 2006), recently investigated the relationship between the anthropometry of children and sash belt anchorage of a sample of Australian cars and found that good sash belt fit is unlikely to be achievable by many children. Furthermore, this work illustrated significant variations in the match between anthropometry and sash geometry between different models of vehicles.

In this sample there was only one case where a cervical fracture occurred in a frontal impact without evidence of a head strike. This child was 10 years old and this case might provide an example of the type of injury that could occur when the sash sits across the neck.

Apart from the lumbar 'seat belt syndrome' cases and this single cervical fracture, there were only 3 other cases of serious spinal injury in this sample. Two of these cases involved roll over and one a high severity side impact with a fixed road side object.

Road safety advocates in many countries recommend the rear seat for child occupants regardless of restraint type used. In NSW Australia, recent observational studies indicate that 60% of rear seat occupants are aged 14 years or less (personal communication D Carseldine NSW Roads and Traffic Authority 2005). In North America, Huang and Reed [28] analyzed NASS-GES data to determine the age distribution of rear seat occupants and found that approximately 70% are children less than 18 years old. Despite this the work by Tylko and Dalmotas [29]cited above is one of the very few published pieces of work critically examining the protection offered in the rear seat by existing restraint systems to rear seat occupants, and/or rear seated child occupants in adult seat belt systems. This is distinctly different to the situation for young children and dedicated child restraint systems, and for adult front seat occupants.

Also in contrast to dedicated child restraint systems and crash protection systems provide din front seating positions, in most jurisdictions, there is no regular review (either regulatory or consumer based) of the protection offered to these larger children in the rear seat. Yet evidence from recent work cited here, suggests that there is likely to be significant variations in the level of protection currently being provided to these occupants by different makes and models of vehicle.

The case series presented here illustrates the scope for significantly reducing spinal trauma among children through addressing mechanisms associated with seat belt like syndrome injuries. To realize these reductions, vehicle manufacturers need to acknowledge that for older children, the rear seat and its restraint systems are the only protective systems available, and design the rear seat environment with this in mind. Vehicle safety advocates should encourage manufacturers to do this. One obvious way to encourage improved protection for older children is to include rear seated surrogates for these occupants in consumer based test programs.

Limitations

There are a number of potential problems associated with using data extracted from medical records to evaluate crash details. However, in recent work using a similar methodology [30] accuracy of the crash and restraint data collected in this way was cross-validated against that obtained from an in-depth crash investigation in a larger sample of crashes and was found to be adequate in approximately 60-85% of cases, depending on the crash factor.

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APPENDIX 1: Summary of International Child Occupant Legislation (personal communication M Griffiths Road Safety Solutions Australia 2007).

Country	Legislation
Australia	Children 0 – 12 months in dedicated child restraint but currently under review.
New Zealand	Children up to age 5 in dedicated child restraint
Canada (British Columbia)	Children 0-9kg in rear facing restraint. Children from 9 – 18 kg in dedicated child restraint system but if no CRS available can use lap part of belt. Children from 18kg -6 years of age required to be in lap part of seat belt.
USA	Every state has own regulations All states require dedicated restraint use by children up to 3 years. Many have or are moving towards requirements for dedicated restraint use by children up to 60 or 80lb (approximately 6 or 8 years)
European Union	All members of the European Union have dedicated child restraint use up to 1.35 or 1.5m
Germany	Dedicated child restraint use up to 12 years or 1.5m tall
UK	Dedicated child restraint use by children 0-1.35m or 12 years for front and rear occupants. There are exemptions for rear seated children on short trips.
France	Dedicated child restraint use up to 12 years and under 1.35m.
Italy	Children from 0-1.5m must use and appropriate restraint but appropriate restraint includes adult belt
Spain	Children 0 -3 required to use dedicated child restraint, Children 3 years to 1.5 m are required to use dedicated child restraint in front seat but may use adult belt if in the rear seat.
Sweden	Children up to 1.35m must be in appropriate child restraint system
Switzerland	Children 0-7 years in dedicated child restraint system.
Japan	Children from 0-5 in dedicated child restraints
Israel	Children from 0 -8 in dedicated child restraint.

PROTECTION FOR THE SMALLEST OCCUPANT – STATUS QUO AND POTENTIALS CONCERNING THE DEVELOPMENT OF CHILD RESTRAINT SYSTEMS

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ABSTRACT

The use of proper child restraint systems (CRS) is mandatory for children travelling in cars in most countries of the world. The analysis of the quantity of restrained children shows that more than 90% of the children in Germany are restrained. Looking at the quality of the protection, a large discrepancy between restrained and well protected children can be seen. Two out of three children in Germany are not properly restrained. In addition, considerable difference exists with respect to the technical performance of CRS. For that reason investigations and optimisations on two different topics are necessary: The technical improvement of CRS and the ease of use of CRS.

Consideration of the knowledge gained by the comparison of different CRS in crash tests would lead to some improvements of the CRS. But improvement of child safety is not only a technical issue. People should use CRS in the correct way. Misuse and incorrect handling could lead to less safety than correct usage of a poor CRS. For that reason new technical issues are necessary to improve the child safety AND the ease of use. Only the combination of both parts can significantly increase child safety.

For the assessment of the safety level of common CRS, frontal and lateral sled tests simulating different severity levels were conducted comparing pairs of CRS which were felt to be good and CRS which were felt to be poor. The safety of some CRS is currently at a high level. All well known products were not damaged in the performed tests. The performance of non-branded CRS was mostly worse than that of the well known products.

Although the branded child restraint systems already show a high safety level it is still possible to further improve their technical performance as demonstrated with a baby shell and a harness type CRS.

INTRODUCTION

The project “Optimisation of CRS” was funded by BASt and was finalised at the beginning of 2007. The use of Q-dummies for these crash tests allowed the assessment of a variety of dummy readings. However, for a complete assessment of the safety level of child restraint systems the interpretation of dummy readings and dummy kinematics from high speed video analysis is necessary. There is a high variation in the safety level between different types of CRS.

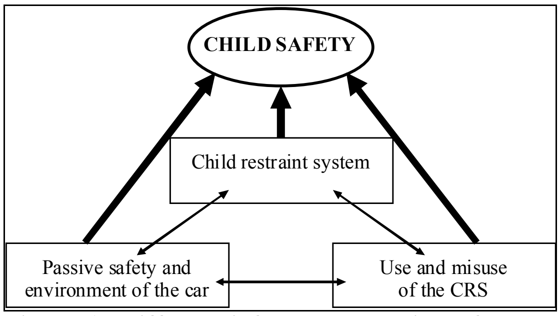

Figure 1. Different influences on child safety.

The safety of children travelling in cars is not solely dependent on the CRS used (Figure 1). Field studies published in the last years [LANGWIEDER, 1997; LANGWIEDER, 2003; FASTENMEIER, 2006] show that there is a high percentage of misuse of CRS. “Misuse” stands for all failures of handling and insufficient use of CRS. For that reason 3 different factors are responsible for child safety in cars:

- the technical behaviour of the CRS
- the use of the CRS
- the car around the CRS

Altogether these 3 factors help to define the level of safety for children in cars. It is necessary to improve all of the above factors affecting child safety at once and not just one at a time.

STATISTICAL INFORMATION

The analysis of the statistical information is focused on Germany. Corresponding to the German legal requirements, “children” means children from 0 up to the age of 12 years.

The good news is that the number of children killed in road accidents has decreased over the years

(Figure 2). The bad news is that the number of children killed as car occupants is still higher than the number of children killed as cyclists or pedestrians.

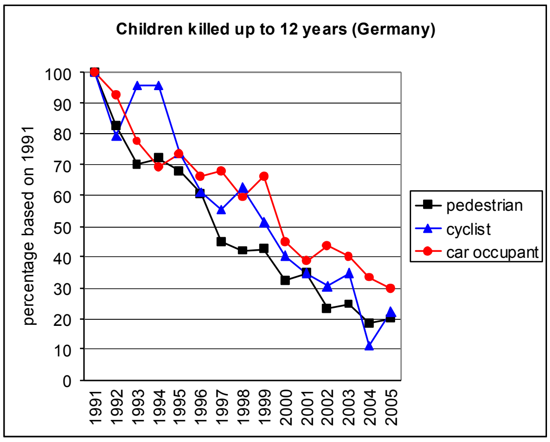

Figure 2. Children killed in road accidents in Germany in the last years [STATIS, 2006].

In comparison to the unprotected pedestrian and cyclist, the car is able to absorb energy and protect the child against outside objects. Therefore, travelling inside of a car should be the safer form of transportation.
In 2005 in Germany 24,247 children up to the age of 12 years were involved in road accidents. 38% of them were injured in the road accidents as car occupants, 28% as cyclists and 29% of the children injured were pedestrians (Figure 3).

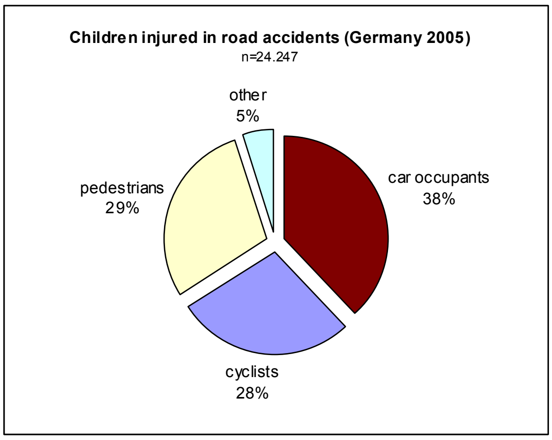

Figure 3. Children injured in road accidents in Germany in 2005 [STATIS, 2006].

102 children died due to road accidents in Germany in 2005. Almost half of them died within a car, one third died as pedestrians and 16% as cyclists (Figure 4).

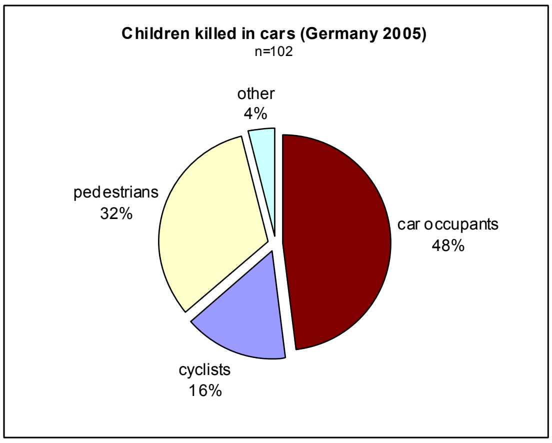

Figure 4. Children killed in road accidents in Germany in 2005 [STATIS, 2006].

The high number of children killed in cars is most likely due to the higher collision speeds in car accidents, the higher kinetic energy, inappropriate CRS and last but not least, misuse and non-use of CRS.

BIOMECHANICAL BASICS

Children are different from adults in:

- body shape (mass, proportions, inertia, size)
- anatomy (bones, ligaments, muscles)
- mental issues

These differences lead to the well known sentence: "Children are not miniature adults." This means that it is not possible just to scale down the size of an adult to have the correct child proportions (Figure 5).

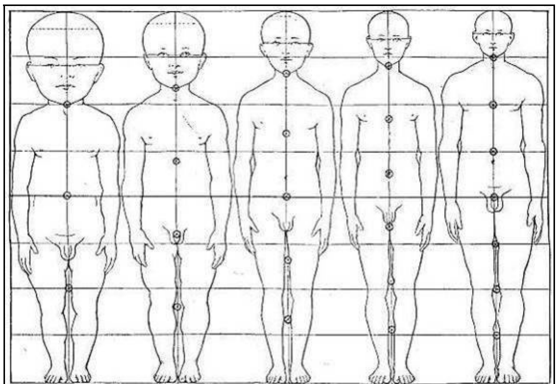

Figure 5. Proportions of the body of a new born baby up to an adult [HUELKE, 1992].

The average size of an adult is about 1.5 to 2.0 meters. Therefore, most of the belt and airbag systems are developed for these sizes. Children's body parts are not able to withstand the loads applied by a normal car restraint system during a car crash: The iliac wing in children is not able to support the belt, causing the belt to override the pelvis and to penetrate the abdominal area. Here the internal organs are located and severe injuries could occur. The belt has to be adjusted to the height of children otherwise the contact between the neck and the belt could lead to injuries. Due to the proportions of a child – influencing the high centre of gravity – children tend to turn out of the standard 3-point-belt in case of a crash/accident. Therefore the belt placement should be adapted to the child. For that reasons it is necessary for children to use a CRS to prevent injuries.

For the development of CRS it is necessary to take all of these facts into account.

ANALYSIS OF DATABASES

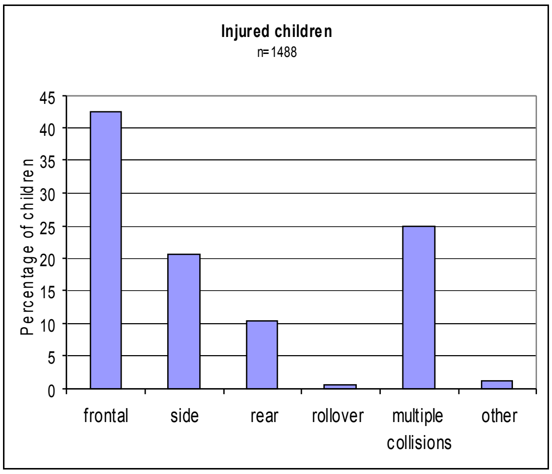

Figure 6. Injured children of car accidents vs. type of collision [OTTE, NOT YET PUBLISHED].

Figure 6 shows the percentage of 1,488 children involved in car accidents as car occupants in different types of collision from 1985 to 2004 from the German In-depth Accident Study database (GIDAS). These accidents are collected from the areas around Hannover and Dresden. They are meant to be representative for Germany.

Most occupants (more than 40%) were injured during frontal accidents. 25% of all children were injured in accidents with multiple collisions. After these kinds of accidents side and rear impacts follow. The number of single rollover accidents was irrelevant.

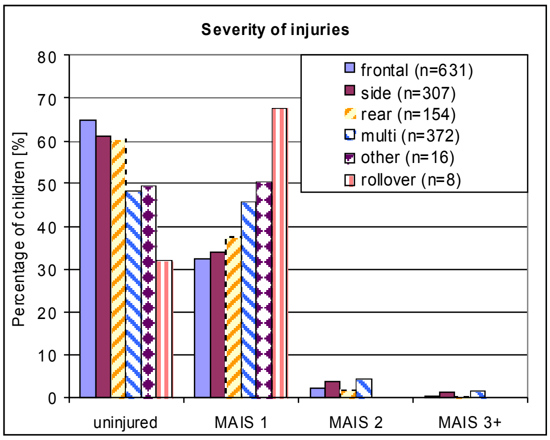

Figure 7. Injury severity vs. type of collision [OTTE, NOT YET PUBLISHED].

During side impact and multiple collisions with more than one severe impact the severity of injuries of children were much higher than in frontal collisions (Figure 7). The CRS should be tested in these configurations as well, today only the frontal test configuration is mandatory.

For the following study it was not possible to use the whole GIDAS information. Some special restrictions (accidents not before 1994, children are restrained in CRS) and additional cases from GDV (association of the German insurance institutes) and the "Unfallforschung Greifswald" (accidentology teams of the University in Greifswald, Germany) lead to a data set of 280 children in 205 accidents.

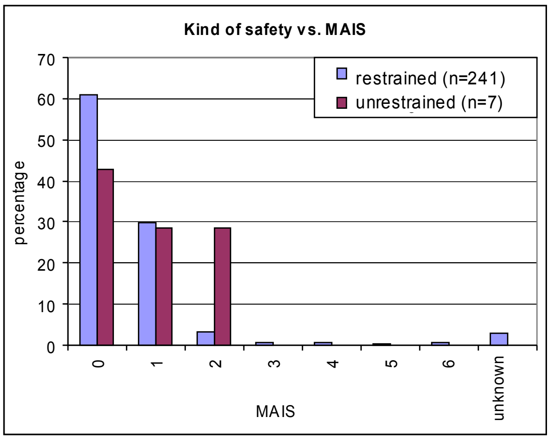

Figure 8. Consequences of the kind of safety to the severity of injuries (GIDAS, GDV, UfoGw).

Figure 8 shows the differences between restrained and unrestrained children with respect to injuries. Restrained children were more often uninjured than unrestrained children. The relative share of MAIS 2+ injuries is much higher in unrestrained children than in retrained ones. The number of investigated accidents was small; therefore only a tendency is visible.

Different dummies are required for the mandatory dynamic tests of the CRS groups. The features of these dummies and the height and the weight are exactly described. The dummy should represent an average child of the age group of the dummy.

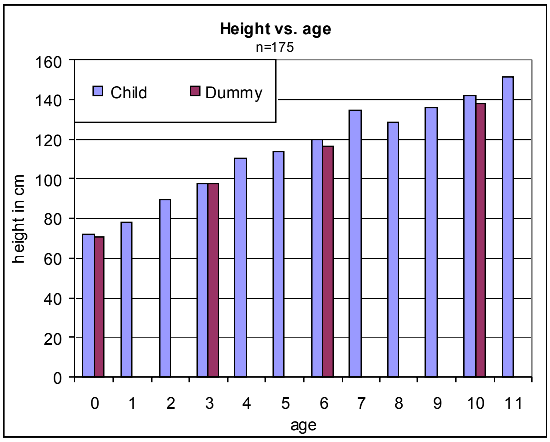

Figure 9. Height comparison of child vs. dummy (GIDAS, GDV, UfoGw).

In most of the cases the height of children involved in the accident is given. In Figure 9 the height of the dummies is compared to actual children. The height of the dummies is within the same range as the height of the children. Therefore, there is today no need to change the height of the dummies.

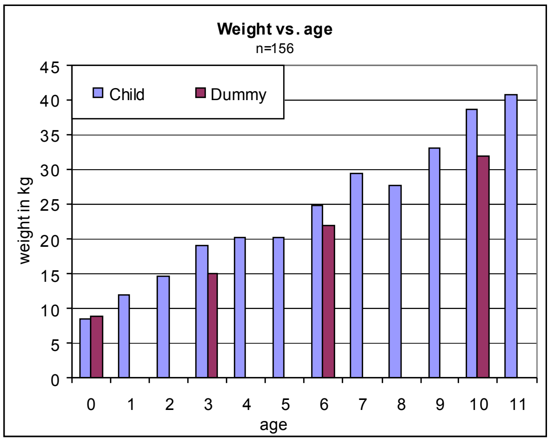

Figure 10. Weight comparison of child vs. dummy (GIDAS, GDV, UfoGw).

When comparing the difference in weight between dummies and actual children, the results are different compared to the dummy height.
Today's children are heavier than the dummies used. Therefore two issues have to be altered: the dummies and the ECE classes of CRS.
Because of the weight of the child and an insufficient CRS size some parents switch to a higher class of CRS too early. The safety level in the lower class CRS is higher for children and depends more on the height than on the weight.
The use of an appropriate CRS is mandatory for children up to the age of 12 years or the height of 1.5 m in Germany. Unfortunately there are some children smaller than 1.5 m, under 12 years old and weighing more than 36 kg. In these cases, they still have to use a CRS but due to the approved weight limit of 36 kg of CRS there is an unclear situation leading to children without any CRS. The car belt has a lower safety level for children than an appropriate CRS. Therefore it is necessary to update the regulation and CRS to the size of today's children.

SINGLE CASE INVESTIGATIONS

Probable reasons leading to death	**Number**
CRS (Misuse/failures of design)	**5**
children without any safety device	*4*
Severely destroyed car	**3**
No possible explanations (50/50)	**4**
Not enough information	**1**

Figure 11. Sample of 13 children killed in Germany 2006 (TUB).

Figure 11 shows the result of a small case study. This study was performed from July 2006 until December 2006. During this time many web sites and newspapers were reviewed. In cases of children that were killed in car accidents in Germany the police were called for more information.
Approximately half of all the accidents during July-December 2006 in Germany were studied. This study does not represent all accidents in Germany but it shows the high occurrence of misuse.
The car was completely destroyed in one quarter of all cases at the seating place of the child. That means that there was a limited chance to survive independent from the CRS usage.
In 4 out of 13 cases it remained unclear whether inappropriate use and/or use of a poor CRS or the accident severity lead to the death.
One third of the children killed in the car crashes died without a CRS or safety device or due to using a CRS incorrectly.
This study already indicates the high risk of misuse and non-use. In addition several very severe accidents were published by databases or newspapers showing children with minor injuries properly using a CRS. Misuse dramatically reduces the safety level of CRS.

During an accident the lives of children could depend on two issues:

- The use of an appropriate CRS reducing the risks of dying due to an accident
- Misuse decreasing the safety level of a CRS

TEST PROCEDURES

World wide there are many different types of test procedures for CRS. It is not clear, which is the best one. In the EU one test procedure is mandatory for a CRS before it can be put on the market. This is the ECE-R44 [ECE-R44]. In this regulation a frontal and a rear test procedure is described. The frontal tests are performed at a standardised test bench. The collision speed is equal to 50 km/h. The deceleration pulse is mandatory. For this test P-dummies have to be used. For any CRS the ECE-R44.04 gives only the minimum requirements. If CRS fail it, they are not approved for the market. But this test configuration has not been changed for some years - regarding the test configuration the last change was 1995. At the moment there is no side impact test procedure included. Regarding accident data there is a need to improve this regulation.

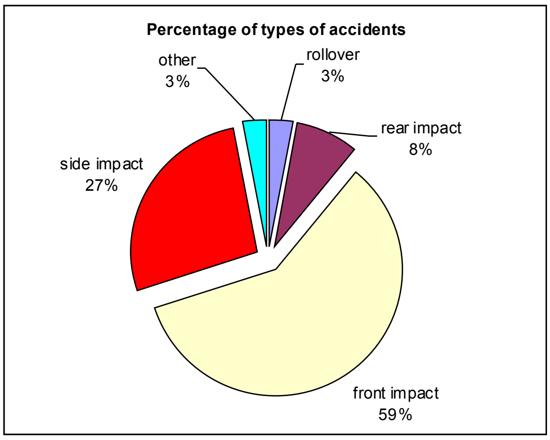

Figure 12. Percentage of all types of accidents for all occupants [DETER, 1996].

In Figure 12 only single collisions are included. However, in real world a large number of accidents are multiple collisions. Side impact occurs only in one quarter of all accidents.

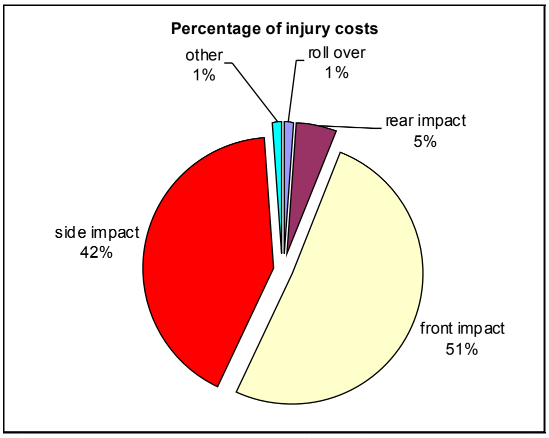

Figure 13. Percentage of injury costs in different types of accidents for all occupants [DETER, 1996].

Side impact accidents cause more than 40% of the injury costs, so the injuries are more severe than in other types of accident. Side impacts and multiple collisions lead to a high injury severity for children, too. For that reason new test procedures should be developed to include all kinds of accidents. To define new test procedures it is necessary to analyse real accident situations first. Test procedures have to replicate most of the real configurations. Acceleration, intrusion and kinematics should be replicated as best as possible.
Consumer test procedures make higher demands on CRS. They test CRS under more severe conditions and not only in frontal tests but include side impact tests. The side impact test is very important for the safety level of a CRS because in most cases side impacts lead to higher injury severities.
But there are too many test procedures with different assessments of the CRS and parents could ask: Which test procedure is the correct one? At the moment the answer is not clear but NPACS (New Programme for the Assessment of Child Restraint Systems) proposed test procedures which are harmonised and under further consideration by technical experts from governments in Europe.
For a deeper look inside the technical development of the side impact test procedure please see ESV Paper (Number 07-0241: Review of the development of the ISO side impact test procedure for CRS [JOHANNSEN, 2007]).
The assessment of NPACS is divided into frontal and side impact ratings. The test procedures for CRS are technically described. The assessment of the CRS is focussed on different body parts of the Q-dummies. The preliminary measurements and the maximum scores in the frontal tests are [NPACS, 2006]:

- Head acceleration (120-51 g) 55 points
- Head excursion (600-270 mm) 55 points
- Chest acceleration (65-33 g) 20 points
- Chest compression (50-6 mm) 20 points
- Neck moment (35-7 Nm) 20 points
- Neck force (3000-900 N) 20 points
- Pelvis acceleration (90-24 g) 10 points
    - Max. 200 points possible

In the side impact the preliminary measurements and maximum scores are [NPACS, 2006]:

- Head acceleration (160-50 g) 30 points
- Head containment (contained/marginal/not contained) 80/20/0 points
- Chest acceleration (100-41 g) 20 points
- Chest compression (39-6 mm) 20 points
- Neck moment (35-10 Nm) 20 points
- Neck force (1900-200 N) 20 points
- Pelvis acceleration (120-40 g) 10 points
    - Max. 200 points possible

The overall assessment is calculated by the addition of the single scores of the different body parts. The lower score of the frontal or side impact rating will be used for the entire assessment of the CRS.
This proposal of scoring for CRS was used for the tests. The technical procedures were not absolutely identical with the described NPACS procedures. For that reason the differences in the scoring between the test procedures are not sensible to predict the difference in the safety level of the CRS. The requirements in these tests are too different.

RESULTS OF SLED TESTS

To compare different test procedures for different CRS classes, several sled tests were conducted at TUB. The selected CRS should not only be assessed in one of today's test procedures, for that reason they were tested in four different procedures taking into account different severity levels for frontal and lateral impact. Q-dummies were used, because they are more biofedelic than P-dummies.
For frontal tests the ECE-R44 test procedure was chosen. Additionally a more severe test procedure was introduced, based on a real accident from the (EC funded) CHILD project. The test bench was the ECE-R44 bench but the deceleration pulse was increased from 21 g to 40 g. The test velocity was increased from 50 km/h to 61 km/h. This test configuration comes from a real accident, included in the database of the CHILD project. With this new test velocity, almost 100% of all accidents inside towns and almost 66% of accidents outside towns are covered (Figure 14).

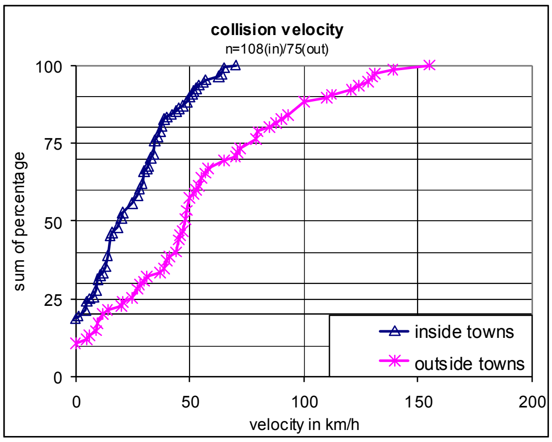

Figure 14. Collision velocity of accidents inside and outside of towns (GIDAS, GDV, UfoGw).

Two different side impact test procedures were used. The first procedure is called TUB-SIPCRS. It was developed at TUB. The test bench is comparable to the ECE-R44 one. To reproduce the loads during a side impact using just the deceleration is not effective. In addition a hinged door is used to represent intrusions according to ECE R95 tests. The test velocity represents an accident with 50 km/h.
The second test procedure is built up like the ADAC side impact test of CRS, using a body-in-white of a Golf-IV equipped with a fixed door.
The results of more than 100 sled tests with CRS were analysed.
For the assessment of the test results the preliminary NPACS rating was used. The ratings were published in 2006 [NPACS, 2006], but changes may occur until the end of the NPACS validation phase. For this assessment different loads were measured: Head, chest and pelvis acceleration, neck moments and forces and chest displacement. With regard to the NPACS protocol the measurements were assessed and points were given.
Detailed investigations at the crash facility of TUB showed differences between good and poor CRS. In tests with higher loads to the CRS than in the ECE-R44 test procedure the measurements of dummy loads were higher and this means the level of safety for children was lower. Also in the side impact test procedures bad results were achieved.
The next two figures show the results of the sled tests. The entire comparison of all CRS is not possible because different types of CRS or different dummies were used and different assessments of the measurements exist. Only a similar couple of CRS should be assessed and could be compared.

		Frontal test						
		ECE-R44					Highspeed	ADAC Frontal
		Q0	Q1	Q1,5	Q3	Q6	Q3	Q3
0+	A	108						
	B	109		117				
	C			110				
1	D		45					
	E		80		70			65
	F				67			66
	M						26	
	N						22	
2/3	G				48			
	H				73			
	J					66	21	23
	K					49		
	L					55		20
	O						17	

Figure 15. Results of sled tests (frontal impact).

In every test the more expensive CRS show better results.
All CRS have to be tested in ECE-R44 conditions before they go on the market. That is the reason for the minor differences between these tests.
If the test conditions are more severe, design problems become visible. The highlighted fields show critical structural problems. In all of these cases non branded CRS were damaged. The design of these CRS is only developed to comply with the ECE-R44 targets.

		Side impact test							
		TUB SIPCRS					ADAC Seite		
		Q0	Q1	Q1,5	Q3	Q6	Q1,5	Q3	Q6
0+	A	110		20					
	B	135		115			158		
	C						55		
1	D							71	
	E		109		114			145	
	F		121		117				
	M								
	N								
2/3	G							50	45
	H							157	153
	J				114	63			
	K								42
	L				22	38			
	O								

Figure 16. Results of sled tests (side impact)

Also during the side impact tests design problems became visible. Again the highlighted fields show critical structural problems and again all of this damage occurred on non branded CRS. The side impact is not addressed by ECE-R44. The design of these CRS is only developed to reach the ECE-R44 targets, not to protect children against side impact.

In addition to the dummy readings the high speed movies were analysed. The following pictures show screenshots of the kinematics during a test.

Figure 17. Baby shells during tests according to ECE-R44.

The left picture shows the Q1,5 in a badly performing class 0+ CRS. The dummy does not have sufficient head support. The loading to the dummy's neck and head are high.
In the right picture the CRS has a good safety level.

Figure 18. CRS of class 2/3 during tests according to TUB-SIPCRS.

The left picture (Figure 18) shows a CRS with insufficient side protection devices. The dummy has contact to the door panel. This would lead to severe injuries.
To be sufficient during a side impact, a CRS has to protect the head. The best side impact protection is to have a shell around the whole child to avoid any contact between the child and the door. Most of the good CRS have head and pelvis protection devices. Some of them have also chest protection devices.

Figure 19. Different severe damage on non branded CRS.

During the tests some non branded CRS were severely damaged. Figure 19 shows examples of severe structural damage of the tested CRS. The damage ranged from small deformation, to destroyed parts of the CRS, up to the destroyed shell itself. For expensive CRS no visible damage occurred.

PROPOSALS FOR OPTIMISATION OF CRS

Two different approaches are possible to improve CRS. First of all testing during the development phase is today's state of the art. Prototypes with different properties could be used in test procedures. The results could lead to some direct improvements at the prototype. This needs time and money to build up several prototypes. Sometimes the prototype materials have other properties than the later CRS. Therefore the results may be not valid.
Numerical simulation is a helpful tool to improve CRS. It is possible to investigate different possibilities to improve a CRS without prototypes. Small changes, e.g. stiffness of belt systems, or simulations without slack in the belt system are quickly possible. For the simulation it is necessary to analyse and validate the CRS, the dummy and the test procedure.
At TUB both tools were used. First in the numerical simulation different measures were proved. After that, some measures were used to build up prototypes for testing.

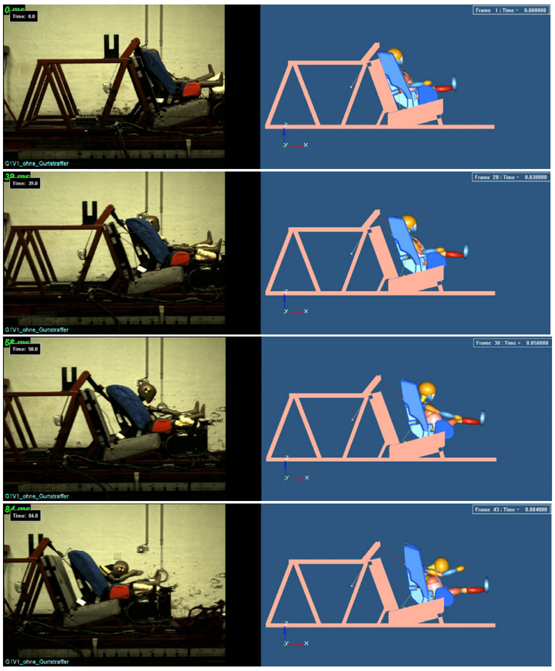

Figure 20. Validation process of numerical simulations by testing [NAAMANE, 2005].

Both (testing and numerical simulation) lead to the following measures to improve child safety in cars:

- Belt routing: The belt should be on the middle of the shoulder going over the chest to the pelvis and belt routing devices. If there is any contact between the belt and the neck in the normal seating position, severe injuries can be expected in case of an accident. The 3-point-belt should only be used on taller children.
- Rigid connection between CRS and car (ISOFIX)
- The car-belt should be as tight as possible (tensioning devices at the CRS)
- Structure of CRS should be able to absorb energy without damage
- Belt routing of car belt should be exact, so that no slipping is possible in loading conditions
- The CRS-belt should be as tight as possible
- Reduction of rotation around the Y-axis

The next Figure 21 shows the benefit of the two last points. The basis model is compared with the two different optimisations. First the rotation around the Y-axis is blocked by a top tether. In the second CRS the slack in the harness is reduced to a minimum before the test started.

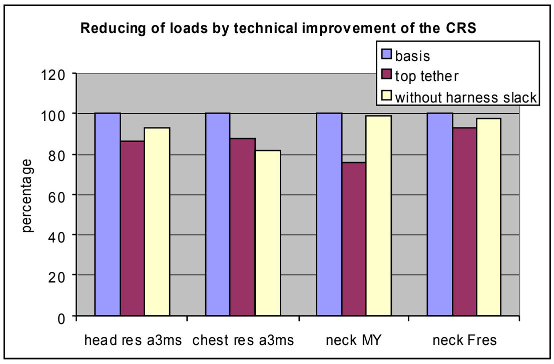

Figure 21. Technical improvements of the CRS and the benefit.

The anti-rotation device significantly reduced the loads on the head and on the neck. The loads also decreased if the slack in the harness was minimised. A combination of these and/or the other named optimisations leads to improved CRS and a high safety level for children.

Sled tests with different types of belt systems were used to investigate the influence of the different devices. For that investigation three belt systems were used:

1. standard belt system
2. belt system with load limiter
3. belt system with load limiter and pretensioner

The used CRS were:

1. Group 2/3, child and CRS were installed together by the 3-point-belt
2. Group 1, the CRS was installed by the belt system, the child used the internal 5-point-belt system of the CRS for securing
3. no CRS, just the belt system
4. Group 3, booster
5. Group 1, like number 2 but rearward facing
6. Group 1, like number 2 but installed with a pre-tensioned belt system

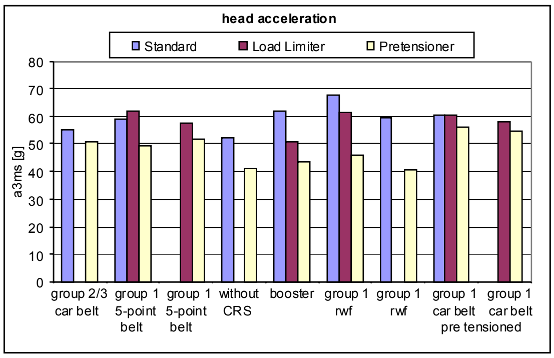

Figure 22. Influence of different belt systems on the head acceleration.

The measurement in Figure 22 show decreased loads when using load limiters and pretensioners. If only load limiters were used the benefit is not clearly visible. That comes from the force level of 4 kN, which is seldom exceed in the performed tests.
The use of additional belt devices could reduce the head acceleration up to 30%.

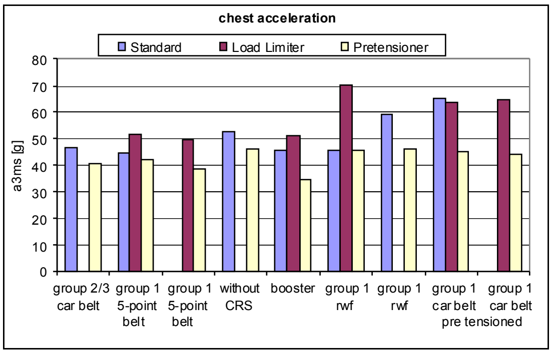

Figure 23. Influence of different belt systems on the head acceleration.

The same influence is visible in Figure 23 for the chest acceleration. The use of load limiter and pretensioner decreases the values of acceleration.

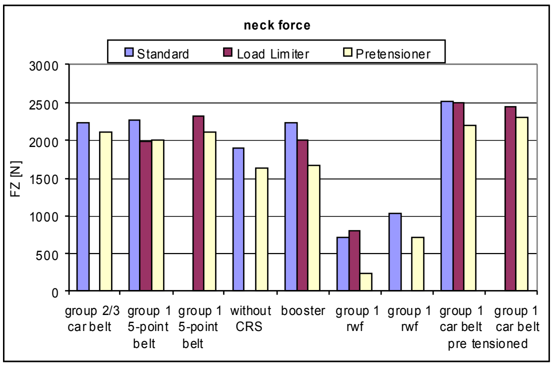

Figure 24. Influence of different belt systems on the head acceleration.

The neck forces were also reduced by the load limiter and pretensioner. In Figure 24 the advantage of rearward facing CRS is visible. The neck forces are about 200 N in this configuration while in the 5-point harness the forces are more than 2000 N. The risk for neck injuries is less for rearward facing CRS.
In the end it is clear that belt systems with additional tensioning devices, as developed for the safety of adults, increase the safety of children too. The same results were found in [BOHMAN, 2006].

RECOMMENDATIONS ON THE RATING PROCEDURE

With respect to the preliminary NPACS ratings (but also generally for CRS ratings) the following thoughts could be discussed in the future:

- In the side impact rating it is possible to have the same number of points as in the frontal impact rating. Taking into account the injury severities in the different accident types it is sensible to emphasise the need for side impact protection by the scoring.
- The assessment of 55 points for the head excursion leads to an advantage for CRS without back rest, because of the measurement between a fixed point of the test bench and the head excursion.
- The present state of the art does not measure the head excursion online during the test. The value is read from high speed videos afterwards or calculated. Some optical errors are the reason for wrong results. New configurations (like online distance measurements) should be used.

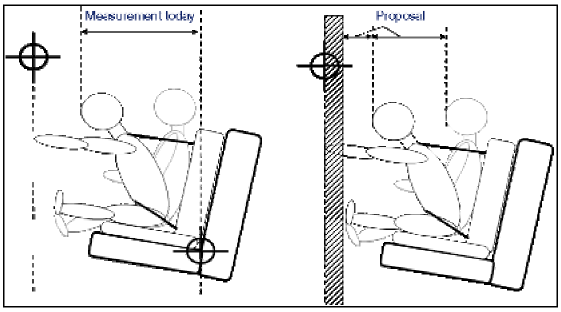

Figure 25. Today's measurement (left) and proposal for independent measurement (right) of the head excursion.

The left picture (Figure 25) shows the most recent measurements of head excursion. It starts on a fixed point (CR-Point) at the bench. This is an advantage for CRS without any back rest - but these CRS have considerable disadvantages, especially in lateral impacts.
The most important target it to avoid any head contact. But in every car there is different space between the seating rows or the passenger seat and the dashboard. For that reason an assessment for the head excursion should be given by the special combination of CRS and car. Here it would be possible to assess the real excursion.
Another solution could be to measure the relative displacement of the head (Figure 25, right). But for this configuration it is necessary to define a global maximum (e.g. 550 mm). The head of the dummy is not allowed to contact a defined safety zone in front of this maximum. If the measurement is higher it is necessary to reduce the overall assessment of the CRS.

SUMMARY AND OUTLOOK

The risk of a child to be injured or killed in car accidents is still high. From the safety point of view two different types of CRS are available: CRS with good protection in some accident configurations and CRS without protection other than the mandatory ECE regulation. But the effectiveness of CRS depends on more than one topic: not only technical issues are responsible for children's safety. Use and handling of CRS should be easy and understandable. In all CRS-groups some improvements are possible to reduce the loadings.
ISOFIX is the best basis for new investigations. It reduces misuse compared to CRS which use the car belt for installation. The rigid connection between the ISOFIX-CRS and the car, especially when supported by an anti-rotation device, leads to decreased loads to the dummy. Starting at this point the CRS could be developed and improved for different accident situations to absorb energy on a high safety level. Numerical simulation should be included in the design process of CRS at an early stage.

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THE DEVELOPMENT AND APPLICATION OF A CHILD RESTRAINT USABILITY RATING SYSTEM

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ABSTRACT

This paper describes the development, validation and application of a usability or "ease of use" rating system for child restraints and the design changes that have evolved.

The rating system was developed in response to concerns about the high incidence of child restraint misuse and the potential for reduced protection during a collision. The objectives were to help consumers choose child restraints that are easier to use and to encourage manufacturers to improve the usability of their products.

A research program to develop the rating system was undertaken by RONA Kinetics with the support of the Insurance Corporation of British Columbia in Canada. It included participation by members of the ISO child restraint working group, regulatory authorities, vehicle and child restraint manufacturers, child passenger safety technicians, IIHS and consumers. A sample of some 30 child restraints (from N. America and Europe) was used to identify key child restraint use features that were ranked according to the risk of injury if misused. Objective criteria and tests for rating the individual features and a method for calculating the rating scores were developed.

The rating system was first used to rate 80 child restraints for ICBC consumer guides. It is the basis for the NHTSA child restraint ease of use rating program. It is being used in new ISO work related to the usability of ISOFIX (LATCH/UAS) features. Its current use and areas in which the rating system may be upgraded are considered.

The rating system provides an objective means of evaluating the usability of child restraints. It addresses features related to the safe use of child restraints that are not included in current regulations. Since its application, child restraint manufacturers have improved the usability of their products thereby reducing the risk of misuse and increased child passenger protection.

INTRODUCTION

In this paper, unless specified otherwise, the term "child restraint" is used to refer to rear-facing and forward-facing restraint systems as well as booster cushions as described in the Canadian Motor Vehicle Safety Act (RSSR). The effectiveness of child restraints in preventing or reducing collision trauma is well established. Their effectiveness depends, however, on their proper use. The misuse of child restraints is reportedly high and child restraint inspection clinics often report misuse of up to 90%. There is a shortage, however, of data on the type and nature of misuse. Misuse observed and reported at child restraint clinics ranges from minor errors, with no or little effect on safety, to gross misuse which is likely to significantly reduce the performance of child restraints in real collisions. Available data indicates that the incidence of "gross" misuse is relatively low and may be less than 5-10% of the observed misuse (Legault and Pedder, 1999). Field data demonstrates that the children who are most likely to be seriously injured in an otherwise non-injurious or survivable collision, are those who are either unrestrained or are secured in a restraint system too large for their size. Test data also shows that some of the types of misuse included in child restraint clinic reporting is relatively minor and will not have a significant effect on child restraint performance (Lalande et al., 2002).

In exploring how best to get all child occupants in an appropriate restraint, consideration was given to concerns about the complexity of using current child restraints properly. In a usability study conducted for Transport Canada in BC (Noy and Arnold, 1995) to identify features to determine which product features contribute to proper and prolonged use of child restraints, it was confirmed that some types of misuse were associated with poor instruction or complicated design features. The study was conducted so that such features may be addressed in the regulations governing restraint systems for children. It has been known for a long time that child restraints that are easier to use are more likely to be used correctly.

Current child restraints are often complicated or difficult to use properly.

In an effort to promote child restraints which are easy to use properly and to reduce the opportunity of misuse, the Insurance Corporation of British Columbia funded a project to develop objective tests and criteria to rate the usability of child restraints. The Insurance Corporation of British Columbia is a public agency in Canada which was established in 1973 to provide universal auto insurance to motorists in British Columbia, Canada. ICBC is also actively involved in provincial child passenger safety efforts.

DEVELOPMENT OF THE USABILITY RATING SYSTEM

The final rating system was developed by RONA Kinetics and Associates in North Vancouver, Canada in 1999 for the Insurance Corporation of British Columbia with input from local and international child restraint and safety experts. Initial work in the development of the usability rating system took place during two consecutive two-day meetings in July 1999 which were organised by RONA Kinetics and hosted by ICBC in Victoria, British Columbia, Canada. The first two-day meeting involved six invited members of ISO/TC22/SC12/WG1 (child restraint systems) and one safety restraint expert who was actively involved in the development and use of educational material for proper child restraint use. The primary purpose of this meeting was to identify child restraint use features and rank their importance according to risk of injury if misused. Samples of different types of child restraints as well as four vehicles (a 2-door and a 4-door car, van and sports utility vehicle) were used to assist in this work. Based on Misuse Mode and Effects Analysis procedures (Czernakowski and Müller, 1991) individual features pertinent to child restraint use were identified, their function noted and the potential misuse modes considered. The effects of the different misuse modes were then examined and according to the severity or effect on safety, the importance of each feature was ranked as A, B or C according to the risk of injury if misused. An "A" rating was used if the proper use of the feature was essential for the full protection of the child and if there was a high risk of injury if the feature was misused. In comparison, a "C" rating was assigned to features deemed less important to the proper use of the child restraint, with no or insignificant effect on safety if misused. At the same time, work was also initiated on the development of criteria and objective tests for rating the individual features.

The ranking of the level of importance of each feature was conducted by the team of experts based on their combined and considerable knowledge and experience of child restraint systems which included collision investigation, child restraint laboratory testing, vehicle and child restraint manufacturing as well as the use of child restraint systems by parents and caregivers. Reference was also made to published work by other authorities.

INPUT FROM INVITED CPS SPECIALISTS

The second meeting involved six invited safety specialists and consumers. The primary purpose of this meeting was to rate individual products using the usability criteria developed during the first meeting. A rating form based on the outcome of the first meeting was prepared and different versions of the form were tried during day one. The rating form included only three options for each feature. Initially, consideration was given to allowing for more options, however for many features it was difficult to provide more than three options and often they were no longer meaningful. It was decided that the ease of use characteristics were best rated according to three options, i.e. good, average, and poor. During day two, the rating form was used to rate individual restraints by three teams of two. Each restraint was rated by two or more teams and the results of the rating compared for repeatability. The rating form was revised to address repeatability problems. Not surprisingly, the repeatability of the features reflected the potential to objectively assess the features. For example, ease of tightening the tether was rated as good if it could be tightened by a simple pull with one hand and poor if otherwise. There was 100% repeatability in the rating of this feature. In comparison, the rating of the child restraint manual was initially less repeatable where it depended on the interpretation by the evaluator. To improve repeatability, brief descriptions of usability characteristics were included on the rating form within each rating category. Repeatability was further improved by the fact that the overall usability rating of each different usability category was calculated from the rating of several features pertinent to that category.

The rating form was finalised by RONA Kinetics after the meetings to ensure that the rating of different restraints was repeatable with at least a 95% confidence level. To further promote repeatability, a rating manual was prepared that included illustrations of examples of good, average and poor features.

USABILITY FEATURES

The child restraints were rated on the following features.

1. Ready to use

This rating was based on whether the restraint required additional assembly or if it was ready to use. A "good" rating was given to restraints which did not need any assembly (of safety features) before use.

2. Instructions for use

This rating was based on whether instructions were easy to understand, included clear illustrations and contained all the information necessary for securing the child in the child restraint and installing the restraint in a vehicle.

3. Ease of Conversion

Child restraints that could be used in different modes were rated on how easy it was to convert them from one mode to another. This included ease of changing the harness strap position. Also considered was the ease of removal and replacement of the seat cover or pad for cleaning.

4. Labelling on the child restraint

This rating was based on the clarity and completeness of the labelling on the restraint itself. A "good" rating included clear seat belt routing diagrams or markings, clear tether use illustrations, airbag warnings, usable harness slots and clear identification of the size of child that could use the restraint.

5. Securing the child in the restraint

This rating was based on the ease of tightening or loosening the harness, the number of harness height adjustment slots (more than one is better), whether the buckle could be released when secured in the correct or reverse position, whether the restraint had a belt positioning guide, and whether the guide could be used easily without causing belt slack.

6. Installation of child restraints

The child restraints were not installed in a motor vehicle, however consideration was given to such features as whether there was sufficient hand clearance or access to the seat belt routing path.

7. Tether straps

The ease of tightening or loosening the tether strap was an important feature as Canada requires forward-facing child restraints to meet head excursion limits that are typically met through the use of a tether strap. Tethers which tighten with a single pull were rated "good". Tether straps requiring tightening by threading through a buckle were rated "poor".

CHILD RESTRAINT RATING PROTOCOL

Three sets of forms were developed and colour-coded to rate each mode of use of each child restraint, viz. rear-facing, forward-facing with harness and tether, and booster seats. Each child restraint was rated independently by two evaluators. The rating of the child restraints was initially conducted at RONA Kinetics by technicians experienced in child restraint performance in collisions. The rating was later undertaken by child passenger safety (CPS) technicians who were given a one-day training in the completion of the rating forms. The rating by each evaluator was then compared and when a feature had been rated differently by the evaluators, the feature was re-examined and a decision made. If appropriate, the feature was documented and photographed for inclusion in the manual and consistent future ratings. Hard copies of the forms were preferred by the evaluators as it enabled them to annotate or comment on features that may be new or they were unclear how to rate. The data was then entered into an excel table for calculation of the final rating in each category.

CALCULATION OF RATING SCORES

As noted above, the importance of each feature was ranked as A, B or C according to the risk of injury and severity of misuse. In the calculation of the rating scores, this importance ranking was used as a fixed weighting factor for each feature. Each weighting factor was assigned a numerical value of A=3, B=2, and C=1. The individual features of each child restraint were then assessed using the rating form and rated as "good", "average", or "poor". These were also assigned a numerical value where good=3, average=2, and poor=1. The overall rating was calculated by multiplying the weighting factor by the score given during the rating of that feature by the evaluator. If a feature was not applicable for a given child restraint, both the rating and the weighting factor became zero and the feature was excluded in the calculation of the final rating. The final rating of each usability category was calculated from the sum of the weighted ratings of individual features divided by the total number of features.

ICBC CONSUMER GUIDE

The usability rating system was first used by the Insurance Corporation of British Columbia in the rating of child restraints for the ICBC consumer guide "Buying a Better Child Restraint" published in 1999. Based on the premise that a child restraint that was easy to use was more likely to be used and used correctly, the guide rated child restraints sold in Canada on their usability. The guide provided the individual scores for each of the rating category. The guide was published to help parents and caregivers make informed decisions when buying a child restraint. The guide included infant and child restraints as well as combination harness/booster systems and booster seats sold in British Columbia. The seats were also available across Canada. The guide also provided information to help consumers select the appropriate type of restraint for best fit and had a shopping checklist with key safety and usability features.

The ICBC "Buying a Better Child Restraint" was updated annually for four years with ratings on current and new child restraints products Informal feedback indicated that the guides were used by consumers when they purchased a new child restraint. The guide was used by some local retailers in the selection of child restraints to be offered for sale in British Columbia.

In the ICBC guide, the ratings were not combined to provide an overall rating of each child restraint. An overall rating was not provided out of concern for the possibility that consumers would assume a restraint with the "best" overall rating would be the best and safest restraint in their vehicle. Emphasis was given in the ICBC guide to ensure the restraint properly fits the consumer's vehicle.

At the time of publication, there were no child restraints sold with the universal attachment system (UAS). These systems are known as LATCH (Lower Anchors and Tethers for CHildren) in the United States and based on the ISOFIX concept. It was anticipated that when UAS became mandatory in Canada in 2002, the usability of these systems would be considered.

ISO CHILD RESTRAINT TASK FORCE

The same rating system model was adopted by the child restraint usability task force of ISO/TC22/SC12/WG1. The task force is currently developing a rating system specifically for ISOFIX features. It includes the rating of ISOFIX features on the child restraint and in vehicles, as well as the ease of installing an ISOFIX child restraint in a specific vehicle.

NHTSA RATING SYSTEM

In 2002, NHTSA introduced an ease of use child restraint rating system that was modelled in the rating system used by ICBC (NHTSA, 2002). The ratings are posted on the NHTSA website (www.nhtsa.gov).

The NHTSA rating system included most of the same features, however, child restraints were rated under four ease of use categories: assembly; evaluation of labels and instructions; securing the child; and installation in the vehicle.

The rating score for individual features was determined in the same manner (weighting factor x feature rating score). The weighted average for the category was calculated by dividing the sum of the feature rating score by the weighting factor. Each category was then given a rating based on the weighted average: A = 2.40 to 3.00; B from 1.70 to < 2.40; C < 1.70.

The ICBC website now links directly to the NHTSA ratings for those products sold in Canada (http://www.icbc.com). Only products that meet the Canadian Motor Vehicle Safety Standards are legal in Canada.

EFFECTIVENESS OF THE RATING SYSTEM

It is difficult to know what, if any, effect the ICBC child restraint usability rating guide had on products and buying trends. It did, however, provide a means of educating parents, caregivers, and educators on the importance of checking the ease of use of different features of the child restraints. It provided them with a guide in finding the appropriate restraint for their child. It also provided child restraint manufacturers with a tool for the assessment of the usability of their new and current products.

There appeared to have been an improvement in the labelling of some products since the first usability guide in 1999, although further enhancements will probably only be realised with regulatory revisions, such as the need to include pictograms for our multicultural population, many of whom can speak little English. Current French/English text requirements may prevent the use of visible pictograms on the sides of the child restraint.

With the implementation of the NHTSA ease of use rating program, there was a noticeable improvement in the usability of the child restraint features that were rated. These improvements were observed on products sold in Canada and the United States. Some examples of the improvements that seem reasonable to assume were promoted by the ease of use rating system follow.

Ready to Use
Significant reduction in products that came disassembled or products that required harness removal to enable the child restraint cover to be fitted.

Instruction and Labelling
Increase in the use and clarity of illustrations including pictograms on both the child restraints and in the child restraint manual. Routine attachment of the manual to the child restraint at point of sale, so the manual remains with the child restraint itself when first purchased. Better consistency in the size and mass limits given on the child restraint labels compared to the manual.

Securing the Child in the Restraint
Harness height adjustment systems that could assume multiple positions without the need to re-route the harness.

Installation
Fewer belt positioning guides on boosters that could introduce inadvertent seat belt slack. Separation of the seat belt path from the harness system.

Tether Straps
The increase in easy to use tether straps that could be tightened with a single pull in replacement of tether straps requiring threading through the buckle to tighten.

AREAS FOR IMPROVEMENTS

The significant improvement of those child restraint features considered in the ease of use rating is reflected in the latest NHTSA rating where the majority of products were rated A or B. The rating system has clearly been successful in promoting some ease of use features, however, as observed by CPS advocates, many child restraints remain difficult to use and to use properly.

There is now a need to better discriminate between the ease of use of new child restraints. This includes the need to rate the ease of use of UAS/LATCH systems.

It is also important to recognise better and easier to use products that include such features as: easy to use manual storage pockets accessible in all modes of use; uniform harness adjustment; better size range to promote longer use of harness systems and discourage premature graduation to booster seats and seat belt systems; continued awareness of airbag related safety issues.

Issues of child restraint/motor vehicle incompatibility are not addressed by the ease of use rating system. In Canada and the United States, any child restraint can be bought and used in any motor vehicle. Even child restraint systems which are rated as easy to use may not be the best for the intended vehicle. It was hoped that some problems of compatibility would be overcome with the introduction of the universal anchorage system. Usability problems have been observed with some LATCH (UAS) systems (Decina, 2006). Hopefully, they will be addressed through improved design and also the possible introduction of criteria for rating LATCH (UAS) systems by NHTSA. It would probably be of benefit if the rating of these systems harmonised with the work of the ISO/WG1 task force on usability.

CONCLUSIONS

The usability rating system has provided an objective means for assessing the ease of use of different child restraints. The repeatability of the rating system was better than 95% among trained evaluators.

It addresses many features related to the safe use of child restraints that are not included in current regulations.

Since the introduction of the usability or ease of use rating system, the usability of child restraints has improved with a resulting reduced risk of misuse and increased child passenger protection.

The child restraint usability system provides an educational tool for parents and caregivers.

The rating system needs to be regularly updated to reflect new design features and to encourage manufacturers to continue to improve their products and make them easier to use.

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DISCLAIMER

The conclusions reached, and opinions expressed, in this paper are solely the responsibility of the authors.

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