ABSTRACT

This study examined the performance of a booster seat in different seating configurations in side-impact hyGe sled tests (crash severity 30 km/h) with two attachment systems: a standard seatbelt and ISOfix (rigid). The objectives of the study were twofold: (i) to identify the relative benefits of ISOfix attachment compared with seatbelt attachment of a near-side booster seat in a 3-abreast seating configuration with adjacent occupants in child restraints (CRS); and (ii) to examine the effects of 3-abreast seating configurations compared with no adjacent passengers on booster seat crash protection characteristics. Overall, the findings confirmed the superior performance of the rigid anchorages in reducing lateral motion of the booster as well as the two adjacent CRS. However, the expected benefits of the rigid attachment in reducing head accelerations were not uniformly observed across the three occupants/seating positions and also appeared to be influenced by seating configuration (3-abreast versus no adjacent occupant). Further research is warranted to explore the applicability of the findings for different CRS types and seating configurations.
The effectiveness of booster seats and other child restraint systems (CRS) in reducing injuries is influenced by a complex array of variables including the characteristics of the vehicle and the restraint systems, the size of the child, the suitability and use (or misuse) of the CRS, and the crash severity and direction of impact. Additionally, the seating position relative to the crash impact and interactions between adjacent occupants are likely to affect injury mechanism and severity, especially in side impact crashes. The main focus of this paper is on the performance of boosters in near-side impact crashes and the relative effectiveness of seatbelt and ISOFIX attachments. The influence of adjacent occupants on injury severity as measured by instrumented dummies in dynamic sled tests is also explored.

While there is ample evidence of the benefits of CRS in reducing injury severity, there is general agreement that the current generation of boosters and other CRS does not offer optimum protection and that there is room for design improvement, particularly for side impact crash protection. The compromised capacity for side impact protection was highlighted in a recent buyer’s guide to child restraints [RTA, 2000].

Most serious and fatal injuries in restrained children occur to the head [Newgard and Jolly, 1998], mainly due to contact with the vehicle interior [Henderson, 1994]. Several studies have reported higher fatal and serious injury rates for children in side impact crashes compared with frontal crashes [e.g. Arbogast, Chen, Durbin and Winston, 2004; Fildes, Charlton, Fitzharris, Langwieder and Hummel, 2003; Orzechowski, Edgerton, Bulas, McLaughlin and Eichelberger, 2003]. In particular, Orzechowski et al., reported that for restrained children, severe head injury (AIS 3+) rates were three times higher and chest injuries five time higher in side impacts compared with frontal crashes (2003). In side impact crashes, head injuries most commonly occur from either contact with the vehicle interior and/or part of the restraint [Agran and Winn, 1989]. These studies suggest that side impact protection remains a significant challenge for child restraint design improvement.

Intuitively, side impact protection is likely to be influenced by seating location and proximity to the side of impact (near-side/struck side versus far-side/non-struck side). Despite its apparent importance, there have been few studies directed towards identifying the optimal rear seating location for children restrained appropriately in CRS and the findings are equivocal. Using data from the US Fatality Accident Reporting System (FARS), Braver, Whitfield and Ferguson (1998) showed that the relative risk of fatality for restrained child occupants aged 0-12 years was around 30% higher for outboard compared with centre rear seating position. However, the findings did not dissociate side impacts from frontals nor near-side and far-side seating effects and the authors did not specify whether the children were restrained in an appropriate CRS or not.
More recently, Lund (2005) investigated the injurious effects to rear-seated children (0-5 years) restrained in CRS in impacts of all directions, using data from the National Automotive Sampling System (NASS). In contrast to the findings of Braver et al. (1998), Lund concluded that children in the centre rear position were no safer than those seated on either side (left seat OR = 0.88, 95% CI = 0.73-1.03; right seat OR 1.03, 95% CI = 0.85-1.20).

Unsurprisingly, proximity to the impact does play a role in determining injury mechanism and severity. Arbogast et al., (2004) reported that the injury risk for children in CRS is significantly higher in struck side crashes (8.9 injured children per 1000 crashes) compared to non-struck side crashes (2.1 injured children per 1000 crashes). Consistent with these findings, Howard et al. (2004) reported that children (0-12 years) seated on the near-side of an impact sustained injuries of higher severity compared to children seated in the centre and far-side position. Interestingly, this finding was independent of restraint use. The authors also reported that children were 2.5 times more likely to suffer fatal injuries when seated on the near-side of an impact compared to those in the centre seat. Further, the far-side position was deemed safer in a side impact compared to the centre position. The principle mechanism of injury was contact with the vehicle interior (intrusion) causing severe head, chest, abdominal and extremity injuries and in the absence of intrusion, lateral translation of the child’s body resulting in non-contact head and neck injuries.

In addition to location of occupants relative to the point of impact, injury risk has also been studied in relation to the presence and location of other occupants in the rear seat. For example, in the study described above, Lund (2005) reported that the odds of injury were reduced when a restrained child was seated with one other person (OR = 0.84, CI 95% = 0.72-0.96) or two or more people (OR = 0.70, CI 95% = 0.85-1.20), compared to when there are no other rear seated passengers. In a similar study, but specifically focusing on side impacts, Maltese, Chen, and Arbogast investigated the effects of multiple rear seat occupancy on injury outcomes (2005). Their sample included children aged 4-15 years who were restrained in adult seatbelts. The results showed that children seated alone in the back row were at an increased risk of injury compared to children sitting with other occupants. Children seated in the centre rear position were 75% less likely to be injured if there was another occupant between them and the struck side, than if they were seated alone in the rear centre position. In general, children who shared the rear row with other occupants were found to be 58% less likely to sustain serious injury during a side impact compared to children who sat alone in the rear seat. This finding is in agreement with that of Arbogast et al., (2004) who found that the absence of an adjacent passenger contributed to an elevated risk of injury of children seated in forward-facing CRS (5.1 vs. 0.9 injured children per 1000 crashes).
Maltese et al. suggested that other occupants absorb kinetic energy during a crash and possibly the injurious energy present during the rebound phase of the crash, reducing the risk of injury to child occupants.

The most promising design options to reduce side impact injuries have focused on minimising head loads and reducing the risk of head contact in two main ways: by reducing lateral displacement of the occupant in a controlled manner; and by providing adequate side wings to contain the head and a soft buffer (padding) between the occupant’s head and hard surfaces within the vehicle. The recent development of ISOfix attachments has been an important advancement towards achieving some of these aspects of side impact safety improvements [International Organisation for Standardisation, 1999].

ISOfix provides a separate method of attachment of CRS to vehicles that does not rely on adult seatbelts. The system comprises two rigid connectors on the base of the restraint, which attach to anchorages located in the rear seat bight of the vehicle. The attachment is commonly used in conjunction with a top tether. In North America, a modified (non-rigid) ISOFIX system is favoured which has connectors and an adjustable belt (Lower Anchors and Tethers for Children or LATCH). Recently, a number of revisions to the Australian Standard for CRS were proposed to include provisions for both the conventional adult seatbelt attachments as well as either the ISOFIX rigid system, favoured in Europe or a ‘flexible’ system similar to LATCH. The development of ISOfix specifically targets the problem of lateral displacement but has almost exclusively been applied to FF and RF CRS. There has been limited exploration of its effectiveness for improving booster seat performance [Charlton et al., 2006].

While the focus of the majority of real-world side impact crash injury analyses reviewed above has highlighted the role of seating location and multiple occupant effects, no studies to date have considered the crash performance characteristics of specific types of child restraints and/or restraint attachment systems under different seating and occupant configurations. This paper describes the crash performance characteristics of a booster seat tested in a 3-abreast configuration, with two different attachment systems. Comparisons were also made with CRS in a non-adjacent configuration. The objectives of the study were twofold: (i) primarily to identify the relative benefits of ISOfix attachment compared with seatbelt attachment of a near-side booster seat in a 3-abreast seating configuration with adjacent occupants in child restraints (CRS) (seatbelt vs. ISOfix); and (ii) to examine the effects of 3-abreast seating configurations compared with no adjacent passengers on the near-side booster seat crash protection characteristics.
METHOD

Three CRS: a rear-facing (RF) restraint for infants (< 9 kg and <70cm), a forward-facing (FF) restraint (8-18kg and 70-100cm) and a booster seat (14-26kg and >100cm) were evaluated with a standard seatbelt and a rigid ISOfix anchorage system. The CRS had top tethers attached as per the manufacturers instructions and a top tether was retrofitted to the booster seat in all tests. The RF and FF CRS were selected on the basis of their strong crash protection performance in previous research (Charlton, Fildes, Laemmle, Smith and Douglas, 2004). The booster seat was selected because it was one of the few available on the market with a blow-moulded plastic structure which allowed for the possibility of retro-fitting an ISOfix attachment. Additionally, an important selection criterion was that the three selected restraints were able to fit three-abreast in the rear row of the test buck.

The rigid anchorage systems comprised two connectors, attached in a rigid fashion to the base of the CRS. The connectors were retro-fitted to the RF restraint and the booster, while the FF restraint had a purpose-built rigid system which could be retracted for use with a conventional seatbelt. The rigid connectors were attached to the vehicle at two prototype ISOfix anchorage points, which were bolted to the sedan buck and located at the vehicle seat cushion and seat back.

HyGe sled tests were conducted simulating a side impact crash severity of approximately 30km/h without intrusion, using a large sedan vehicle buck. Two tests were conducted with CRS in a 3-abreast configuration with the booster in the right (near-side), the RF CRS in the centre (C) and the FF CRS in the left (far-side) rear seating. A comparable test was conducted with the booster seat attached with ISOfix in the near-side with no adjacent occupants. Due to constraints on test time and resources, it was not possible to test all combinations of CRS and anchorage systems.

Rear seat belt anchor points were reinforced to withstand numerous tests. The front seats were positioned mid-way between full forward and the 95th percentile positions and the front seatback angle was 25º from vertical.

Kinematics from CRABI 6 month (RF) and TNO P1.5 (FF) and TNO P6 (Booster) dummies were used. While these dummies have limited biofidelity in side-impact crashes, they were selected because they were the best available for these tests. Due to the limited biofidelity of the child dummies and the lack of biomechanical knowledge about injury mechanisms in infants and young children, dummy kinematics were compared across CRS/anchorage types rather than against specified criteria. Resultant head accelerations and Head Injury Criteria (HIC36) are reported. High-speed digital video footage was captured from four cameras for each test. The digital images were analysed using digitising software to estimate the maximum head displacement (mm). These
measures were computed as the distance travelled by the centre of gravity of the dummy head from the commencement of the test to its point of maximum lateral motion for the initial (impact) phase as well as the rebound phase of the test. The video recordings were inspected for contact with the vehicle interior (and other dummy body parts) by two independent observers, however, since no inter-rater discrepancies were recorded, the data are presented as a single measure.

RESULTS AND DISCUSSION

The focus of this paper is on two key comparisons: first, the comparison of the near-side booster for the seatbelt and rigid ISOfix conditions; and second, the comparison of the near-side booster with rigid attachment with and without adjacent occupants. Performance of the centre and far-side CRS, while not the main focus, is discussed in relation to their influence or interaction with the near-side booster seated occupant.

Summary data for the seatbelt and ISOfix-attached booster, FF and RF CRS in the 3-abreast seating configuration are presented in Table 1. A comparison of the near-side booster seat performance across the two attachment systems revealed some unexpected findings. Intuitively, two outcomes were expected under the rigid attachment condition: (i) that the lateral displacement of the booster would be more effectively restrained; and (ii) that as a result of its increased stability, there would be a reduction in lateral motion of the dummy and consequently, a reduced likelihood of head injury (lower peak head acceleration and lower HIC values), compared with the conventional seatbelt attachment. However, the results showed the HIC value for the ISOfix-attached booster was 33% higher than for the seatbelt-attached booster (662 and 496, respectively). The lateral displacement of the dummy head demonstrated the expected results in the rebound phase with headexcursions around 20% lower for the rigid compared with seatbelt attachment (476mm vs. 406mm). During the impact phase, the dummy head excursions were similar for the two attachment systems (298mm and 280mm) and this can most likely be explained by the fact that the vehicle door constrained the extent of dummy head motion. This was confirmed by observation of a head strike in both the ISOfix- and seatbelt-attached boosters.
Table 1 – Summary measures for seatbelt- and ISOfix-attached CRS in 3-abreast seating position

<table>
<thead>
<tr>
<th>CRS Model</th>
<th>Seating Position</th>
<th>Peak Head Acc (g)</th>
<th>Head HIC36</th>
<th>Head Excurs Impact (mm)</th>
<th>Head Excurs Rebound (mm)</th>
<th>Head Strike</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seatbelt-Attached</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td>Far</td>
<td>45.6</td>
<td>264</td>
<td>470</td>
<td>236</td>
<td>Yes</td>
</tr>
<tr>
<td>RF</td>
<td>Centre</td>
<td>93.1</td>
<td>752</td>
<td>543</td>
<td>285</td>
<td>No</td>
</tr>
<tr>
<td>Booster</td>
<td>Near</td>
<td>67.9</td>
<td>496</td>
<td>280</td>
<td>476</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>ISOfix-Attached</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td>Far</td>
<td>48.9</td>
<td>311</td>
<td>343</td>
<td>116</td>
<td>No</td>
</tr>
<tr>
<td>RF</td>
<td>Centre</td>
<td>56.3</td>
<td>326</td>
<td>398</td>
<td>195</td>
<td>No</td>
</tr>
<tr>
<td>Booster</td>
<td>Near</td>
<td>81.5</td>
<td>662</td>
<td>298</td>
<td>407</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The high HIC value for the ISOfix-attached booster can be explained with closer inspection of the booster and dummy kinematics from the video recordings. As shown in Figure 1, the ISOfix-attached booster (left panel) remained relatively fixed (relative to the vehicle seat), while the dummy head, torso and lower limbs moved laterally in the direction of the impact, ultimately resulting in a head strike to the window. In the seatbelt-attached booster condition (right panel), the booster and dummy shift sideways towards the vehicle door as a single unit, and the dummy’s shoulder is thrust against the side wing of the booster as the booster contacts the door (top right). This absorbs some of the crash forces, thus reducing the energy imparted to the dummy head and in so doing, reduces the HIC values as the head strikes the window (middle right).

While not the primary focus of this study, the kinematics of the other occupants were of interest for their interactions with the near-side booster occupant. Figure 1 (top row, column 2) shows that in the seatbelt attachment condition, the ‘top’ (i.e., the head end) of the capsule struck the near-side booster occupant’s legs which had already contacted the vehicle door. This resulted in a sharp deceleration of the top of the capsule and most likely contributed to the high HIC value for the RF dummy in the seatbelt-attached capsule. In contrast, in the ISOfix-attached condition (lower row), the excursion of the top of the capsule was considerably lower than for the seatbelt attachment (398mm vs. 161...
543mm) and no contact was observed between the top of the capsule and the near-side occupant’s legs, resulting in a lower HIC value.

**Figure 1** - Side impact tests with seatbelt attachment (upper) and ISOfix attachment (lower row) for the booster seat (near-side seating position) for the three-abreast seating configuration during impact (left panels) and rebound (right panels).
Head accelerations were lowest for the far-side occupants in the FF CRS, as would be expected given that they were furthest from the impact. Analysis of the dummy and restraint kinematics indicated that the rigid system held both the CRS and dummy in position more effectively than did the seatbelt attachment (Figure 1, lower row). This was confirmed by the head excursion values which showed considerably more lateral motion of the dummy’s head in the seatbelt attachment condition allowing a head strike compared with the ISOfix attachment condition (impact/rebound: 470/236mm vs. 343/116mm).

The other major point of interest for this study was the comparison between the near-side ISOfix-attached booster with and without an adjacent seated occupant. Previous studies have demonstrated the protective effects of having an occupant seated between the ‘subject’ and the struck side. This study provides additional insights into the effects on a near-side occupant of centre- and far-side occupants. Results presented in Table 2 reveal that the presence of a centre-seated occupant was associated with a HIC value almost 40 percent higher than for no adjacent occupant (662 vs. 407).

Table 2 - Summary measures for ISOfix-attached booster seat in near-side seating position with and without adjacent occupant

<table>
<thead>
<tr>
<th>CRS Model</th>
<th>Occupant Config.</th>
<th>Peak Head Acc (g)</th>
<th>HIC3 6</th>
<th>Head Excur Impact</th>
<th>Head Excur Rebound</th>
<th>Head Strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost r No adjacent occupant</td>
<td>80.9</td>
<td>407</td>
<td>275</td>
<td>188</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Boost r With adjacent occupant</td>
<td>81.5</td>
<td>662</td>
<td>298</td>
<td>407</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

A comparison of the dummy and CRS kinematics from the video recordings captured in the screen images [see Figure 1 (lower panel) compared with Figure 2] reveals differences associated with the adjacent occupant/s. In the three-abreast condition, the RF CRS and its occupant in the centre and the FF CRS and occupant in the far-side are displaced laterally towards the near-side, contacting the occupant of the booster seat on the near-side. This indicates that the adjacent CRS and occupants transfer energy to the near-side occupant during the impact phase, resulting in a higher HIC for the near-side occupant compared with the same occupant without adjacent passengers.
LIMITATIONS OF THE STUDY – The validity of these outcomes is constrained by the limited biofidelity of the dummies in side impact tests. It would be expected that the human body, being less stiff than a dummy, would be subjected to greater excursions and hence is more likely to contact the vehicle interior in the event of a crash. While the HyGe sled tests presented here provide useful information about the interaction of both dummy and child restraint in a real vehicle, they do not demonstrate the likely effects of intrusions. Further research is required to examine intrusion effects using full scale vehicle crash tests. In addition, it would be prudent to conduct additional tests to verify the repeatability of outcomes and to gain a full set of data across the two attachment types. In particular, comparative tests should be conducted to ascertain whether the effect of the adjacent occupants described for the ISOfix attached-booster can be generalised to seatbelt-attached boosters or indeed to other types of CRS and attachment configurations.

CONCLUSIONS AND RECOMMENDATIONS

In the past, there has been limited attention given to the effects of vehicle rear seating configurations in relation to the effectiveness of booster seats and CRS for crash protection. Previous studies of real world crashes suggest a protective effect of an adjacent occupant for rear seat passengers in side impact crashes [Arbogast et al. 2004; Lund, 2005; Maltese et al, 2005]. In contrast, a unique finding of this study was that adjacent occupants appeared to be associated with a disbenefit for the near-side occupant. Specifically, under the controlled impact conditions of a dynamic sled test procedure, this study presents preliminary evidence for a deleterious effect of an adjacent occupant in a RF CRS on a near-side booster seat occupant. Differences between these findings and previous field studies may be explained by differences in occupant
age/mass, restraint and attachment type, impact speed and impact direction and vehicle type.

To the best of our knowledge, the current study provides the first published description of dynamic sled test performance of seatbelt- and ISOfix-attached boosters and CRS in side impact crashes with three rear seat occupants. The data provide some preliminary insights into injury mechanisms of children in multiple rear-seat occupant crashes and have implications for design improvements for CRS for side impact protection; namely, limiting head excursion, preventing head contact and minimising head accelerations.

The findings confirmed the superior performance of ISOfix attachments in reducing lateral motion of all CRS. However, the expected benefits of the rigid attachment in reducing the risk of head injury (HIC) for the near-side booster occupant appeared to be influenced by seating configuration (3-abreast versus no adjacent occupant). Moreover, the beneficial effects of ISOfix were not uniformly observed across the three restraint systems and seating positions. This suggests that installation of ISOfix attachments to all boosters and CRS may not be a ‘fix all’ solution for side impact protection. Rather, rear seat occupant safety needs to be considered as a system of multiple, interacting variables relating to the vehicle, seat, restraint and occupant. This study highlights a need for further development of booster seats with ISOfix attachment, and in particular, there needs to be systematic testing of this solution with multiple rear seat occupants. In this study, a limited number of restraint systems and seating position configurations were studied. The significant improvements that ISOfix delivers in frontal impacts and in some seating configurations for side impacts [Charlton et al., 2004; 2005; Bilston, Brown and Kelly, 2005] may not be applicable to all side impact situations.

It will be important to confirm the findings of this study with a range of restraints in all seating positions. Given that vehicle passenger compartment design has had a greater influence on frontal impact injury mitigation, side impact protection is increasingly becoming the focus for safety countermeasures. Moreover, with the current trend towards smaller cars, the need for side impact injury mitigation technologies is going to increase.

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