AN EVALUATION OF CRASH PROTECTION OF BOOSTER SEATS FOR CHILDREN

Judith L. Charlton, Brian Fildes, Ron Laemmle, Sjaanie Koppel, Liam Fechner, Kristen Moore
Monash University Accident Research Centre, Australia

Stuart Smith, Fiona Douglas, Irena Doktor
GM Holden Limited

ABSTRACT

This study examined the suitability of booster seats for children across a wide age range. HyGe sled tests were conducted using a large vehicle buck with booster seats fitted in the rear seat. Four conditions were evaluated: three with booster seats with (i) standard adult seatbelt, (ii) seatbelt plus H-harness and crotch strap, and (iii) seatbelt plus H-harness with crotch strap disengaged (simulating real-world misuse); and a fourth test (iv) with the dummy restrained in an adult seatbelt only. For tests (ii) and (iii), booster seats were fixed to the vehicle with a retrofitted ISOFIX system and top-tether. This modification was consistent with proposed changes to the AS1754, which apply to forward-facing restraints (but not boosters). Results suggest that, with appropriate modifications, booster seats may provide a suitable option for children represented by 3 year old and 6 year old dummies. Head acceleration and neck injury data suggested that the boosters provided superior protection to that of an adult seatbelt. Tests with H-harnesses showed that the crotch strap was critical in eliminating 'sub-marining'. Findings highlighted the potential for serious injury with H-harnesses misuse and identified areas for design improvement of booster seats.

INTRODUCTION

Motor vehicle crashes are one of the leading causes of child death and acquired disability (NHTSA, 2002). Recent figures for the State of Victoria show that approximately 150 children aged 10 years and younger were killed or seriously injured each year in car crashes (data source: VicRoads, 1998 -2002). This equates to around 900 child injuries or deaths per year in Australia. Of those killed or injured, 62 per cent were aged 5 to 10 years; 32 per cent were aged 1 to 4 years; and six per cent were under 12 months of age. There is no current data directly implicating inappropriate restraint use in Australian crash injury figures. Previous studies in Australia and the USA suggest that inappropriate use of child restraints and especially early graduation out of child seats and boosters into adult seatbelts is widespread (Henderson, 1994; Winston, Durbin, Kallan & Moll, 2000; Durbin, 2000; Ramsey, Simpson & Rivara, 2000; Winston et al., 2000; Winston, Chen, Arbogast, Elliott & Durbin, 2003). This suggests that a significant effort is warranted to reduce child occupant injury, particularly in children in the 5-10 year old age group.

Child restraint systems (CRS) for vehicles are designed to provide specialised protection for child occupants of vehicles in the event of a crash. Recent estimates of CRS effectiveness have suggested that they may reduce injury by approximately 70 percent compared with unrestrained children (Mackay, 2001; Webber, 2000). Adult seatbelts, on the other hand, are not designed for children. Hence, it is not surprising that although children wearing adult seatbelts are better protected (53 percent less likely to be seriously injured) than children who are unrestrained, children in appropriate CRS or booster seats are 60 percent less likely to be seriously injured than children wearing adult seat belts (Durbin, 2001). The effectiveness of child restraint systems, however, is critically dependent on correct installation of the restraint in the vehicle, correct harnessing of the child in the restraint, and use of the appropriate restraint for the child's size and weight. Incorrect and inappropriate fitment and inappropriate use of restraints may reduce or nullify safety benefits (Henderson, 1994; Paine & Vertsonis, 2001).

Australian legislation pertaining to child restraint use requires that children less than one year must be restrained in an approved, properly fitted and adjusted CRS. However, the law relating to use of child restraints by *older children* is less definitive and states that children over one year must be in either an appropriate child restraint or use a suitable seat belt (National Transport Commission, 2000). In the absence of more clear guidelines for CRS use, the responsibility largely rests upon parents to determine what type of restraint is 'appropriate' for their child. Notwithstanding this shortcoming in the legislation, usage rates of child restraints in Australia are relatively high. An observational study conducted in Australia in 1994 estimated that usage rates exceeded 95 percent (Henderson, Brown & Paine, 1994). However, the survey techniques used to obtain these estimates do not allow for accurate estimates of correct installation and appropriateness of restraint for the child's height and weight (Paine & Vertsonis, 2001). Hence, although compliance estimates are high, these figures belie reported error rates in CRS use and inappropriate use, as discussed below.

Installation and use of child seats and boosters is somewhat complicated and there is ample evidence to show that inappropriate use and fitment errors are common (Glanvill, 2000; Paine, 1998; Paine & Vertsonis, 2001; Wren, Simpson, Chalmers, & Stephenson, 2001). In a recent survey of parental attitudes and behaviours in relation to child restraints, Glanvill (2000) reported a number of gaps in knowledge about correct use of child restraints, the risks associated with incorrect installation, and of children travelling in restraints that are inappropriate for their size.

It is important that as children grow, they use a restraint that is appropriate for their size (particularly, height and weight) (Winston, Durbin, Kallan & Moll, 2000). A number of researchers have reported that a relatively high proportion of children who grow out of a CRS suitable for young children move directly into an adult seat belt rather than using a booster seat (Winston et al., 2000; Ramsey, Simpson & Rivara, 2000). Durbin reported that booster usage rates in the United States varies across this age range, from 33 percent amongst 4 year olds to 10 percent for 8 year olds (2000). More recent U.S. figures show that booster usage amongst children in the weight range 18.6-22.7 kg (41-50lb) has increased from 5 percent in 1999 to 17 percent in 2002 (Winston, Chen, Arbogast, Elliott & Durbin, 2003). The authors note that these improvements in usage rates suggest the success of a number of community, corporate and government campaigns to promote appropriate restraint for children.

In the absence of more definitive legislation regarding appropriate CRS for older children, we have sought alternative solutions to promote the use of boosters for children up to 10 years. One possible approach is to offer a restraint system that takes children from toddler age to booster age in one child restraint system. This could be thought of as a *hybrid child seat/booster*, which would function as a forward-facing child seat with an H-harness for younger children and as a booster when used with a seatbelt only for older children. A small number of restraints of this kind are currently available on the market in Australia, however, none have been subjected to vigorous crash testing and none have been developed with ISOFIX anchorage systems which are currently under consideration for the Australian Standards on CRS (AS1754). With these developments in mind, the current study aimed to examine the relative effectiveness of selected boosters, used as *hybrid child seat/boosters,* that would be suitable for children across a wide age span, from around 3 years, when a forward-facing CRS with harness would be suitable, to 10+ years, when conventional boosters with seatbelts, or adult seatbelts only may be appropriate. Of particular interest was the effectiveness of the boosters compared with a standard adult seatbelt. In addition, we considered the crash effectiveness of selected boosters when used with a harness with the crotch strap disengaged (to simulate the effects of real-world misuse conditions).

METHOD

Two child booster seats were tested. These are referred to as Booster A and Booster B and are designed for children in the weight range 14-26 kg and 15-36 kg respectively. Four tests were conducted with a dummy restrained as follows:

- (i) booster seats with a standard adult lap-sash seatbelt,
- (ii) booster seats with a seatbelt plus H-harness and crotch strap combination (H+C), or
- (iii) booster seats with a seatbelt plus H-harness with the crotch strap disengaged from the lap part of the seatbelt (H-C) (simulating real-world misuse)
- (iv) an adult lap-sash seatbelt only.

In the case of tests (ii) and (iii), where the booster was used as a forward-facing restraint (with harness) suitable for a toddler, both ISOFIX and top-tethers were retrofitted. This modification is in line with proposed changes to the AS1754 which apply to this type of restraint (but not required for boosters). The ISOFIX anchorage system comprised two connectors that were attached in a rigid fashion to the base of the booster seat. The connectors were then attached to the vehicle at two prototype ISOFIX anchorage points, which were welded to the sedan buck and located at the junction between the vehicle seat cushion and seat back.

Booster A was selected on advice from the local manufacturer. Booster B was a European import, selected because of the wide side wings around the head and adjustable height of seat back; characteristics thought to be important in crash protection.

HyGe sled tests were conducted using a large sedan vehicle buck. The booster seats were fitted in the right or left side rear seating positions in a simulated offset deformable barrier frontal impact with an impact speed of 64 km/h. A limited number of side impact simulations (near-side) were also conducted representing an impact speed of around 15 km/h. New seatbelts and booster seats were used in each test and the rear seat belt anchor points were reinforced to withstand numerous tests. The front seats were positioned mid-way between full forward and the 95^{th} percentile positions and the front seatback angle was 25º from vertical.

Kinematics from Hybrid III 6 year old and 3 year old dummies were used for frontal tests and from a TNO P6 6 year old dummy for side impact tests. A sub-set of these measures are reported in this paper. These are Peak Head Acceleration values and Neck Injury Criteria (N_{ij}), which were computed from the neck axial forces and flexion bending moments. High-speed digital video footage was captured from two on-board 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 forward motion in the horizontal plane. In side impacts, maximum lateral head displacement was measured both for the initial (impact) phase as well as the rebound phase of the test. Video recordings were inspected by two independent observers for evidence of contact with the vehicle interior (and other contact points) and 'sub-marining'. Sub-marining is an undesirable effect in which the dummy slides pelvis first, forward and under the harness/seatbelt. Since there were no discrepancies in observer judgements, a single measure of these data is presented.

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 restraint systems rather than against specified criteria.

RESULTS

The results are presented in two sections: First, a comparison frontal test results of the restraint types suitable for older children using a 6 year old dummy. In this section we compare performance of the two boosters with each other and with an adult seatbelt only. Side impact tests for the two boosters are also compared. In the next section we compare the results of frontal tests for restraint types suitable for younger children using a 3 year old dummy. Comparisons were made between the two boosters with ISOFIX anchorages and top tethers and used with a full H-harness (with and without a crotch strap). In addition, the boosters are compared with an adult seatbelt only.

Comparison of restraint systems with a 6 year old dummy

Figure 1 shows the peak acceleration of the head for tests with the 6 year old dummy. Peak Head Acceleration was highest for the 6 year old dummy restrained in a seatbelt only (89g). Head acceleration values for Booster A and Booster B with the standard seatbelt were not notably different (62g and 60g, respectively). The head acceleration results suggest that both boosters provided a considerably superior level of protection to a seatbelt.

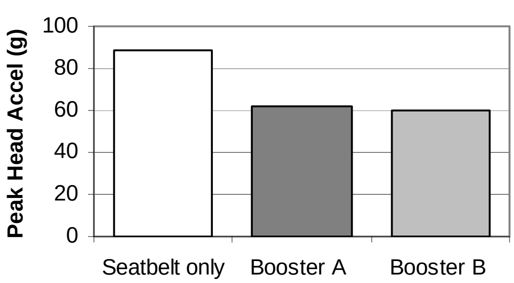

Figure 1. Peak Head Acceleration for tests with HIII 6 year old dummy

Neck injury (N_{ij}) values were calculated from the axial forces and flexion bending moments, providing a composite neck injury indicator. While no direct comparisons are made with the conventional injury threshold of 1.0 (FMVSS 208), the higher the N_{ij} value, the higher the potential for neck injury. As shown in Figure 2, the pattern of results for N_{ij} across restraint types mirrors the results for head acceleration. That is, the highest neck injury value was recorded with use of the adult seatbelt only. The two boosters used with the conventional seatbelt restraint did not differ notably (0.82 and 0.75 for Boosters A and B, respectively). Taken together with the

Peak Head Acceleration measures, the results for neck injury suggest that use of the adult seatbelt only offers the weakest level of occupant protection for the 6 year old dummy.

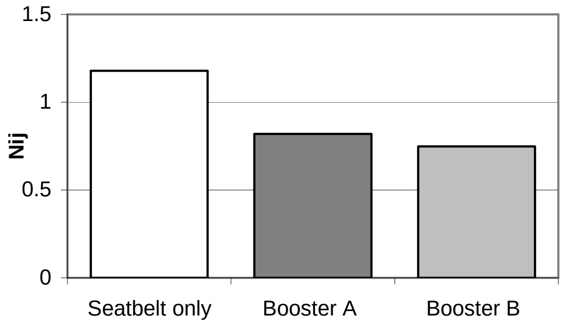

Figure 2. N_{ij} Tension Flexion for tests with HIII 6 year old dummy

Analysis of the maximum forward motion of the dummy head showed similar patterns for boosters with seatbelts (see Table 1). Interestingly, the restraint of the 6 year old dummy in a seatbelt only, provided better restraint of head motion than the two boosters which did not differ notably from each other. This is likely to be due to the added mass of the booster behind the dummy, contributing to its forward momentum. Despite the increased forward motion, inspection of the video recordings showed that the dummy head was well clear of the rear of the front seat in each of the three tests and, importantly, none of the restraint systems permitted the dummy's head to contact the vehicle interior or the dummy's knees. The seatbelt guides also maintained the sash and lap belts in a good position over the dummy's shoulder and pelvis throughout the tests.

Table 1. Summary measures for frontal tests with 6 year old dummy

Restraint Type	Max Head Excursion Impact Phase (mm)	Head Contact
Seatbelt only	530	No
Booster A		
Seatbelt	850	No
Booster B		
Seatbelt	800	No

Results for the side impact tests with the TNO P6 dummy are summarised in Table 2. Peak Head Acceleration values were the same across the two restraints (24g). Similarly, head excursion during impact did not differ (360mm and 330mm). Despite its considerably wider side wings around the head, Booster B failed to contain the dummy head during the rebound phase and the amount of head motion was considerably greater than for Booster A (680mm and 260mm, respectively). In crash configurations with multiple rear seat occupants, this could place the Booster B occupant at risk of an occupant-to-occupant collision. Given the very low head acceleration values, it could be argued that head contact was not problematic. However, it is noted that this result occurred in a relatively low crash speed; hence, it would be prudent to repeat the test at high crash speeds and with multiple rear seat occupants.

Table 2. Summary of dummy measures for side impact tests with 6 year old dummy

Restraint Type	Head Accel Peak (g)	Max Head Excursion (mm)		Head Contact
		Impact	Rebound	
Booster A				
Seatbelt	24	360	260	No
Booster B				
Seatbelt	24	330	680	No

Comparison of restraint systems with a 3 year old dummy

Figure 3 shows the Peak Head Acceleration values for tests with the 3 year old dummy. The head acceleration for Booster A, used with harness and crotch strap, was 10g higher than for Booster B tested in the same configuration (78g and 68g, respectively). In addition, when used with the harness and crotch strap, both boosters performed better than the test in which the 3 year old dummy was restrained in a seatbelt only (102g). Notable increases in Peak Head Acceleration were evident for the boosters plus harness combination when the crotch strap was disengaged. Indeed, in the case of Booster A, these ‘misuse’ simulations yielded head acceleration values that were comparable to the seatbelt only condition.

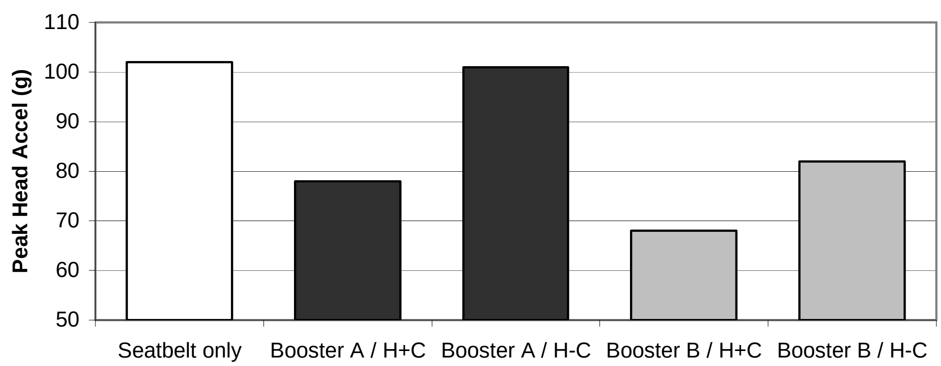

Figure 3. Peak Head Acceleration for tests with HIII 3 year old dummy

Results for N_{ij} Tension Flexion for tests with and without a crotch strap followed a similar pattern to the head acceleration values as discussed above (see Figure 4), with higher neck injury values observed when the crotch strap was disengaged. Interestingly, N_{ij} values for the seatbelt only condition did not differ from the boosters with the harness and crotch strap.

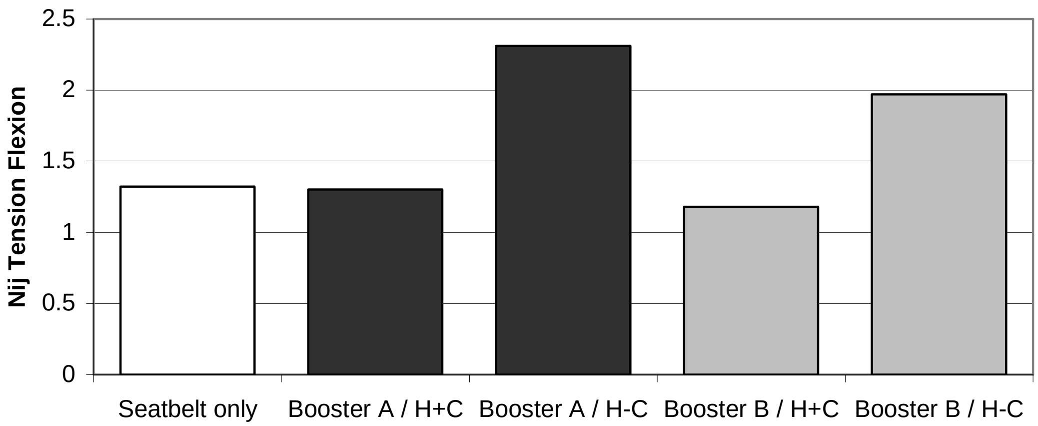

Figure 4. N_{ij} Tension Flexion for tests with HIII 3 year old dummy

Results of analyses of the video data are summarised in Table 3. The maximum forward motion of the dummy head at the time of impact did not vary greatly across restraint types (range was 386 – 443 mm). There was no evidence of head contact with either the vehicle interior or with the dummy's knees. However, sub-marining was evident for both boosters when the crotch strap was not engaged.

Table 3. Summary measures for frontal tests with 3 year old dummy

Restraint Type	Max Head Excursion Impact Phase (mm)	Head Contact	Sub-Marine
Seatbelt only	443	No	No
Booster A			
Seatbelt/H+C	426	No	No
Seatbelt/H-C	401	No	Yes
Booster B			
Seatbelt/H+C	386	No	No
Seatbelt/H-C	397	No	Yes

Figure 5 shows the post-test dummy position for frontal tests for Booster A. The figure on the left shows the dummy restrained with a harness and crotch strap, remaining well positioned at the end of the test. The figure on the right demonstrates the sub-marining effect that resulted when tested with the crotch strap disengaged. Booster B with harness and crotch strap disengaged also resulted in the same sub-marining effect. Without the crotch strap, the dummy slides forward and under the lap portion of the adult seatbelt. This effect is likely to place the occupant at serious risk of injury.

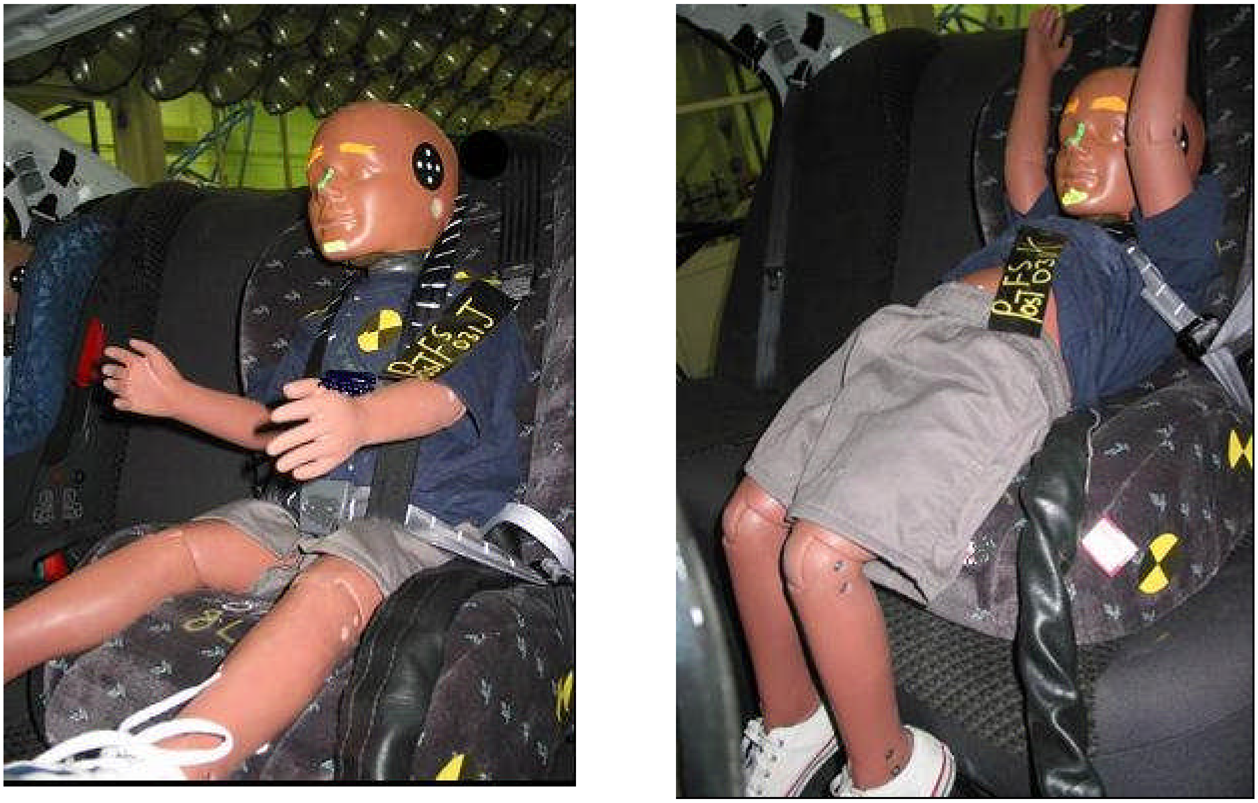

Figure 5. Frontal test for Booster A with seatbelt and harness with crotch strap (left) and with the crotch strap disengaged (right)

CONCLUSIONS

This study aimed to explore the suitability of two boosters for use with children across the age range for which toddler child seats and boosters would be appropriate. The motivation for this was that if parents were offered a single seat (a hybrid child seat/booster) that could take the child through the transition from forward-facing restraint to booster, that this might promote greater use of boosters amongst older children and reduce the complexity of decisions about what restraint might be appropriate for a child once they ‘graduate’ from the forward-facing child seat.

The results demonstrated that the two boosters selected for this study provided a suitable option for children represented by the 3 year old and 6 year old dummy. Based on head acceleration and neck injury measures, these restraint systems provided superior protection to that of an adult seatbelt. Importantly, no head contact was observed with the vehicle interior during any of the tests.

Of some concern, however, was the considerable lateral motion of the dummy and failure to contain the head during the rebound phase in the side impact test for Booster B. In contrast, Booster A restrained the 6 year old dummy in a good position throughout both impact and rebound phases. The result for Booster B was somewhat surprising given its considerably larger side wings and higher back. These findings need to be explored further at higher impact speeds.

An important finding was that when the H-harness was used to restrain the 3 year old dummy, correct use of the crotch strap was critical in eliminating 'sub-marining'. The effect of sub-marining places the occupant at serious risk of injury to the neck region, including vital airways, blood vessels and spinal cord. This finding raises serious concerns, given the relative ease with which the crotch strap can be disengaged by a child occupant during a trip, or not engaged with the lap portion of the adult seatbelt when fitting the child into the restraint.

The simulated misuse errors highlight the need for a crotch strap connection mechanism that cannot be easily disengaged. Ideally, this might be a mechanism similar to that used in the integrated 6-point harness provided in forward-facing restraints for toddlers. If the same booster is to be used with a seatbelt for older children, the design would need to allow for such an integrated harness to be removed.

Several other areas for design improvement should be explored further. For example, it will be important to develop a design feature that would allow the ISOFIX connectors to telescope into the child seat when used as a booster seat for older children. Alternatively, it is possible that the ISOFIX anchorages could offer a desirable method of attachment for both booster configurations. In addition, there is a need to consider the child restraint and rear seatbelt restraint as an integrated system. For example seatbelt pretensioners and belt load limiters should offer desirable solutions.

Limitations

The validity of these outcomes is constrained by the limited biofidelity of the dummies. 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 restraints in a real vehicle, they do not demonstrate the likely effects of intrusions, particularly in a side impact crash. Further research is needed to examine intrusion effects using full-scale vehicle crash tests. In addition, it would be prudent to conduct more tests to gain a full set of data across the various restraint types in side impact and also to verify the repeatability of key test outcomes.

REFERENCES

Durbin, D. (2001). Booster seat use and effectiveness in crashes. Booster Seats for Children. Closing the Gap Between Science and Public Policy. Association for the Advancement of Automotive Medicine, April 23-24, Washington DC.

Durbin, D.R., Cornejo, R.A., Chen, I, Williams, A. & Wells, J. (2003). Variation in child restraint transitions and consistency of restraint use. 47th Annual Proceedings of the Association for the Advancement of Automotive Medicine, Sept 22-24, Lisbon.

Glanvill, L. (2000). Child Restraint Issues in Victoria. Report PP 00/01, Noble Park Victoria. Australia, Royal Automobile Club of Victoria.

Henderson, M. (1994). Children in car crashes: An in-depth study of car crashes in which child occupants were injured. Child Accident Prevention Foundation of Australia, New South Wales Division.

Henderson, M., Brown, J., & Paine, M. (1994). Injuries to restrained children. 38th Annual Proceedings of the Association for the Advancement of Automotive Medicine, September 21-23, Lyon, France.

Mackay, M. (2001). A global view of real world effectiveness of booster seats. Booster Seats for Children. Closing the Gap Between Science and Public Policy. Association for the Advancement of Automotive Medicine, April 23-24, Washington DC.

National Highway Transportation Safety Authority. (2002). Children's health topics: fact sheet. http://www.nhtsa.dot.gov/people/injury/ems/Child_Health/chmfacts.htm.

National SafeKids Campaign (2004). Closing the Gaps Across the Map. A Progress Report on Safe Kids' Efforts to Improve Child Occupant Protection Laws. February 2004. http://www.safekids.org/.

National Transport Commission. (2000). Australian Road Rules.

Paine M, (1998). Child Restraint Survey in New South Wales. Research Report 98/3, Rosebury, New South Wales, Roads and Traffic Authority.

Paine, M. & Vertsonis, H. (2001). Surveys of child restraint use in New South Wales. Paper 214, Proceedings of 17th International Technical Conference on the Enhanced Safety of Vehicles, June 4-7, 2001.

Ramsey, A., Simpson, E. & Rivara, F.P. (2000). Booster seat use and reasons for nonuse. Pediatrics, 106(2), 20-29.

Roads and Traffic Authority (RTA) (2001). Road Traffic Accidents in New South Wales 2001 Statistical Statement: Year ended 31 December 2001. Roads and Traffic Authority Road Safety Strategy Branch.

Webber, K. (2000). Crash protection for child passengers: A review of best practice. UMTRI Research Review, 31(3), 1-28.

Winston, Chen, Arbogast, Elliott & Durbin (2003). Shifts in child restraint use according to child weight in the United States from 1999 to 2002. 47th Annual Proceedings for the Advancement of Automotive Medicine, September 22-24, Lisbon, Portugal.

Winston, F., Durbin, D., Kallan, M., & Moll, E. (2000). The danger of premature graduation to seat belts for young children. Pediatrics, 105(6), 1179-1183.

Wren, J., Simpson, J., Chalmers, D., & Stephenson, S. (2001). "Obviously a man designed it". Barriers to using child car seats. Presented at the Barriers Childhood Injury Prevention Symposium, Children and Young People: Their Environments Conference, 28-30 June, Child Issues Centre, University of Otago.

Acknowledgements

We wish to thank Holden Australia for funding this research. We gratefully acknowledge the contribution of Dr Laurie Sparke, Holden Innovation Chief Engineer, for his expert guidance throughout the project. We also thank the engineering and technical staff at Holden Proving Ground at Lang Lang who conducted the sled tests, and Vassili Kitsios and Michael Brown who contributed at various phases of the study. Lastly, we thank David Stroud (MUARC) for IT support.