Title: A Preliminary Evaluation of Child Restraint Crash Performance with Three Anchorage Systems in a Holden Commodore

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ABSTRACT

This study compared the crash performance of rear-facing and forward-facing child restraints (CRS) with three anchorage systems: standard seatbelt, LATCH (flexible) and ISOFIX (rigid). Frontal (64 km/h) and side impact (15 km/h) HyGe sled tests were conducted using a Holden Commodore sedan buck. Overall, although differences in crash performance measures were evident across restraint types, preliminary findings suggested superior performance of rigid over seatbelt and flexible anchorages, particularly in side impacts. The results also highlight the potential for design improvements for side impact protection including better head containment in forward-facing restraints and improvement in lateral stability afforded by seatbelt and flexible anchorages. The findings have important implications for the proposed introduction of changes to Australian Standards for CRS to permit both flexible and rigid systems to co-exist with conventional seatbelt anchorage systems.

Motor vehicle crashes are one of the leading causes of death and acquired disability for children (NHTSA, 2002). In Australia, during the five-year period between 1998 and 2002, a total of 425 child passengers under 16 years were killed, representing an annual average of around 85 fatalities for this age group (ATSB, 2002). Approximately 56% of these fatalities were children under the age of 10 years, the age range for whom child restraint systems, including booster seats, are appropriate. In addition, approximately 990 children under 16 years were seriously injured (hospital admissions) as vehicle occupants on average each year during this period[3] (ATSB, 2002). While these injury figures are of concern, previous research suggests that deaths and serious injuries represent a relatively small percentage of all restrained child passengers involved in crashes (approximately 12% of cases with injuries greater that MAIS 2) (Henderson, 1994). These data reflect the relative effectiveness of restraint systems for protecting children in a crash. Restraint systems are, however, subject to misuse and there is considerable scope for design improvements to enhance protection, particularly in side impact crashes. The absolute effectiveness of child restraint systems is influenced by a number of variables including appropriate use of the restraint, its design characteristics and compatibility with the vehicle seat, and the quality of installation of the restraint in the vehicle. This paper describes a preliminary investigation of the role of different anchorage systems in enhancing restraint effectiveness in frontal and side impact crashes. This study was part of a larger project that was undertaken in order to find a suitable CRS for use in a Holden Commodore sedan.

Recent estimates of child restraint effectiveness have suggested that overall, child restraints may reduce injury by approximately 70% compared with unrestrained children (Carlsson, Norin and Ysander, 1991; Durbin, 2001; Isaksson-Hellman, Jakobsson, Gustafsson, et al., 1997; Mackay, 2001; Tingvall, 1987; Webber, 2000). Most injuries sustained by restrained child passengers are minor in nature. Several

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[3] Injury data were available only for the two-year period between 2000 and 2001.

studies have found significantly greater reductions in serious injuries for children using a CRS compared with those restrained by an adult seat belt (Durbin, 2001; Henderson, 1994; Korner, 2001).

Notwithstanding the clear benefits of CRS in reducing injury severity, there is general agreement that the current generation of child restraints does not offer optimum protection. 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). In side impact crashes, head injuries most commonly occur from either contact with the vehicle interior and/or contact with some part of the restraint (Agran and Winn, 1989). Limiting head excursion in frontal impacts and preventing head contact and minimising head loads in side impacts remains a challenge for good child restraint performance (Fildes, Charlton, Fitzharris et al., 2003; RTA, 2000).

Effectiveness of CRS is critically dependent on the quality of their installation in the vehicle. However, evidence from field studies has revealed poor fitting rates and/or serious misuse of child restraints (Glanvill, 2000; Vertsonis, 2001). Common errors posing safety concerns include incorrect placement and loose adjustment of the seatbelt and top tether strap (Paine, 1998).

In a significant response to international evidence of installation misuse and the recognition of a need for firmer attachment of CRS in vehicles, the International Standards Organisation Committee developed a new standard for an improved fitment procedure called ISOFIX (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 snap on to anchorages located in the rear seat bight of the vehicle. The system also requires a method of limiting the pitch rotation of the CRS, generally by means of a top tether. In North America, a modified (non-rigid) ISOFIX system with connectors and an adjustable belt, used in conjunction with a top tether, is favoured (Lower Anchors and Tethers for Children or LATCH).

The Australian Standard for CRS (AS/NZ 1754) has recently undergone revision and further amendments for the inclusion of alternative anchorage systems are currently under consideration. The proposed changes include provisions for both the conventional adult seatbelt attachments as well as either the ISOFIX rigid system, favoured in Europe or a ‘flexible’, LATCH-type system. It is timely, therefore, that the crash performance of these different anchorage systems is evaluated.

METHOD

Three rear-facing restraints (RF A, B and C) for infants (<9kg for capsules or <12kg for convertible-style, and <70cm) and two forward-facing restraints (FF A and B) for children (8-18kg and 70-100cm) were tested with three types of anchorage systems: a standard adult seatbelt anchorage system, a flexible lower anchorage system and a rigid lower anchorage system. All had top-tethers. Due to constraints on test time and resources, it was not possible to test all possible combinations of restraints and anchorages. Further tests are planned to complete the test matrix. Selection of CRS was based previous test performance (Charlton, Fildes, Olsson, et al., 2003) or, in the case of RF B and FF B, on manufacturer’s advice on new models.

The flexible anchorage systems comprised an adjustable webbing/strap with two lower attachment connectors at each end. The strap was attached around or through the CRS, using the routing mechanism provided for the seatbelt attachment system. The rigid anchorage systems comprised two connectors that were attached in a rigid fashion to the base of the CRS. The connectors were retrofitted to RF restraints A, B and C, as well as FF restraint A (Figure 1, right). One restraint, FF B had a purpose-built rigid system (Figure 1, left). The flexible and rigid connectors were attached to the vehicle at two prototype ISOFIX anchorage points, which were bolted to the sedan buck in the rear seat bight.

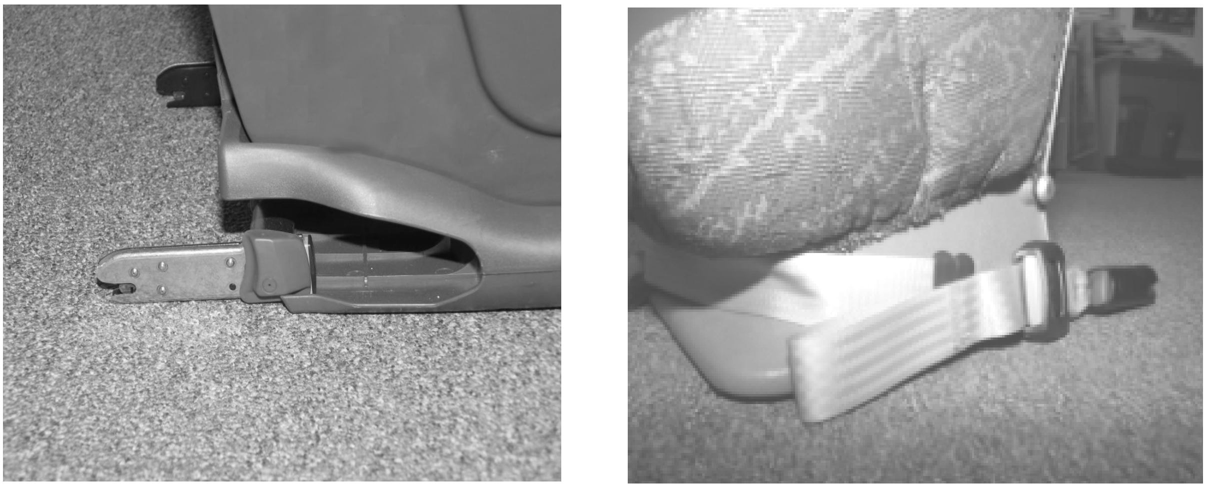

Figure 1 Close-up image showing examples of two forward-facing restraints with an ISOFIX rigid anchorage system (left) and a LATCH flexible system (right).

HyGe sled tests were conducted using a Holden Commodore sedan buck. The CRS were fitted in the right or left side rear seating positions in a simulated 64 km/h offset deformable barrier frontal impact with a crash severity of around 71 km/h. Side impact simulations of 50 km/h (near and far-side) were conducted with a crash severity of around 15 km/h. New seat belts, CRS, and top tether anchors 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 95th percentile positions and the seatback angle was 25º from vertical.

Kinematics from Crabi 6 month (RF CRS) and Hybrid III 3 year old dummies (FF CRS) were recorded for frontal tests. For side impact tests, Crabi 6 month (RF) and TNO P3 (FF CRS) dummies were used. Only Head Injury Criteria (HIC36), derived from head acceleration data and neck flexion moments (Nm) and the maximum load (kN) on the top tether strap (for frontal tests with FF CRS) are reported here. High-speed digital video footage was captured from four cameras for each test. The digital images of the dummies during impact and rebound were analysed using digitising software to estimate the maximum fore-aft head displacement (mm) in frontal impacts and maximum lateral displacement (mm) in side impacts. Due to the limited biofidelity of the child dummies and the lack of biomechanical knowledge about injury mechanisms in young children, dummy kinematics were compared across CRS/anchorage types rather than against specified criteria.

RESULTS AND DISCUSSION

Table 1 summarises the data for rear-facing CRS. For RF A, acceleration forces on the head, represented by HIC36, were higher with a seatbelt than with flexible and rigid anchorages. For RF B and RF C, HIC values were reasonably similar for seatbelt and flexible anchorage types. Forward excursion of the head during the impact phase tended to be lower for restraints with seatbelt anchorages compared with flexible or rigid (RF A only) systems. Overall, forward head movement (towards the back of the vehicle front seat) was minimal compared with movement during rebound (toward the rear seat). However, no head contact was observed with the vehicle interior during either the impact or rebound phase.

Table 1 Performance measures for infant RF CRS for frontal tests

CRS/ Anchorage Type	HIC36	Max Head Exc Impact (mm)	Max Head Exc Rebound (mm)	Head Contact Yes/No
RF A/Seatbelt	547	120	-	No
RF A/Flex	361	250	690	No
RF A/Rigid	399	250	550	No
RF B/Seatbelt	593	280	670	No
RF B/Flex	565	350	670	No
RF C/Seatbelt	415	89	359	No
RF C/Flex	395	220	800	No

For the forward-facing CRS, HIC36 values differed across the six different CRS/anchorage types (see Table 2). The HIC value for FF B with the seatbelt anchorage was considerably higher than for all other restraints (1122). Lowest HIC values were recorded for FF A with flexible and rigid anchorages (702 and 704, respectively) and for FF B with the rigid anchorage system (735).

Maximum forward motion of the dummy head also differed across CRS/anchorage combinations. Generally, head excursion was lower for FF A compared with FF B for each of the anchorage types. The greatest range of forward motion was observed for FF B with the flexible anchorage system. However, none of the restraint/anchorage types allowed contact of the dummy head with the back of the front seat. Neck moments reflecting the forward rotation/flexion torques acting on the dummy neck did not differ notably across the three anchorage systems but were considerably lower for FF A than FF B. Tether loads ranged from 2.4 to 6.6. It was expected that there might be a negative association between tether loads and head and neck kinematics. The concern was that if there was a rigid connection between the vehicle and the CRS, that this might result in the full impact of the crash forces being transferred to the dummy head and neck, rather than allowing the CRS to effectively ‘ride-down’ some of the impact. However, there did not appear to be any systematic relationship between these measures.

Table 2 Performance measures for FF CRS for frontal tests

CRS/ Anchorage Type	Head Injury Criteria (HIC36)	Max Head Exc (mm)	Head Contact (Yes/No)	Neck Flex Moment (Nm)	Max Tether Load (kN)
FF A/Seatbelt	803	516	No	14.0	6.6
FF A/Flex	702	650	No	11.2	5.9
FF A/Rigid	704	610	No	15.3	5.2
FF B/Seatbelt[1]	1122	-	No	20.0	4.4
FF B/Flex	887	780	No	23.0	4.0
FF B/Rigid	735	690	No	19.7	2.4

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[1] Head excursion data for FF A/Seatbelt was not available due to a failure of the side-view camera. Head contact information for this restraint was confirmed using overhead and far-side camera images.

Kinematic data for rear-facing restraints in side impact tests are summarised in Table 3. Note that RF A and RF C were tested in the left (far-side) and RF B was tested in the right (near-side) rear seating positions. HIC values for all restraints in side impact tests were very low and in the range expected, given the relatively low crash speed. It is worthy of note, however, that the HIC36 value for RF restraint B was considerably greater than for all other CRS/anchorage types. This finding is difficult to explain since there was no head strike during impact and no apparent instrument failure. An important indicator of protection in side impact is the extent to which the head is contained within the CRS and particularly the ability of the restraint to prevent head contact with the vehicle interior (door or window). For the limited data available, maximum head excursions appear to vary as a function of seating position: excursion is greater in the impact phase than rebound phase for far-side conditions because the vehicle door constrains movement of the CRS during the rebound (and vice-versa for near-side). For RF A, the range of lateral motion in both directions was considerably smaller for the rigid compared with the seatbelt and flexible anchorage systems. However, for all RF restraint types, inspection of the video recordings revealed that the dummies' heads were well contained at all times and there was no contact of the head with the vehicle interior.

Table 3 Performance measures for RF CRS for side impacts

CRS/ Anchorage Type	HIC36	Max. Head Exc (mm)		Head Contact (Yes/No)	
		Impact	Rebound	Impact	Rebound
FAR-SIDE					
RF A/Seatbelt	25	521	426	N/A	No
RF A/Flex	28	700	390	N/A	No
RF A/Rigid	29	320	200	N/A	No
NEAR-SIDE					
RF B/Flex	119	440	740	No	N/A
FAR-SIDE					
RF C/Seatbelt	4	-	-	N/A	No
RF C/Flex	10	740	340	N/A	No

Results for the forward-facing restraints in side impact tests are summarised in Table 4. Note that FF A was tested in the left (far-side) and FF B was tested in the right (near-side) rear seating positions. Low HIC values were recorded for all FF restraint types. Head excursion was greater in the impact phase than the rebound phase for FF A, on the far-side, while the reverse was observed for the near-side test for FF B with the seatbelt anchorage only. These differences were consistent with the effects that would be expected to arise from the physical constraint imposed by vehicle door. One possible explanation for the absence of this effect in FF B for the flexible and rigid systems may be an overall 'dampening' effect on restraint excursions for these attachment systems. Head excursions for the different CRS with flexible anchorages were comparable (with near- and far-side reversals taken into consideration). During the rebound phase, lateral head excursion for both FF A and FF B was considerably less with the rigid anchorage compared with the seatbelt and flexible systems. For FF A, the excessive rebound motion resulted in head contact with the vehicle interior when anchored with seatbelt and flexible systems. However, the same restraint anchored with the rigid anchorage provided good head containment and prevented head contact with the door.

Table 4 Performance measures for FF CRS for side impacts

		Max Head Exc (mm)		Head Contact (Yes/No)	
CRS/ Anchorage Type	HIC36	Impact	Rebound	Impact	Rebound
FAR-SIDE					
FF A/Stblt	46	450	380	N/A	Yes
FF A/Flex	26	460	410	N/A	Yes
FF A/Rigid	47	280	250	N/A	No
NEAR-SIDE					
FF B/Stblt	36	330	430	No	N/A
FF B/Flex	49	360	310	No	N/A
FF B/Rigid	62	320	200	No	N/A

Given the relatively low HIC values, it could be argued that head contact was not problematic. However, the fact that this occurred in a relatively low crash speed suggests that at high crash speeds, serious head injury may result.

Generally, the capacity of the forward-facing restraints to contain the head and prevent head contact is determined by two key features: the size and angle of the side wings and the stability provided by the lower anchorage system and top tether. FF A had large side wings, which were positioned approximately perpendicular to the direction of the crash impact whereas the side wings on FF B were more oblique, which may allow the head to rotate/roll out in a side impact more easily. The restraints also differed in their attachment configuration of the seatbelt and flexible straps. In FF A, the lap portion of the seat belt (and the strap for the flexible system) is routed around the front of the base of the CRS. In previous research, we have demonstrated that this routing provides superior stability compared with a more common configuration in which the belt is routed through the back of the child seat, as in FF B (Charlton et al., 2003). Interestingly, while both the side wings and belt configurations should have limited the motion of the head in FF A better than FF B, this was not the case and indeed, when anchored with the seatbelt and flexible systems, FF A failed to prevent the dummy head from contacting the side window during the rebound phase (see Figure 2).

An artefact of the near-side positioning of FF B determined that its rebound motion when anchored with seatbelt and flexible systems, was towards the centre of the vehicle. This meant that the dummy was unlikely to contact the vehicle interior. Observation of the video recording revealed that the dummy’s left arm and leg extremities came close to contacting the restraint installed in the opposite (far-side) seating position. As with FF A, the rebound motion of FF B was considerably reduced with the rigid anchorage.

Seatbelt anchorage at impact

Seatbelt anchorage in rebound

Flexible anchorage at impact

Flexible anchorage in rebound

Rigid anchorage at impact

Rigid anchorage in rebound

Figure 2. Side impact tests (far-side) for FF A with seatbelt, flexible and rigid anchorages showing maximum lateral head excursion during impact and rebound.

CONCLUSIONS AND RECOMMENDATIONS

Notwithstanding the effectiveness of current CRS (with seatbelt anchorages) in real-world crash studies, it is clear that improvements are possible. The study demonstrated that with minimal change, a standard CRS currently available in Australia could be successfully modified to accept a rigid attachment system that, overall, offered superior crash performance compared with the standard seatbelt option. Furthermore, the study showed that while a flexible anchorage system could be fitted to a standard CRS much more easily and more cost effectively than the rigid system, on the whole, its performance was inferior to the rigid system.

Evidence from dummy kinematics and video recordings demonstrated an advantage of the rigid ISOFIX system over the flexible LATCH system in reducing lateral excursion and rotation of the restraint and the dummy occupant in side impacts The findings also highlighted an advantage of the rigid system in reducing potential head injury (HIC36) in frontal impacts for one of the two forward-facing restraints. The results suggest that further design improvements to restraints attached with seatbelt and flexible anchorage systems may be useful to enhance their stability and reduce the risk of contact with the vehicle interior or another restraint or occupant.

The validity of these research outcomes is constrained by the limited biofidelity of the dummies, particularly in side impact tests. Moreover, 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, particularly in a side impact crash. Further research is planned to examine intrusion effects using full-scale vehicle crash tests. In addition, it would be prudent to conduct additional tests in order to gain a full set of data across the three restraint types. Further testing will also be conducted to verify the repeatability of key test outcomes and to explore the asymmetries observed for near and far-side seating positions.

The findings of this study support previous research by Kelly, Brown and Griffiths (1995) showing superior side impact test performance of a rigid system over a seatbelt anchorage. Similar results have also been reported by Lowne, Le Claire, Roy et al. (2002) for both side and frontal impact sled tests using a simulated vehicle buck. The study presented here has extended this work, comparing crash performances of flexible anchorages as well as conventional and rigid systems and demonstrating their protective characteristics in a real vehicle buck. These comparisons are particularly relevant given the proposed changes to the Australian Standards for child restraints (AS/NZ 1754). The proposed revisions to CRS standards allow for the introduction of both rigid and flexible anchorage systems as well as a provision for conventional seatbelt anchorages in vehicles that do not support ISOFIX systems. To date there has been little evidence demonstrating the relative effectiveness of the flexible and rigid attachment systems.

There is a strong international interest in child restraint anchorage systems. Despite the preliminary nature of this investigation, the study has provided informative findings demonstrating differences in crash performance measures of conventional and new anchorage systems and has highlighted some areas for design improvements.

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