THE EFFECT OF VARIED SEAT BELT ANCHORAGE LOCATIONS ON BOOSTER SEAT SASH GUIDE EFFECTIVENESS

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Paper Number 11-0135

ABSTRACT

High-backed booster seats provide good protection to child occupants primarily by promoting good posture and positioning the adult seatbelt correctly across the torso and pelvis. Sash belt-positioning features (also known as sash guides) assist with this. The position of the upper seat belt anchorage is known to affect static sash belt geometry in booster seats. However dynamic testing is commonly performed using a single standard location, not representative of the wide variability seen in the rear seat of the vehicle fleet.

This study investigates the effectiveness of three booster seat sash guide designs during moderate-speed frontal impacts across a range of upper seat belt anchorage locations seen in Australia. On the basis of previous static studies, it was hypothesised that more outboard located anchorages would produce the most challenging belt geometry for the sash guides to overcome.

34 frontal crash tests (Δv=31.5 km/hr, 16.9 g) using the Hybrid III 6 year old test dummy were conducted. The tests were filmed using a high speed camera and head excursions were determined using Phantom software. Seat belt forces, head accelerations and neck loads were measured. The upper D-Ring position was varied over five vertical and horizontal (inboard/outboard) conditions, representing maximum and minimum anchorage height and distance between upper and lower inboard anchorage points. Two different booster seat models incorporating three different sash guide designs were tested with and without the sash guides engaged. The influence of lap-belt placement on dynamic sash belt fit was minimised by use of an anti-submarining feature.

Head excursions with all sash guides at the standard anchorage position, and for standardised belt geometry were comparable. Excursions were substantially lower when no sash guide was used for the integrated head restraint type sash guide. Wide variation in excursion was seen between the minimal and maximal combinations of anchorage position. The integrated sash guide outperformed both variations of strap type in the lower anchorage positions, but produced substantially greater head excursion in the highest, most outboard anchorage position. The strap type sash guides performed worse in the lower positions. The highest, most outboard position yielded comparable excursions for both strap type guides which were similar to excursion at the standard position.
These results suggest that the sash guides were not uniformly effective in maintaining dynamic sash belt position across the range of anchorage positions tested.

This study is the first to demonstrate that both sash guide design and upper belt anchorage position interact to control head excursion in booster seats. While the sash guides produced comparable excursions in the standard anchorage position and for standardized belt geometry, large variations are observed when tested over the range of anchorage positions seen commonly in the rear seat.

BACKGROUND

Booster seat use is advocated to improve the fit of the rear seat for child passengers. In Australia, federal road rules state that children must use a booster seat until an age of at least seven years (National Transport Commission, 2007). Beyond this, recommendations exist to support children using booster seats until they are at least 145 - 148 cm tall, or around ten to twelve years of age (Bilston and Sagar, 2007, Klinich et al., 1994).

When used appropriately and not misused, high-backed booster seats have been shown to provide increased protection to child occupants (Durbin et al., 2003, Arbogast et al., 2005, Arbogast et al., 2009, Bilston et al., 2007). Reed et al. (2009) ascribed the superior protection afforded by correctly used booster seats to a threefold mechanism:

1. The child is elevated off the seat, improving the path that the seat belt follows;
2. Potentially harmful postures such as slouching are limited by effectively shortening the seat cushion;
3. Additional static lap and sash belt positioning features direct the seat belt webbing comfortably on load-bearing structures of a child's body.

Booster seat features that act to position the sash part of the seat belt are commonly called 'sash guides'.

Sash guides can exist as structural and/or non-structural features of booster seat design. Structural designs include open or closed guides that are integrated into the headrest or fixed onto the sides of the booster seat. Non-structural sash guides exist frequently as a plastic clip connected to a flexible strap located at the child's shoulder, or a Velcro strap.

In addition to statically positioning the sash correctly over the mid shoulder and clavicle, the sash guide needs to assist in maintaining this sash position during the impact to ensure head and torso excursion is minimised.

There is now some assessment of sash belt fit and sash guide performance in the Australian child restraint standard. Following a recent revision, the Australian child restraint standard (AS/NZS 1754:2010) now requires boosters to achieve adequate static sash belt placement, and for sash guides to maintain contact with (engage) the sash belt for the entire impact (Standards Australia, 2010a).

The quality of torso and head protection provided by booster seats is also monitored in North America through head excursion limits in FMVSS 213 (813 mm for boosters). However standards testing in North America, Australia and elsewhere use only a single, standard, upper seatbelt anchorage location (Standards Australia, 2010b, National Highway Saftey Bureau, 2001). In reality, the location of this anchor (the D-ring) varies widely between vehicles (Bilston and Sagar, 2007, Reed et al., 2008).

Different sash guide designs are known to produce varied belt fit and occupant kinematics when assessed both at the standard upper anchorage position (Brown et al., 2009) and also with anchorage positions that vary from the standard (Reed et al., 2008, Klinich et al., 2008). What has not been determined however, is the potential interaction between different sash guide designs and varied anchorage geometries. In other words, the ability of different sash guide designs to achieve and maintain good sash belt fit across a range of realistic seat belt anchorages is unknown.

In this study we examine three different sash guide designs over a range of upper seat belt anchorage positions during frontal impact testing. We hypothesised that the guides would vary in their ability to maintain good seat belt placement, particularly when the upper seat belt anchorage was located more laterally (outboard).
The characteristics of sash guide design and upper anchorage location on the propensity for seat belt/sash guide disengagement were also examined.

METHODS

The performance of three different, commonly available sash guide designs over a range of upper anchorage conditions during 34 frontal impacts was investigated. All tests were conducted on a custom-built rebound sled at Neuroscience Research Australia (formerly the Prince of Wales Medical Research Institute).

1. Variable anchorage geometry

The upper seat belt anchorage position specified for the AS/NZS 3629.1:1999 test seat assembly is of height 650 mm above the seat cushion, located 490 mm outboard of the lower inboard anchorage point, and 265 mm behind the seat back (Standards Australia, 2010b).

Variable anchorage geometries were achieved by manufacturing an accessory frame for the test seat, which was fitted in place of the standard frame. Using the frame, the position of the upper anchorage could be altered vertically to achieve either a low or high position at either 465 or 675 mm above the seat cushion, and also laterally to achieve either an inboard or outboard position, at either 240 or 480 mm outboard of the buckle anchorage. The positions are representative of the range of locations seen in a survey of 50 late model Australian cars (Bilston and Sagar, 2007, Cheung, 2007).

A "cross booster standard" anchorage position was also established by manipulating the location of the D-Ring to produce identical, optimised sash belt

placement for all three sash guides. In this way, the effect that differing belt geometry, with respect to the dummy torso, had on the effectiveness of each design was minimised. This was achieved by using a different anchorage location for each sash guide. The height of the anchorage was chosen such that it was above the back of the booster, and produced effective belt routing over the shoulder centre. The lateral position of the anchor was chosen such that the booster seat could fit between the D-ring and buckle stalk. This proviso was chosen with the rear seat environment in mind: if this width is less than the width of the booster seat, then closing the vehicle door would reposition the booster more towards the car centre, and potentially position the sash belt off the shoulder.

2. Test Dummy and Instrumentation

The tests used a Hybrid III 6 year old test dummy (mass 23.4 kg, seated height 635 mm), representative of the anthropometry of children who must legally use a booster seat in Australia. The dummy was modified to prevent the lap belt becoming trapped in non-biofidelic gaps between the pelvis, abdomen and thighs by attaching a fabric lap shield to the dummy as shown in Figure 1. The dummy was then clothed as required by AS/NZS 1754.

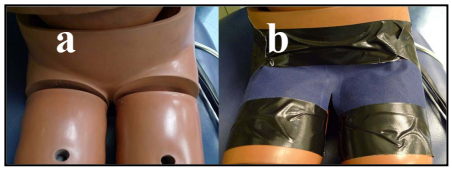

Figure 1. Pelvic modification a) before and b) after.

The dummy was seated according to a standardised protocol for each test and was fitted with triaxial head accelerometers and upper neck force and moment transducers. A seat belt force transducer was also used to determine peak belt forces.

3. Booster Seat and Sash Guide Selection

The sash guide designs investigated represented the most common designs currently seen on Australian boosters. These were:-

1. A head restraint integrated sash guide *(type 1* seen in Figure 2a);
2. A plastic clip on a long flexible strap attached at shoulder height *(type 2* seen in Figure 2b) and;
3. A plastic clip on a long flexible strap attached near the lower back *(type 3* seen in Figure 2c).

Two commonly available hard-shelled booster seat models were used. The first (*Booster 1*) features the head rest integrated sash guide *type 1*. The second was a forward facing/booster seat convertible model (*Booster 2*) and features the strap type sash guide *type 2*. The strap type sash guide *type 3* was not available in a hard-shelled design. To overcome this, the back of *Booster 2* was retrofitted with sash guide *type 3*. This modification involved cutting (and reinforcing) a slot in the centre of the back and attaching the sash guide to the existing sash guide attachment points.

Figure 2. Sash guides examined - a) *Type 1* b) *Type 2* c) *Type 3*.

The effect of any potential differences in lap-belt placement on dynamic sash belt fit was minimised through use of the anti-submarining clip (ASC) featured on both these booster designs.

Table 1. Test matrix for study

Test Number	Sash Guide (* = sash guide not engaged)	Position Number:	Anchorage Position Description:	Standard/ Accessory Frame	Height of Anchor Above Cushion	Distance Between Upper and Lower Anchors
1 & 2	1*	1	*Australian Standard Position*	*Standard*	650mm	490mm
3 & 4	1					
5 & 6	2/3*					
7 & 8	2					
9 & 10	3					

Test Number	Sash Guide (* = sash guide not engaged)	Position Number:	Anchorage Position Description:	Standard/ Accessory Frame	Height of Anchor Above Cushion	Distance Between Upper and Lower Anchors
11 & 12	1	2	*Minimum Height & Minimum Distance*	*Accessory*	465mm	240mm
13 & 14	2					
15 & 16	3					
17 & 18	1	3	*Minimum Height & Maximum Distance:*	*Accessory*	465mm	480mm
19 & 20	2					
21 & 22	3					
23 & 24	1	4	*Maximum Height & Maximum Distance:*	*Accessory*	675mm	480mm
25 & 26	2					
27 & 28	3					
29 & 30	1	5	*Cross Booster Standard*	*Accessory*	555mm	440mm
31 & 32	2				495mm	480mm
33 & 34	3				615mm	480mm

4. Test Matrix

Overall, 17 different sash guide/anchorage position combinations were tested, with two tests carried out for each combination. The booster seats were initially tested with and without the sash guides engaged at the standard position, and at the anchorage position required to achieve standardized belt geometry. Each sash guide design was then assessed with varied anchorage position at the minimum height and distance position, minimum height and maximum distance position, and maximum height and maximum distance position. The complete test matrix is summarized in
Table 1.

In all tests, the booster seats were installed and adjusted as per the manufacturers' instructions for use and sash guides engaged in a standardized way. An emergency locking retractor (ELR) lap-sash seat belt as specified in Australian Standard dynamic specifications was used in all tests.

High speed film footage of the impact was recorded at 2 ms intervals, with the camera positioned to capture the side view. The top view of the impact was simultaneously recorded through the use of a 45 degree angled mirror. Tests were conducted with a mean velocity change of 31.5 km/h and peak deceleration of 16.9 *g*.

5. Data Analysis

Custom designed software was used to filter and process the test data according to SAE J211/1. Resultant head acceleration, neck forces and moments were determined and plotted for each test and used to calculate HIC and Nij.

High-speed film was analysed using Phantom analysis software for head excursion, dummy kinematics, dynamic sash belt placement and sash guide interaction. Head excursion was calculated as the relative excursion of the centre of gravity (COG) of the dummy's head from its initial, pre-test position in the direction of impact.

Frontal pre-test photographs were used to measure the sash belt offset of the lateral belt edge from the dummy's neck at the shoulder contact point (seen in Figure 3).
Offsets were rated according to whether they were too far inboard (producing neck contact); good; or too far outboard (greater than the width of the shoulder).
Specifically, 'good' scores were designated for offsets positioning the outer sash belt edge more than 5mm inwards of the shoulder edge, and the inner belt edge more than 5mm outwards from the neck.
Unacceptable scores were allocated to offsets that placed the outer belt edge within 5mm of the shoulder edge; or the inner belt edge within 5mm of the dummy's neck.

Figure 3. Sash belt geometry determinants.

Head excursion was objectively compared with static belt offset to determine whether a linear relationship existed between the two measurements.

Statistical analyses were performed on the averaged results for each sash guide, anchorage position combination. Data were analysed in two stages. The first stage compared offsets and excursions at the standard anchorage position with and without the sash guides engaged, and for standardised sash belt geometry. The second group comprised the standard location, and three minimal/maximal combinations of anchorage height and lateral position all using sash guides.

RESULTS

1. Sash Offset

Shown in Figure 4, all three sash guides were effective in improving the sash belt position on the dummy's shoulder compared to when the sash guides were not used. Black dotted lines in the figures denote the 'acceptable offset' range.

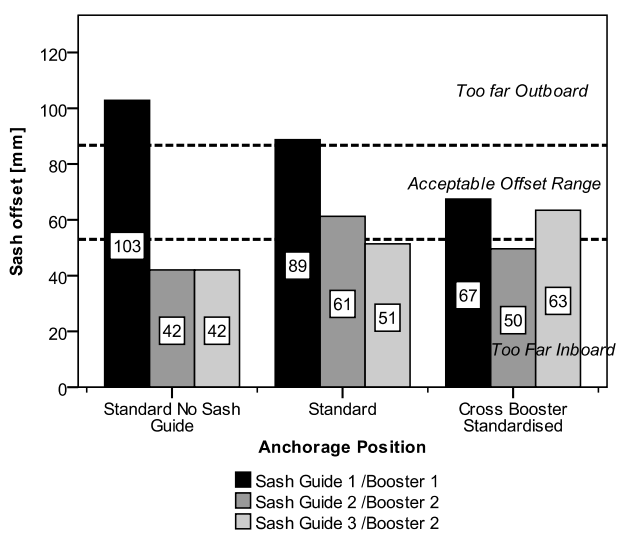

Figure 4. Comparison of sash offsets produced when sash guides disengaged/engaged, and for standardised belt geometry.

Booster 1 resulted in the outer belt edge being positioned off the edge of the dummy's shoulder. When the sash guide (*type 1*) was engaged however, the belt was repositioned more medially, in from the shoulder edge.
When the sash guides were not used, the belt routing of *Booster 2* resulted in neck contact. When either sash guide (*type 2* or *3*) was engaged, the belt was routed away from the neck, to a more central position on the shoulder.

When belt geometry was standardised, a difference in offset of roughly 15 mm was seen between sash guide *types 1* and *3*, and sash guide *type 2*. This difference was due to a sash guide exit position located more medially than the dummy's shoulder. This resulted in the sash belt being pulled inwards at the shoulder when this sash guide was engaged.
When sash guides were engaged and the anchorage position varied, sash guide type influenced the static position of the belt. This is shown in Figure 5.

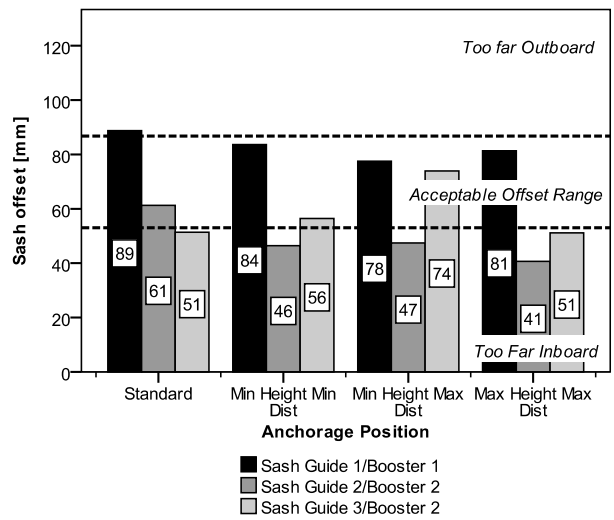

Figure 5. Comparison of sash offsets produced when sash guide used at the standard position, and when used at varied anchorage positions.

On average, sash guide *type 1* produced the largest offsets. Sash guide *type 2* produced the smallest offsets and was often ineffective at routing the belt away from the neck. Sash guide *type 3* generally produced offsets that were between sash guide *types 1* and 2. Of note was the offset produced by this type of sash guide (*type 2*) at the lower, more outboard located anchor position (Min Height Max Dist in Figure 5), which was discernibly larger than any of the other offsets it created at the other anchorage positions.

No sash guide was able to replicate the belt placement achieved at the standard position across the range of anchorage locations tested.

2. Head Excursion

Head excursion results are presented in Figure 6 and Figure 7. Head excursion varied from 267 to 366

mm. The mean excursion for the tests was 313 mm, shown as a black dotted line in the figures.

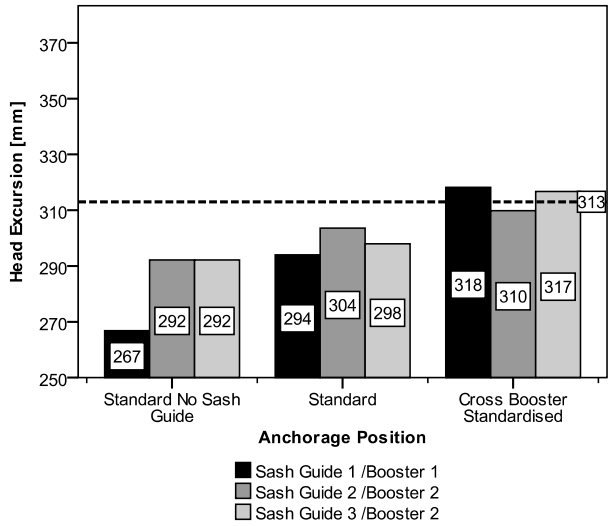

Figure 6. Comparison of head excursion with sash guides disengaged/engaged, and for standardised belt geometry.

Use of the sash guides at the standard anchorage position (Figure 6) resulted in greater head excursion for all three types compared to when the guides were not used. This difference was slight between *Booster 2* and sash guide *types 2* and *3*, but substantial between *Booster 1* and sash guide *type 1*. The smallest head excursions and largest sash offsets of the test series were produced by *Booster 1* at the standard position without the sash guide.

Head excursions at the standard anchorage position and for standardised belt geometry were comparable, approaching the mean excursion for the test series. However when anchorage position was varied, head excursion ranged widely both for different anchorage positions and for sash guide types (see Figure 7).

Sash guide *type 1* outperformed both strap types of sash guide (*types 2* and *3*) in the lower anchorage positions (min height), but produced substantially larger excursion at the highest, most outboard anchorage position (max height, max dist, Figure 7). The excursions produced by the strap type sash guides *2* and *3* were similar at each anchorage position tested. These forms of sash guide performed worst in the lower anchorage positions, with the largest head excursion of the series produced by sash guide *type 3* in lowest, most outboard anchorage position (min height, max dist, Figure 7). The excursions yielded at the highest, most outboard anchorage position (max height, max dist, Figure 7) were similar to those produced in the standard position.

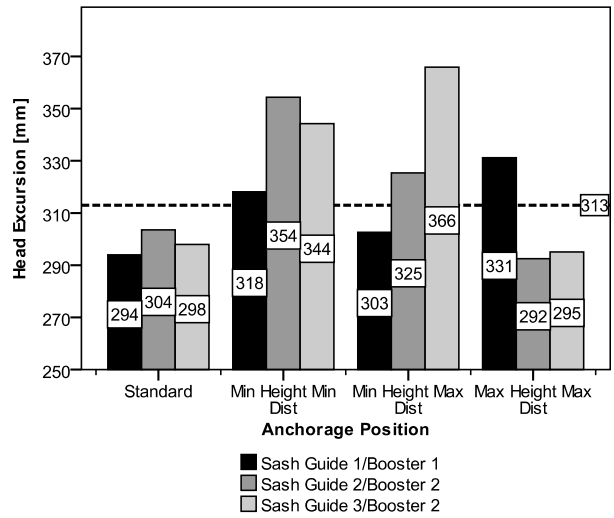

Figure 7. Comparison of head excursion when sash guides sash guide used at the standard position, and when used at varied anchorage positions.

Statistical analysis found no significant relationships between head excursion and either sash guide type or anchorage position. Furthermore, no linear relationship was seen between sash offset and head excursion. However, the number of tests is small, and the study therefore has limited statistical power.

3. Dynamic Observations

A summary of dynamic observations are presented in Table 2. Contact between the sash belt and the dummy's shoulder was partially lost in two instances involving *Booster 1*. The first was at the standard anchorage position when the sash guide was not used, and the second with the *type 1* sash guide engaged at the high, outboard anchor position. In both these tests the sash belt partially slipped off the dummy's shoulder after the impact. Despite these two instances, no complete dummy rollout was observed during testing and for all other tests good dynamic shoulder/sash contact was maintained.

The effectiveness of the ASC was demonstrated as the lap belt was held low on the dummy's pelvis in all tests. Seat belt retraction was affected in some tests when the location of the upper anchor was varied from the standard.
Post-test observation revealed the retractor to have locked with varying amounts of slack in the seat belt in:

- One test with sash guide *type 3* at the standard position;
- One test involving sash guide *type 1* and both tests involving *type 3* at the minimum height maximum distance position and;
- Five out of six tests at the minimum height minimum distance anchorage location.

This anchorage position resulted in the highest average head excursion of all the positions evaluated, however sash belt offsets were mostly within the acceptable range.

The tests involving sash guide *type 3* with the lower, more outboard position resulted in the highest excursion of the series. In this case, slack was also seen post-test.

Of the sash guides evaluated in this study, the seat belt disengaged from sash guide *type 2* at all anchorage positions between 43 to 45 milliseconds after impact. However, this did not result in the sash belt sliding off the dummy's shoulder.

Sash guide *type 3* also became partially disengaged in one instance but again, shoulder contact was maintained.

Table 2.
Summary of dynamic observations and instrumentation recordings.

Sash Guide (* = not engaged)	Anchor Position Number	Sash Belt Held on Shoulder Dynamically?	Normal Belt Retraction?	Sash Guide Disengaged? [ms after impact]	Head Acceleration (g)	HIC 15	Fx (kN)	Fz (kN)	Resultant Neck Force (N)	My (N.m)	Sash Belt Force (kN)
1*	**1.** *Standard*	×	Yes	-	36.5	108.6	0.06	0.95	1.06	36.2	-4.64
1		Yes	Yes	-	37.7	118.2	0.06	1.02	1.13	34.6	-4.65
2/3*		Yes	Yes	-	38.2	116.0	0.07	1.04	1.13	30.0	-4.48
2		Yes	Yes	43ms	39.6	131.0	0.07	1.08	1.18	33.3	-3.72
3		Yes	×	-	43.0	143.9	0.07	1.15	1.27	37.6	-3.88
1	**2.** *Min Height Min Dist*	Yes	×	-	41.1	134.5	0.07	1.08	1.20	36.7	-3.56
2		Yes	×	43ms	45.0	180.0	0.07	1.29	1.39	35.8	-3.43
3		Yes	×	-	46.2	187.7	0.07	1.34	1.45	39.8	-3.36
1	**3.** *Min Height Max Dist*	Yes	×	-	41.9	147.0	0.07	1.14	1.24	34.5	-4.41
2		Yes	Yes	43ms	40.5	140.7	0.07	1.09	1.17	35.6	-3.73
3		Yes	×	-	43.1	164.6	0.08	1.20	1.27	35.2	-2.61
1	**4.** *Max Height Max Dist*	×	Yes	-	42.4	148.2	0.07	1.16	1.24	37.2	-4.49
2		Yes	Yes	40ms	46.8	185.1	0.07	1.23	1.36	39.0	-4.48
3		Yes	Yes	52ms (partial)	47.1	177.9	0.07	1.28	1.41	38.9	-4.49
1	**5.** *Cross Booster Standard*	Yes	Yes	-	42.4	145.7	0.07	1.11	1.23	37.6	-4.39
2		Yes	Yes	45ms	37.9	111.8	0.07	1.01	1.09	30.5	-3.43
3		Yes	Yes	-	46.2	169.7	0.07	1.22	1.36	42.6	-4.50

4. Peak Head Acceleration, HIC, Upper Neck Loads and Sash Belt Forces

The data recorded by onboard instrumentation is also presented in Table 2.

The pattern of HIC values follows those of peak resultant accelerations. HIC 15 and 36 millisecond window values were comparable. All are well below injury reference values. The lowest head accelerations and HIC 15 occurred in tests with the lowest head excursions, when no sash guide was employed. Even though excursions were equivalent between sash guides at the standard and cross-booster standardised anchorage positions, head acceleration was varied.

The maximal resultant, *x* and *z*-components of upper neck force experienced by the dummy were tensile. The range of peak F_z forces varied between 950 N and 1.34 kN. M_y values ranged from 30 to 42.6 N.m, identifying a maximal flexion moment force on the neck.

The seat belt force transducer located 100 mm from the upper anchorage recorded peak forces in the range of 2.6 to 4.7 kN, with a median of 4 kN. Sash guide *type 1* produced consistently high peak seat belt

forces except in the case of the minimum height and minimum distance anchorage position. Comparable forces were generated by all three kinds of sash guide in this position.

DISCUSSION

The key finding of this work confirms our hypothesis that sash guides are not uniformly effective when used at anchorage positions varying from the Standards testing position. However, instead of the outboard anchorage positions proving the most challenging for the sash guides as hypothesised, the lower, inboard located anchorage position produced higher average head excursion than either of these.

Effectiveness was defined by the sash guide's ability to maintain acceptable dynamic belt placement and to minimise head excursion.

At the Australian Standard anchorage position and when seat belt geometry was standardised, comparable head excursions were produced by the three sash guide designs. Away from these conditions however, large variations in excursion were observed both for different anchorage positions and for different sash guide designs. From this result, it appears that sash guide effectiveness may be optimized for the standard anchorage location.

The static belt placement produced by the strap type sash guides frequently resulted in neck contact. These types of sash guides produced the largest excursions at lower anchorage positions. Conversely, the static placement produced by the sash guide integrated into the moving head restraint often resulted in large sash offsets. The largest excursions produced by this type of sash guide were seen when tested at the higher, more outboard anchorage position.

Our results indicate that neither sash guide design nor the upper belt anchorage position alone control head excursion. Instead, these two factors appear to have a joint effect in controlling head excursion.

1. Dummy Kinematics

The impact severity and dummy size used in these tests are limited by our hardware, and are lower than other similar studies. Brown et al. and Klinich et al. both used a 10 year old representative dummy, and velocity changes of 56 km/h and 48 km/hr respectively (Brown et al., 2009, Klinich et al., 2008).

The higher severity impacts used by Brown et al. might explain the large incidence of rollout observed in that test series. It is possible that the partial loss of shoulder contact seen in two instances in these tests would have resulted in rollout at higher test severities.

The smaller size of the dummy used in this current work may have also had reduced the incidence of rollout. Brown et al. (2009) hypothesised that using a smaller dummy would result in smaller offsets and hence, less rollout. This is what was observed here, with the smaller dummy and the strap type sash guides resulting in a high incidence of neck contact. Interestingly, the tests where partial rollout was observed in this study involved the booster seat with the integrated head restraint type sash guide. That type of sash guide produced the highest proportion of rollout per sash guide type observed in Brown et al.'s tests. Together these results suggest that integrated type sash guides may be less effective at maintaining dynamic belt placement.

2. Sash Guide Disengagement

Brown et al (2009) observed that the seat belt disengaged from the sash guide in all cases tested with sash guide *type 2*. The authors also noted that despite this, the sash belt lost contact with the shoulder in only 2/6 of these tests. The time of disengagement was not mentioned in that study. Klinich et al. observed that of the three booster seats tested at the outboard anchorage position, two sash guides failed to keep the seat belt engaged. The sash guide that disengaged after 45-55 ms maintained good sash belt/shoulder contact however the guide that disengaged after 60-70 ms resulted in poor dynamic belt placement (Klinich et al., 2008). Of the sash guides evaluated in this study, the seat belt disengaged from sash guide *type 2* for all positions. Despite this, the sash belt still maintained good contact with the dummy's shoulder. The timing of disengagements occurred between 40 and 52 ms after impact, which is in line with the results of Klinich et al. It appears that the timing of the disengagement may be important in whether or not the sash belt remains in contact with the shoulder. While it is not yet clear why this is the case, this might be because the belt is in a better position, or in greater contact with the torso, at the time of disengagement. Further work is warranted to determine more fully the relationship between timing of disengagement and the effects on maintenance of contact between the sash belt and the shoulder. Whether these observations in dummies (which have rubber skins and relatively stiff torsos compared to humans) translate to real children also remains to be seen. The criteria in the Australian Standard requiring the belt

to remain engaged may need to be amended to allow disengagement within a certain time frame.

3. Sash Guide Effectiveness

In the current work, no clear relationship existed between sash offset and resulting head excursion. Further, substantially different responses were produced with similar offsets. Some of the smallest and largest head excursions of the test series were generated when offsets were within 10 millimetres of each other. However, as mentioned previously, there was also no single anchorage position that produced the highest excursions for all three sash guide designs. The largest excursions generated by the strap type sash guides (*2* and *3*) were at the lower anchorage positions, with a difference in excursion of over 50 mm for *type 2* and over 65 mm for *type 3* from the standard seen. Strap type sash guides produced, on average, more medially located sash belt placement. This is a product of the construction of the booster seat where the belt is routed up over the back of the seat before being held down on the shoulder by the sash guide.

The head restraint sash guide *type 1* produced the largest head excursions at the high, outboard anchorage position 4. A difference of almost 40 mm in excursion was seen from the standard in this position. To engage the seat belt in this type of sash guide, it must be routed underneath the head rest. The distance of the sash guide from the booster seat centreline hence appears to affect the belt position. For more inboard-located anchorage positions, the belt routing must change in direction from outwards to inwards again.

In dynamic assessment of the effectiveness of sash guides, dynamic belt placement should be considered. When *Booster 1* was tested without the sash guide engaged, the belt did not maintain contact with the dummy's shoulder dynamically. As such, work to reduce misuse associated with booster seats such as unused sash guides is important. Good contact was also lost when sash guide *type 1* was engaged at the maximum height, maximum distance position. This suggests that the position of the upper anchorage has a stronger effect on dynamic belt placement than sash belt offset alone.

4. Implications

This work suggests that current sash guides may not be effective in a realistic rear seat environment because they do not perform comparably across a wide range of anchorage positions representative of those in the current vehicle fleet. Not only did head excursion change for sash guides at different anchorage positions, but also between sash guide types at the same position. This means that the effectiveness of current sash guide designs is anchorage position-dependent, and different designs may be ill-suited for certain rear seat conditions. For example, the integrated head restraint sash guide may not be ideal for use with higher, outboard anchorages such as seen in larger model cars and SUVs. In contrast, the strap type sash guides performed poorly with lower anchorage positions seen in smaller model cars. Further work is recommended to ascertain whether certain sash guide designs should be avoided in these conditions, or whether it is possible to optimise sash guide designs to obtain good performance across a wider range of anchorage positions.

5. Limitations

The impact speeds generated in this study were moderate, and below frontal testing standards. Hybrid III kinematics have been reported to change with increased impact speeds (Menon et al., 2005). Therefore, it may be that dynamic responses are not representative of those that would be produced at higher velocities.

In terms of biofidelity, numerous authors have documented that the design of the neck, lumbar spine and torso of the Hybrid III may not accurately reflect a biofidelic response (Bilston et al., 2007, Menon et al., 2007, Sherwood et al., 2003).

Most important however, is the construction of the dummy shoulder. Mallot et al. (2004) identified that the more rigid squared off dummy shoulder may hold the sash belt in place better than the sloped shoulder of a child occupant. If this is the case, then the incidence of rollout and hence injuries seen in real crashes may be greater than seen here and in other similar work.

Only six year old representative anthropometry and a small subset of sash guide types were tested in this study, not representative of the range of all booster occupants and booster seat designs currently available.
Previous studies have used a ten year old representative dummy to simulate the 'worst case' of child anthropometry for sash guides (Brown et al., 2009, Klinich et al., 2008). However when it comes to the effect of large belt offsets on dummy responses, a smaller dummy may actually be more challenging to accommodate.

The static offsets produced by sash guide *type 1* favoured a more outboard position. This form of sash guide can be adjusted vertically but not laterally. For smaller sized children with narrower shoulders, lower rates of acceptable static belt placement would be expected. This may also affect dynamic responses.

The accessory frame design allowed only vertical and lateral manipulations of the D-Ring position. It is unrealistic to assume that all rear seat upper anchorage points would be in the same fore-aft position. Further, the position of the seat belt retractor was not able to be varied with that of the D-Ring, and issues in retraction were observed when assessing sash guides at lower anchorage positions. In any given vehicle design, it would be expected that the relative horizontal positions of the retractor and upper anchorage would be fixed and optimised. As such, future tests using a frame that could vary the location of the anchor and retractor in *three* directions might better represent true rear seat conditions.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study clearly indicate that current sash guide designs are not equally effective over a range of upper anchorage positions.

When evaluated at the anchorage position used in Australian Standards testing, comparable head excursions were produced by the three designs. Equivalent head excursions were also produced when sash belt geometry was standardised relative to the dummy's torso. The lateral positions of the D-Ring in these tests were similar to that of the standard. However when upper anchorage position was changed to commonly seen locations, the sash guides varied widely in their ability to ensure good seat belt fit and minimise head excursion.

ACKNOWLEDGMENTS

The authors of this paper would like to thank the RTA Crashlab facility for the loan of the Hybrid III 6 year old dummy.

REFERENCES

ARBOGAST, K., KALLAN, M. J. & DURBIN, D. R. Year. Effectiveness of high back and backless belt-positioning booster seats in side impact crashes. *In:* 49th Annual Proceedings Association for the Advancement of Automotive Medicine, 2005.

ARBOGAST, K. B., JERMAKIAN, J. S., KALLAN, M. J. & DURBIN, D. R. 2009. Effectiveness of belt positioning booster seats: an updated assessment. *Pediatrics,* 124**,** 1281-6.

BILSTON, L. E. & SAGAR, N. 2007. Geometry of rear seats and child restraints compared to child anthropometry. *Stapp Car Crash J,* 51**,** 275-98.

BILSTON, L. E., YUEN, M. & BROWN, J. 2007. Reconstruction of Crashes Involving Injured Child Occupants: The Risk of Serious Injuries Associated with Sub-Optimal Restraint Use May Be Reduced by Better Controlling Occupant Kinematics. *Traffic Injury Prevention,* 8**,** 47 - 61.

BROWN, J., KELLY, P., SURATNO, B., PAINE, M. & GRIFFITHS, M. 2009. The Need for Enhanced Protocols for Assessing the Dynamic Performance of Booster Seats in Frontal Impacts. *Traffic Injury Prevention,* 10**,** 58 - 69.

CHEUNG, C. 2007. *Assessing the Effect of Different Car Seat-Belt Geometry on Occupant Motion.* B Mechatronic Engineering/M Biomedical Engineering, University of New South Wales.

DURBIN, D. R., ELLIOTT, M. R. & WINSTON, F. K. 2003. Belt-Positioning Booster Seats and Reduction in Risk of Injury Among Children in Vehicle Crashes. *JAMA,* 289**,** 2835-2840.

KLINICH, K., PRITZ, H., BEEBE, M. & WELTY, K. 1994. Survey of older children in automotive restrains. *38th Stapp Car Crash Conference.* Fort Lauderdale, FL: Society of Automotive Engineers.

KLINICH, K. D., REED, M. P., MANARY, M. A., RITCHIE, N. L., SCHNEIDER, L. W. & RUPP, J. D. 2008. Assessing child belt fit, volume II: effect of restraint configuration, booster seat designs, seating procedure, and belt fit on the dynamic response of the hybrid III 10-year-old ATD in sled tests. University of Michigan, Ann Arbor, Transportation Research Institute.

MALLOTT, A., PARENTEAU, C., ARBOGAST, K. & MARI-GOWDA, S. 2004. Sled Test Results Using the Hybrid III 6 Year Old: An Evaluation of Various Restraints and Crash Configurations. *SAE International,* 2004-01-0316.

MENON, R. A., GHATI, Y. & JAIN, P. 2007. MADYMO Simulation Study to Optimize the Seating

Angles and Belt Positioning of High Back Booster Seats. . *Proc. 20th Enhanced Safety of Vehicle*

MENON, R. A., GHATI, Y. & ROBERTS, S. 2005. Performance Evaluation of Various High Back Booster Seats Testes at 56Km/h Using a 6-Year-Old Hybrid III Dummy. *19th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Washington DC.

NATIONAL HIGHWAY SAFTEY BUREAU 2001 Federal Motor Vehicle Safety Standard 213: Child Restraint Systems. Washington DC: Code of Federal Regulations.

NATIONAL TRANSPORT COMMISSION 2007. Australian Road Rules: 7th Amendment Package 2007, Regulatory Impact Statement. Melbourne.

REED, M. P., EBERT-HAMILTON, S. M., KLINICH, K. D., MANARY, M. A. & RUPP, J. D. 2008. Assessing child belt fit, volume I: effects of vehicle seat and belt geometry on belt fit for children with and without belt positioning booster seats. University of Michigan, Ann Arbor, Transportation Research Institute.

REED, M. P., EBERT, S. M., SHERWOOD, C. P., KLINICH, K. D. & MANARY, M. A. 2009. Evaluation of the static belt fit provided by belt-positioning booster seats. *Accident Analysis & Prevention,* 41**,** 598-607.

SHERWOOD, C. P., SHAW, C. G., VAN ROOIJ, L., KENT, R. W., CRANDALL, J. R., ORZECHOWSKI, K. M., EICHELBERGER, M. R. & KALLIERIS, D. 2003. Prediction of Cervical Spine Injury Risk for the 6-Year-Old Child in Frontal Crashes. *Traffic Injury Prevention,* 4**,** 206 - 213.

STANDARDS AUSTRALIA, S. N. Z. 2010a. Child restraint systems for use in motor vehicles: Australian/New Zealand Standard (AS/NZS). *1754:2010.*

STANDARDS AUSTRALIA, S. N. Z. 2010b. Methods of Testing Child Restraints (Method 1: Dynamic Testing). *AS/NZS 3629.1:2010*