

Protection of Rear Seat Occupants in Frontal Crashes

Suzanne Tylko

Dainius Dalmotas

Crashworthiness Division,

Transport Canada

Canada

Paper Number 05-258

ABSTRACT

Regulations and vehicle design optimization have traditionally focused on the occupants of front seats. Stringent requirements exist for the driver and front right passenger but there are no dynamic crash test requirements for rear seat occupants. The introduction of frontal airbags and the concurrent increased incidence of child fatalities in low speed frontal collisions brought urgency to the public health message advising parents to place children 12 years and under in the rear seat.

Anthropometric test dummies representative of a 5th percentile adult female or 12-year-old child were used together with the recently introduced Hybrid III 10-year-old dummy and the Hybrid III 6-year-old dummies to evaluate rear seat occupant protection in full frontal rigid barrier tests and frontal offset deformable barrier tests. The 6-year-old dummy was restrained with a belt-positioning booster while the 10-year-old was restrained with either a belt positioning booster or the vehicle 3-point seatbelt. Dummy responses were examined as a function of seat position and in the case of child dummies, booster seat type.

Successful restraint of the chest was associated with high belt loads and pronounced chest deflections while slippage of the belt from the shoulder led to extreme flexion of the torso, head strikes and elevated neck loads. Booster seats had no effect on shoulder belt translation during the dynamic event but were observed to maintain the abdominal portion of the belt in place, over the pelvis. Opportunities for rear seat occupant protection and child dummy enhancements are discussed.

INTRODUCTION

In 2003 Transport Canada began adding dummy occupants to the rear seating positions of vehicles being tested in Full Frontal Rigid Barrier (FFRB) compliance tests (CMVSS 208) and Offset Deformable Barrier (ODB) research tests to evaluate rear seat restraint performance. Testing began with an evaluation of booster seat performance for the Hybrid III 6-year-old dummy and evolved to include a comparison of the Hybrid III 5th female dummy seated in the front and rear seats of different vehicle models. The Hybrid III 10-year-old dummy, being a relative newcomer to the family of frontal dummies, was included in a small number of tests to try and gain a better understanding of this dummy's attributes. Furthermore, because this dummy represents an older child it provided an opportunity to compare the response of a dummy restrained with the lap/shoulder belt with and without of a booster seat.

The paper will first describe the results of the small female as this will quantify the differences observed between the front and rear seats in the context of a dummy that is familiar to most and highlight certain key measurement parameters. Trends and responses observed with the Hybrid III 6-year-old will be presented and compared to the responses of the 6-year-old in two modified restraint configurations. The results of the paired comparison for the 10-year-old with and without a booster seat will complete the analysis and illustrate the importance of including a suite of measurement parameters in the dynamic testing of rear seat performance.

TEST MATRIX

The vehicle sample for this study included 77 vehicles shared with the frontal compliance test programme and the frontal protection research programme. The vehicles were of model year 2003 through 2005, included passenger cars, minivans, crossover vehicles and SUV's ranging in test mass from 1400 to 2900 kg. All were equipped with a three-point lap shoulder belt in the centre rear seating position and the majority had LATCH anchors in place.

The child restraints were purchased from local retail outlets and were selected on the basis of seat geometry, advertised weight limits, tether attachment and internal harness configuration and belt guide design. In vehicles where three adjacent booster seats needed to be fitted to the vehicle, selection was based exclusively on the width of the seat as even in the largest of SUV's, the fitment of three child restraints across one bench seat was found to be a challenge.

Selection of the child seat for a particular test was dependent on seat placement and intended comparison. For example, if two outboard positions were being compared and the test was a FFRB with evenly distributed loads to the front of the vehicle, the options were either to select two identical seats and vary the attachment configuration or to select two different seat types but retain identical attachment methods. A number of comparisons were carried out including:

- Centre rear VS rear outboard with identical booster seats;
- High back booster with tether/latch attachments VS high back with only the lap/shoulder belt in two outboard positions;
- Second row VS third row with identical booster seats.

An overview of the different restraint types and the attachment configurations employed in the study are presented in Table 1. The sample contained a total of 20 high back models and 2 low back models. Each of the above comparisons was carried out with a minimum of 2 different model types. The booster seats with LATCH and tether attachment were convertible child seats. These are forward facing child seats, which can be converted to a booster seat by removing the harness.

Table 1: Test Matrix with Hybrid III Child Dummies and Small Female.

	6 Year Old	10 Year Old	5th Female
CRS	X		
Low back booster	X		
High back booster	X	X	
High back booster with harness latch & tether	X		
Lap & shoulder belt	X		X

TEST METHODOLOGY

Vehicle preparation was conducted as per the FMVSS/CMVSS 208 procedure for the full frontal rigid barrier tests. A small number of low and high speed offset deformable barrier (ODB) tests were also conducted by following the ODB procedure in FMVSS 208. Tests for the small female front to rear comparison and for the 10-year-old were carried out at 48 km/h FFRB, while tests with the 6-year-old were conducted at speeds ranging from 40 km/h to 60 km/h in FFRB and ODB.

Positioning Procedures

The Hybrid III 5th female dummy was seated in the front right passenger seat as per the FMVSS 208 procedure. In the rear seat, since there is no regulatory procedure in place, the dummy was seated in the rear right passenger seat by aligning the mid-sagittal line of the dummy with the seat centerline. The head level and thorax orientation of the dummy were dependant on the vehicle seat back angle and the arms and legs were placed in a neutral position. A piece of surgical tape was placed on the dummy thorax to record pre-test shoulder belt position and to assist in identifying belt position at peak load with the indentations left on the tape.

The Hybrid III 6-year-old dummy was placed in a booster seat and restrained with the vehicle seatbelt. The seatbelt was deployed, as one would expect a child to deploy the belt that is without engaging the locking mechanism. The booster seat itself was either used as a traditional booster seat using the vehicle seatbelt alone or by attaching the booster seat to the vehicle seat

with the LATCH and upper tether anchor and then using the vehicle seatbelt to restrain the child. When used as a forward facing child restraint the seat was installed in the vehicle as per manufacturer's instructions and the upper tether always used.

Instrumentation and Filtering

The dummy instrumentation included a tri-axial accelerometer at the head CG, a 6-axis load cell at the upper and lower neck; a potentiometer at the sternum, a lumbar load cell and numerous linear accelerometers on the sternum, spine box and in the pelvis. All data recording and filtering was performed in accordance with SAE J211.

Rear occupant motions were filmed at 500 to 1000 frames/second, depending on light quality, from the front and side.

RESULTS

Small female front and rear. The vehicles used for this comparison included a Japanese mid-sized sedan, a small SUV and a large SUV/truck. The two females were seated one behind the other with the front female seated in the foremost track position. The mid-sized sedan (Model 'A') was the only test where the rear occupant femurs were observed to contact the seat back. The relative timing of the dummy kinematics was such that the effect of this loading on the front dummy responses was undetectable in the front occupant lumbar or seatbelt force responses.

The responses of the Hybrid III 5th female seated behind the right front passenger were more elevated than those of the front passenger in all three FFRB 48 km/h tests. Kinematic responses sharply contrasted the kinematics of the front occupant as the abdominal belt translated up and penetrated the abdominal cavity in two of the three tests.

The comparison of sternum deflections, 3 ms chest clips and the corresponding seatbelt forces for the front and rear dummies are presented in Figures 1 through 3 respectively. The order of presentation is the same for all plots such that the sedan is Model 'A' and is always the first pair of bars; the large SUV/truck or Model 'B' is represented by the middle bars and the small SUV, Model 'C', is the final set.

Chest deflections were always greater in the rear seat. The difference for Model 'A' was of the order of 7 mm; however in Model 'B' deflection increased from 17 mm in the front to 41.7 mm in

the rear. Similarly in model 'C' deflections in the rear almost doubled by increasing 22mm over the front passenger response.

The 3 ms chest clips were also more elevated in the rear, though the increment did not reflect the deflection trends. For example, in Model 'B' where deflections more than doubled, the clipped chest accelerations were essentially identical.

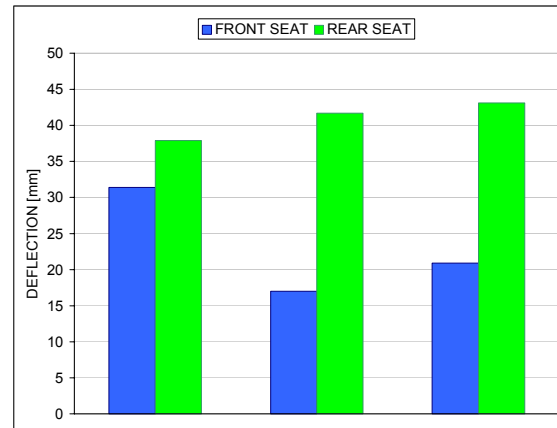


Figure 1: Deflection measures for the front & rear seat occupant in Models A, B and C respectively.

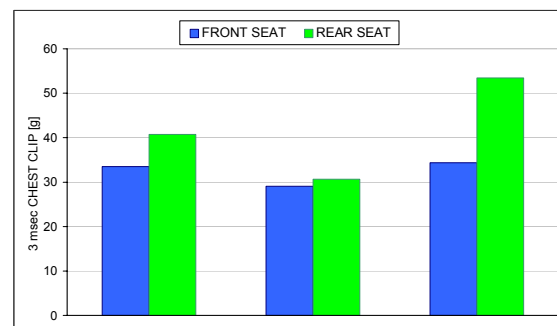


Figure 2: Chest clip for the front and rear seat occupant in Models A, B and C respectively.

Both lap and shoulder belt loads increased in the rear seat position, as did the proportion of shared load between the lap and shoulder belt. In Model 'A' the lap and shoulder belt loads are comparable but in the rear seat the relative distribution of load changes rather significantly as the shoulder belt attains three times the peak load of the lap belt. A similar change but in the reverse was observed in Model 'C' where both the shoulder and lap portions of the seatbelt attain values that are of the order of 7 kN.

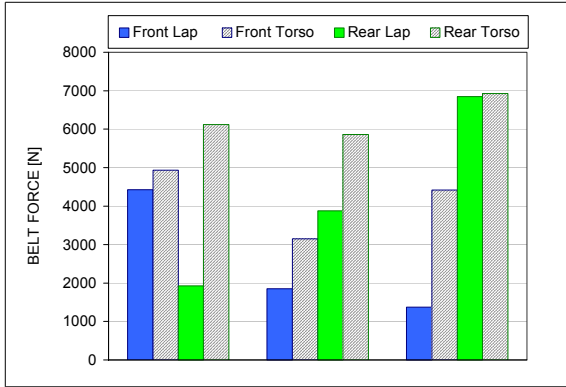


Figure 3: Lap and shoulder belt force measures for the front and rear seat occupant in Models A, B and C respectively.

Video analysis of the rear passenger kinematics suggests that lap belt migration into the abdominal cavity is most pronounced in Model ‘A’ and occurs in Model ‘B’ but to a lesser extent. In Model ‘C’ the lap belt appears to remain in place as the belt is loaded. These findings are consistent with the resultant lumbar forces shown in Figure 4. The elevated lumbar force resultant in Model ‘A’ correlates well with belt intrusion into the abdominal cavity and the associated forward pivoting motion that was observed for the rear passenger. In contrast the resultant lumbar forces are lowest for Model ‘C’ where the belt remained in place and pivoting was minimal.

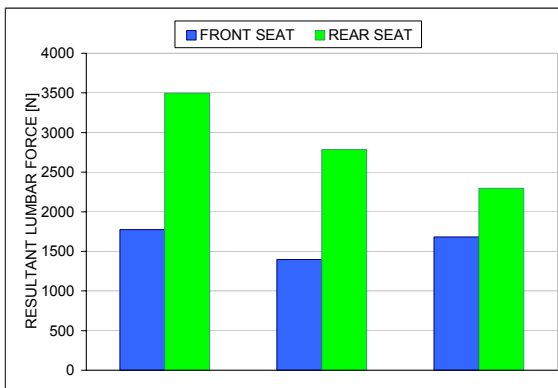


Figure 4: Resultant lumbar force for the front and rear seat occupant in Models A, B and C.

Hybrid III 6-year-old booster results: In all of the testing conducted to date, the Hybrid III 6-year-old restrained by the vehicle lap/torso belt in a booster seat, behaved in one of two ways. Either the torso belt would translate up towards the neck; or the torso belt would slide down towards the shoulder as the dummy was pitched forward.

As soon as the child dummy begins to load the shoulder belt, the webbing extends in the direction of the seatbelt anchor points. Upward motion of the belt into the neck, results in compression of the extreme upper quadrant of the chest, off-loading onto the neck and sternum deflections that are uncharacteristically low for the observed belt loads. Downward movement of the shoulder belt is associated with increased dummy excursion as the dummy slips out of the belt. At the moment of peak loading, the belt passes directly over the sternum or in very close proximity, producing high deflections. In some tests the dummy was found to slip out of the belt entirely, pivoting forward until the dummy head and thorax struck its lower extremities resulting in elevated head accelerations and chest deflections.

Figure 5 displays peak resultant head accelerations obtained in 48 km/h FFRB tests. There was one head strike into a seat frame resulting in a peak resultant acceleration of 324 g. A number of head contacts with the lower extremities resulted in accelerations that were as high as 225 g while accelerations arising from strikes with the upper extremities or chin to chest contacts were closer to 100 g. In the absence of head contact no head accelerations in excess of 80 g were observed. Accelerations above 80 g were not observed on rebound.

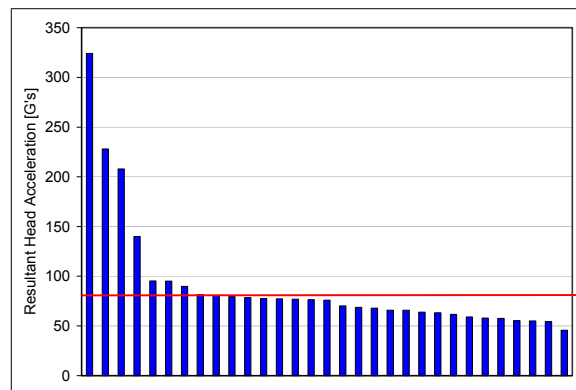


Figure 5: Peak head resultant accelerations for the Hybrid III 6-year-old in a booster seat at 48 km/h FFRB.

Neck tension surpassed the Injury Assessment Reference Value (IARV) of 1490 N in all but the 40-km/h ODB tests. Peak upper neck tensions as high as 4500 N were observed and tended to be highest in those cases where the child dummy torso flexed forward and the head was projected to the feet.

Chest deflections ranged between 17 mm and 52 mm. Low thoracic deflections, below 25 mm, were associated with shoulder belts that translated up into the neck while the higher deflection values were observed in cases where the belt slipped off the shoulder.

Shoulder belt loads were high for all rear seating positions, irrespective of booster seat model and ranged from between 2000 N and 3000 N for low speed offset deformable barrier tests and between 4000 N to 6000 N for full frontal rigid barrier tests conducted at 40 to 56 km/h. Figure 6 displays the relationship between vehicle longitudinal acceleration at the CG and shoulder belt loads ($R^2 = 0.68$).

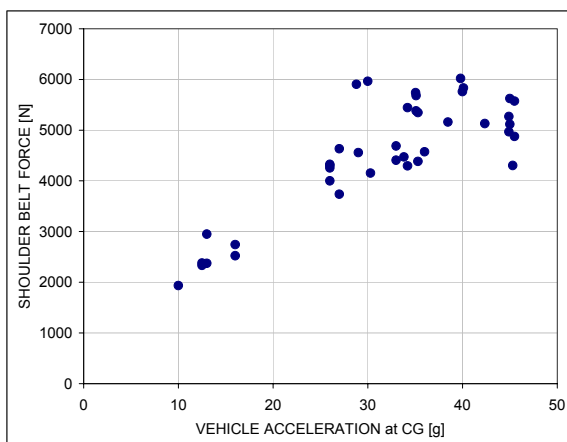


Figure 6: Correlation between rear seat shoulder belt force and longitudinal vehicle acceleration at the CG.

Six tests comparing dummy responses in outboard seating positions to responses in the centre seat position were carried out. The results of this comparison were inconclusive. Belt loads were equivalent while chest deflections were higher for three of the six centre positions and equal in one.

A preliminary comparison between second and third row seating suggests that dummy responses were equally elevated in the second and third row seats. In one case the third row centre seated child was launched upward towards the tailgate window during rebound. In another vehicle, the

distance between the third and second row seat was less than between the first two rows and lead to a head strike with the second row seat frame.

Two alternative restraint configurations were explored in an attempt to reduce the dummy responses observed in lap/shoulder booster seats. The first was to place the 6-year-old dummy weighing 24 kg (52.5 lbs) into a CRS rated to 21 kg (47 lbs) or 21.3 kg (48 lbs) so that restraint now relied on the child seat 5-point harness instead of the vehicle seatbelt; and the second was to rigidly attach the convertible booster seat by way of the available LATCH and tether while still using the vehicle seatbelt to restrain the child dummy.

Figure 7 displays the normalized responses for one high speed ODB test at 60 km/h represented by the first set of bars, and 6 FFRB tests carried out at 48 km/h. The vehicle accelerations for these tests were of the order of 27 to 30 g, with the second and third sets of bars representing the results two different child seats in a single vehicle crash test. Chest deflections (Dx) were dramatically reduced though neck loads remained elevated. The two occurrences of elevated head acceleration were due to head strikes into the seatbacks of the front seats when the harness system failed. There were no failures of the LATCH or tether anchoring systems.

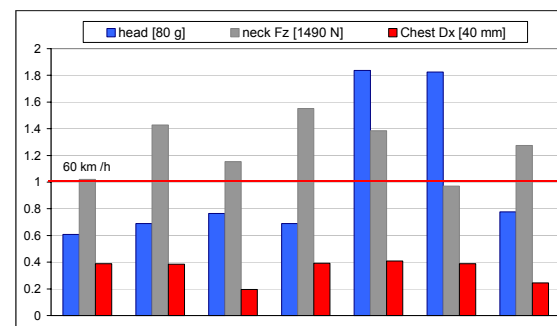


Figure 7: Normalized responses for the HIII 6-year-old in a forward facing 5-point harness CRS.

The effects of anchoring a booster seat to the vehicle seat by way of the LATCH and tether were compared to the conventional attachment method of a lap/shoulder belt and booster seat. Head accelerations, axial neck forces, chest deflections, seatbelt loads, lumbar forces and moment responses were examined as were the overall dummy kinematics.

There were no significant differences in head acceleration responses. The occasional 90 g to

100 g peak responses were typically due to upper extremity or chest to chin strikes and could not be definitely associated to seat attachment method.

Peak axial and shear neck loads were typically higher for the shoulder/lap belted booster seat. In the three cases where the latched booster seat produced higher responses the differences ranged from 5 to 15 % whereas in the remaining cases the increase in axial force for the shoulder/lap belted booster ranged from 5% to 68%.

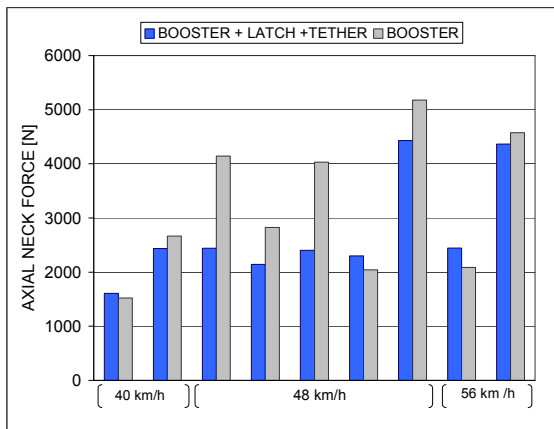


Figure 8: Comparison of axial neck force for the 6-yr-old in booster seat anchored with latch & tether and booster seat with belt only.

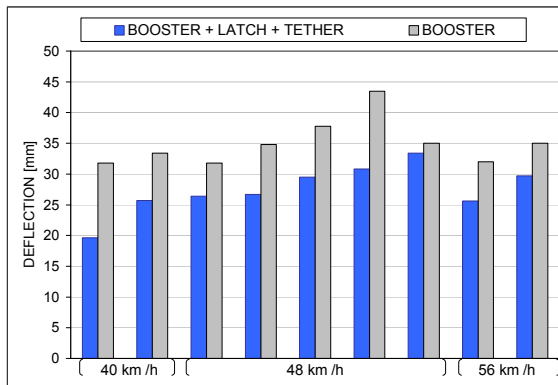


Figure 9: Comparison of peak chest deflection for the 6-yr-old in booster seat anchored with latch & tether and booster seat with belt only.

Chest deflections were consistently higher in the shoulder/lap belted booster. Figure 9 presents the comparative deflections for FFRB tests conducted at 40, 48 and 56 km/h. Consistent with the increase in deflection, shoulder belt loads were found to be higher for seven of the 9 shoulder/lap belt restrained boosters. Chest acceleration was unaffected by seat attachment method.

Peak resultant lumbar forces for the latched and shoulder/lap belted booster seat comparison are shown in Figure 10. The peak resultant lumbar forces found to be associated with greater abdominal penetration and rotation about the pelvis, in the small female, were more elevated in the shoulder/lap belt restrained booster. There were two tests wherein the lumbar forces were marginally higher (5 % to 8%) for the latched booster seat however, for the remaining tests, lumbar forces were 15 % to 90 % greater for the shoulder/lap belted boosters.

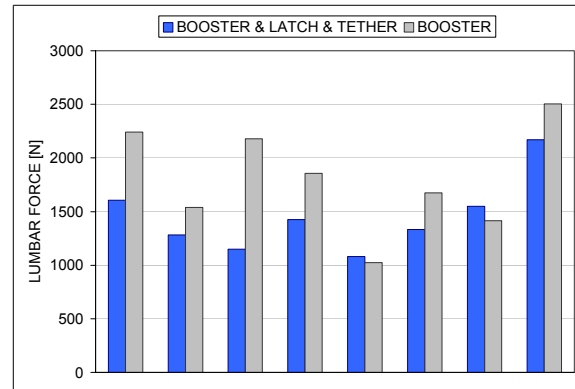


Figure 10: Comparison of peak lumbar forces for the 6-yr-old in booster seat anchored with latch & tether and booster seat with belt only.

The kinematics of the dummies in the two booster seat attachment configurations differed in their loading and rebound behaviours. During the loading phase, the shoulder/lap belted booster seats displayed greater forward excursion, rotation and vertical displacement than did the latched boosters. The dummy rebounded more rapidly and exhibited greater vertical displacement. Generally motion in the shoulder/lap belted booster seat was less controlled.

The armrests in one booster seat model sheared during impact in four tests with the LATCH attachment and once for the lap/shoulder belted both attachment configurations. There were no failures of the LATCH, or tether anchorages in the latched booster seat.

Hybrid III 10-year-old with and without booster:

Two comparative tests were carried out to gain a better understanding of the Hybrid III 10-year-old responses and to compare responses for a 10-year-old dummy restrained in a booster seat and by the lap/shoulder belt alone. The comparison included two crash tests of identical model vehicles tested in a FFRB at 48 km/h. The longitudinal accelerations at the vehicle CG were

26 g for the non-booster seat test and 27 g for the booster seat test.

Chest deflection responses and associated shoulder belt force measurements are shown in Figure 12. The belt loads were equivalent for both test conditions, yet the deflections for the booster-seated dummy far exceeded the deflections recorded for the shoulder/lap belted dummy, both in magnitude and duration.

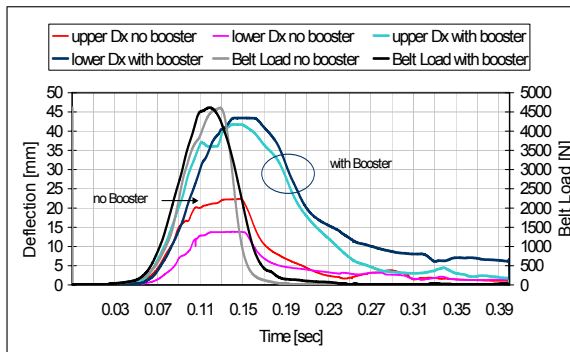


Figure 11: Comparison of upper and lower chest deflections for the Hybrid III 10-year-old with and without of a booster seat.

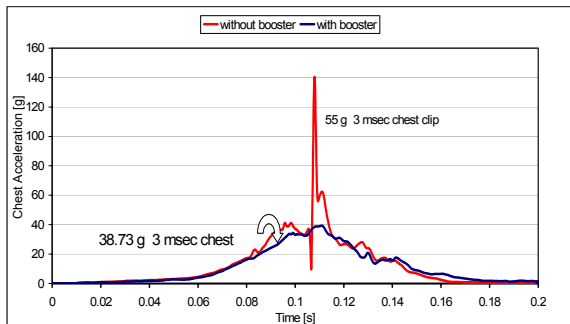


Figure 12: Comparison of resultant chest accelerations for the Hybrid III 10-year-old in and out of a booster seat.

The chest acceleration resultant shown in Figure 13 was primarily the result of a 121 g longitudinal component and a 71 g lateral component, which occurred 108 ms into the event. Video analysis failed to identify any external causes for this noise. Sternum and spine accelerometers failed to provide further information on the possible source of the noise.

The comparison of the Hybrid III 10-year-old dummy underlines the importance of including a variety of measurement parameters including video analysis in the evaluation of restraint performance. In the case of the shoulder/lap belted 10-year-old, the shoulder belt translated up into the neck placing the belt high on the chest while the lap belt penetrated the abdominal

cavity. The resulting deflections which occurred in the uppermost quadrant of the chest were too remote to be detected by either of the two sternum IRTACCs .

In the booster seat, the belt slipped off the shoulder of the 10 year-old dummy and was directly over the sternum at the moment of peak load, resulting in high upper and lower sternum deflections. There was significant excursion as the dummy rotated out of the shoulder belt. The lap belt remained on the pelvis throughout the event.

Limiting the analysis to the chest responses could lead to the false conclusion that the shoulder/lap restraint is better when in fact neither condition is desirable.

DISCUSSION

All booster seats effectively retained the lap portion of the seatbelt in the pelvic region and prevented the upward translation of the lap belt into the abdominal cavity. In contrast, the small female and 10-year-old dummies restrained with the shoulder/lap belt in the rear seat, all experienced abdominal penetration of the lap belt with one exception.

Lumbar force measurements in the small female were well correlated to lap belt migration in this small sample of six tests. Deflection should be evaluated in conjunction with the belt loads, particularly for rear seat occupancy where the dummy undergoes much less controlled displacements than the front occupant. This motion, which can in some cases be rather extreme, increases the potential for a redirection of the load application, away from the instrumented sternum. Analysis of shoulder and lap belt loads, in particular the proportion of lap to shoulder belt load should also be monitored. This can provide further insight into the relative distribution of forces between the thorax and pelvis, important in the detection of belt penetration or partial ejection of the thorax from the shoulder portion of the belt.

Booster seats were found to influence the pre-test belt placement but had insignificant effect on the kinematics of the upper body during the dynamic event. The motion and compressive response of the child dummy thorax was controlled almost exclusively by the vehicle seatbelt geometry. The belt loads generated in FFRB tests were simply too large and could not be redirected by way of plastic clips fastened to fabric or other non-structural seat components.

Other seat parameters, which may have influenced the booster seated dummy responses, include seatbelt webbing length, the relative seat pan and seatback angles, the seat stiffness and the upholstery. Such analysis was beyond the scope of this study but may be considered in future work.

The elevated chest responses for the booster seated child dummy are consistent with findings by Durbin et al. In a study investigating crashes of insured vehicles involving children the reduction of chest injury resulting from booster seat use was not statistically significant. The Transport Canada crash investigation teams will be intensifying their search for frontal crashes involving rear seated, restrained children for future crash reconstructions and dummy validation.

Restraining the dummy in a CRS rated to the appropriate weight limit may be a viable option for children between the ages of four and six. The chest is restrained by a 5-point harness, which distributes the loads well and effectively couples both the upper and lower torso of the dummy to the vehicle. Though the neck loads remained elevated, the level of injury risk that may be associated with these values is not known and further investigation, through accident reconstruction is needed to validate the biofidelity of the dummy neck. In a 2002 study Sherwood et al conducted sled testing with the Hybrid III 6-year-old dummy and compared the responses to a cadaver test. The authors concluded that the stiffness of the dummy spine contributed to high neck forces and moments that were not representative of the injury potential.

Larger children can benefit from the abdominal protection provided by booster seats. The results of this study, though still preliminary, suggest that protection, specifically of the chest, may be enhanced if the booster seat is anchored to the vehicle seat, as one would attach a CRS. Use of the LATCH and tether produce a more effective coupling than typically produced by the vehicle's lap/shoulder belt.

Child seat manufacturers are introducing more products designed for the upper weight limits and are exploring design options to improve booster seat performance. Testing of the rear seat continues to identify significant measurement parameters, test protocols and ultimately appropriate safety interventions.

CONCLUSION

Transport Canada began evaluating rear seat occupant protection in 2003 by introducing the Hybrid III 5th percentile female dummy and the Hybrid III 6 and 10-year-old child dummies in the rear seats of compliance and research test vehicles.

Balancing energy management and kinematic control of the small female dummy in a high-speed crash appeared to be problematic as either abdominal penetration occurred or very high chest responses developed.

The booster seat effectively prevented the lap belt from penetrating the abdominal cavity. However, restraint of the dummy and control of the kinematics was very strongly dependant on the vehicle seatbelt geometry and not the booster seat model type.

The evaluation of booster seat performance should be conducted during dynamic crash testing. Multiple test parameters such as head accelerations, neck forces, chest deflections and lumbar forces must be considered to obtain an accurate interpretation of the potential for injury.

ACKNOWLEDGEMENT

The authors would like to acknowledge Denton ATD for the loan of a much needed twin six year-old Hybrid III dummy, Pierre Beauchamp, Jean Marc Fiore, Alain Bussières and the staff of PMG Technologies for their assistance in the conduct of this study.

The opinions expressed and conclusions reached are solely the responsibility of the authors and do not necessarily represent the official policy of Transport Canada.

1. Durbin DR, Elliott MR, Winston FK. Belt-positioning booster seats and reduction in risk of injury among children in vehicle crashes. *JAMA*. 2003 Jun 4; 289(21):2835-40.

2. Sherwood, C.G., Shaw, L., van Rooij, R.W. Kent, P.K. Gupta, J.R. Crandall, Orzechowski, K.M., Eichelberger, M.R., Kalliaris, D. Prediction of cervical spine injury risk for the 6-year-old child in frontal crashes. 46th Annual Proceedings Association for the Advancement of Automotive Medicine September 30, October 2 2002.