Responses of the Hybrid III 5th Female and 10-year-old ATD Seated in the Rear Seats of Passenger Vehicles in Frontal Crash Tests

Suzanne Tylko[1] , Alain Bussières[2]

Abstract Full-scale rigid barrier crash tests were conducted at 40, 48 and 56 km/h to investigate the responses of seat belt restrained Hybrid III 5th percentile and Hybrid III 10-year-old anthropometric test devices (ATD) in motor vehicles. The 5th percentile responses were evaluated as a function of seating position in the vehicle and the seat track location. Hybrid III 10-year-old responses were evaluated in rear seating positions with and without booster seat installations.

Impact speed had little influence on the chest deflection of the front seat occupants but was found to be positively correlated for rear seat occupants. Head, neck and chest responses of the 5th percentile were consistently higher for rear seating positions. At least 45% of the 76 tests conducted with the 10-year-old with and without a booster seat had a HIC36≥1000 in the absence of head impact, while approximately 80% surpassed the neck injury assessment reference values. Chest deflection responses were elevated in tests where the torso belt was correctly positioned on the shoulder while chest acceleration appeared unrelated to the kinematic responses observed during the crash sequence. Implications for the future evaluation of rear occupant safety and booster seats are discussed.

Keywords Rear seat, booster seats, Hybrid III 5th percentile, Hybrid III 10-year-old, chest response.

I. INTRODUCTION

The current Canadian Motor Vehicle Safety Standard for frontal protection (CMVSS 208) does not include a requirement for dynamic testing with the 5th percentile female ATD in any seating positions of motor vehicles. While Canada has proposed to align with the United States and adopt frontal dynamic testing with the 5th percentile female adult occupant in the front seats, rear seat occupant protection is not included in any North American frontal regulatory or frontal new car assessment program. Transport Canada has placed significant emphasis on investigating the responses of the Hybrid III 5th percentile and 10-year-old dummies in frontal crashes to monitor existing rear occupant protection and to help guide future regulatory initiatives.

A previous study comparing the kinematic and thoracic response of the Hybrid III 5th percentile in 40, 48 and 56 km/h frontal rigid barrier tests was presented at the 2007 ESV [1]. That study explored dummy measurement parameters that could potentially be employed to quantify dummy kinematics and belt loading conditions. In the present study the responses of the 5th percentile ATD are presented as a function of seating position and seat track location to provide context for the responses observed in the rear seat. Specifically, the kinematic responses of the more familiar 5th percentile ATD are used to explain head, neck and chest response patterns that are observed with the recently introduced Hybrid III 10-year-old. The objective of the present study is to examine the responses of the Hybrid III 10-year-old, in what may be assumed to be optimal and sub-optimal restraint configurations with the ATD placed either directly on the vehicle seat or in an approved booster seat for its size. The extent to which the ATD responses and the associated injury criteria, traditionally referenced by regulatory and/or consumer test protocols can discriminate between optimal and sub-optimal restraint configurations are examined.

II. METHODS

Hybrid III 5th percentile female

Frontal rigid barrier tests were carried out at 40, 48 and 56 km/h with model year 2000 through 2011 vehicles.

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The Hybrid III 5th percentile female ATD was placed in the front and rear seats of test vehicles. Test set-up, vehicle preparation and dummy positioning in the front seats were done in accordance with the respective sections of the FMVSS 208 requirements for the full frontal rigid-barrier tests (FFRB).

ATD response as a function of seating location within the vehicle was evaluated by placing Hybrid III 5th percentile female ATDs in the front outboard seating locations and in at least one rear seat location. Depending on the vehicle model this could be the second or third row. For rear seat placement, the small female was seated in a slightly slouched posture by translating the H-point 30 mm forward from the H-point recorded at the rearmost attainable position.

Paired comparisons of 11 vehicles were conducted to examine the effect of seat track location on chest response. Each vehicle pair had identical trim packages and test masses were matched to the extent possible. In one vehicle the small female driver and passenger were positioned as per the FMVSS 208 procedure in the foremost seat track position. In the second matched test vehicle the small female driver and passenger were positioned as per the FMVSS 208 procedure but with the seat placed rearward at the mid-point between the foremost and rearmost fore-aft seat track positions. The only exception was the Ford Edge where the passenger seat was placed in the rearmost seat track location.

An additional eight paired tests were conducted to compare the relative effect of seat track location and test velocity. In one vehicle the small female was placed in the front passenger seat installed at the mid seat track location as above. The vehicle then underwent a FFRB test at 48km/h. In the corresponding paired vehicle the small female was placed as per the FMVSS 208 seating protocol in the foremost seat track position and the vehicle was subjected to a 56 km/h FFRB test.

Hybrid III 10-year-old

Frontal rigid barrier tests were carried out at 40, 48 and 56 km/h with model year 2005 through 2011 vehicles. The Hybrid III 10-year-old ATDs were placed exclusively in the rear seats of test vehicles. The 10-year-old lower spine was set to 00, which corresponds to a slouched posture and positioned either directly on the vehicle seat or on a booster seat. The knees were bent and the back of the tibias were in light contact with the forward edge of the vehicle seat.

Instrumentation and Video Imaging

Data were recorded at 10 kHz and filtering was performed in accordance with SAE J211. High-speed videos at 1000 frames/second were obtained and included lateral views of the front seat occupants; lateral and a frontal view of the rear seat occupants. The rear doors were removed to provide optimized camera views of the dummy kinematics. Pre and post-test dimensions were obtained to monitor for B-pillar displacement during the test should it occur.

The baseline ATD instrumentation included a tri-axial accelerometer at the head CG; a 6-axis load cell at the upper and lower neck and lumbar spine; a 3-axis clavicle load cell; tri-axial accelerometers at the upper, mid and lower spine and pelvis; accelerometers at the top, mid and lower sternum; and single axis load cells in the femurs. The 10-year-old ATD was similarly instrumented. The chest was instrumented with either a potentiometer or two IR-TRACCs (Infra Red – Telescoping Rod for Assessment of Chest Compression) installed at the lower and upper sternum.

III. RESULTS

Hybrid III 5th Percentile Female Head and Neck Responses

Figure 1 displays the peak upper neck tension as a function of HIC_{15} for Hybrid III 5th percentile female ATDs seated in front and rear seat locations. All of the 74 ATDs tested in the front seats had neck and head responses that were within the recommended injury assessment reference values HIC_{15} 700 [2]. For ATDs placed in the rear seating position 20/105 (19%) surpassed the recommended neck tension (2620N) [2], 23/105 (22%) surpassed the HIC_{15} limit (700) and 16/105 (15%) surpassed both the neck tension and HIC_{15} recommended values. Results for the rear ATDs displayed a linear relationship of R^2 =0.79. No linear relationship was observed for ATDs tested in front seating positions.

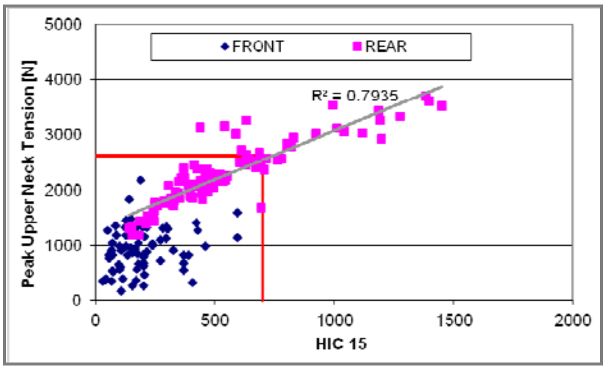

Fig. 1. Peak upper neck tension as a function of HIC_{15} for front and rear seated HIII 5th ATD

Hybrid III 5th Percentile Female Chest Response

A total of 136 48 km/h FFRB tests were conducted with the Hybrid III 5th percentile female dummies in the foremost seat track position of the driver and/or front passenger seats. The average peak chest deflection for the sample of drivers (n=136) was 29.3 mm ± 3.3 mm with a maximum of 42.8 mm. The average chest deflection for the complete sample of passengers (n=136) was 25.2 ± 6.3 mm with a maximum of 45.1 mm.

Figure 2 presents the average chest deflections calculated for those vehicles where a small female was placed in the driver seat, the front passenger seat and at least one rear seating location. Sample sizes are identified in Table A1 of the appendix due to space limitations within the plots. Driver chest deflections were slightly greater than those of the front passenger but both front occupant deflections were generally unaffected by test speed. Rear occupant deflections were greater than front occupant deflections and increased as a function of speed. Standard deviations ranged from 3.6 to 7.1 mm for the front seats and from 6.8 to 9.0 mm for rear seated ATDs.

Figure 3 presents the corresponding average torso belt loads. Both the driver and front passenger belt loads were of the order of 4 kN independent of impact speed. Rear occupant loads ranged from just above 6 kN at 40 km/h to above 7 kN at 56 km/h and were associated with the largest standard deviations.

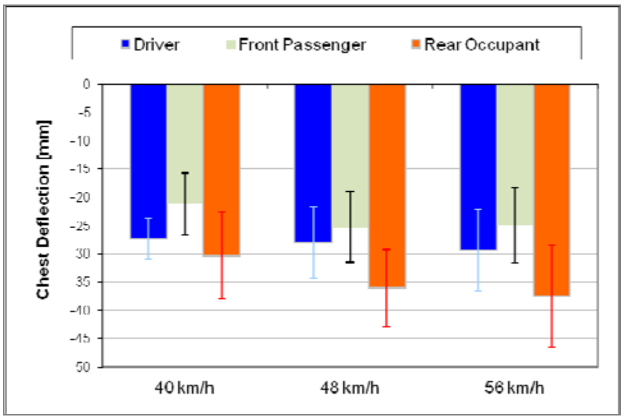

Fig. 2. Comparison of the average chest deflection ±1 standard deviation (SD) for front and rear seated HIII 5th percentile ATD as a function of test velocity.

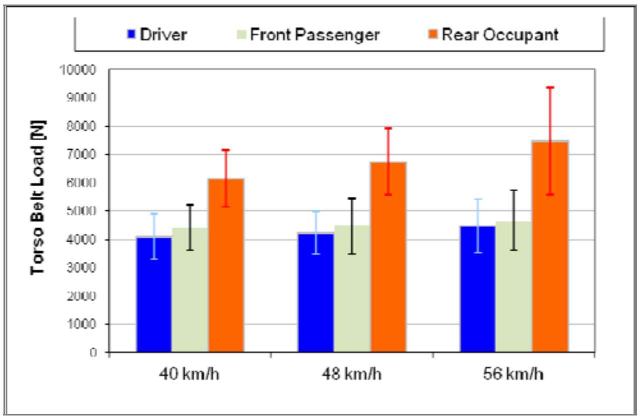

Fig. 3. Comparison of average torso belt load ±1 SD for front and rear seated HIII 5th percentile ATD as a function of test velocity.

Influence of Seat Track Location

The peak deflections for the passenger seated in the foremost seat track location are represented by the blue or first bar in each pair displayed in Figure 4 and the corresponding response for the mid seat track location is shown in beige or to the right. In all but three of the 11 pairs of tests, deflection of the right front passenger chest was greater when the seat was placed in the mid seat track location. Differences in chest deflection ranged from 4 to 12 mm, and deflections at the mid seat track were on average 7 mm greater than those recorded at the foremost seat track location. The two Corolla tests shown on the left of the bar chart were conducted at 40 km/h, the Focus on the far right was tested at 56 km/h and all other paired vehicles were tested at 48 km/h. Shoulder belt placements, relative to the measurement sensors were not observed to change when the seat was brought from the foremost to the mid seat track locations.

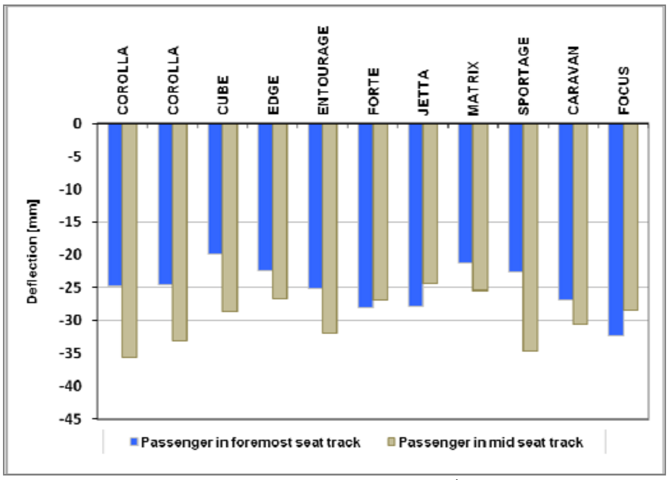

Fig. 4 Paired comparison of the HIII 5th seated at the mid and foremost seat track locations.

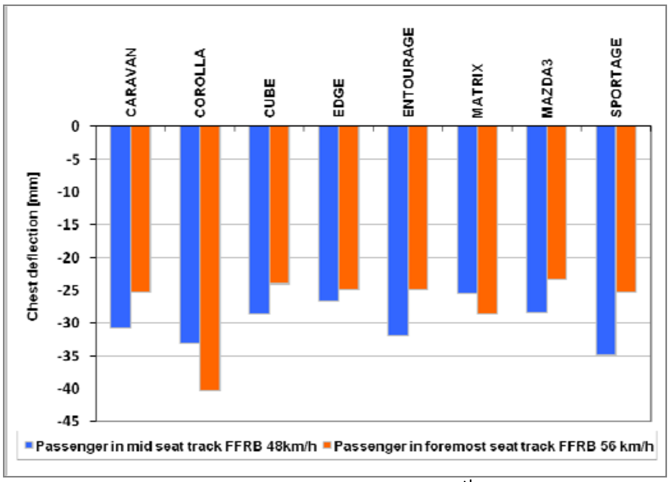

Fig. 5 Paired comparison of the HIII 5th seated at the mid and foremost seat track locations in 48 & 56 km/h tests respectively.

Values recorded in the mid-seat track location at test speeds of 48 km/h were similar to the deflections recorded in tests conducted at 56 km/h in the foremost seat track location. Figure 5 displays the results of peak chest deflections for the passenger seat. The blue bars on the left represent the deflections recorded at the mid seat track location and the adjoining orange bars on the right display the peak deflections for the paired vehicle tests carried out at 56 km/h with the ATDs placed in the foremost seat track locations. In five of the eight comparisons ATD deflections of the passenger placed at the mid seat track locations were at least 5 mm greater than the comparison test conducted with the seat in the foremost seat track location at 56 km/h. The Toyota Corolla was the only vehicle in the sample where chest deflection was greater at 56 km/h in the foremost position then at 48 km/h in the mid-track.

Kinematic Observations

The kinematics of the 5th percentile ATD differed for the front and rear seats and were influenced by the seat and restraint characteristics. In the front row seats, ATD excursions were controlled by the airbags and the knee bolsters. In rear seats, ATD excursions were controlled by the seat belt and to varying extents, the seat cushion. Relative displacements were consistently observed between the ATD and the belt restraint as well as between the seat cushion and the vehicle structure.

Figure 6 illustrates three predominant types of motions that were observed. In the left image the ATD translated forward, the lap belt remained on the pelvis and the head neck complex pivoted about the top of the spine box, this was an example of a ‘good’ restraint. In the central image, the ATD has moved to the front edge of the seat, the neck is severely flexed, the lap belt has penetrated the abdomen and the seat cushion has separated. In the far right image the ATD torso has pivoted rearward and the pelvis has slipped under the lap belt. These two images were examples of ‘poor’ restraints. The neck flexions, forward excursions of the dummies and the belt displacements shown in Figure 6 were never observed in the front row seats.

Fig. 6 Examples of typical kinematic responses observed in the rear seats of vehicles at peak excursion.

Hybrid III 10-year-old in the Rear Seat

A total of 77 FFRB tests were conducted with the Hybrid III 10-year-old and distributed as shown in Table 1. The ATD was placed directly on the vehicle seat in 29 tests and on a booster seat in 48 tests. The majority of the tests were conducted in the second row outboard locations; eight of the 29 tests carried out without a booster were placed in the center rear and three were placed in the third seating row. Only one booster seat was installed in the center of the second row and six were placed in the third seating row. No tests were conducted with the 10-year-old in the front seat.

Kinematic Observations

Table 1 summarizes the principal types of motions that were observed during testing. In 25 of the 29 tests (86%) conducted with the 10-year-old seated directly on the vehicle seat the torso belt was observed to load the neck at peak excursion. Torso belt loading of the neck was observed in 15 of the 48 tests (31%) conducted with the booster seats. In its mildest form the torso belt became wedged into the neck but, in extreme cases, the torso belt crossed the neck and slipped up underneath the in-board arm of the ATD. Lap belt migration as defined by the upward displacement of the lap belt into the abdominal cavity occurred in 17 out of 29 tests (59%) on vehicle seats compared to 15 out of 48 tests (31%) with booster seats.

In certain cases where the 10-year-old was placed on the vehicle seat, the lap belt tended to ride high at or above the estimated location of the anterior superior iliac spines (ASIS), on at least one side of the pelvis. During the forward excursion of the dummy, the vehicle seat cushion compressed and facilitated the upward displacement of the lap belt into the abdominal region. In vehicles equipped with rear seat pretensioners, the force exerted during deployment of the pretensioners caused the lap and torso belt to shift upwards above the ASIS and into the neck, well before any forward excursion occurred.

Lap belt migration on booster seats was observed during forward excursion of the ATD in some vehicles. The relative motion of the 10-year-old as it translated forward on the booster seat caused the front edge of the booster cushion to tip forward and compress the vehicle seat. The result of this interaction created a ramp like surface which tipped downward and caused the pelvis to slip down and forward, while the lap belt translated up into the abdomen. In more extreme cases, most notably with booster seats that were rigidly attached to the vehicle with the LATCH / ISOFIX or with inflatable booster cushions, the dummy was observed to drop off the front edge of the booster cushion. This occurred in eight tests, four of which were 40 km/h FFRB tests.

Only one head impact occurred during excursion with the front seat back while eight occurred during rebound into the vehicle roof, door or C-pillar trim. One of these impacts involved the seat back locking mechanism, situated on the upper surface of the second row seat back. The upper torso rolled out of the torso belt twice while on the vehicle seat and five times when placed on a booster seat. Two of these booster seats had a back rest and shoulder belt guides. Roll out is defined as an axial rotation of the torso which causes the outboard shoulder to slip out of the belt, an example is shown in the lower right photo of Figure 1A in the appendix.

TABLE 1
SUMMARY OF OBSERVED KINEMATIC RESPONSES OF THE HIII 10-YEAR-OLD ATD AS A FUNCTION OF TEST SPEED AND SEAT CONFIGURATION

Seat configuration	Test speed km /h	n	Torso belt in neck (%)	Lap belt migration (%)	Head impact excursion (%)	Head impact rebound (%)	Rolls out of torso belt (%)	Slides off booster (%)
Directly on seat	40	**11**	8 (73)	7 (64)	0	2 (18)	0	n/a
	48	**15**	14 (93)	7 (47)	0	1 (7)	1 (7)	n/a
	56	**3**	3 (100)	3 (100)	0	1 (33)	0	n/a
Booster	40	**19**	5 (26)	5 (26)	0	3 (16)	2 (10)	4 (21)
	48	**23**	10 (43)	9 (39)	1(4)	4 (17)	1 (4)	3 (13)
	56	**6**	0	0	0	1 (17)	2 (33)	1 (17)

Peak Average Lap and Torso Belt Loads

Figure 7 summarizes the lap and torso belt loads recorded as a function of test speed and seat configuration. Torso belt loads ranged from just above 4.3 kN at 40 km/h to 6.6 kN at 56 km/h for the on seat condition; and from 5.2 kN at 40 km/h to 6.7 kN at 56 km/h for the booster seats. The greatest torso load for the sample was 8.6 kN and was recorded during a 56 km/h test with a booster seat. Lap belt loads were lower than torso belt loads and generally did not display the same degree of sensitivity to test speed as did the torso belts.

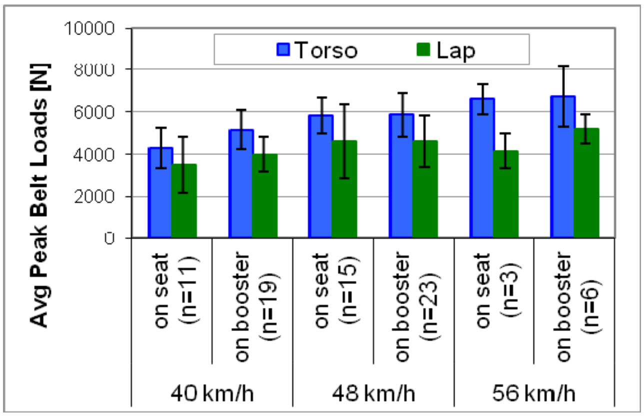

Fig. 7. Average belt loads ±1SD as a function of test speed and seat configuration for the HIII 10 year-old

Head and Neck Response

The left hand plot in Figure 8 presents the upper neck tensile responses as a function of the peak resultant head acceleration for the 10-year-old seated on the vehicle seat and on the booster seat. The solid blue squares represent the on seat condition and reflect a linear correlation of 0.75. The hollow squares represent the booster seated condition and reflect a linear correlation of 0.86. The peak resultant head accelerations exclude the single head strike into the front seat back and exclude head impacts that occurred on rebound. The responses are exclusively due to inertial loading of the head and neck complex. In both the on seat and booster seat condition the peak head and neck responses occurred at approximately 91 ms into the event.

The linear correlation weakens when peak head acceleration is replaced by HIC_{36} (right hand plot) but again one can observe a large proportion of HIC_{36} values extending beyond the anticipated regulatory limit of 1000 (used in US child seat regulations for all other dummy sizes) [3]. HIC calculations exclude head impacts that occurred during rebound. For the booster seated ATDs, 22/47 (47%) had a $HIC_{36} \geq 1000$ while 13/29 (45%) of the ATD's seated directly on the vehicle seat had a $HIC_{36} \geq 1000$ despite the absence of head impacts.

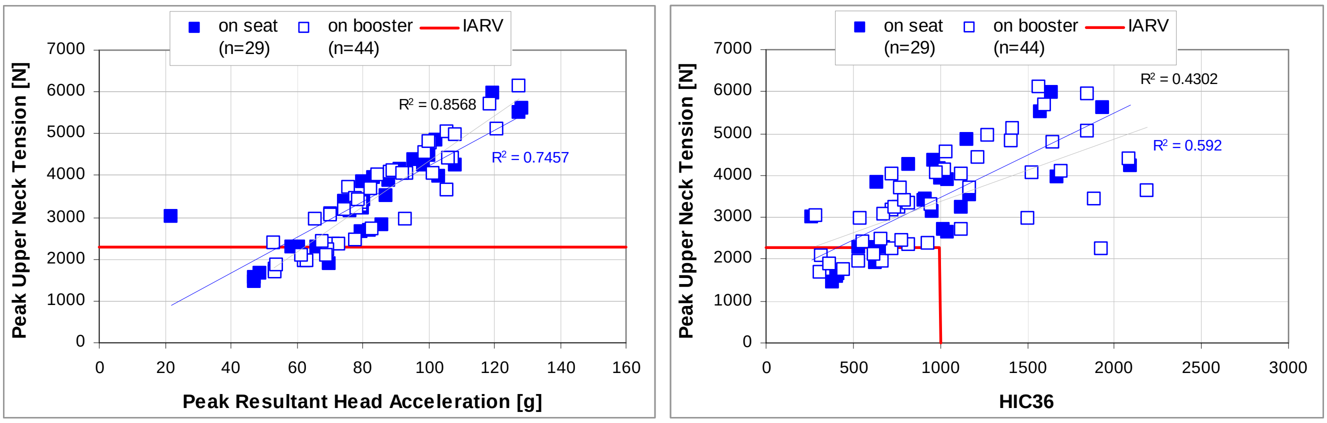

Fig. 8. Peak upper neck tension as a function of peak resultant head acceleration (left) and HIC_{36} (right) for the HIII 10-year-old when tested on the vehicle seat and on a booster seat.

The combined axial force and moment, N_{ij} [2] for the complete sample are tabulated in Table A2 of the appendix. Over 78% of the combined sample (n=77) had a N_{ij} value that was ≥ 1; 23/29 (79%) of ATDs seated directly on the seat and 37/48 (77%) seated on booster seats had N_{ij} values ≥ 1. A remarkable 86% of tests conducted on the vehicle seat and 82% of tests conducted on booster seats had a peak upper neck tension that surpassed the injury assessment reference value (IARV) of 2290 N [2]. Of the 14 cases that fell below the IARV, nine were conducted at 40 km/h; five were conducted at 48 km/h. Examination of the video recordings revealed the following interesting finding: In one of the 48 km/h tests, one 10-year-old dummy was seated directly on the vehicle seat behind the driver seat and registered a peak upper neck tension of 3389 N. The other 10-year-old was seated adjacently on a backless booster seat, behind the right front passenger seat and registered a peak upper neck tension of only 1944 N. Figure 9 is a freeze frame obtained as the two ATDs approached peak excursion. The torso belt on the ATD shown on the left is loading the shoulder distally (away from the neck) whereas the torso belt on the right hand side is loading the ATD shoulder much closer to the neck. The distal shoulder loading appears to induce an upper body rotation which likely causes the instrumentation to be out of alignment with the axis of measurement and record lower loads. There is a notable absence of twist in the dummy on the right.

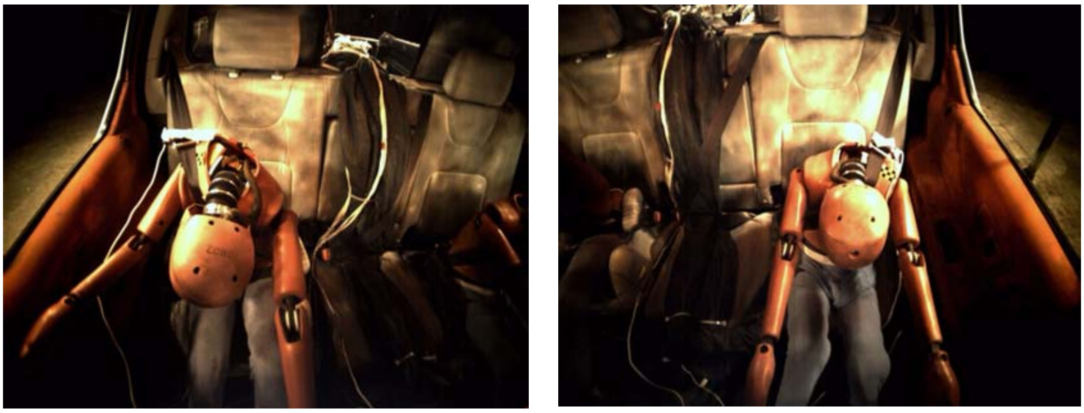

Fig. 9 Torso belt placement and head /neck alignment of two adjacent 10-year-old ATDs at excursion. The ATD shown in the left image was seated on a backless booster seat behind the front passenger; the ATD on the right was seated directly on the seat behind the driver.

Chest Response

Chest responses were measured in terms of deflection and the peak resultant 3ms chest clip. Some of the 10-year-old ATDs were instrumented with dual IR-TRACCs to measure upper and lower sternum deflection while a smaller sample of tests were carried out with a 10-year-old ATD that was instrumented with a single potentiometer in the center of the sternum. Figure 10 compares torso belt forces and peak deflections as measured by either the potentiometer or the IR-TRACC pairs for the booster and on seat conditions. Peak deflections measured at the center of the sternum tended to be less than deflections measured by the upper IR-TRACC. All deflections measured by the center potentiometer for the on seat condition shown by the solid dots in the left plot were below 30 mm. Deflection values obtained from the upper IR-TRACC, shown by the solid squares, were greater than both the central potentiometer and the lower IR-TRACC for the ATD seated directly on the vehicle seat (left plot). In the booster seat cases, the central, upper and lower sternum deflections were more comparable. A photo of the relative placement of the measurement sensors is presented in Figure A1 of the appendix together with examples of belt loading conditions to illustrate the effect this has on recorded deflection measurements.

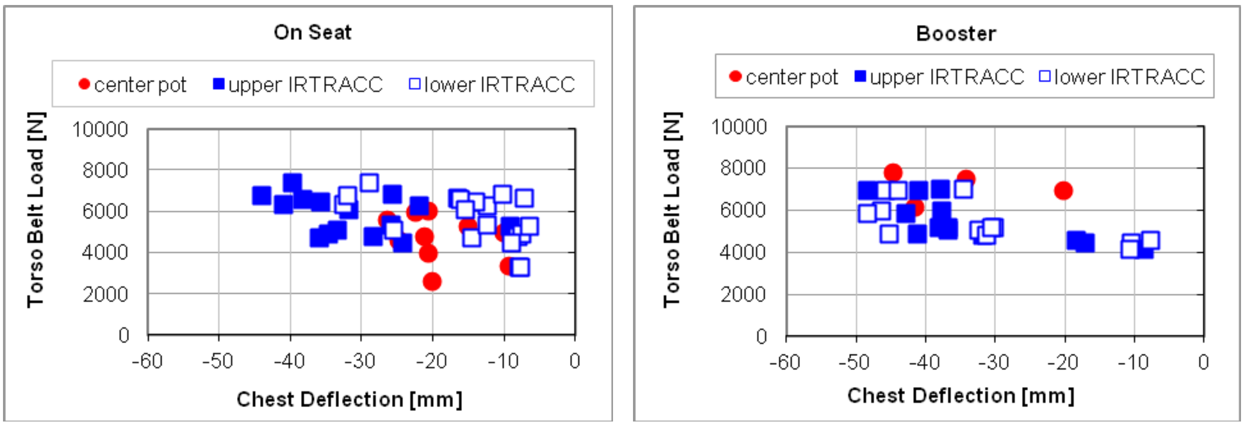

Fig. 10 Peak torso belt load as a function of peak chest deflection for the on seat and booster seat conditions. Additional plots displaying deflection measures relative to belt path are shown in Figure A2 of the appendix.

Elevated peak resultant chest clips, above the recommended 60g [2] occurred at all three test speeds: 40, 48 and 56 km/h. No correlations were observed between the peak resultant chest clip and vehicle peak longitudinal acceleration or the peak torso belt loads or the kinematic responses.

Chest and lumbar Response as a predictor of Belt Migration

Cases where the lap belt remained on the pelvis throughout the loading phase are labeled as ‘seat good’ or ‘booster good’; tests that resulted in the lap belt being displaced upwards into the abdomen are labeled as ‘seat poor’ or ‘booster poor’. Examples are shown in Figure 11. In the left image the ATD pelvis translates forward with the booster and the lap portion of the seat belt remains on the pelvis. In the center image the ATD has slipped off the front edge of the booster seat, the lower arrow points to lap belt migration into the abdomen while the upper arrow points to the torso belt loading on the neck. The third image on the far right is an example of the 10-year-old ATD seated directly on a seat. As the pretensioner fires and the ATD begins to move forward, the lap belt is lifted into the abdominal cavity and the torso belt is displaced into the neck and underarm thus bypassing the deflection sensing instruments.

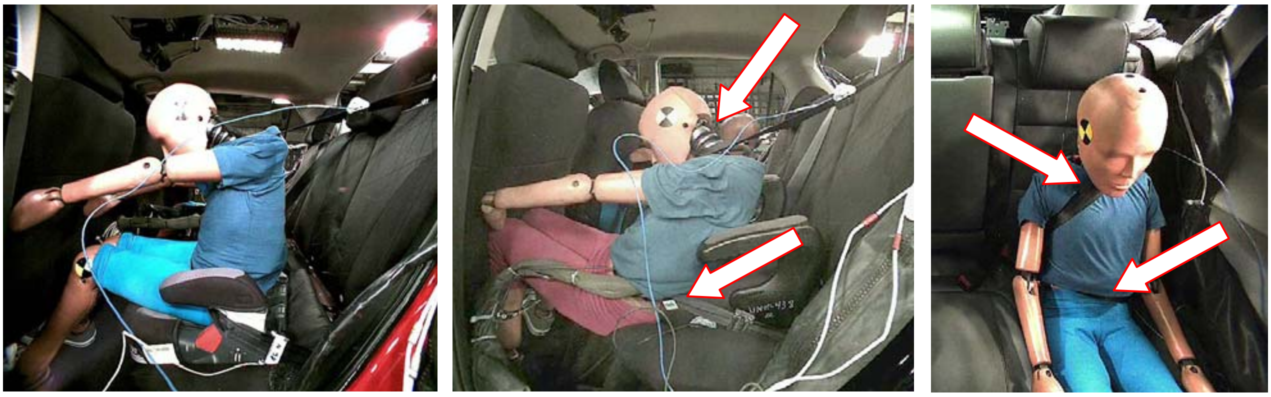

Fig. 11 Examples of “good” booster on the left; “poor” booster in the center and poor seat on the right.

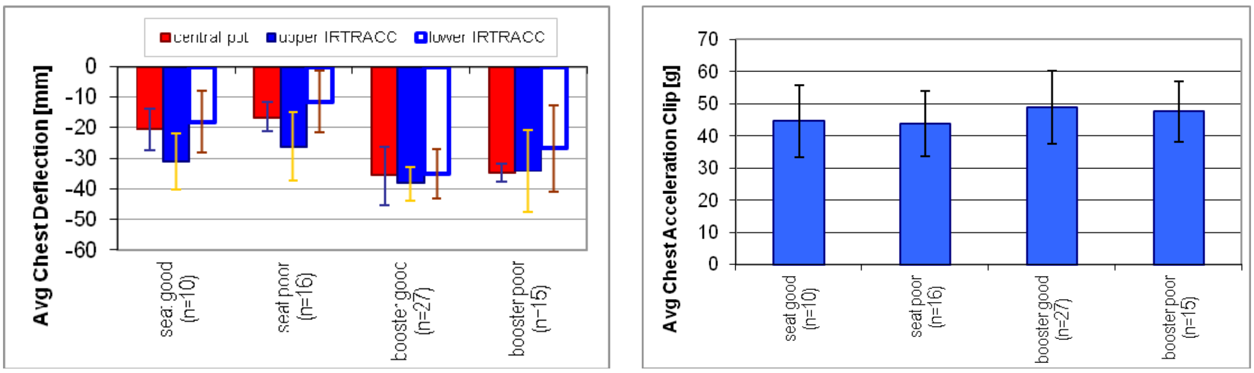

Fig.12 Plot on the left displays the average chest deflections ±1SD, the plot on the right displays average chest clips ±1SD for tests where the lap belt remained on the pelvis (good) and was displaced into the abdomen (poor).

Based on the average chest deflections that are shown in the left hand plot of Figure 12, better restraint performance is associated with higher chest deflections. The two sets of bars on the right side of the plot that display the average chest deflections of the ATDs on booster seats are higher than the two sets of bars on the left which display the average chest deflection for the ATDs that were tested directly on the vehicle seat. We note that chest deflections are greater for the booster than for the on seat condition and that each of the ‘good’ categories have slightly greater chest deflections than the corresponding ‘poor’ category. The trend is consistent for all methods of measurement. The average peak resultant chest acceleration clips obtained for each of the four categories in the right hand plot of Figure 12 do not show much of a difference for the seat and booster category. In fact, use of a booster seat whether good or poor led to slightly higher dummy chest accelerations.

Lumbar axial loads were examined to gain a better understanding of pelvic motion and the association that this may have on lap belt motion. The top left plot in Figure 13 presents the lumbar responses for tests where the ATD was seated directly on the vehicle seat and the lap belt remained in place on the pelvis throughout the loading event. The lumbar spine responds by an initial compression followed by tension within a boundary of ± 2 kN. The trace identified by the arrow is somewhat different from the other three traces in that it displays a small initial tension prior to entering the compression phase. The ATD in this particular test was seated in the center seating position of the second row where the seat cushion is less compliant than the outboard seat cushions.

The top right plot presents the lumbar spine responses of tests where the lap belt was observed to migrate upwards into the abdominal cavity. In these tests the lumbar spine loads were predominantly in tension throughout the loading phase. The peak tension of 4000 N occurred when the upper torso of the ATD was being pulled from the lower body by the seat belt. The arrow in this plot points to the trace of an ATD that was subjected to a pretensioner.

The bottom two plots present the lumbar spine time history traces for ATDs that were seated on booster seats. The left side includes the tests where the booster seat successfully maintained the lap belt in position. The traces are characterized by an initial compression followed by tension. The magnitude of response ranges from ± 3 kN. The final plot shown in the bottom right quadrant displays the lumbar response for ATDs that slipped off the front edge of the booster seat and where the lap belt was not maintained in position. These responses are characterized by an initial tension followed by compression. The axial forces in these tests ranged from – 3 kN and + 1 kN. Lumbar moments were recorded but no trends were observed for either the 5th percentile or 10-year-old ATD.

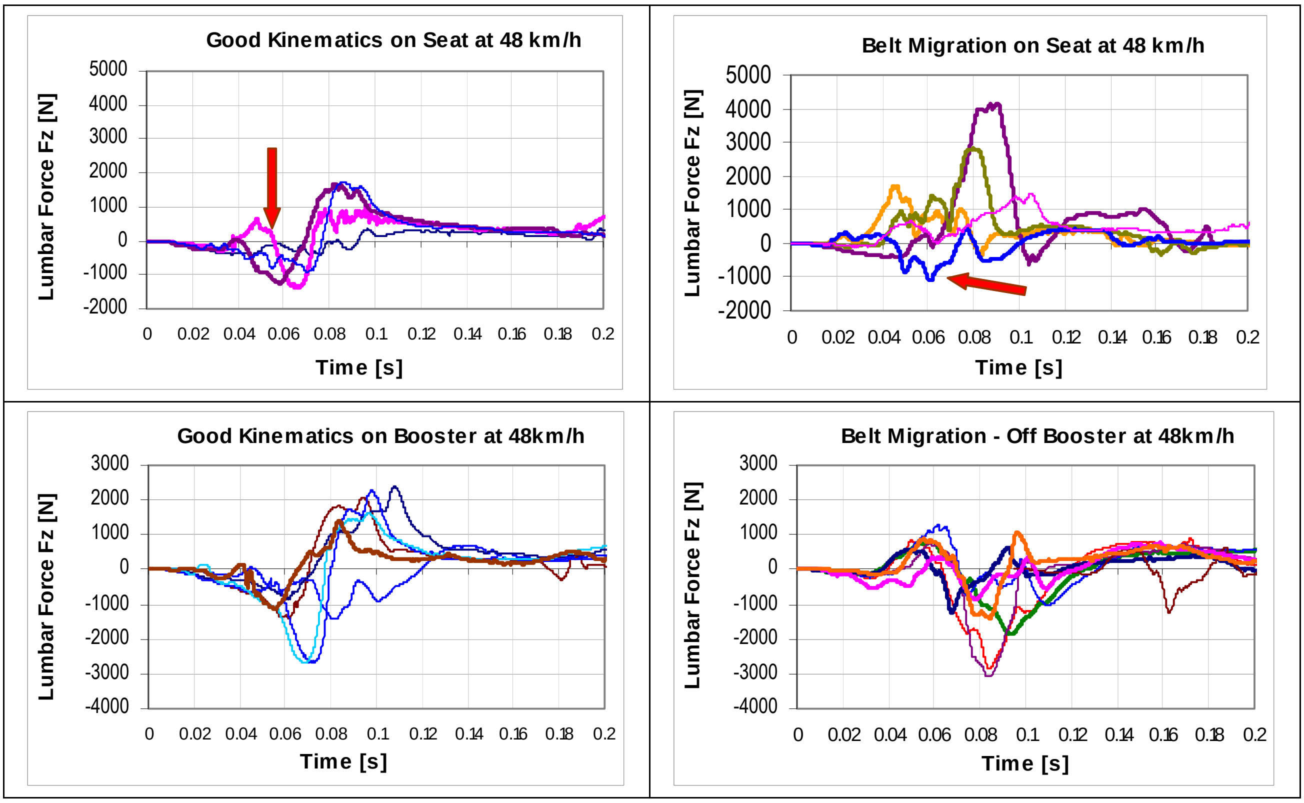

Fig.13 Comparison of axial lumbar response for the HIII 10-year-old placed on the vehicle seat (top two plots) and on booster seats (bottom two plots) in FFRB tests conducted at 48 km/h.

IV. Discussion

The rear seat environment is very different from the tightly regulated front occupant compartment. Geometry of the seats and belt restraint systems are different, there are no frontal airbags, no load limiters and no knee bolsters to help decelerate the belt restrained occupants. Esfahani et al [4] reported that for occupants aged 16 to 50 the risk of MAIS2+ injuries had significantly increased in model year 2000 vehicles when compared to vehicle models in the 90s. In this study, the chest deflection measured for front seated occupants, in vehicles from model years 2000 through 2011 was below 30 mm for the driver and below 25 mm for the front passenger (Figure 1) independent of test speed. Belt loads, shown in Figure 3, were consistently below 4.5 kN for both front occupants, independent of test speed. The pattern of deflection and belt loading was quite different for the ATDs seated in the rear seats of the same vehicle sample where average deflections were greater than 35 mm and belt loads attained levels well above 7 kN. Since these vehicles were all being tested to the FMVSS 208 test protocol, the driver and passenger seats were all placed at the foremost seat track location, leaving minimal clearance between the knees and the front bolsters. When the ATDs were placed rearward at the mid-track location, thus eliminating knee contact, deflections were found to increase by 7 mm and approach those obtained for occupants in the rear seat. In fact, moving the seat rearward and eliminating knee contact during loading had a greater effect on deflection then did increasing the energy of the crash.

The need to control the forces imparted to the ATD while managing the kinematic responses was previously found to be a necessary countermeasure to prevent belt migration in the 5th percentile female [5, 6]. In the absence of design features within the rear occupant space of the vehicle, occupants seated in the rear are decelerated primarily by the seat belt. The kinematics and resulting injury outcomes are therefore strongly influenced by crash severity and the belt placement on the ATD which is in turn determined by belt geometry and the movement of the ATD during the crash. As was illustrated in the sample freeze frame images of the 5th percentile, the more the dummy translates forward, the greater the likelihood that the front edge of the seat cushion will compress and the lap belt will penetrate into the abdominal region. Furthermore, as the dummy translates forward and reaches the limit of the seat belt, the motion of the chest is abruptly arrested by the belt. The neck, which is fixed to the top of the dummy's rigid spine box, extends under the inertial load of the head and the head rotates forward until it is stopped by the front of the chest. This response, which likely would not be observed in human occupants who lack a rigid spine, magnifies the head and neck responses well beyond what is typically observed in the front seats, where motion is constrained by airbags and knee bolsters.

The absence of knee contact for the rear seat occupant space also poses significant challenges for the older school age child. Whether the older child, represented in this study by the HIII 10-year-old, is placed directly on the vehicle seat or on a booster seat, his/her legs will likely not be long enough to benefit from load sharing with the front row seatback. Once again, this implies that the load management will rely almost exclusively on the seat belt. If the seatback is placed sufficiently rearward to obtain knee contact during loading, then the risk of head impact with the front seat would be expected to increase. However, while there were four occurrences of knee contact, there was only one single case of head contact with the front seat in the entire sample. Ash et al [3] reported that they were unable to reproduce sufficient head excursion in a series of tests designed to reconstruct a real world crash.

Despite the notable absence of head contact during forward excursion, 28% of ATDs placed on the vehicle seat and 38% tested on booster seats recorded head accelerations that resulted in HIC_{36} values that were greater than 1000. Concurrently, 86% of tests conducted on the vehicle seat and 82% of tests conducted on booster seats resulted in peak upper neck tensions that surpassed the IARV of 2290 N. These trends, particularly for the neck were more exaggerated than with the 5th percentile female. The dimensions and mass of the head for the 10-year-old and the 5th percentile are supposed to be the same however, variations of up to 46 grams were observed in the ATD fleet containing two 10-year-olds and five 5th percentile females.

Sherwood [7] reported that the stiff thoracic spine of the Hybrid III 6-year old contributed to high neck forces and moments that were not representative of non-contact injuries observed in the field. The schematic used by Sherwood to illustrate the differences between the kinematics of the ATD spine and a 12-year-old cadaver was remarkably similar to the profiles observed in this study and replicated in Figure A3 of the appendix. As was observed in this study the ATD head rotates into the chest instead of extending forward and striking the vehicle interior.

Chest deflection and acceleration measures have customarily been referenced for the assessment of injury risk to guide the design of countermeasures and to monitor compliance of motor vehicles and child restraints [2,3]. The results of this study suggest that the use of these parameters in isolation of kinematic analysis could lead to sub-optimal designs. Measures of deflection are affected by the proximity of the belt to the sensors. If the torso belt is positioned high on the torso and impinges on the neck, as was observed in the right most image of Figure 12 and, the central potentiometer is bypassed and the deflection results look quite favorable. The upper IR-TRACC demonstrated a greater capacity to capture upper thoracic deflection; however, as was illustrated in Figure A1 of the appendix these too can be circumvented. Belt placements judged to be optimal for good restraint, that passed over the central portion of the shoulder and central sternum were found to result in greater chest deflections and high chest acceleration clips. It should be noted that while shoulder belts were observed to pass close to the neck for numerous front row seat tests with the 5th percentile, the observed loading to the neck was never as extreme as was seen in the rear seat locations. Neither chest criterion appeared able to distinguish between tests displaying stable lap belt placement on the pelvis and tests resulting in lap belt migration. Chest deflections were greatest for all booster seats and lowest for the on seat condition with demonstrated evidence of poor seat belt geometry. The 'better' the booster seat the greater the chest deflections. Chest clip results, on the other hand, could not discriminate between seemingly good belt geometries or indeed the presence or absence of a booster seat. It was not possible to identify any dummy, seat or booster seat characteristics that clearly influenced the chest acceleration response.

The last parameter to be investigated was the lumbar spine response. Past studies [1] had identified trends for the lumbar force response when comparing the kinematics of the 5th percentile female ATD. The time history patterns presented in this paper for the 10-year-old are similar to those previously reported for the 5th percentile female ATD. Good kinematics where the lap belt remains on the pelvis throughout the loading event are characterized by an initial compressive load in the lower spine. The response suggests that the buttock of the dummy is fully engaged with the vehicle seat or booster seat prior to attaining peak excursion. The deceleration forces are shared between the belt and the seat. In cases where belt migration is observed there is a tendency for the lumbar spine to be in tension almost as if the ATD is skimming across the seat surface. In tests where the ATD actually slid off the front edge of the booster seat, the lumbar spine response is found to reverse from a state of initial tension to compression. While these responses are interesting and helpful for test conditions wherein the motion of the belt cannot be readily observed, the practical applications for this parameter have yet to be determined.

The data which included 11 vehicle model years showed no correlation between peak longitudinal acceleration at the center of gravity of the vehicle and any of the following parameters: peak upper neck tension, peak chest resultant 3 ms clip or peak torso belt loads. Two possible explanations for this may be that dummy responses are highly directionally sensitive. As was demonstrated in the side by side comparison of the two 10-year-old ATDs in Figure 9, rotation of the ATD beyond the alignment planes of the sensors could be mistakenly interpreted as a reduction of load. The second explanation may be that peak acceleration of the vehicle is not sufficiently descriptive of vehicle dynamics. Rather than rely on a single point in time it may be more informative to rely on the time history of the change in velocity experienced by the vehicle. The time required to attain a certain change in velocity may help better explain the energy management of the vehicle and the subsequent risk to the occupant.

Limitations of the study & Future work

Dummy instrumentation was not identical for both 10-year-old ATDs, limiting some of the analysis that could be completed. For example, it was difficult to compare chest deflection measured with the central potentiometer to those measured with the IR-TRACC. The effects of dummy variations, within the respective anthropometric tolerances were not taken into consideration for this study. Field data and more specifically, crash reconstruction data were not available to validate the responses obtained in this study.

The next phase of the study will focus on reconstructions of case accidents to validate the responses of the Hybrid III 5th percentile and 10-year-old ATDs. The sample, obtained by the Collision Investigation and Research Division of Transport Canada includes fully-restrained rear seat occupants and children restrained by three-point belts in booster seats who are involved in frontal crashes where front seat occupants escaped with minor to moderate injuries but the rear seated passenger(s) were severely or fatally injured.

V. CONCLUSIONS

Seat location in the vehicle, including proximity to the knee bolsters in front row seats was found to influence the kinematic responses of the Hybrid III 5th percentile ATD. In front row seats, frontal airbags and knee bolsters control the forward motion of the head, thorax and pelvis however, reducing the proximity of the ATD to the knee bolsters was found to increase the deflection of the chest. When compared to front row seats, and in the absence of airbags and knee bolsters, the ATDs restrained in rear seat locations exhibited much greater forward displacements relative to the seat cushion and lap and shoulder belt. Kinematic responses observed during forward excursion of the 5th percentile and especially the Hybrid III 10-year-old ATDs were found to have an important effect on the responses measured in the head, neck, chest and lower spine. Inertial loading of the head and neck in combination with a rigid spine design led to head and neck injury reference values that frequently surpassed limits referenced in compliance and consumer test protocols. Chest deflections recorded with restraint systems that successfully maintained the torso belt in the center of the shoulder and across the sternum, throughout forward excursion, were greater than the deflections measured with restraint configurations that allowed the belt to be displaced upwards and load the neck. Chest accelerations could not discriminate between any of the restraint characteristics included in this study. Reliance on chest deflection or chest acceleration to evaluate the performance of a restraint system could lead to inaccurate conclusions if the placement of the belt during loading is not taken into consideration.

Evaluation of rear seat protection for school age children who are seated directly on the vehicle seat and on booster seats should rely on a comprehensive assessment of parameters that includes kinematic analysis. Reliance on conventional assessment methods which have been extensively used for adult size ATDs in front row seats, where forward motion is much more controlled may not be adequate to describe the kinematics and true injury potential for rear seats. Relying exclusively on head, neck and chest responses could lead to sub-optimal restraint systems and booster seats.

VI. Acknowledgement

The authors would like to extend their sincere appreciation to the crash investigation teams led by Mr. Jean Louis Comeau, to Dominique Charlebois for his invaluable assistance in mining the data and to the dedicated crash lab staff of PMG Technologies.

VII. Disclaimer

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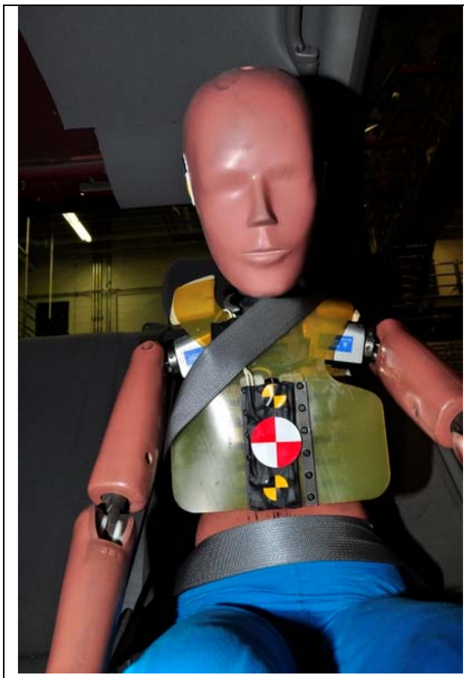
IX. APPENDIX



Relative location of
ITRACCs : yellow/ black targets
Central potentiometer: red/white target

Belt in neck: belt passes above deflection sensors

Low deflection values

Belt on shoulder: belt passes close to upper IR-TRACC & potentiometer

Moderate deflection values

Roll out: passes directly over deflection sensors

High deflection values

Fig. A 1 Examples of belt loading relative to deflection sensor locations.

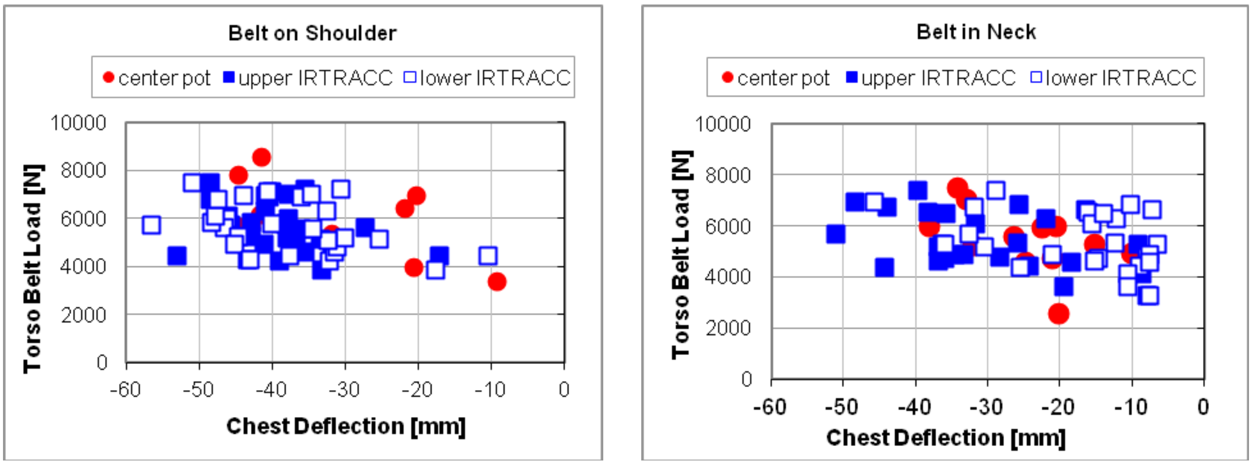


Fig. A 2 Effect of belt position on recorded chest deflections

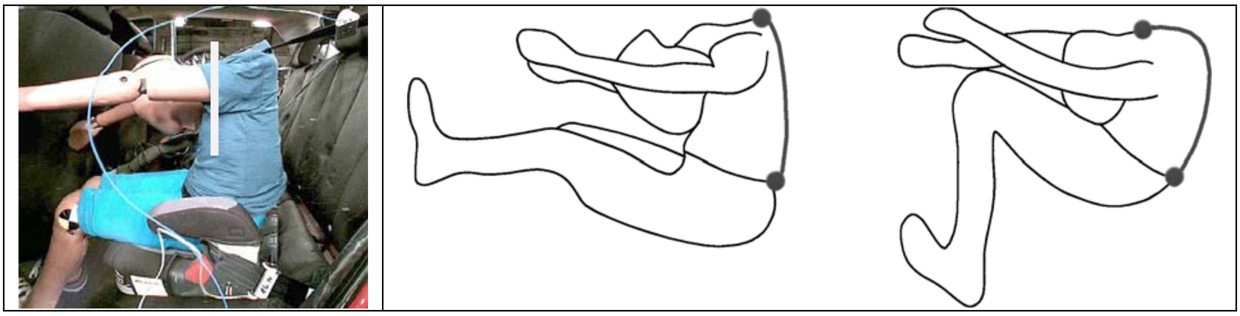


Fig. A 3 Comparison of the Hybrid III 10-year-old profile at peak excursion in this study and profiles of the Hybrid III 6-year-old and 12-year-old cadaver illustrated by Sherwood [7].

TABLE A 1
Torso belt and chest deflection values for the matched in-vehicle samples.

Drivers						
	Chest deflection [mm]			Torso belt load [N]		
	Average	Stdev	n	Average	Stdev	n
40 km/h	-27.3	3.6	16	4100.8	800.4	15
48 km/h	-28.0	6.3	22	4231.0	754.6	21
56 km/h	-29.4	7.1	25	4450.3	944.2	25
Front Passengers						
40 km/h	-21.3	5.4	16	4399.2	818.5	15
48 km/h	-25.3	6.3	22	4461.2	970.7	21
56 km/h	-25.0	6.7	24	4650.2	1063.7	24
Rear Occupants						
40 km/h	-30.4	7. 7	28	6158.5	1011.8	26
48 km/h	-36.2	6.8	40	6736.2	1173.3	38
56 km/h	-37.5	9.0	42	7457.8	1901.0	42

TABLE A 2

Combined axial force and moment (Nij) for the Hybrid III 10-year-old sample

Test ID	Test speed	ATD ID	SEAT	Ntf	Nte	Ncf	Nce	Nij	Test ID	Test speed	ATD ID	SEAT	Ntf	Nte	Ncf	Nce	Nij
TC03-127	47.8	YA-021	15	0.82	1.11	0.05	0.03	1.11	TC08-201	56.2	YA-021	15	1.27	1.19	0.02	0.83	1.27
TC03-130	47.7	YA-021	15	1.32	0.83	0.07	0.55	1.32	TC08-204	56.2	YA-021	14	1.29	1.2	0.12	0.11	1.29
TC05-124	47.8	YA-021	18	1.02	0.52	0.05	0.5	1.02	TC08-205	55.5	YA-021	14	1.18	1.62	0.12	1.04	1.18
TC05-125	47.8	YA-021	15	1.35	1.04	0.1	0.57	1.35	TC08-224	40.0	YA-021	16	1.26	0.93	0.04	0.43	1.26
TC05-211	39.0	YA-021	18	0.95	1.01	0.03	0.23	1.01	TC08-225	40.1	YA-021	16	0.92	1.01	0.1	0.02	1.01
TC06-128	47.9	YA-021	14	1.12	0.47	0.09	1	1.12	TC09-205	40.2	YA-021	16	1.31	1.26	0.12	0.5	1.31
TC06-133	48.1	YA-021	14	1.09	0.86	0.04	0.93	1.09	TC09-207	40.2	YA-021	16	0.91	0.64	0.01	0.3	0.91
TC06-133	48.1	YA-018	16	0.78	0.85	0	0.59	0.85	TC09-209	39.9	YA-021	16	0.62	0.55	0.08	0.04	0.62
TC06-134	47.7	YA-021	15	0.57	0.74	0	0	0.74	TC09-210	47.7	YA-021	16	1.14	1.2	0.54	0.3	1.2
TC06-134	47.7	YA-018	16	1.07	1.18	0.02	0.19	1.18	TC09-214	40.2	YA-021	16	1.2	0.62	0.07	0.32	1.2
TC06-135	47.9	YA-021	15	0.95	0.91	0.01	0.47	0.95	TC09-218	40.0	YA-021	16	1.06	0.91	0.13	0.98	1.06
TC06-135	47.9	YA-018	16	1.15	1.08	0.03	0.94	1.15	TC09-221	47.9	YA-021	14	1.3	1.48	0.31	0.06	1.48
TC06-208	40.3	YA-021	15	1.27	0.81	0	0.47	1.27	TC09-224	40.1	YA-021	18	0.86	1.13	0.25	0.31	1.13
TC06-209	56.2	YA-021	14	0.66	0.75	0.02	0.03	0.75	TC09-228	40.1	YA-021	16	1.02	0.76	0.34	0.52	1.02
TC06-209	56.2	YA-018	19	1.05	1.54	0.09	0.27	1.54	TC09-232	48.1	YA-025	14	0.38	0.68	0.34	0.58	0.68
TC06-210	40.2	YA-021	17	0.66	1.17	0	0.18	1.17	TC09-232	48.1	YA-021	16	0.49	1	0	0	1
TC06-210	40.2	YA-018	19	0.67	0.71	0.03	0.44	0.71	TC09-234	40.1	YA-021	16	1.01	0.62	0.77	0.53	1.01
TC06-211	56.0	YA-018	19	0.94	1.42	0.39	0.31	1.42	TC09-240	47.6	YA-025	14	1.06	0.61	0	0.4	1.06
TC06-212	40.4	YA-021	14	1.45	0.96	0.01	0.48	1.45	TC09-240	47.6	YA-021	16	1	0.63	0.07	0.21	1
TC06-212	40.4	YA-018	17	0.75	1.06	0.02	0.32	1.06	TC09-243	40.4	YA-021	16	1.03	0.8	0.01	0.29	1.03
TC06-213	56.2	YA-021	14	1.75	1.19	0.01	0.7	1.75	TC09-256	47.8	YA-025	14	1.77	1.58	0.05	0.02	1.77
TC06-213	56.2	YA-018	18	1.08	0.85	0.08	0.77	1.08	TC09-256	47.8	YA-021	16	1.54	1.67	0.01	1.04	1.67
TC06-217	40.3	YA-021	14	0.83	0.92	0.2	0.56	0.92	TC09-259	40.9	YA-021	16	1.05	1.09	0.05	0.41	1.09
TC06-217	40.3	YA-018	16	1.18	0.83	0.34	0.65	1.18	TC09-263	40.2	YA-025	14	1.22	0.94	0.01	0.21	1.22
TC06-218	47.6	YA-021	14	1.34	1.33	0.01	0.84	1.34	TC09-263	40.2	YA-021	16	1.2	0.93	0.01	0.02	1.2
TC06-227	56.3	YA-021	14	1.62	1.62	0.21	0.91	1.62	TC10-128	47.8	YA-021	16	1.56	1.29	0.07	0.08	1.56
TC06-237	40.0	YA-021	14	0.8	0.48	0.08	0.44	0.8	TC10-134	47.9	YA-021	16	1.43	1.5	0	0.74	1.5
TC06-239	48.2	YA-021	14	0.8	0.79	0.06	0.5	0.8	TC10-135	47.7	YA-021	16	0.87	0.89	0	0.17	0.89
TC07-201	40.7	YA-021	14	0.7	0.76	0.08	0.36	0.76	TC10-140	47.7	YA-021	16	1.25	1.04	0.14	0.46	1.25
TC07-203	40.4	YA-021	14	0.7	0.73	0.05	0.05	0.73	TC11-126	47.9	YA-021	14	1.44	1.25	0.05	0.54	1.44
TC07-203	40.4	YA-018	15	0.77	0.7	0.07	0.39	0.77	TC11-126	47.9	YA-025	16	1.19	0.85	0.32	0.62	1.19
TC07-218	47.8	YA-021	14	0.17	1.38	0.41	1.75	1.75	TC11-133	47.7	YA-021	14	1.15	1.19	0.08	0.31	1.19
TC07-247	48.0	YA-021	16	1.24	0.62	0.17	1.23	1.24	TC11-133	47.7	YA-025	16	1.35	0.97	0.04	0.55	1.35
TC07-248	39.8	YA-021	16	1.2	0.96	0.04	0.89	1.2	TC11-134	47.7	YA-021	14	1.67	1.88	0.08	1.44	1.67
TC07-256	40.0	YA-021	16	1.15	0.73	0.2	0.57	1.15	TC11-134	47.7	YA-025	16	1.75	1.4	0.01	1.16	1.75
TC07-257	40.0	YA-021	16	0.95	0.77	0.1	0.61	0.95	TC11-136	47.8	YA-021	14	1.35	1.18	0.02	1.26	1.35
TC08-118	40.2	YA-021	15	0.55	0.67	0.04	0.47	0.67	TC11-136	47.8	YA-025	16	1.33	1.13	0.08	0.93	1.33
TC08-125	47.8	YA-021	14	1.44	1.27	0.01	0.68	1.44	TC12-126	47.6	YA-021	14	1.46	1.25	0.28	0.54	1.46
TC08-126	47.8	YA-021	14	1.18	1.25	0.02	0.31	1.25									
								TOTALS	n = 77	≥ 1.0			0.69	0.47	0.00	0.10	0.78
										≥ 0.95			0.69	56.7	0.0	0.1	0.8