Responses of the Hybrid III 5th percentile ATD tested outside of regulatory protocols

Kathy Tang, Suzanne Tylko, Alain Bussières

Abstract The Hybrid III 5th percentile ATD was seated in positions and subject to crash configurations that differ from those specified in regulatory protocols. The test sample included 88 moving car-to-moving car frontal offset tests with a 40% overlap and 9 full-frontal rigid barrier tests. The Hybrid III 5th percentile ATD was seated on the right side of the first- and second-row seats of vehicles in the sample, with the first-row seat in the mid or rearmost track position. Comparisons of kinematic and kinetic responses between first- and second-row ATDs showed greater head accelerations, neck loads, chest deflections, and chest and pelvis accelerations in the second row than in the first only when the second-row belt assembly did not include a pretensioner. In all seating positions, the peak thoracic deflection measured by the RibEye system was better correlated to shoulder belt loading than the peak deflection measured by the central chest potentiometer. In the second row only, differences in the relative accelerations between the chest and pelvis during the onset to peak was associated with changes in ATD motions as well as peak responses at the head, neck, chest, and pelvis. Elevated responses observed in second-row seats may be linked to the rigid non-humanlike posture of the ATD. Optimizing protection for passengers not seated in the foremost seat track location of the first-row passenger seat will require enhanced ATD designs to better replicate the motion of human occupants and advanced measurement tools to more precisely quantify responses. These tools will become increasingly important as alternative modes of transportation, such as autonomous vehicles and shuttles, replace the family vehicle.

Keywords **Hybrid III 5th percentile, frontal impact, chest deflection, RibEye sensor, second-row seats.**

I. Introduction

The Canadian Motor Vehicle Safety Standard for frontal occupant protection (CMVSS 208) includes a full-frontal rigid barrier (FFRB) test with the Hybrid III 5th percentile anthropomorphic test device (ATD) seated in the driver and first row passenger seats in the foremost seat track position. Similar dynamic tests also exist in the United States' Federal Motor Vehicle Safety Standard (FMVSS 208) and the United States' New Car Assessment Programme (NCAP). In North American regulatory and consumer testing, protection of the 5th percentile occupant in frontal impacts is not assessed for any other position in passenger vehicles.

Recently, shifts in commuter preferences and the increasing adoption of advanced and autonomous technologies in vehicles have highlighted the need to investigate occupant safety in seating positions other than those specified by regulatory protocols. Recent accident analyses have also revealed that in newer vehicles, the risk of fatality is greater in the second row than in the first [1-2], with injuries in the second row most frequently reported to occur at the head (due to contact with the vehicle interior), thorax (due to shoulder belt loading), and abdomen (due to lap belt loading) [3-5]. In first-row seats, occupants are restrained by an airbag and knee bolster in addition to a belt assembly equipped with a pretensioner and load limiter. In the second row, however, the primary mode of restraint is the seatbelt, which, in the majority of North American vehicles, is not equipped with a pretensioner or load limiter [1].

Transport Canada conducts research to provide the necessary scientific evidence for the development of regulations. Since 2003, this research has included testing of the 5th percentile occupant undergoing frontal impacts when seated in positions other than that defined by the CMVSS 208 protocol [6-8]. Previous studies where the first-row seat track position was varied in full-frontal rigid barrier (FFRB) tests have reported that placement of the 5th percentile ATD in the mid track position resulted in greater chest deflections than placement in the foremost track position [7]. In FFRB tests where the 5th percentile ATD was placed in second-row seats, the ATD was observed to exhibit forward translation that exceeded those observed in the first row as well as rearward rotations and neck flexions that were not observed in the first row [6-7]. In this study, we investigated the responses of the 5th percentile ATD seated in the first- and second-row seats of vehicles undergoing frontal offset and FFRB tests, where the first-row seat track was varied between the mid and rearmost track positions. Implications on interpretation of the responses recorded by the Hybrid III 5th percentile ATD when seated in

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positions outside those specified by regulatory protocols are discussed.

II. Methods

Crash Configuration

The sample consisted of 88 vehicles tested in the moving car-to-moving car 40% frontal offset crash configuration at 48 km/h (Fig. 1A) and 9 vehicles tested in the FFRB crash configuration at 56 km/h (Fig. 1B). The overlap between vehicles in frontal offset tests was calculated as 40% of the width of the narrower vehicle. Vehicles were propelled by a Messring closed loop electrically powered system and guided by a Messring MicroTrack rail (MESSRING Systembau GmbH, Krailling, Germany). Uni-axial accelerometers (Endevco 7264B, Meggitt, Irvine, California, USA or MSI 64B, TE Connectivity, Schaffhausen, Switzerland) were mounted on a triaxial block and installed at the approximate centre of gravity of each vehicle. Uni-axial accelerometers were placed at the base of each B-pillar.

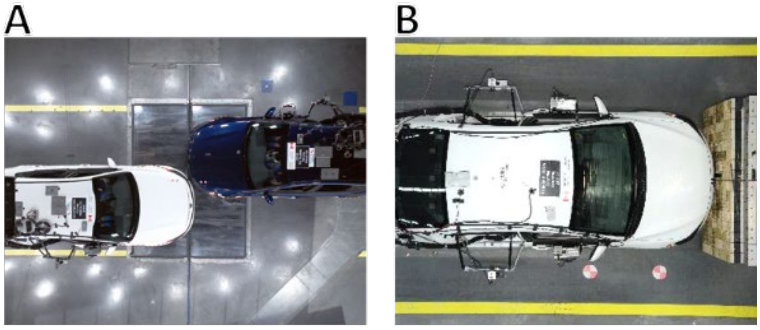


Figure 1. Top views of (A) the moving car-to-moving car 40% frontal offset and (B) the full-frontal rigid barrier crash configurations.

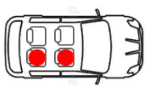
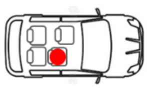
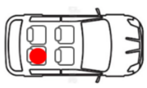
ATD Placement and Instrumentation

The placement of the Harmonized Hybrid III 5th percentile ATD (Humanetics Innovative Solutions, Farmington Hills, Michigan, USA) followed one of three arrangements (Table I, Appendix Table A1):

A. 76 vehicles were tested in the frontal offset configuration with the 5th percentile ATD in the right-side seats of the first and second rows of the vehicle. The first-row seat was in the mid track position.
B. 12 vehicles were tested in the frontal offset configuration with the 5th percentile ATD in only the first-row right-side seat (the second-row right-side occupant was not a part of the study). The first-row seat was in the rearmost track position.
C. 9 vehicles were tested in the FFRB configuration with the 5th percentile ATD in the second-row right-side seat. The first-row seat (whose occupant was not a part of the study) was in either the foremost or mid track position.

The first-row seats of all vehicles were equipped with belt pretensioners, but second-row pretensioners were not present in the majority of the vehicles (Table I, Appendix Table A1).

TABLE I
TEST MATRIX.

Arrangement	Schematic	Crash configuration	5th percentile ATD occupancy	Sample size	Second-row pretensioner
A		Frontal offset	First and second row right-side seats, with the first-row seat in the mid-track position	76	4
B		Frontal offset	First-row right-side seat, with the first-row seat in the rearmost track position	12	N/A
C		FFRB	Second-row right-side seat, with the first-row seat in the foremost or mid-track position	9	3

In all vehicles, the ATD was positioned in the centre of the seat with the calves touching the front of the seat cushion, feet flat on the floor, and hands on the thighs (Fig. 2A-B). In vehicles where the 5^{th} percentile ATD occupied the first-row seat only, the seatback angle was adjusted such that the head angle measured ±0.5 degrees from the horizontal. In vehicles where the 5^{th} percentile ATD occupied both first- and second-row right-side seats, the first-row seatback angle was adjusted to match that of the second-row seat. The pelvis and head angles of first- and second-row ATDs were matched to the closest extent possible. Both ATDs were pushed rearward to minimize the gap between the pelvis and the seatback. However, to maintain contact between the calves and the front of the seat cushion, a gap generally remained present behind the pelvis of the second-row ATD. The D-ring, if it was adjustable, was set to the lowest position. ATD positioning was recorded using a FaroArm Platinum Arm 3D metrology system (FARO, Lake Mary, Florida, USA). The seatback and pelvis angles measured (from the vertical) in each vehicle are summarized in Table II.

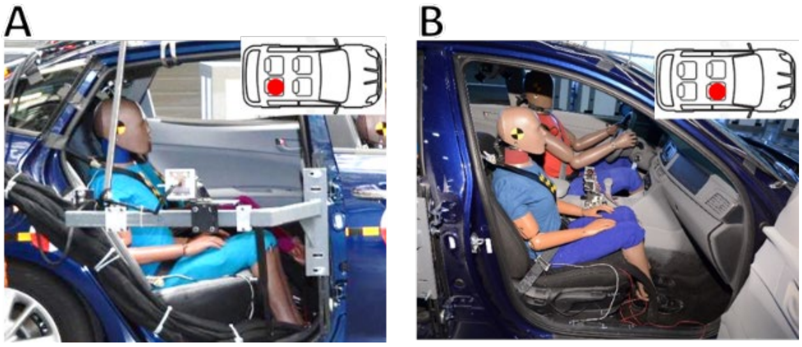


Figure 2. Installation of the 5^{th} percentile ATD in the (A) second-row and (B) first-row seats of a vehicle.

TABLE II

SUMMARY OF SEATBACK AND PELVIS ANGLES OF THE HYBRID III 5^{TH} PERCENTILE ATD.

Arrangement and Seat Position	A, first row	A, second row	B, first row	C, second row
Seatback angle [deg]	21.6 ± 4.1	23.4 ± 1.5	20.0 ± 5.5	22.4 ± 2.0
Pelvis angle [deg]	24.5 ± 2.8	23.7 ± 2.6	25.5 ± 3.3	23.8 ± 2.2

Instrumentation of the ATD included accelerometers at the head, chest, and pelvis; and load cells in the upper and lower neck, lumbar spine, and femurs. Rib deflections were measured at the centre of the chest with a potentiometer. Additional deflection measurements were recorded using the RibEye system (Boxboro Systems, Boxborough, Massachusetts, USA), which is an electro-optical measurement device described in [6]. The RibEye was installed at 12 locations across the chest in accordance with the RibEye User's Manual for Model 7530B. Load cells were also installed on the shoulder and lap belts restraining the ATD. Data were recorded at 10 or 20 kHz and filtered in accordance with SAE J211.

High-speed videos, recorded at 1000 frames/sec, included side views of the first- and second- row ATDs as well as a front view of the second-row ATD. The second-row doors were removed to provide unobstructed lateral camera views of the ATD.

Data Analysis

Shoulder belt slip and lap belt migration were identified by examining the lateral video view for first-row ATDs (Fig. 3A) and the front (Fig. 3B) and lateral (Fig. 3C) views for second-row ATDs. Belt slip was considered to have occurred when the belt slipped off the distal edge of the jacket and into the gap between the arm and shoulder (Fig. 3A). Partial lap belt migration (on either the left or right side) was determined to have occurred if the lap belt remained on the pelvis on one side of the ATD but slipped off the pelvis and entered the abdominal cavity on the other side (example shown in Fig. 3B). Complete lap belt migration was recorded if the lap belt slid off both sides of the pelvis and the entire length of the lap belt became entrapped in the abdominal cavity.

Quantities computed from the kinematic and kinetic responses included the peak RibEye deflection and the mean chest-pelvis difference. The peak RibEye deflection was defined as the magnitude of the greatest peak deflection measured among the 10 upper RibEye sensors (five left and five right sensors). Deflections recorded at the left and right sixth ribs were excluded because displacement of the abdominal insert interfered with the measurement. Signal interference in other RibEye locations was characterized by a plateau of the deflection at approximately 90 mm. Ribs where signal interference was found to have occurred were excluded from analysis.

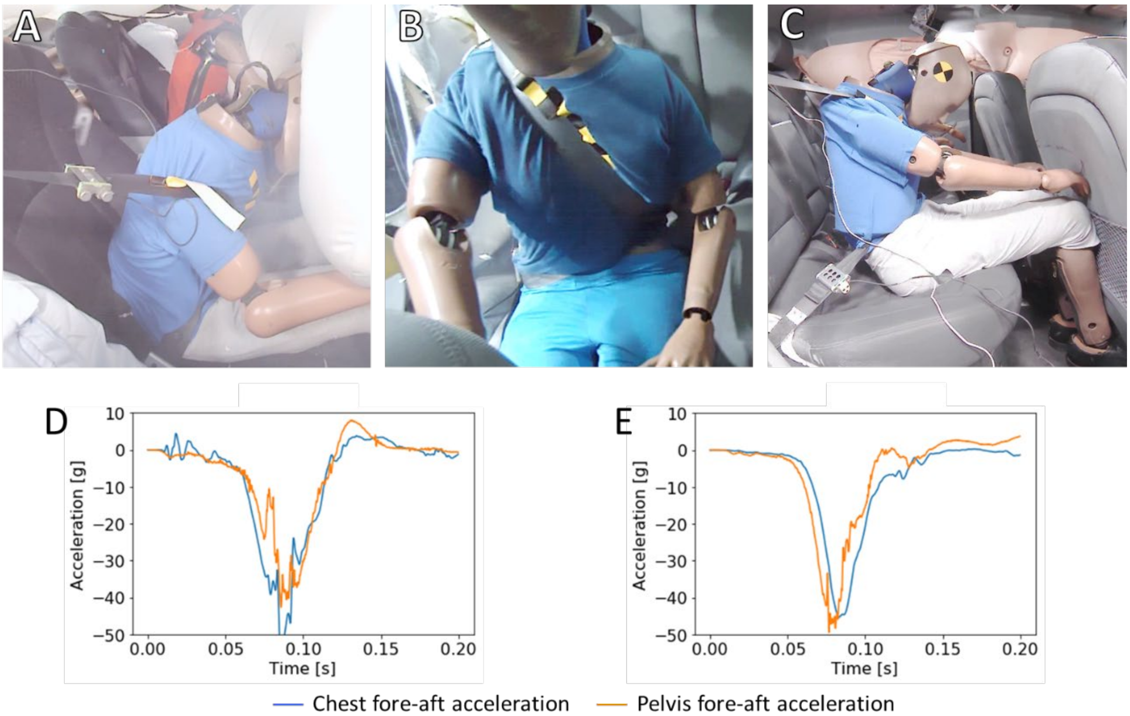


Figure 3. Freeze frames of (A) shoulder belt slip observed from the lateral view of the first-row ATD, (B) partial lap belt migration of the second-row ATD observed from the front view, (C) lap belt migration of the second-row ATD observed from the lateral view; and examples of chest and pelvis fore-aft accelerations in tests where (D) the mean chest-pelvis difference was positive and (E) the mean chest-pelvis difference was negative.

The mean chest-pelvis difference was defined as the mean difference between the time-varying chest and pelvis fore-aft accelerations, computed from the moment of impact ($t = 0$) to the time of peak chest acceleration ($t = argmax(A_{Chest,x}(t))$):

$$\text{Mean chest-pelvis difference} = \frac{1}{argmax(A_{Chest,x}(t))} \int_{t=0}^{t=argmax\left(A_{Chest,x}(t)\right)} \left(A_{Chest,x}(t) - A_{Pelvis,x}(t)\right) dt \quad (1)$$

where $A_{Chest,x}(t)$ and $A_{Pelvis,x}(t)$ are the magnitudes of the time-dependent fore-aft chest and pelvis accelerations. The mean chest-pelvis difference is positive when prior to reaching its peak, the chest acceleration tends to exceed the pelvis acceleration in magnitude (example shown in Fig. 3D), whereas the opposite is true of negative values (example shown in Fig. 3E).

Statistical testing at the 5% significance level was conducted by the paired t-test, two-sample t-test, and one-way ANOVA implemented in the Python module SciPy version 1.2.1. The Bonferroni correction was applied when conducting multiple t-tests using the same sample. Regression models were constructed using the Python package statsmodels version 0.9.0.

III. Results

Video Observations

In vehicles with the first-row seat in the mid track position, the first-row ATD (Fig. 4A, left) exhibited a slight forward rotation of the torso, which led to contact between the head and the airbag. At the time of airbag contact (Fig. 4A, middle), the ATD generally appeared to be upright. Subsequently, forward torso rotation ranged from slight to moderate, and at the approximate time of peak head excursion, the orientation of the torso ranged between upright (not shown) and moderately rotated forward (as in Fig. 4A, right). As shown in the right panel of Fig. 4A, flexion of the neck was also observed at the approximate time of peak head excursion, and the chest was not in contact with the airbag. The forward torso rotations observed in the rearmost track position of some vehicles appeared to be greater than any of those observed in the mid track position (Fig. 4B, right).

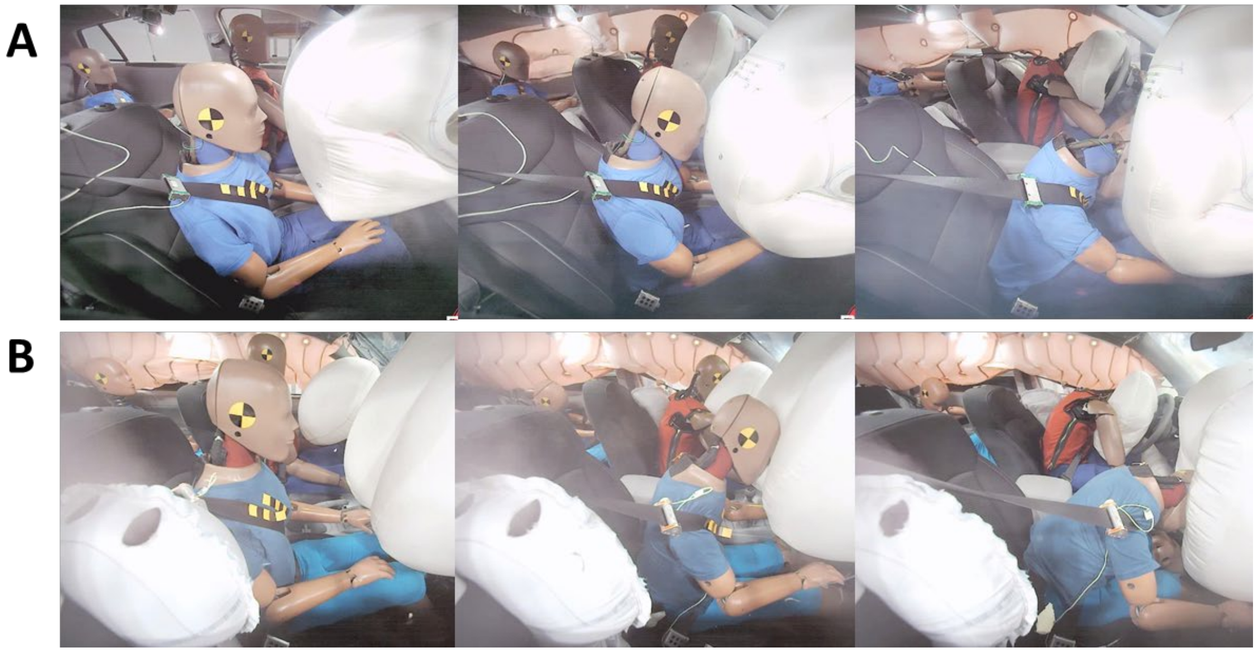


Figure 4. Freeze frames of the first-row ATD in frontal offset tests with the seat track in the (A) mid and (B) rearmost track positions prior to airbag contact (left), at the moment of airbag contact (middle), and at the approximate time of peak head excursion (right).

In frontal offset tests, the second-row ATD exhibited forward translation of the torso, pelvis, and lower extremities. The degree of forward pelvis translation varied between tests, with the pelvis reaching as far as the edge of the seat (Fig. 5A) or traveling as little as less than half the distance between the seat bight and seat edge (Fig. 5B-C). In some vehicles, forward pelvis translation led to contact between the lower legs and the seatback. In other vehicles, forward pelvis translation stopped before the lower legs could contact the seatback. Instead of contacting the seatback, the legs extended, and the shins and feet swung upwards until they contacted the bottom of the seat in front. The motion of the torso relative to the pelvis, and therefore the orientation of the torso, also varied between vehicles. The ATD appeared to rotate rearward when forward translation of the pelvis surpassed that of the torso (Fig. 5A), whereas if the pelvis and torso travelled forward simultaneously and their motions were both stopped at approximately the same time, the ATD appeared to remain upright (Fig. 5B). Finally, if the motion of the torso continued after forward pelvis translation stopped, the ATD appeared to rotate forward (Fig. 5C). Apparent rearward rotation was always accompanied by lap belt migration into the abdominal cavity, although lap belt migration did not necessitate rearward rotation. The mean initial pelvis angle measured in vehicles where the ATD rotated forward (22.4 ± 2.2 degrees) was less than that measured in vehicles where the ATD remained upright (24.3 ± 2.5 degrees); the difference in mean pelvis angle was statistically significant ($p=0.004$). In vehicles where the ATD rotated rearward, the mean initial pelvis angle was 25.3 ± 3.9 degrees, which was not statistically significantly different from the mean angles associated with forward rotation or an upright posture. In all cases, as forward translation of the torso stopped, the neck flexed, and the head rotated towards the upper chest. There was no occurrence of head contact with the interior of the vehicle.

Figure 5. Freeze frames of the second-row ATD at the approximate time of peak head excursion in vehicles tested in the frontal offset crash configuration showing (A) rearward rotation of the ATD and contact between the knees and the seatback in front of the ATD; (B) the ATD in an upright posture; and (C) forward rotation of the ATD and contact between the ankles and the bottom of the seat in front.

In general, in FFRB tests, the motions exhibited by the second-row ATD qualitatively resembled those observed in frontal offset tests. However, forward rotation of the torso was not evident in any of the FFRB tests; only rearward rotation and an upright posture of the ATD torso were observed. In FFRB tests, the orientation of the ATD was not found to significantly change as a function of initial pelvis angle.

The frequency of lap belt migration on at least one side was greater in FFRB tests (0.89) than in frontal offset tests (0.28), and the mean time of lap belt migration was earlier in FFRB tests than in frontal offset tests by 15 and 21 msec on the right and left sides, respectively. Shoulder belt slip of the second-row ATD was not observed in any of the nine FFRB tests.

Incidence of shoulder belt slip and lap belt migration, grouped by crash configuration and seat position, are recorded in Table III.

TABLE III.
INCIDENCE OF SHOULDER BELT SLIP AND LAP BELT MIGRATION.

Crash configuration and seat position	Sample size	Incidence of shoulder belt slip	Incidence of lap belt migration		Time of lap belt migration [msec]	
			Right side	Left side	Right side	Left side
Frontal offset						
First row, mid track	76	19	9	N/A	84 ± 14	N/A
First row, rearmost track	12	8	1	N/A	85	N/A
Second row	76	21	19	21	82 ± 10	78 ± 11
FFRB						
Second row	9	0	7	8	67 ± 4	57 ± 6

Paired Comparison of Peak Kinematic and Kinetic Responses

Responses recorded from the subset of vehicles where the 5th percentile ATD occupied both the first- and second-row seats (Arrangement A in Table I) were used to compare the peak kinematic and kinetic responses associated with each row of seats. The first-row ATD in each vehicle was seated in the mid track position. The difference between the responses of first- and second-row ATDs in the same vehicle, denoted the "paired difference", was computed. Paired differences were grouped by whether the second-row belt assembly included a pretensioner.

In vehicles without second-row pretensioners, the mean peak head fore-aft acceleration, neck fore-aft shear, neck tension, chest fore-aft acceleration, chest (potentiometer) deflection, and pelvis fore-aft acceleration were all statistically significantly greater for the second-row ATD than the first-row ATD (Fig. 6, $p < 0.001$). In vehicles with second-row pretensioners, none of the paired differences were statistically significantly different from zero.

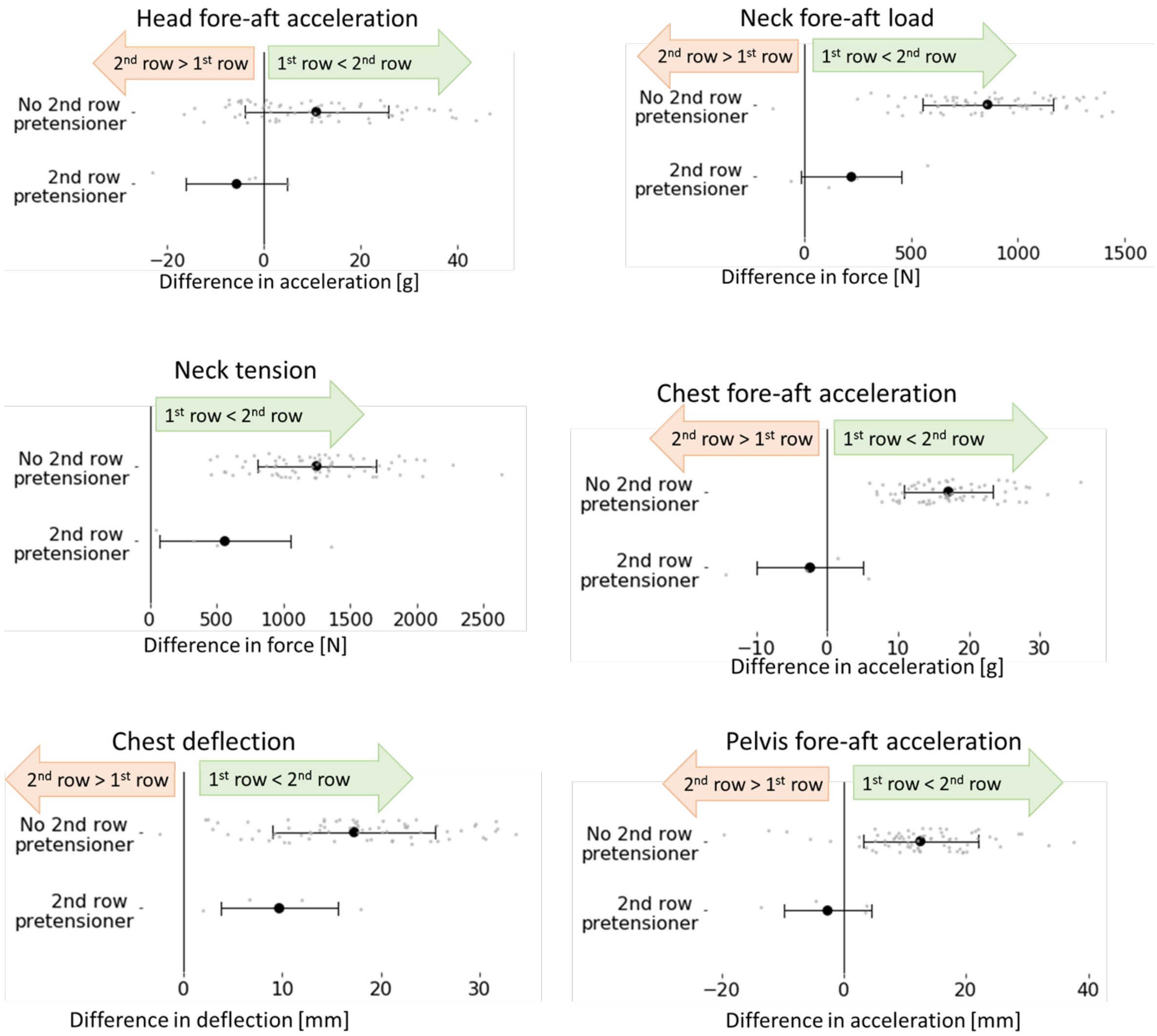


Figure 6. Paired differences of the first- and second-row ATD in vehicles tested in the frontal offset configuration, grouped by whether the second-row seat was equipped with a second-row pretensioner.

Additional Kinematic and Kinetic Responses Associated with ATD Motions

Both the motions and the peak kinematic and kinetic responses of the ATD appeared to vary according to whether it occupied the first- or second-row seat of a vehicle. To investigate the existence of a relationship between the motions and the peak recorded responses, the time-varying kinematic and kinetic responses were examined to identify objective and consistent measures that could be indicative of the observed motions. Since the kinematic and kinetic responses of second-row ATDs appeared to differ in vehicles with and without second-row pretensioners, only the responses recorded in vehicles without second-row pretensioners were examined.

In second-row seats, the ATD torso appeared to rotate rearward if forward pelvis translation stopped after the chest; remain upright if the chest and pelvis stopped in unison; or rotate forward if pelvis translation stopped before the chest. Additionally, the legs either contacted the seatback in front of the ATD or extended to contact the bottom of the seat in front. For second-row ATDs tested in the frontal offset configuration, differences in both torso orientation and leg motion were associated with statistically significant changes in the mean chest-pelvis difference (Eq. (1)), which ranged from -3.3 g to 4.2 g. In frontal offset tests, the mean chest-pelvis difference associated with rearward rotation, an upright orientation, and forward rotation of the second-row ATD were 1.5 ± 1.6 g, -0.39 ± 0.89 g, and -1.8 ± 1.0 g, respectively (Fig. 7A, $p<0.001$ by the one-way ANOVA test; $p<0.001$ by the two-sample t-test comparing the chest-pelvis difference associated with any two torso orientations). The mean chest-pelvis difference of the second-row ATD was 0.33 ± 1.3 g when the legs contacted the seatback and -1.3 ± 0.93 g when the legs extended (Fig. 7B, $p<0.001$).

For second-row ATDs tested in the FFRB configuration, differences in torso orientation (Fig. 7C) but not leg motion (Fig. 7D) were associated with statistically significant changes in the mean chest-pelvis difference. The mean chest-pelvis difference of the second-row ATD in FFRB tests was 3.3 ± 0.49 g when rearward rotation was observed and -0.60 ± 0.34 g when an upright orientation was observed ($p<0.001$).

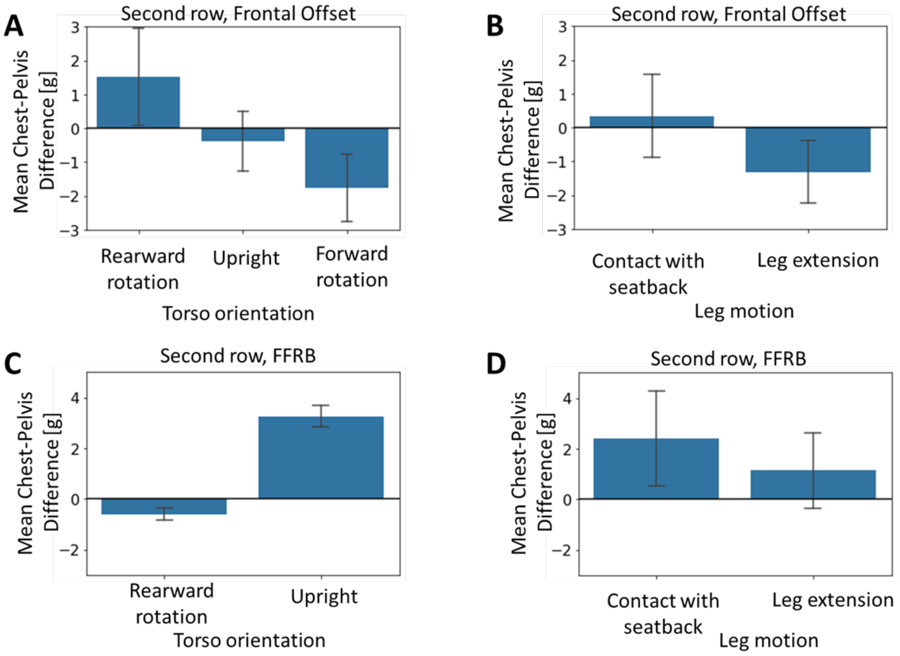


Figure 7. Association between second-row ATD motions and the mean chest-pelvis difference in (A-B) frontal offset and (C-D) FFRB tests.

No statistically significant association was found between the mean chest-pelvis difference and the motion of the first-row ATD. The mean chest-pelvis difference of first-row ATDs ranged -3.3 g to 1.4 g when the ATD was seated in the mid track position (mean ± standard deviation of -1.6 ± 1.1 g), and -3.1 g to 3.3 g (mean ± standard deviation of -1.2 ± 1.7) when seated in the rearmost track position.

Relationship of peak kinematic and kinetic responses to ATD and belt motions

Using the belt motions recorded in Table III together with the computed mean chest-pelvis difference as quantitative measures associated with ATD motions, the relationship between each measure and the peak recorded kinematic and kinetic responses was investigated. Again, only the responses recorded in vehicles without second-row pretensioners were examined.

In frontal offset tests, second-row but not first-row ATDs recorded statistically significantly greater peak chest deflections (by 8.3 mm, $p<0.001$), greater pelvis accelerations (by 4.6 g, $p=0.029$), and lower peak fore-aft neck shear (by 150 N, $p=0.047$) when shoulder belt slip was observed than when it was not (Fig. 8). In FFRB tests, belt slip did not occur for the second-row ATD.

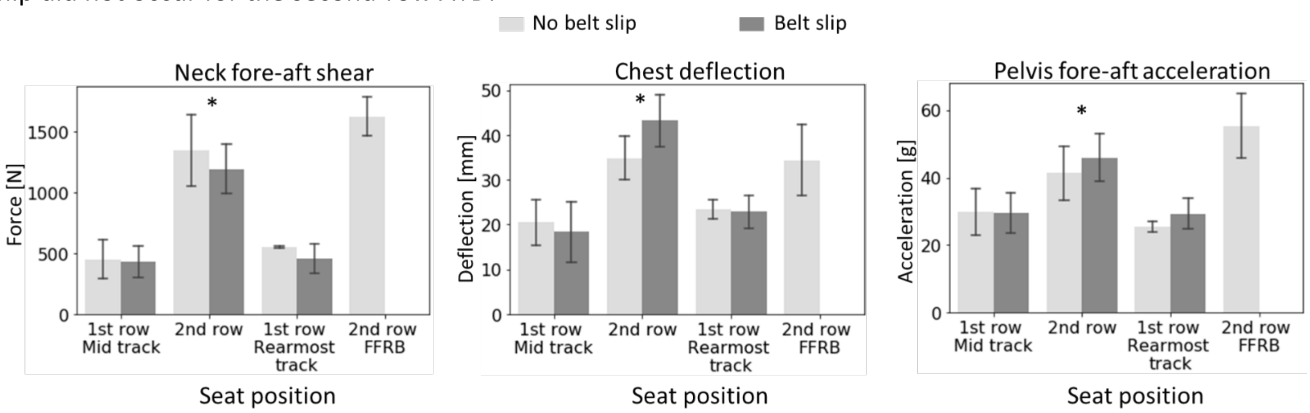


Figure 8. Changes in neck fore-aft shear, peak chest (potentiometer) deflection, and pelvis fore-aft acceleration associated with occurrence and absence of belt slip, grouped according to seat position and crash configuration.

To further investigate the relationship between belt slip and chest deflection of second-row ATDs in frontal offset tests, the peak deflection measured by the central potentiometer was compared to the peak RibEye deflection (as defined in the Methods). The effects of shoulder belt slip and shoulder belt load on peak deflection (both potentiometer and RibEye) were then compared by constructing linear regression models to predict either the peak potentiometer deflection or the peak RibEye deflection from either peak shoulder belt load (Fig. 9) or incidence of belt slip. Although the peak potentiometer deflection varied with incidence of shoulder belt slip, in vehicles where RibEye sensors were installed in second-row ATDs (n=53), the peak RibEye deflection was not statistically significantly different between tests with and without belt slip ($p=0.730$). For second-row ATDs, the variance in the peak potentiometer deflection was better explained by differences in belt slip ($R^2=0.34$) than by variations in the peak shoulder belt load ($R^2=0.25$). However, the variance in the peak RibEye deflection was better explained by variations in the shoulder belt load ($R^2=0.45$) than by incidence of belt slip ($R^2=0.10$). In comparison, for first-row ATDs in the mid track position, the variance in both the peak potentiometer and the peak RibEye deflections were better explained by variations in peak shoulder belt load ($R^2=0.66$ and $R^2=0.71$ of models predicting peak potentiometer and RibEye deflections, respectively) than differences in belt slip ($R^2=0.03$ and $R^2=0.003$ of models predicting peak potentiometer and RibEye deflections, respectively). For first-row ATDs in the rearmost track position, the variance in the peak RibEye deflection was also better explained by variations in peak shoulder belt load ($R^2=0.58$) than differences in belt slip ($R^2=0.01$). However, interestingly, the variance in the peak potentiometer deflection was not well-explained by shoulder belt load ($R^2=0.14$) or incidence of belt slip ($R^2=0.003$).

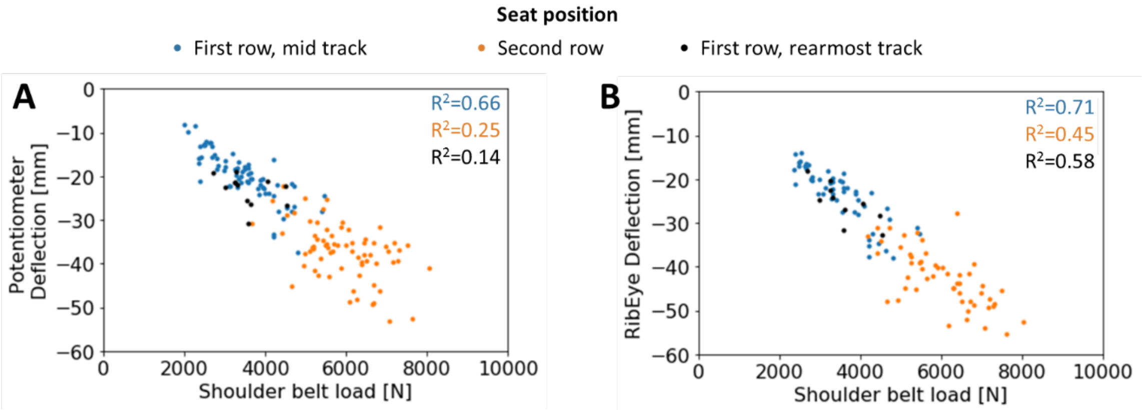


Figure 9. (A) Correlation between peak potentiometer deflection and peak shoulder belt load, and (B) correlation between peak RibEye deflection and peak shoulder belt load, all recorded from first- and second-row seats of vehicles tested in the frontal offset configuration.

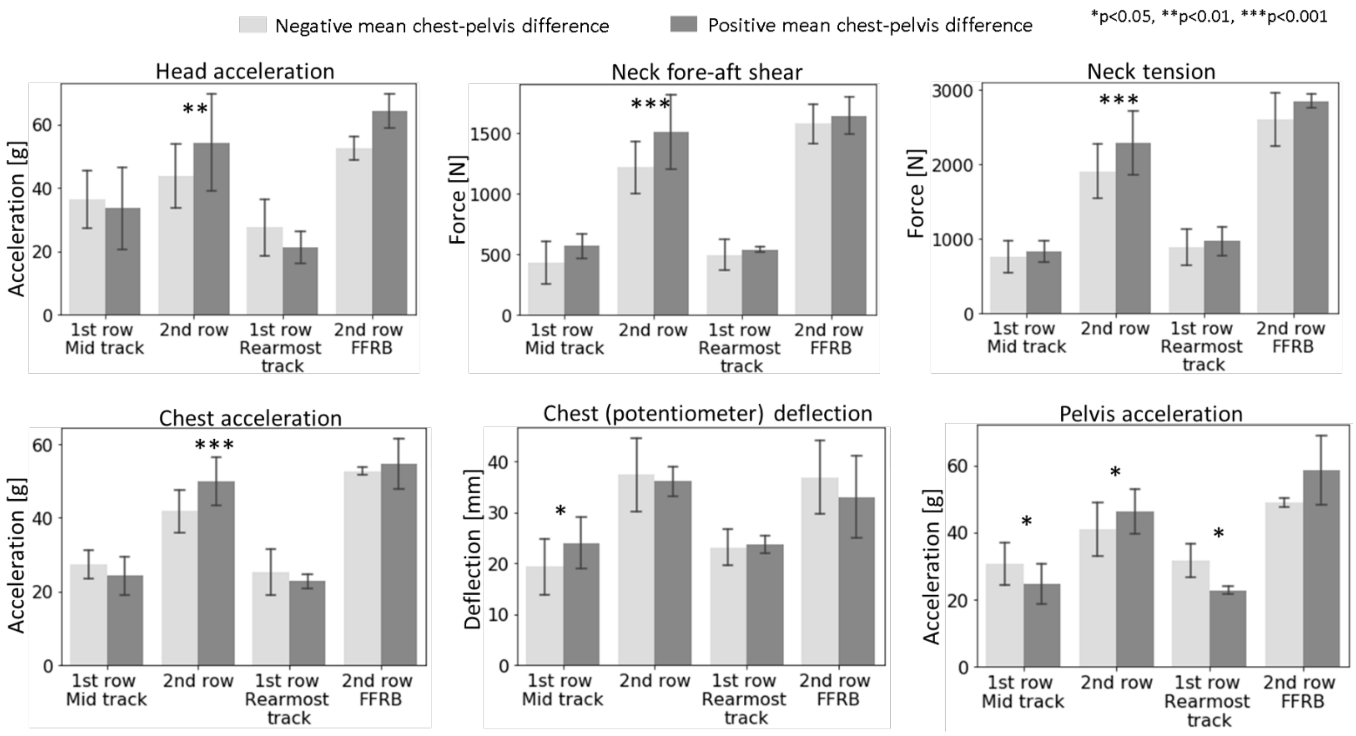


Figure 10. Changes in the head fore-aft acceleration, neck fore-aft shear, neck tension, chest fore-aft acceleration, chest (potentiometer) deflection, and pelvis acceleration associated with differences in the sign of the mean chest-pelvis difference.

In FFRB tests, changes in the chest-pelvis difference were not associated with statistically significant changes in the peak kinematic and kinetic responses of the head, neck, chest, or pelvis (Fig. 10). In frontal offset tests, however, the peak pelvis responses of both second- and first-row ATDs changed with the mean chest-pelvis difference (Fig. 10). For second-row ATDs, a positive chest-pelvis difference was associated with greater magnitude peak pelvis accelerations than a negative chest-pelvis difference, whereas the opposite was true for ATDs in first-row seats, regardless of the track position. Additionally, for second-row ATDs, greater peak head accelerations, neck fore-aft loads, neck tension, and chest accelerations were recorded in tests that yielded a positive mean chest-pelvis difference than in those that yielded a negative mean chest-pelvis difference. For first-row ATDs seated in the mid track position, a positive chest-pelvis difference was also associated with greater magnitude chest deflections than a negative chest-pelvis difference.

IV. DISCUSSION

The purpose of the study was to compare the responses of the Hybrid III 5th percentile ATD in the first and second rows of vehicles undergoing frontal offset and FFRB crashes. Analysis of the responses included characterization of the ATD and belt motions recorded by high-speed video as well as comparisons of the kinematic and kinetic responses recorded by the ATD.

The range of motions exhibited by the ATD varied with seat position. In frontal offset tests, the first-row ATD in the mid track position either remained fairly upright or rotated forward moderately. In the rearmost track position, forward rotation of the first-row ATD in some vehicles appeared to exceed the rotations observed in the mid track position. ATD motions were the most diverse in second-row seats: in both frontal offset and FFRB tests, torso orientation, forward pelvis translation, and leg motions of the second-row ATD varied between vehicles.

In comparisons of second-row motions between frontal offset and FFRB tests, forward rotation of the torso was observed in frontal offset but not FFRB tests, and lap belt migration occurred earlier and more frequently in FFRB tests than in frontal offset tests. The differences found in the likelihood of observing forward rotation and lap belt migration between frontal offset and FFRB tests suggests that specific capabilities and limitations of the ATD in second-row seats may be more prevalent in certain crash configurations.

The motions observed in second-row seats appear to be consistent with those reported in past studies of the Hybrid III 5th percentile ATD in FFRB tests [6-7]. In [7], the ATD was observed in cases of “poor” restraints to translate to the edge of the seat or rotate rearward. Here, ATDs in second-row seats were also observed to translate to the seat edge and rotate rearward. In [7], as in this study, rearward rotation was found to occur with lap belt migration into the abdomen.

In paired comparisons of ATD kinematic and kinetic responses in vehicles without second-row pretensioners, second-row ATDs recorded greater peak responses at the head, neck, chest, and pelvis than first-row ATDs. However, in vehicles with second-row pretensioners, none of the paired differences between first- and second-row ATDs were statistically significantly different from zero. Consistent with the current findings, the addition of either a pretensioner alone or a pretensioner and load limiter in sled tests has previously been reported to reduce chest deflections of the Hybrid III 5th percentile ATD second-row seats [9-10]. In the present study, the sample size of vehicles with second-row pretensioners was small (n=4 in frontal offset tests, n=3 in FFRB tests). However, given the diversity of motions observed in second-row seats, consideration of the second-row ATD motions in addition to the kinematic and kinetic responses will be necessary to better understand the influence of pretensioners on the ATD response in the second rows of vehicles.

In frontal offset tests, peak chest potentiometer deflections measured in the second row increased with occurrence of belt slip. In fact, shoulder belt slip accounted for a greater fraction of the variance in chest potentiometer deflection than did shoulder belt load. In the past, the peak potentiometer deflection of the Hybrid III 5th percentile ATD has been found to decrease as the shoulder belt moves closer to the ATD neck and farther from the location of the potentiometer [6-7, 11]. Unlike the chest potentiometer, the maximum thoracic deflection measured by the RibEye sensors, which are installed in multiple locations across the thorax, is, in theory, less dependent on belt geometry. Indeed, peak RibEye deflections in the second row did not change with occurrence of belt slip, and were better explained by peak shoulder belt load than belt slip. As in the second row, RibEye deflections of first-row ATDs in both the mid and rearmost track positions were better correlated with shoulder belt load than belt slip. Interestingly, while the peak potentiometer deflections of first-row ATDs seated mid track were moderately correlated with shoulder belt load, the same was not true of first-row ATD in the rearmost track position. Thus, in tests where the seat position of the Hybrid III 5th percentile ATD is varied, the peak RibEye deflection generally appeared to be more reliably correlated with shoulder belt loading than peak potentiometer deflection.

The mean chest-pelvis difference computed from second-row ATD responses was found to change with the motion of the ATD. In frontal offset tests, higher mean chest-pelvis differences were associated with prolonged pelvis excursion relative to that of the chest (i.e., rearward rotation) as well as pelvis excursions that enabled leg contact with the first-row seatback. Both rearward rotation and leg-seatback contact were motions suggestive of pelvis excursions that tended to lie close to the upper bound of the range observed in the sample. The association between ATD motions and the chest-pelvis difference, then, may suggest that the chest-pelvis difference could provide quantitative indication of the extent of pelvis excursion. Similarly, in previous studies of ATDs in second-row seats, the measured kinematic and kinetic responses have also been found to be associated with interactions between the ATD and the restraint system. In [6], rearward rotation of the 5th percentile ATD was found to occur in tests where early axial lumbar spine tension was followed by compression, whereas early compression followed by tension was associated with engagement between the ATD buttock and the seat cushion. In second-row seats, where the motions of the ATD are not constrained by belt pretensioners or airbag deployment, objective and quantitative measures associated with ATD motions could provide a more consistent means of measuring the different motions. The same quantitative measures could also serve as a contextual reference that may aid in the understanding of how responses commonly used for the assessment of injury risk may be influenced by ATD motions. Importantly, the apparent association between the mean chest-pelvis difference and the peak kinematic and kinetic responses of second-row ATDs may be indicative of ATD limitations that only become apparent in seating locations where greater motion of the ATD is possible. Further investigation of the potential relationship between pelvis excursion and the chest-pelvis difference may lead to additional insights.

A clearer understanding of the capabilities and limitations of the Hybrid III 5th percentile ATD in second-row seats will become increasingly important as assessments of second-row occupant protection are introduced to consumer testing programmes. In 2015, the European New Car Assessment Programme (Euro NCAP) introduced a full width rigid barrier test conducted at 50 km/h, which includes Hybrid III 5th percentile ATDs seated in the driver and second-row right-side positions [12]. Subsequently, 94% of the vehicles tested by Euro NCAP in 2017 were equipped with second-row load limiters and pretensioners [13]. Recently, the Insurance Institute for Highway Safety (IIHS) has been developing protocols for the new Moderate Overlap 2.0 test, which will include a Hybrid III 5th percentile ATD seated in the second-row left-side seat [14]. Evaluation criteria designed with consideration of ATD limitations, such as the dependence of the chest potentiometer measurement on belt geometry, may be less influenced by ATD artefacts than those designed without such considerations. Additionally, in conjunction with the adoption of rear-seat occupant safety assessments, an important topic of study will be the extent to which crash configuration, impact speed, and seating position may influence the likelihood of observing certain ATD responses and limitations.

Limitations present in this study included the imbalance of sample sizes with respect to seating arrangement and crash configuration (Table I). The sample size of vehicles tested in Arrangement A (n=76) was much greater than the sample sizes of vehicles tested in Arrangements B (n=12) and C (n=9). The asymmetry in sample size may have influenced the results of statistical analyses when comparing differences in responses between seat position or crash configuration. Additionally, the mean chest-pelvis difference appeared to be related to ATD motions observed in the second row, but the relationship was not confirmed by quantitative video analysis.

Further testing will be conducted to compare the responses of the Hybrid III 5th percentile ATD with the responses of the THOR 5th percentile ATD [15]. As vehicles become increasingly equipped with second-row pretensioners, the influence of the second-row pretensioner on both the motions and the kinematic and kinetic responses of the ATD will continue to be studied. Additionally, tests with the first-row ATD in the rearmost track position will continue to be conducted. Finally, more detailed pre-test measurements of vehicle seat characteristics, ATD posture, and belt geometry will be necessary to further investigate how they may influence the observed motions of the ATD as well as the recorded kinematic and kinetic responses.

V. CONCLUSIONS

The Hybrid III 5th percentile ATD exhibited a greater range of motion in second-row seats than in first-row seats.

In the second row, the mean chest-pelvis difference was found to be a quantitative measure associated with both the motions of the ATD as well as the recorded peak head, neck, chest, and pelvis responses.

In all seat positions tested, the peak RibEye deflection was not sensitive to belt slip, and was more consistently correlated with shoulder belt load than the peak chest potentiometer deflection. Compared to the potentiometer, the RibEye system may aid in providing more accurate measures of thoracic deflection when testing ATDs outside of regulatory protocols. Optimizing protection for passengers not seated in the foremost seat track location of the first-row passenger seat will require further investigation into the capabilities and limitations of the ATD.

VI. Acknowledgement

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VII. Disclaimer

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IX. Appendix

TABLE A1
SUMMARY OF VEHICLES TESTED.

Make	Model	Model year	Crash configuration	ATD arrangement[2]	Second-row pretensioner?
Audi	A3	2015	Frontal Offset	A	Yes
Hyundai	Accent	2019	Frontal Offset	A	No
Chevrolet	Bolt EV	2018	Frontal Offset	A	No
Toyota	Camry	2018	Frontal Offset	A	Yes
Toyota	Camry	2015	Frontal Offset	A	No
Toyota	Camry	2017	Frontal Offset	A	No
Toyota	Camry	2017	Frontal Offset	A	No
Toyota	Camry	2016	Frontal Offset	A	No
Toyota	Camry	2016	Frontal Offset	A	No
Jeep	Cherokee	2014	Frontal Offset	A	No
Jeep	Cherokee	2015	Frontal Offset	A	No
Honda	Clarity	2019	Frontal Offset	A	No
Toyota	Corolla	2015	Frontal Offset	A	No
Toyota	Corolla	2015	Frontal Offset	A	No
Toyota	Corolla	2015	Frontal Offset	A	No
Honda	CR-V	2018	Frontal Offset	A	No
Honda	CR-V	2018	Frontal Offset	A	No
Chevrolet	Cruze	2015	Frontal Offset	A	No
Chevrolet	Cruze	2017	Frontal Offset	A	No
Chevrolet	Cruze	2018	Frontal Offset	A	No
Volkswagen	E-Golf	2018	Frontal Offset	A	No
Hyundai	Elantra GT	2018	Frontal Offset	A	No
Hyundai	Elantra GT	2018	Frontal Offset	A	No
Chevrolet	Equinox	2015	Frontal Offset	A	No
Chevrolet	Equinox	2018	Frontal Offset	A	No
Chevrolet	Equinox	2019	Frontal Offset	A	No
Ford	Escape	2013	Frontal Offset	A	No
Ford	Escape	2015	Frontal Offset	A	No
Ford	F150	2018	Frontal Offset	A	No
Ford	F150	2011	Frontal Offset	A	No
Ford	Focus	2012	Frontal Offset	A	No
Subaru	Forester	2020	Frontal Offset	A	Yes
Ford	Fusion	2013	Frontal Offset	A	No
Ford	Fusion	2016	Frontal Offset	A	No
Volkswagen	Golf	2019	Frontal Offset	A	No
Hyundai	Ioniq HEV	2020	Frontal Offset	A	No
Hyundai	Ioniq PHEV	2020	Frontal Offset	A	No
Nissan	Juke	2016	Frontal Offset	A	No
Hyundai	Kona	2019	Frontal Offset	A	No
Hyundai	Kona	2019	Frontal Offset	A	No
Hyundai	Kona EV	2020	Frontal Offset	A	No
Nissan	Leaf	2020	Frontal Offset	A	Yes

[2] As described in Table I.

Nissan	Leaf	2015	Frontal Offset	A	No
Nissan	Leaf	2019	Frontal Offset	A	No
Mazda	3	2019	Frontal Offset	A	No
Mazda	3	2019	Frontal Offset	A	No
Lincoln	MKX	2016	Frontal Offset	A	No
Kia	Niro EV	2020	Frontal Offset	A	No
Kia	Niro HEV	2020	Frontal Offset	A	No
Kia	Niro PHEV	2020	Frontal Offset	A	No
Kia	Optima	2017	Frontal Offset	A	No
Kia	Optima	2018	Frontal Offset	A	No
Kia	Optima PHEV	2017	Frontal Offset	A	No
Kia	Optima PHEV	2019	Frontal Offset	A	No
Mitsubishi	Outlander	2014	Frontal Offset	A	No
Mitsubishi	Outlander	2018	Frontal Offset	A	No
Mitsubishi	Outlander	2018	Frontal Offset	A	No
Mitsubishi	Outlander	2018	Frontal Offset	A	No
Mitsubishi	Outlander PHEV	2018	Frontal Offset	A	No
Mitsubishi	Outlander PHEV	2018	Frontal Offset	A	No
Chrysler	Pacifica PHEV	2020	Frontal Offset	A	No
Toyota	Prius	2017	Frontal Offset	A	No
Toyota	Prius Prime	2018	Frontal Offset	A	No
Nissan	Qashqai	2020	Frontal Offset	A	No
Toyota	Rav4	2020	Frontal Offset	A	No
Toyota	Rav4	2020	Frontal Offset	A	No
Toyota	Rav4	2020	Frontal Offset	A	No
Toyota	Rav4 Hybrid	2018	Frontal Offset	A	No
Kia	Rio	2018	Frontal Offset	A	No
Kia	Rio	2018	Frontal Offset	A	No
Kia	Soul	2020	Frontal Offset	A	No
Kia	Soul	2012	Frontal Offset	A	No
Kia	Soul EV	2020	Frontal Offset	A	No
Scion	TC	2014	Frontal Offset	A	No
Volkswagen	Tiguan	2018	Frontal Offset	A	No
Chevrolet	Volt	2013	Frontal Offset	A	No
Jeep	Cherokee	2018	Frontal Offset	B	N/A
Toyota	Corolla	2016	Frontal Offset	B	N/A
Toyota	Corolla	2008	Frontal Offset	B	N/A
Chevrolet	Cruze	2018	Frontal Offset	B	N/A
Buick	Encore	2018	Frontal Offset	B	N/A
Subaru	Forester	2018	Frontal Offset	B	N/A
Nissan	Murano	2018	Frontal Offset	B	N/A
Mitsubishi	RVR	2018	Frontal Offset	B	N/A
Volvo	S-60	2013	Frontal Offset	B	N/A
Smart	Fortwo	2016	Frontal Offset	B	N/A
Smart	Fortwo PHEV	2017	Frontal Offset	B	N/A
Hyundai	Tucson	2017	Frontal Offset	B	N/A
Honda	Accord Hybrid	2020	FFRB	C	No
Chevrolet	Bolt	2020	FFRB	C	No
Chevrolet	Colorado	2021	FFRB	C	Yes

Toyota	Corolla Hybrid	2020	FFRB	C	No
Mazda	Cx-5	2021	FFRB	C	No
Mazda	3	2018	FFRB	C	No
Tesla	Model 3	2020	FFRB	C	Yes
Subaru	Outback	2020	FFRB	C	Yes
Hyundai	Venue	2021	FFRB	C	No