Comparison of Occupant Protection in Electric vs. Internal Combustion Vehicles

Suzanne Tylko, Kathy Tang, Alain Bussières

Abstract The study compares occupant protection in hybrid, hybrid electric, plug-in hybrid electric, and all-electric vehicles (referred to collectively as EVs) to the protection offered by equivalent vehicle models powered by an internal combustion engine (ICE). Two series of moving car-to-moving car frontal offset tests were conducted, each with the THOR or Hybrid III 50th percentile male anthropomorphic test device (ATD) in the driver's seat and the Hybrid III 5th percentile female in the right front passenger seat. The first series consisted of 17 tests, each involving an EV impacting the equivalent ICE model at the same impact velocity. The second series consisted of five (5) pairs of tests, in which each EV and the equivalent ICE model impacted the same baseline striking vehicle. Statistically significant differences of EV/ICE pairs were found primarily in the upper body responses of the ATDs. Where differences were statistically significant, ATD measurements in ICE vehicles were slightly greater than those in EV counterparts. Occupant protection in EV models was found to be as good as or better than protection in ICE model equivalents.

Keywords crashworthiness, electric vehicles, frontal offset, hybrid vehicles, Hybrid III, THOR.

I. INTRODUCTION

Governments around the world are increasingly adopting policies aimed at reducing greenhouse gas (GHG) emissions. Some of these policies are aimed at decarbonising the transportation sector by imposing emission standards to the automakers [1-2]. These policies, combined with government incentives supporting consumers, have led to an important increase in the number of plug-in electric and hybrid vehicles stock in the last decade. It is estimated that more than 1 million new electric vehicles (battery electric vehicles (BEV); plug-in hybrid electric vehicles (PHEV); fuel cell electric vehicle (FCEV)) were sold in 2017. China, the United States, and Europe represent the three largest electric car markets with 40%, 25%, and 25% of the global electric vehicle fleet, respectively [3].

Canada has pledged as part of the Paris Agreement to reduce national GHG emissions by 30% below 2005 levels by 2030 [4]. This commitment is being pursued through the Pan-Canadian Framework (PCF) on Clean Growth and Climate Change. The federal government is working with the provinces to cut emissions from cars, trucks, and transport vehicles through the introduction of GHG emission regulations and the development of a Canada-wide zero emission vehicle (ZEV) strategy. The 2019 Federal Budget announced a $300 million incentive programme to help make zero-emission vehicles more affordable and accessible to Canadians.

A research programme was initiated in 2013 to investigate the crashworthiness of hybrid, hybrid electric, plug-in hybrid electric, and all-electric vehicles (referred to collectively as EVs). A similar, parallel programme evaluating the protection of vehicles that had undergone light-weighting to improve fuel efficiency was begun the following year. This paper presents the results of a frontal offset study that was conducted to compare occupant protection in EVs to the protection offered by equivalent vehicle models powered by an internal combustion engine (ICE).

These programmes are on-going and support the development of regulations and standards in collaboration with: the United States Department of Transportation (US DOT) under the auspices of the Action Plan for the Canada-United States Regulatory Cooperation Council (RCC); the Global Technical Regulations, developed under the 1998 Global Agreement of the United Nations Economic Commission for Europe (UN ECE); Environment Canada; and the U.S. Environmental Protection Agency, under the auspices of the U.S.-Canada Air Quality Agreement, to support the development of greenhouse gas emissions regulations for light-duty passenger vehicles and trucks.

Suzanne Tylko is Chief of Crashworthiness Research at the Centre for Innovation for Transport Canada (Phone: +1 (613) 797-7803; E-mail: Suzanne.tylko@tc.gc.ca), Kathy Tang and Alain Bussières form part of the crash data analysis team at PMG Technologies, Québec, Canada.

II. METHODS

Paired Frontal Offset Tests

Two series of moving car-to-moving car frontal offset tests were conducted. The first series consisted of 17 tests, each involving an EV impacting the equivalent ICE model (TABLE I). The second series, which consisted of nine (9) vehicles, included three (3) pairs of tests for which an EV and its equivalent ICE model impacted the same baseline striking vehicle. In the remaining three (3) tests belonging to the second series, two ICE equivalents and one PHEV equivalent of the same vehicle model each impacted the same baseline striking vehicle. The ATD responses in the two ICE vehicles were independently compared to the responses in the equivalent EV. As a result, the second test series included a total of five paired comparisons (TABLE II).

In both test series, frontal offset test vehicles were aligned to obtain a 40% overlap on the driver side (Fig. 1A). Overlap was calculated as 40% of the width of the narrower vehicle. Each test vehicle was propelled by a Messring closed loop electrically powered system to a velocity of 48 km/h or 56 km/h 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 (CG) of each vehicle. Uni-axial accelerometers were placed at the base of each B-pillar.

All vehicles were tested with four ATDs on board. Driver seats were occupied by the THOR or Hybrid III 50th percentile male ATD, and front passenger seats were occupied by the Hybrid III 5th percentile female. Second row seats were usually occupied by child-sized dummies. Since child dummies were placed in a wide range of child restraints, the sample was not appropriately controlled for statistical testing. Therefore, the focus in this study was restricted to the ATDs in the front row.

The THOR dummy was positioned as per the THOR-50th Percentile Male Metric Driver Dummy Seating & Positioning Procedures published by NHTSA in the docket NHTSA-2015-0119-0009 [5] (Fig. 1B). The Hybrid III male ATD was positioned as specified in the CMVSS 208 standard (Fig. 1C). The Hybrid III female ATD was placed in the front passenger seat with the seat adjusted to the mid-track position and with the back of the lower legs in contact with the seat cushion (Fig. 1D). ATD placements were recorded using a FaroArm Platinum Arm 3D metrology system (FARO, Lake Mary, Florida, USA). Onboard tilt sensors (ARS PRO-8K, DTS, Seal Beach, California, USA) located in the head and chest of the THOR were also used to ensure repeatability of positioning.

ATD Instrumentation and Video Imaging

The driver ATDs were the THOR-50M Standard SBL-A assembled with the SBL-B version of the neck and the Harmonized Hybrid-III 50th percentile male. The passenger ATD was the Harmonized Hybrid-III 5th Small Female ATD. All three ATDs were obtained from Humanetics Innovative Solutions (Farmington Hills, Michigan, USA). Data were recorded at 10 kHz and filtering was performed in accordance with SAE J211. High-speed videos recorded at 1000 frames/second were obtained and included a rear shoulder view, an oblique view centred behind the two front row seats, and a lateral view from the front passenger window. In some vehicles, additional views included the driver side footwell and a view of the driver's pelvis and upper legs. The pre- and post-test conditions of each vehicle were documented photographically.

Electrical Shock Protection

The electrical isolation test required by FMVSS No. 305/CMVSS 305 (S7.6 of TSD 305) describes performance requirements for electrolyte spillage, the retention of propulsion batteries, and the electrical isolation of the chassis from the high-voltage source during normal operation as well as following a crash. The regulatory test protocol was followed for all EVs in the test programme. Due to the complexity and diversity of electric systems, additional steps were taken to monitor electrical isolation more carefully. First, a multi-channel oscilloscope (Model DEWE2-A4, Dewetron GmbH, Grambach, Austria) was used to ensure that the complete period of the voltage wave was recorded for all measurements (V1-V2). Simultaneous readings were obtained on each side of the high-voltage source with respect to the chassis to ensure that the load placed on the circuit by the impedance of the measuring tool (in this case, the oscilloscope) balanced between V1 and V2. Finally, isolation resistance calculations were carried out both before and after the crash test. A range of known simulated resistive isolation leaks (500kΩ to 30 kΩ) were introduced between the chassis and the negative side of the high-voltage source to validate that the applied resistances corresponded to the theoretical isolation values calculated using the

equations of the CMVSS 305 protocol. The additional pre-test measurements provide a measure of the response of the vehicle's monitoring system to a known isolation leak. These added steps are intended to increase the level of confidence in the calculations in the event of an isolation leak.

TABLE I[1]
SERIES 1 TEST MATRIX

ICE Model Year	ICE Model	EV Model Year	EV Model	Driver	Speed	Weight Difference (EV-ICE) [kg]
2017	*Cooper C.*	2017	Cooper C. PHEV	THOR	48	196.2
2011	*Escape*	2009	Escape Hybrid	THOR	48	165.8
2017	*Fusion*	2017	Fusion PHEV	THOR	48	104.8
2014	*Jetta*	2013	Jetta Hybrid	THOR	48	48.4
2017	*Optima*	2017	Optima PHEV	THOR	48	246.0
2017	*Pacifica*	2017	Pacifica PHEV	THOR	48	296.0
2016	*Fortwo*	2017	Fortwo PHEV	THOR	48	106.8
2012	*Soul*	2017	Soul EV	THOR	48	212.4
2015	*Soul*	2016	Soul EV	THOR	56	225.2
2013	*Accord*	2014	Accord Hybrid	THOR	56	110.2
2014	*Cruze*	2014	Volt (PHEV)	THOR	56	194.6
2012	*Camry*	2011	Camry HEV	Hybrid III	48	117.8
2012	*Focus*	2013	Focus EV	Hybrid III	48	323.0
2013	*Fusion*	2013	Fusion PHEV	Hybrid III	48	226.0
2013	*Sonata*	2013	Sonata HEV	Hybrid III	48	150.0
2012	*Transit*	2011	Transit EV	Hybrid III	48	236.6
2014	*Spark*	2014	Spark EV	Hybrid III	56	269.0

TABLE II
SERIES 2 TEST MATRIX

	Model Year	Model	Type	Striking Vehicle	Driver	Speed	Weight Difference (EV-ICE) [kg]
Pair 1	*2015*	Cruze	ICE	Camry	THOR	48	280.8
	2013	Volt (PHEV)	EV	Camry	THOR	48	
Pair 2	*2017*	Cruze	ICE	Camry	THOR	48	344.0
	2013	Volt (PHEV)	EV	Camry	THOR	48	
Pair 3	*2018*	Golf	ICE	Elantra GT	THOR	48	246.0
	2019	e-Golf (EV)	EV	Elantra GT	THOR	48	
Pair 4	*2018*	Outlander	ICE	Tiguan	THOR	48	377.0
	2018	Outlander PHEV	EV	Tiguan	THOR	48	
Pair 5	*2018*	Optima	ICE	Fusion	THOR	48	205.0
	2019	Optima PHEV	EV	Fusion	THOR	48	

[1]All-electric vehicles are labeled EV.

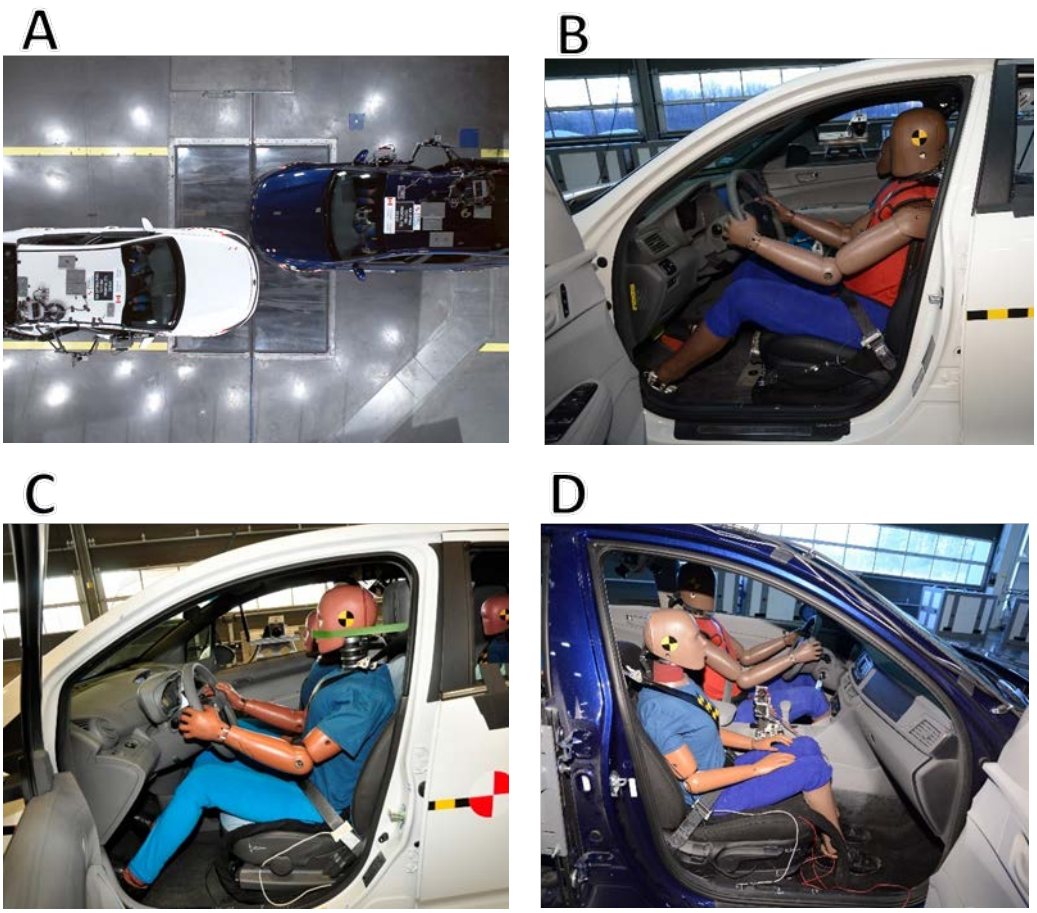

Fig. 1. (A) Top view of a 40% offset configuration. (B) Placement of the THOR in the driver position. (C) Placement of the Hybrid III male in the driver position. (C) Placement of the Hybrid III female in the passenger position.

Data Analysis

Comparisons of occupant responses in EVs and ICE vehicles were paired such that the responses observed in each EV were compared to those observed in the ICE version of the same vehicle model. The two-tailed paired t-test was used to identify occupant responses that were statistically significantly different across pairs of responses. The level of significance was chosen to be 5%.

The Python package Scikit-Learn 0.20.1 [6] was used to model occupant responses. The responses modelled included any of the driver and passenger head and chest responses that were identified in either of the two test series to be statistically significantly different between EVs and ICE vehicles. Each response was modelled as a linear function of vehicle weight only, and model coefficients were estimated using ordinary regression. Samples used for model fitting were from tests at 48 km/h only, and were from both test series (including the striking vehicles used in the second series) but included either only the responses from ICE vehicles or only the responses from EVs. In the ICE sample, six of the 17 different vehicle models used were tested more than once. In the EV sample, two of the 16 different vehicle models used were tested more than once. The inclusion of multiple tests with the same vehicle model was not expected to bias the estimation of model coefficients, since vehicles of the same model were expected to have similar weights and yield similar occupant responses. The linear models fitted to data from EVs were used to predict the responses in the specific ICE vehicles detailed in TABLE I and TABLE II that were tested at 48 km/h. Similarly, linear models fitted to data from ICE vehicles were used to predict the responses in the EVs detailed in TABLE I and TABLE II that were tested at 48 km/h. The error between predicted and actual response values was calculated as the difference between predicted and actual responses. Paired t-tests were used to test whether error values for a given response were statistically significantly different from zero.

III. RESULTS

Comparison of Vehicle Responses & Damage

Vehicle fore-aft accelerations obtained at the approximate centre of gravity and at the base of the struck side B-pillar for the vehicles in Series 1 that were tested at 48 km/h are presented in Figure 2A and 2B, respectively. Scatter plots illustrating the differences between peak acceleration values are shown below the time history plots. The median responses for the ICE and EV sample were comparable. Differences in the peak accelerations tended to be somewhat greater for the ICE responses but these were not statistically significant.

Each propulsion battery was found to be undamaged and un-displaced following the crash test. No electrolyte spillage was detected at any time and all batteries remained isolated from the vehicle chassis. While the extent of damage to each vehicle in a pair sometimes differed quite substantially, damage characteristics for ICE and EVs were not distinguishable.

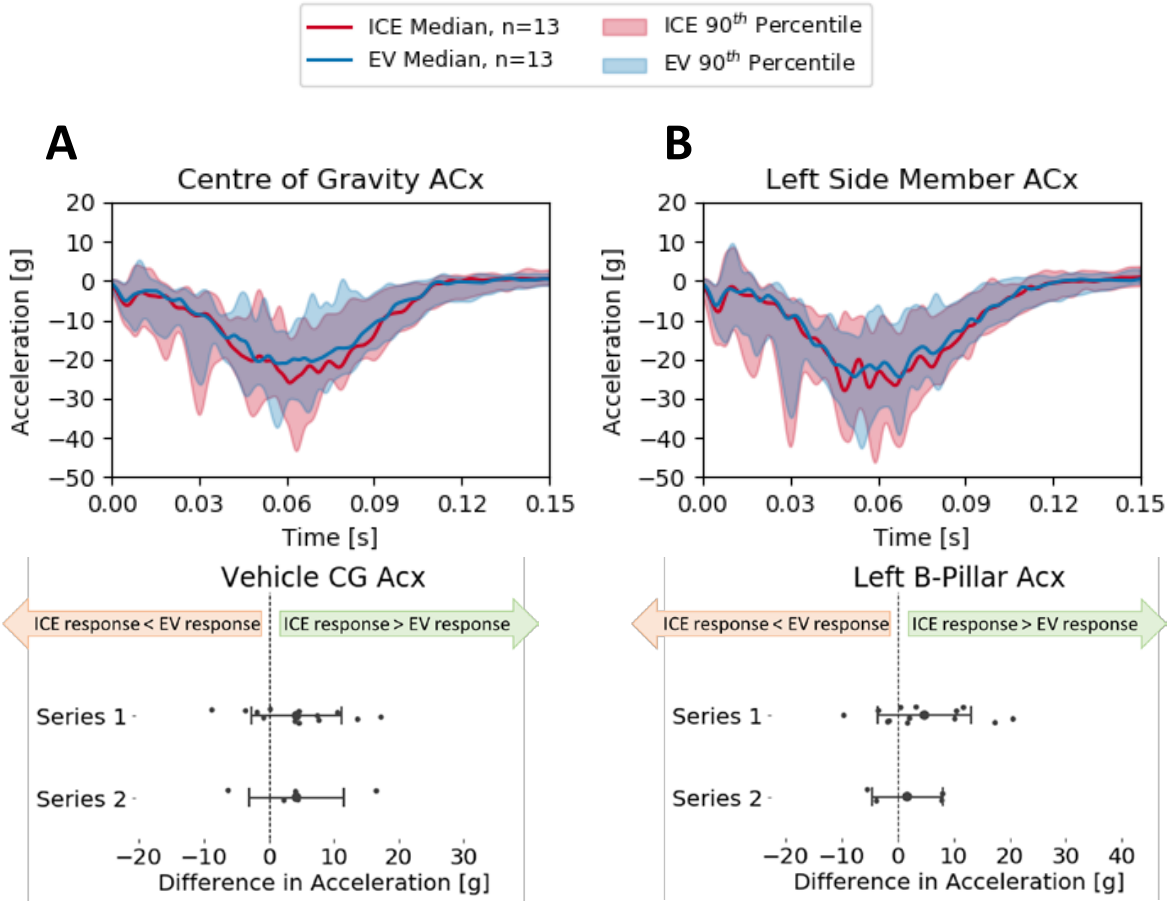

Fig. 2. Median acceleration-time history plots (top) and peak accelerations (bottom) of the vehicle at (A) the centre of gravity and (B) the left side members in ICE vehicles (red) and EVs (blue). Error bars represent the standard deviation of the mean.

Aggregate Paired Comparisons and Statistical Testing

Paired t-tests were used to identify statistically significant differences between driver responses in electric and ICE versions of the same models (referred to hereafter as EV/ICE pairs). Samples were grouped by driver ATD (Hybrid III or THOR), test series (series 1 or 2), and speed (48 km/h or 56 km/h). Since the number of paired tests conducted at 56 km/h was small, only the tests conducted at 48 km/h were used for statistical testing. However, observations of paired comparisons from tests conducted at 56 km/h yielded similar results to those presented here. The mean paired differences in driver responses and their respective p-values are provided in TABLE AI and TABLE AII.

Figure 3 shows, for each test group, the difference in driver responses in EV/ICE pairs, where a positive difference indicates a greater magnitude response in the ICE vehicle. Resultant head responses were statistically significantly greater in ICE vehicles only for tests with the THOR and only in the first test series. For tests in the second series and tests with the Hybrid III, resultant head responses were not statistically significantly different

in EV/ICE pairs (Fig. 3A). Head accelerations in x were not statistically significantly different for any of the paired driver comparisons (Fig. 3B).

In the first test series, chest resultant and x-accelerations of the THOR and Hybrid III male tended to be greater in ICE vehicles than in EVs (Fig. 3C-D). The differences were statistically significant for all directions and ATDs except for the x-acceleration of the Hybrid III. In the second test series, THOR chest responses in the resultant and x directions were not statistically significantly different in EV/ICE pairs (Fig. 3C-D).

Upper neck axial loads of the THOR in the first test series were statistically significantly greater in ICE vehicles; in the second series, neck loads tended to be greater in ICE vehicles but the difference was not statistically significant (Fig. 3E). In tests with the Hybrid III, neck loads were not statistically significantly different for EV/ICE pairs (Fig. 3E). Peak pelvis accelerations in x were significantly greater in the ICE vehicle only in tests from the first series with the THOR (Fig. 3F).

Paired comparisons of the responses of the Hybrid III female seated in the front passenger position (Fig. 4) were also grouped by speed and test series. Again, only tests conducted at 48 km/h were used for statistical testing. In both test series, peak head accelerations in the resultant and x directions tended to be greater in ICE vehicles (Fig. 4A-B). The differences were statistically significant for all directions and test series except for the x-acceleration in the first test series. In the first test series, chest accelerations in the resultant and x directions were also statistically significantly greater in the ICE vehicle (Fig. 4C-D). Mean differences in responses and their respective p-values are provided in TABLE AI and TABLE AII.

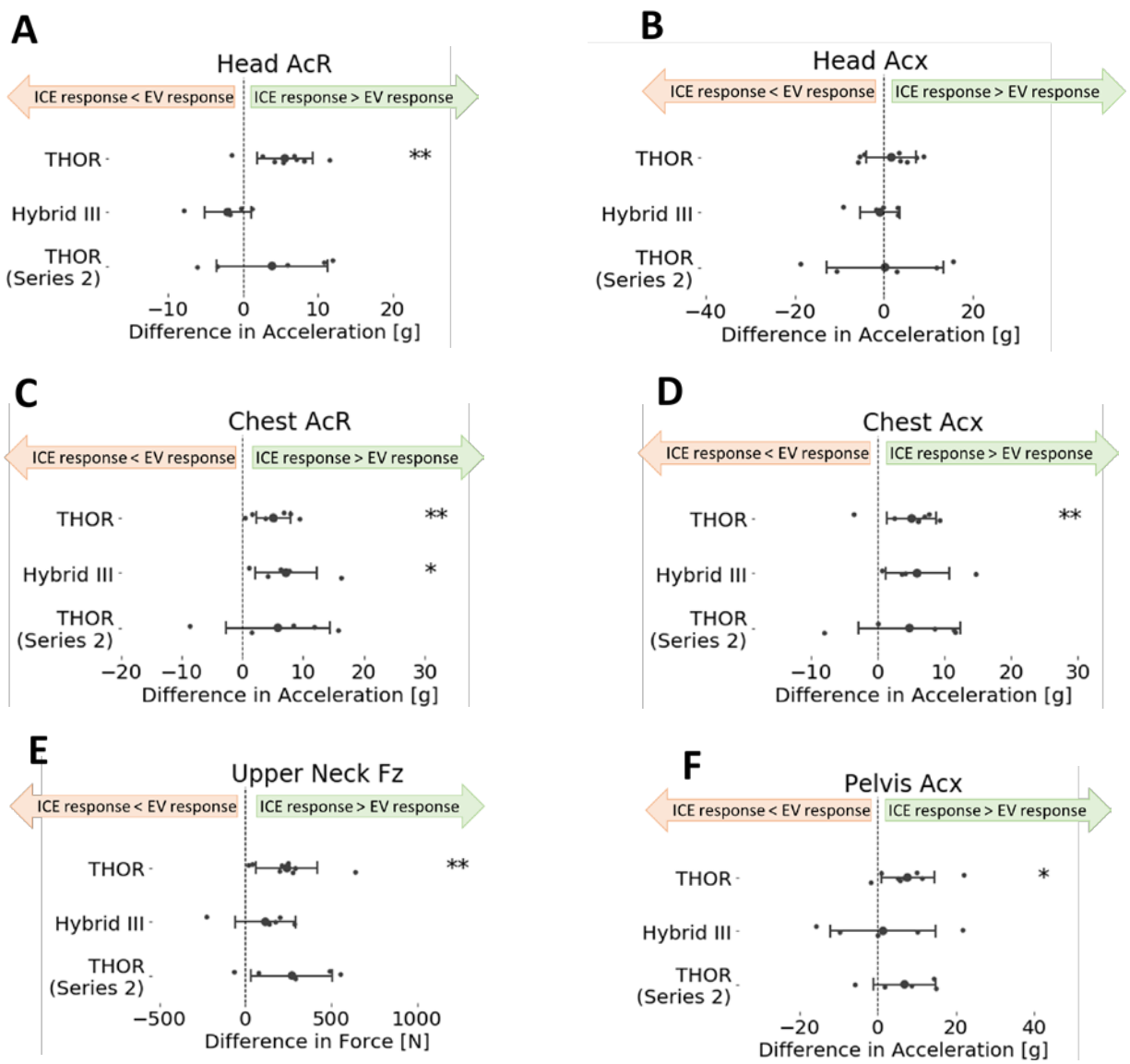

Fig. 3. Paired responses of the THOR and Hybrid III drivers in the first and second test series. Asterisks indicate statistical significance (* for $p < 0.05$, ** for $p < 0.01$).

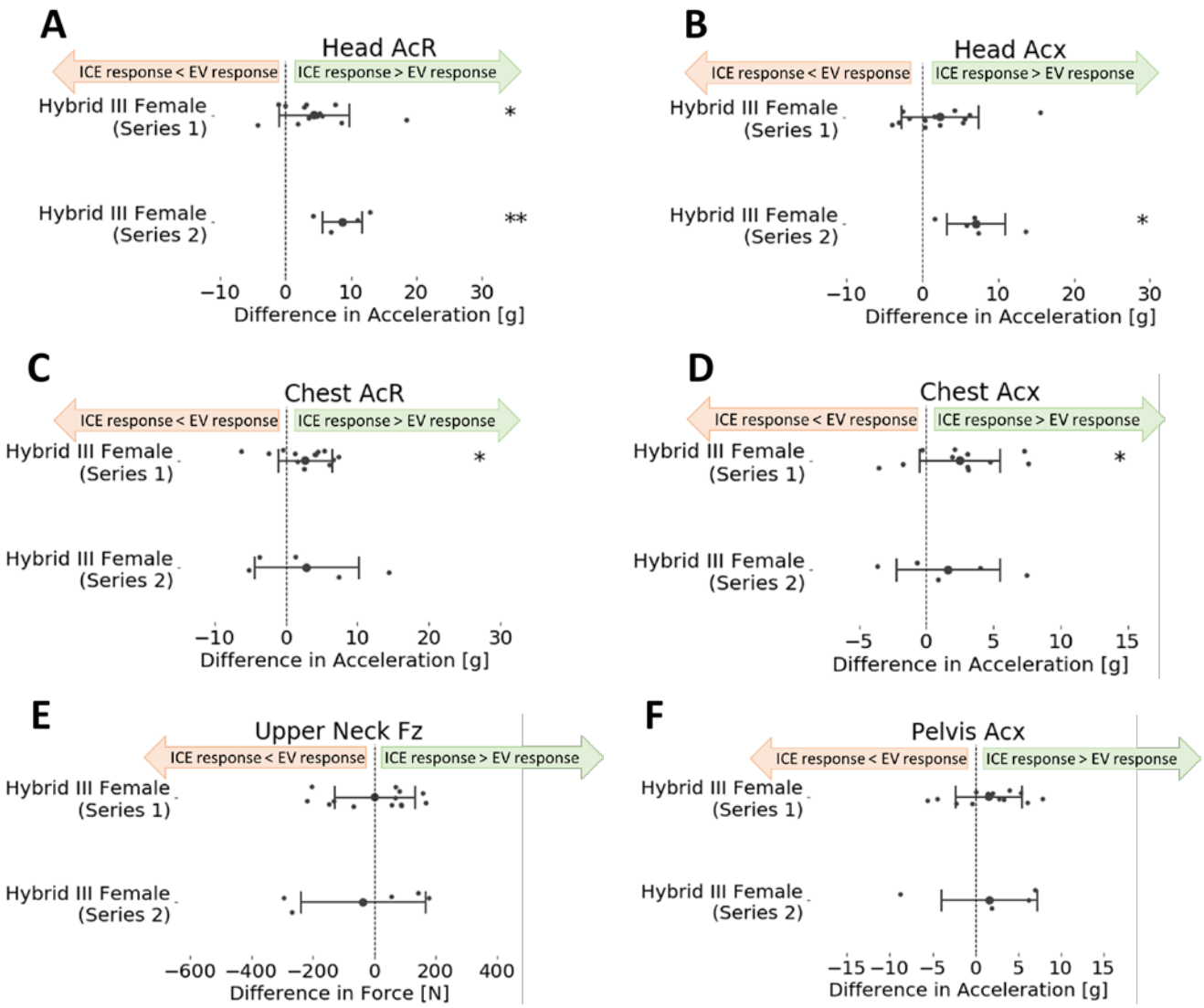

Fig. 4. Paired responses of the Hybrid III female passenger in the first and second test series.

In plug-in hybrid electric vehicles but not hybrid vehicles, peak head accelerations of the THOR were delayed in time by up to 5 milliseconds compared to the THOR head responses in ICE vehicles. Video analysis suggested that contact between the THOR and the airbag was delayed by up to 5 milliseconds in plug-in vehicles.

Estimating the Effect of Vehicle Weight

One obvious difference between EVs and their ICE-powered equivalents is their masses: the added weight of the battery causes EVs to be heavier than ICE models. On average, EVs were 190 ± 76 kg heavier than ICE vehicles in the first series and 291 ± 70 kg heavier in the second series (TABLE I and TABLE II). For this reason, the difference in the vehicle weights of EV/ICE pairs was identified as a potential cause for the differences observed in the driver and passenger responses.

To assess the extent to which weight differences alone could account for the differential occupant responses observed within EV/ICE pairs, linear models were constructed. We modeled the responses in ICE vehicles as a function of vehicle weight and used the model to predict the responses in the corresponding EV. Since the models were fitted independently of the responses seen in EVs, they predict how responses in an ICE vehicle would change if only the vehicle weight was changed. The strength of the relationship between each response and vehicle weight was varied: R^2 values between vehicle weight and the sample of responses used to fit the linear models ranged from 0.004 to 0.275 (TABLE III, left columns).

Figure 5A compares the responses seen in ICE vehicles, i.e., the sample used for the regression, (red), the expected responses in EVs as predicted by the linear model (purple), and the actual responses seen in EVs (blue). Predicted THOR head responses and Hybrid III female chest responses appeared to be close to the actual responses seen in EVs. The error between predicted and actual values were not statistically significantly different from zero by the paired t-test (p=0.194 for THOR head AcR, p=0.376 for female chest AcR, p=0.547 for female chest Acx). Predicted THOR chest response values lay between those seen for ICE vehicles and EVs, and the mean error between the predicted and actual values was greater than zero (p=0.006 for resultant and x-acceleration). The predicted Hybrid III female head responses were also between values seen in ICE vehicles and EVs (p=0.033 for resultant acceleration; p=0.060 for x-acceleration). Similar results were obtained by predicting ATD responses in ICE vehicles with linear models fitted using responses observed in EVs (Fig. 5B). For models fitted with data from EVs, the R^2 values between vehicle weights and the sample of responses used to fit the models ranged between 0.009 and 0.459 (TABLE III, right columns).

TABLE III
R^2 VALUES BETWEEN VEHICLE WEIGHT AND OCCUPANT RESPONSES

ICE Response vs. Vehicle Weight		EV Response vs. Vehicle Weight	
Response	R^2	Response	R^2
THOR Head AcR	0.275	THOR Head AcR	0.459
THOR Chest AcR	0.100	THOR Chest AcR	0.186
THOR Chest Acx	0.090	THOR Chest Acx	0.248
HF Head AcR	0.004	HF Head AcR	0.045
HF Head Acx	0.013	HF Head Acx	0.009
HF Chest AcR	0.094	HF Chest AcR	0.315
HF Chest Acx	0.100	HF Chest Acx	0.325

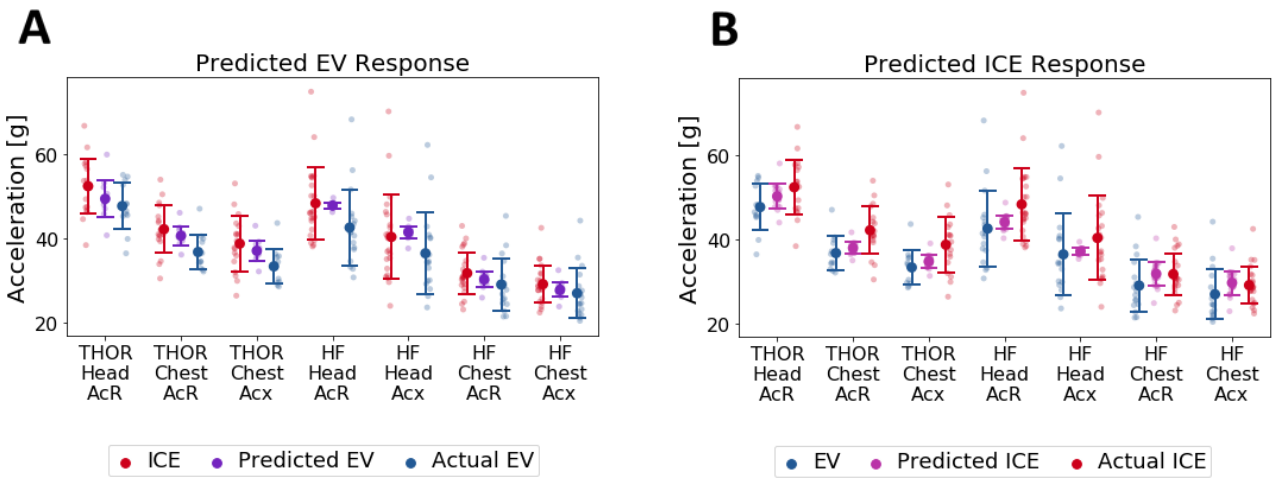

Fig. 5. (A) Comparisons of occupant responses in ICE vehicles (red), responses predicted to occur in EVs (purple), and actual responses observed in EVs (blue). (B) Comparisons of occupant responses in EVs (blue), responses predicted to occur in ICE vehicles (purple), and actual responses observed in ICE vehicles (red).

IV. DISCUSSION

In this study, ATD responses in electric vehicles were compared to those in ICE-powered vehicles. Comparisons were paired so that ATD responses observed in a given EV model were compared to those observed in the ICE version of the same model. Two test series were conducted, the first of which involved EVs impacting their ICE equivalents, and the second of which involved EVs and equivalent ICE models impacting the same striking vehicle. The paired t-test was applied to assess the statistical significance of differences observed in the sample of EV/ICE pairs. Trends in differential ATD responses were also reported if they were qualitatively observable but statistical

significance was not strictly achieved (p>0.05). Significance values of the reported differences ranged from p=0.069 to p=0.132.

Both statistical testing and qualitative comparisons suggested that multiple upper body responses, i.e. head accelerations, chest accelerations, and neck forces, showed tendencies to be slightly greater in ICE vehicles than in EV counterparts. Tests with the THOR in the first test series additionally showed statistically significantly greater pelvis fore-aft accelerations in ICE vehicles compared to EVs. Little evidence was found to suggest that any of the recorded ATD responses tended to be greater in EVs than ICE vehicles. Based on these comparisons, EVs appear to provide at least the same level of protection as ICE vehicles in the moving car-to-moving car frontal offset impact configuration.

Paired comparisons of the THOR and Hybrid III male head responses yielded somewhat different results. In the first series, tests with the THOR yielded greater head responses in ICE vehicles in the resultant but not in x. For the Hybrid III male, neither head response was statistically significantly different in EV/ICE pairs. Additionally, statistically significant differences in the peak neck axial load were found only for the THOR. The THOR neck was designed to allow for greater flexion compared to the Hybrid III male [7], and differences in the neck tension, flexion, and extension of the two ATDs have been reported [7] [8]. In frontal offset deformable barrier tests, the differences in HIC36, HIC15, and head 3ms clips between the Hybrid III male and the THOR-NT were found to be greater than the differences in other injury measurements [8]. These differences in head kinematics were attributed to the differences in the structural designs of the two ATDs' head-neck assemblies [8].

In contrast to head and neck responses, differences in chest responses in EV/ICE pairs were more consistent across ATDs, although statistical significance was varied. In the first test series, the chest responses (resultant and in x) of all three ATDs tended to be greater in ICE vehicles. Interestingly, in the second series, chest responses were comparable in EV/ICE pairs for both the THOR and Hybrid III female, even though the average weight differential was greater in the second series. Since the increase in weight differential associated with the second series did not correspond to greater differences in chest responses, a direct correlation between difference in chest response and difference in EV/ICE vehicle weight appears unlikely. A key difference between the two test series is that the weight of the striking vehicle was controlled in the second test series but not the first. Controlling for the weight of the striking vehicle in the second series reduced the differences in chest response, suggesting a possible role for the striking vehicle's weight in influencing chest responses. Other factors such as vehicle alignment and geometric compatibility may also have accounted for the differences in chest responses in EV/ICE pairs observed in the first series.

To assess how well vehicle weight alone could account for the differences observed in the occupant responses of EV/ICE pairs, the responses in EVs (or ICE vehicles) were predicted by linearly scaling the responses seen in ICE vehicles (or EVs) according to the weight of the EV (or ICE vehicle). Errors between predicted and actual THOR chest responses were statistically significantly nonzero, and mean predicted values were between the mean responses seen in EVs and in ICE vehicles. Together, these results suggest that the models did not sufficiently correct for differences in chest response by simply scaling according to vehicle weight. However, the apparent dissociation between chest response and vehicle weight cannot be conclusively confirmed, because the correlation between chest responses and vehicle weight were weak at the onset (TABLE III).The relationship between weight and chest response, if indeed one exists, may not be well-represented by the statistical models used here. The models serve as tools to explore trends between occupant response and vehicle weight. A more complete model where ATD responses (such as the chest response) are accurately predicted should be used to draw conclusions about the significance of these trends.

The work presented here is limited by the small sample size of each test group (n=5-8). For such small sample sizes, trends in the differences of EV/ICE pairs needed to be very strong in order for statistical significance to be reached. For example, to obtain a p-value below 0.05 with a sample size of five and a nonparametric test of the mean, e.g., the Wilcoxon signed-rank test or a permutation test, the samples used would need to be either all above or all below zero. This relatively strict requirement may cause differences to be nonsignificant despite qualitatively observable trends. With the paired t-test, the requirement is slightly relaxed, although the validity of the test relies on the assumption that the paired differences are normally distributed. To supplement statistical analyses, qualitative observations on the trends seen in the paired differences in responses were also made.

Differences in ATD responses were observed in EV/ICE pairs. However, the contribution of vehicle characteristics to these differences remains largely unstudied. In this study, only vehicle weight, centre of gravity

acceleration, and B-pillar acceleration were quantified. Post-test photos of the vehicle damage were examined and an attempt was made to group vehicles by type or extent of damage, but this was largely unsuccessful. The offset crash configuration causes significant disruption of the left front corner that is very difficult to quantify in a reliable and repeatable manner. Overall, the occupant compartment remained intact and no notable differences between EV and ICE vehicles were observed. Other characteristics of EVs and ICE vehicles and their respective responses should be investigated.

The extent to which the linear models constructed here represent the true relationship between occupant responses and vehicle weight will be examined in future work by consolidating the EV/ICE sample of vehicles with a sample of vehicles from the light-weighting programme. The relationships (or lack thereof) presented here between occupant responses and vehicle weight could be validated by merging the EV/ICE and light-weighting samples together to widen the observed range of vehicle weights. Investigations into the effect of light-weighting on occupant responses could also be useful to this end.

The current study focused on ATD responses in EVs as compared to ICE vehicles. Future work will also examine the protection of occupants in partner vehicles, i.e., occupant protection when the vehicle is impacted by an EV compared to occupant protection when the vehicle is impacted by an ICE vehicle.

V. CONCLUSIONS

Statistically significant differences in the driver responses of EV/ICE pairs tended to occur in the head, neck (tension), and chest. Where differences between the responses in EV/ICE pairs were identified, responses tended to be greater in ICE vehicles compared to equivalent EVs. The results of comparisons of driver responses within EV/ICE pairs differed by ATD (THOR or Hybrid III male). The differences in the results obtained with the THOR and Hybrid III illustrate the differences between the two ATDs, especially differences in the head-neck assemblies. Evaluations of electrical isolation showed that the propulsion batteries remained isolated from the vehicle chassis after every test. All batteries remained in place and undamaged. The results presented suggest that in the moving car-to-moving car frontal offset configuration, EVs appear to provide at least the same level of protection as ICE vehicles.

VI. ACKNOWLEDGEMENT

The authors gratefully acknowledge the staff at PMG Technologies for conducting the tests, and the technical assistance of Victor Chirila and Francois Giguère.

VII. DISCLAIMER

This paper shall not be construed as an endorsement, warranty, or guarantee, expressed or implied, on the part of Transport Canada for any evaluated material, product, system or service described herein. Readers should not infer that Transport Canada's evaluation is for any purpose or characteristic other than as stated herein. All information in this document is for information purposes, only, and is not intended to provide any specific advice. Any reliance on or use of the information contained in this document is at the user's sole risk and expense.

VIII. REFERENCES

[1] EU. (2014) European Union (EU) Regulation No 333/2014 of the European Parliament and of the Council of 11 March 2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars. Internet: [https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2014.103.01.0015.01.ENG], 2014-05-04 [Accessed: 2019-29-03].

[2] US Environmental Protection Agency, NHTSA. (2010) Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule. 75 FR 25323.

[3] International Energy Agency. (2018) Global EV Outlook 2018. *9th Clean Energy Ministerial Meeting*, 2018, Copenhagen, Denmark.

[4] United Nations. (2015) Paris Agreement. Internet : [https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement], [Accessed: 2019-29-03].

[5] NHTSA. (2015) THOR-50th Percentile Male Metric Driver Dummy Seating & Positioning Procedures. Internet: [https://www.regulations.gov/document?D=NHTSA-2015-0119-0009], 2015-17-12 [Accessed: 2019-29-03].
[6] Pedregosa, F., et al. (2011) Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, 12: 2825-2830.
[7] Shaw, G., Crandall, J., Butcher, J. (2000) Biofidelity evaluation of the THOR advanced frontal crash test dummy. *Proceedings of IRCOBI Conference*, 2000, Montpellier, France.
[8] Yaguchi, M., Ono, K., Masuda, M., Watamori, T., Seshita, T., Hibino, T. (2009) Comparison of dynamic responses of the THOR-NT and Hybrid III in Offset frontal crash test. *21st International Technical Conference on the Enhanced Safety of Vehicles*, 2009, Stuttgart, Germany.

APPENDIX

TABLE AI
DIFFERENCES IN PAIRED OCCUPANT RESPONSES AND SIGNIFICANCE: SERIES 1

ATD	Response [unit]	Mean change in response (ICE-EV)	p-value
THOR	Head AcR [g]	5.6	0.005
	Head Acx [g]	1.7	0.455
	Upper Neck Fz [N]	240	0.009
	Chest AcR [g]	5.1	0.002
	Chest Acx [g]	5.1	0.009
	Pelvis Acx [g]	7.6	0.021
Hybrid III Male	Head AcR [g]	-2.1	0.251
	Head Acx [g]	-0.9	0.710
	Upper Neck Fz [N]	120	0.256
	Chest AcR [g]	7.2	0.048
	Chest Acx [g]	5.9	0.069
	Pelvis Acx [g]	1.4	0.850
Hybrid III Female	Head AcR [g]	4.4	0.014
	Head Acx [g]	2.4	0.132
	Upper Neck Fz [N]	2	0.957
	Chest AcR [g]	2.7	0.028
	Chest Acx [g]	2.5	0.013
	Pelvis Acx [g]	1.6	0.176

TABLE AII
DIFFERENCES IN PAIRED OCCUPANT RESPONSES AND SIGNIFICANCE: SERIES 2

ATD	Response [unit]	Mean change in response (ICE-EV)	p-value
THOR	Head AcR [g]	3.9	0.351
	Head Acx [g]	0.2	0.972
	Upper Neck Fz [N]	270	0.083
	Chest AcR [g]	5.8	0.246
	Chest Acx [g]	4.8	0.280
	Pelvis Acx [g]	6.9	0.157
Hybrid III Female	Head AcR [g]	8.8	0.004
	Head Acx [g]	7.1	0.021
	Upper Neck Fz [N]	-40	0.742
	Chest AcR [g]	2.9	0.470
	Chest Acx [g]	1.6	0.440
	Pelvis Acx [g]	1.7	0.586