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Impact of Speeds on Drivers and Vehicles — Results from Crash Tests

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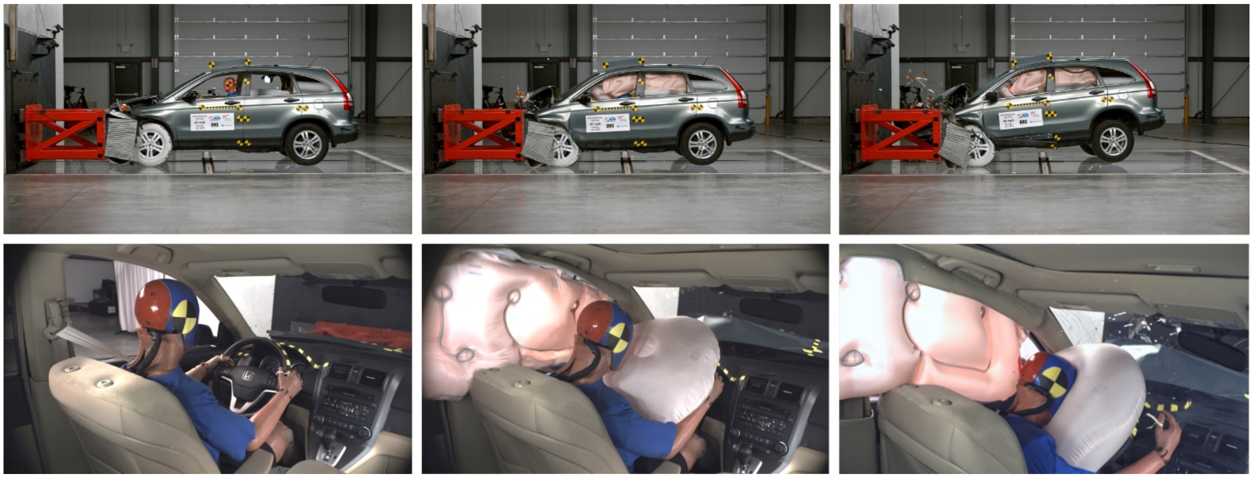
AAA Foundation for Traffic Safety | IIHS HLDI | HUMANETICS



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Foreword

AAA Foundation for Traffic Safety, in collaboration with the Insurance Institute for Highway Safety and Humanetics Innovation Solutions, conducted three vehicle crash tests in October 2019 to assess the effects of speed on vehicles and drivers. This joint effort represents our organizations' commitment to improve traffic safety by sharing study findings with researchers, practitioners, governmental transportation authorities, and the general public.

Speed continues to play a key role in traffic safety, and posted speed limits offer motorists information on the appropriate speeds they should travel. Multiple studies have found obvious correlations between speed, crash risk, and injury severity. In the recent years, however, some states and cities in the U.S. have steadily raised the posted speed limits on their roads based on average travel speeds of vehicles. Information presented in this technical report will hopefully serve as a helpful reference for decision makers and encourage them to use multiple criteria when considering changes to posted speed limits in their jurisdictions.

Work described in this report would not have been possible without the additional financial support from AAA Auto Club Group and in-kind assistance from AAA Western and Central New York during the vehicle crash tests.

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Founded in 1947, the AAA Foundation for Traffic Safety in Washington, D.C., is a nonprofit, publicly supported charitable research and education organization dedicated to saving lives by preventing traffic crashes and reducing injuries when crashes occur. Funding for this report was provided by voluntary contributions from AAA/CAA and their affiliated motor clubs, individual members, AAA-affiliated insurance companies and other organizations or sources.

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Executive Summary

Introduction

Despite numerous studies reporting the negative impacts of increased speeds on roadways, many states have steadily raised their posted speed limits. In response to these concerns, the AAA Foundation for Traffic Safety initiated a multi-phased study to investigate the effect of posted speed limit changes on traffic safety. The first phase entailed gathering feedback from traffic engineers on how posted speed limits are set and what factors they consider in changing posted speed limits (Kim et al., 2019). The second phase, which is the subject of this report, entailed a collaborative effort with the Insurance Institute for Highway Safety (IIHS) and Humanetics Innovative Solutions to examine how vehicle crashworthiness and occupant protection degrade as impact speed increases. Towards this, three vehicle crash tests were conducted.

Methodology

Following the IIHS test protocol, the crash tests were set up and executed between October 28 and 30, 2019. The following summarizes details of the tests:

- **Test type:** Tests were conducted at a moderate overlap frontal impact crash mode. In this mode, 40% of the maximum width of the test vehicle crashed into a deformable barrier on the driver side with the forces concentrated on the driver side of the vehicle. This test setup simulates a head-on, partial-overlap crash between two vehicles of the same weight and size travelling at the same speed.
- **Crash speed:** Tests were conducted at three different impact speeds – 40 mi/h for the baseline test (Test 1) and 50 mi/h and 55.9 mi/h for two higher speeds (Test 2 and Test 3, respectively).
- **Test vehicle:** Three 2010 Honda CR-V EX vehicles were selected as they represented the average age of vehicles (11.8 years in 2019) on today's U.S. roadways and earned the top rank in crash test ratings. All three had comparable specifications including manufacture date, vehicle mileages, and drive type.
- **Barrier type:** Test vehicles were crashed into a barrier face that was fixed and composed of aluminum honeycomb materials.
- **Crash test dummy type:** This study used a Hybrid III 50th percentile male dummy positioned in the driver seat to represent an average-sized male driver. The dummy in each test was instrumented to record measures from the head, neck, chest, thighs, and legs.

Main Findings

Overall, as the crash speed increased, the additional occupant compartment deformations and higher crash energy resulted in higher peak injury measures recorded by dummy sensors over the entire body region. Key findings included the following:

Vehicle response

- The increased impact speed of 10 mi/h in Test 2 and 15.9 mi/h in Test 3 corresponded to an increase in kinetic energy of 54% and 95%, respectively, relative to Test 1.
- Test 1 had minimal occupant compartment intrusion. Test 2 resulted in some deformation of the driver side door opening and to the instrument panel and footwell (brake pedal). In contrast, the occupant compartment was significantly compromised in Test 3, narrowing the driver door opening by 4 inches and having 5 to 16 inches greater interior intrusion than in Test 1.
- In Test 1, there was minimal movement of the steering wheel (1 inch both forward and upward) because of the dummy loading the steering wheel through the airbag. In Tests 2 and 3, there was some rearward movement of the steering wheel (1 inch and 3 inches, respectively) and large upward movement (4 inches and 7 inches, respectively), which compromised the position of the airbag.

Injury measures from the dummy

- **Head:** Severe injury measurements for the dummy were observed only in Tests 2 and 3. The higher energy combined with the large upward movement of the steering wheels resulted in the dummy's head going through the deployed airbag (also known as "bottoming out"). This caused the face to make hard contact with the steering wheel rim, hub or both and produced high values on the Head Injury Criterion that are indicative of a high risk (52% – 67%) of facial fracture and severe brain injury (Consumer Information; New Car Assessment Program, 2008).
- **Neck:** Test 3 showed a high value of peak neck tension, which corresponds to a 19% risk of a serious neck injury (Consumer Information; New Car Assessment Program, 2008).
- **Chest:** Peak accelerations to the chest increased with test severity, but the maximum chest compression was similar between the three tests. There was no indication of severe chest injury in any of the tests.
- **Lower extremities:** Loads to the lower extremities and, as a result, the likelihood of fracture to the long bones in the lower leg (tibia, fibula, or both) also increased with impact speed.

According to National Highway Traffic Safety Administration (Consumer Information; New Car Assessment Program, 2008), the injury measures from the baseline test (Test 1) represent a

15% risk of serious or worse[1] *overall* injury. In contrast, the result from Test 2 indicates a 59% risk, while the result from Test 3 indicates a 78% risk of serious or worse *overall* injury.

As shown in the table below, using IIHS protocols (IIHS, 2006, 2007, 2014, 2017), only the baseline test vehicle would earn a rating of good in the overall evaluation, which is derived from the ratings for the injury measures, structure, and restraints and kinematics components. Tests 2 and 3 would earn a poor overall score, with Test 2 results heavily influenced by the elevated head injury measures, and Test 3 by elevated injury measures to vital body regions and the heavily compromised occupant compartment.

Table ES1. Vehicle crashworthiness and occupant protection ratings based on IIHS protocols

	Test 1 40 mi/h (64.4 km/h)	**Test 2** 50 mi/h (80 km/h)	**Test 3** 55.9 mi/h (90 km/h)
Overall evaluation	G	P	P
Structure	G	G	P
Restraints & Kinematics	G	A	P
Driver injury measures			
Head/neck	G	P	P
Chest	G	A	P
Left leg	G	G	A
Right leg	G	P	P

Note: The overall rating and each measurement for a vehicle's crashworthiness can be good (G; the highest rating), acceptable (A), marginal (M), or poor (P; the lowest rating).

Conclusion

These results show that the impact speeds in Tests 2 and 3 increased the kinetic energy to the level that exceeds the capacity handled by the vehicle's energy-absorbing structures. The remaining crash energy transferred to the occupant compartment and resulted in increased

[1] A score of 3 or higher on the Abbreviated Injury Scale (AIS) (Associate for the Advancement of Automotive Medicine, 1990)

injury severity in the test dummies. This implies that the survival likelihood of the driver in the Test 2 and 3 vehicles would be considerably lower than that of the Test 1 vehicle.

Speeds on the roadway are often significantly higher than those of posted speed limits and those used in crash tests. Even after accounting for braking and/or other factors that decrease impact speed, some portion of serious injury crashes in the real world occur at severities higher than those from these crash tests. Further, this study clearly shows that relatively small increases in absolute speed (5 and 10 mi/h) not only degrade the occupant survival space in vehicles with state-of-the-art crashworthiness designs but also proportionally increase the driver's injury and fatality risk.

The results and implications from the present study convey that there is a rise in occupant injury risk and compromised occupant compartment due to an increased impact speed, given other factors remaining constant. This information suggests advocating the importance of road safety improvement in speed limit policies and prioritizing safety when setting maximum speed limits should continue.

Introduction

Study Motivation and Background

In 1995, U.S. legislation repealed the 55 mph national maximum speed limit on interstate highways, an act that provided complete freedom for states to set their own speed limits. Since then, many states have steadily raised their posted speed limits.

Meanwhile, many studies (Nilsson, 2004; Vadeby and Forsman, 2018; Kibar and Tuydes-Yaman, 2020) have reported the negative impact of increasing posted speed limits on traffic safety. For example, Castillo-Manzano et al. (2019) conducted a meta-analysis to examine the effects of increasing speed limits on traffic fatalities in the United States. They examined the fatality count both on U.S. rural interstates, where speed limits were increased in 1987 and 1995, and on statewide road networks including rural interstates and found that while both counts went up, the effect was larger on the rural interstates. A study by Warner et al. (2019) also reported that on roadway segments where speed limits increased to 75 or 80 mph, the increases in fatal crashes involving speeding and driver distraction were greater than the increases in the total count of fatal crashes. In addition, Wang et al. (2018) showed that both mean speed and speed variation on urban arterials were positively associated with total crashes.

In response to these findings, as well as public concerns about the potential safety implications of such increases, the AAA Foundation for Traffic Safety (AAAFTS) initiated a multi-phase study to investigate the effect of posted speed limit changes on safety. AAAFTS completed Phase 1 in 2018, which reviewed the current practices for setting posted speed limits (Kim et al., 2019). As part of this effort, an extensive literature review was conducted and a subsequent online survey was developed and administered to traffic engineers across the nation. The survey revealed that although many respondents consider multiple factors in their decision to change posted speed limits, including crash frequency statistics and surrounding land use, the most common factor (considered by 98% of respondents) was the 85th percentile operating speed — "the speed at or below which 85 percent of the motor vehicles travel" (Federal Highway Administration, 2009). Findings from Phase 1 suggest that traffic engineers generally consider mobility more often than they do safety when changing speed limits.

To further their investigation on the impacts of posted speed limit changes on road safety, in 2019 the AAAFTS launched the second phase of their study. In collaboration with the Insurance Institute for Highway Safety (IIHS) and Humanetics Innovative Solutions, the team conducted vehicle crash tests to examine the relationship between speed and crashworthiness performance metrics. As states have steadily enacted policies increasing the maximum speed limit with 41 states currently having speed limits of 70 mph or higher, more studies on the outcomes of high speed crashes are needed.

Vehicle Crashworthiness Test

Vehicle crash tests have been widely used in many countries, including the U.S., to evaluate the level of occupant protection when vehicle structures and restraint systems are compromised. Crash tests employ different laboratory crash modes in a variety of configurations: front crash tests (full-width and partial overlap configurations), side crash tests, roof strength tests for rollover protection, and rear impact tests.

The IIHS, which is one of the entities executing crashworthiness programs for consumer information in the U.S., evaluates vehicles by combining measurements from crash dummy injury, occupant compartment intrusion, occupant restraint system, and dummy kinematics during a crash test. The overall rating for a vehicle's crashworthiness can be good, acceptable, marginal, or poor. An analysis of real-world crash data indicates drivers in vehicles with a good rating have a 46% lower fatality risk in frontal crashes compared with drivers in poor-rated vehicles (IIHS, 2020).

Unlike standard crash tests for these safety ratings, this study focused on how vehicle crashworthiness degrades as impact speed increases. The results and implications convey a solid message of increased occupant injury risk and compromised occupant compartment with increased impact speed, given other factors remaining constant. The information is valuable to policy/lawmakers and practitioners who advocate for more safety considerations when setting maximum speed limits.

This report summarizes the crash test designs, protocols followed, and results from data analyses. A discussion on the implications of these results and future work is presented as well.

Study Methodology

A series of crash tests requires an appropriate facility and specialized equipment, along with detailed preparation work for setup and execution. The test design includes a consideration of various parameters including but not limited to test type, impact speed, vehicle type, barrier type, and dummy type. This section presents the setup of each parameter for this study following the IIHS test protocol (IIHS, 2017) and the rationale for the selected setup.

Test Type

Since 1979, the National Highway Traffic Safety Administration (NHTSA) has performed the New Car Assessment Program (NCAP) to evaluate front crash protection in a frontal crash into a flat rigid barrier at 56 km/h (35 mi/h). The NCAP test is based on the U.S. frontal regulatory test, Federal Motor Vehicle Safety Standard (FMVSS) 208, which is conducted at 48 km/h (30 mi/h). NHTSA's FMVSS 208 and NCAP tests led the way for improvements in occupant protection and occupant restraint systems (Hackney, 1993; Kahane, 1994).

Despite the progress made with the flat rigid wall test, analyses of real-world crashes indicate partial overlap (or offset) crashes are an important consideration that could help in the assessment of frontal crashworthiness (Zeidler et al., 1981; Hobbs 1991; Killina et al., 1992; Witteman, 1993). The offset test mode concentrates crash loads on only part of the front structure, resulting in different challenges for maintaining occupant survival space.

For this study, a moderate overlap frontal impact test was conducted following the IIHS test protocol version XVIII (IIHS, 2017) for all three tests, except we increased the impact speed in Tests 2 and 3. In this crash mode, 40% of the maximum width of the test vehicle crashed into a deformable barrier on the driver side with the forces concentrated on the driver side of the vehicle. Figure 1 illustrates the vehicle aligned with the barrier from the overhead view. This test setup simulates a head-on, partial-overlap crash between two vehicles of the same weight and size travelling at the same speed.

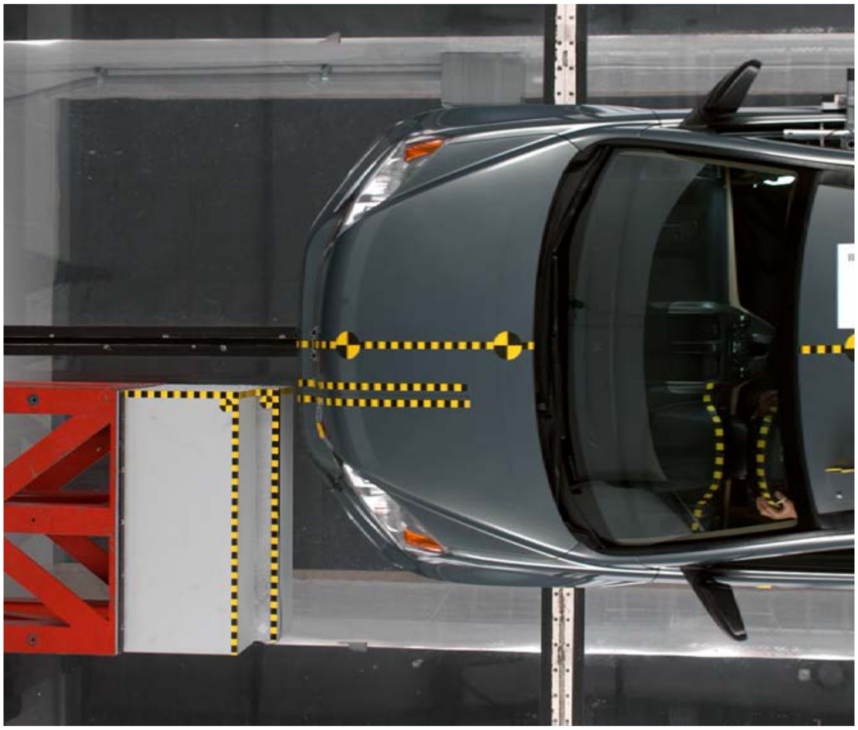

Figure 1. The overhead pre-crash view for the 40% offset frontal crash test mode

Crash Speed

Crash tests were conducted at three different impact speeds. Because the purpose of this study was to investigate the effects of progressively higher impact speeds on occupant protection, as well as vehicle performance, the tests were conducted at the standard consumer information test speed of 64.4 km/h (40 mi/h) and two higher speeds, 80 km/h (50 mi/h) and 90 km/h (55.9 mi/h).

It is important to note that the impact speed of these tests do not necessarily represent a driving speed or a speed limit. In these tests, the vehicles contact an unmovable barrier with a deformable element attached. The barrier does not move away as an impacted vehicle would in a moving-car to stopped-car crash. In addition, real crashes may involve braking or other slowing factors prior to impact. Thus, the crash speeds tested here may be representative of crashes that occur on roadways with posted speed limits that are higher than the test speeds.

Test Vehicle

To select an appropriate test vehicle for this study, several criteria were considered. First, the tests included secondhand vehicles, as they represent the average age of vehicles (11.8 years in 2019) on U.S. roadways today (USDOT, 2018; Statista, 2019). Second, small to midsize sport utility vehicles were used for testing due to the popularity of these vehicles. At the time of testing, the demand for these vehicles in the market was increasing and forecasts indicated this trend would continue. Third, tests included vehicle models that received good safety ratings in crashworthiness tests in order to examine how the differences in vehicle speed would affect driver injuries in a vehicle that earns high marks for frontal crash protection. Lastly, vehicle history was examined to exclude vehicles with salvaged titles, flood vehicles, vehicles with underbody corrosion, and vehicles with evidence of a prior crash and associated repairs.

The aforementioned selection criteria identified the 2010 Honda CR-V EX as the desired year/make/model for the subject vehicle. Table 1 summarizes key specifications of the selected test vehicles and Figures 2 – 4 present the selected vehicles after setup for the crash tests.

Table 1. Test vehicle specifications

	Test 1	**Test 2**	**Test 3**
Impact velocity	64.4 km/h (40 mi/h)	80 km/h (50 mi/h)	90 km/h (55.9 mi/h)
Make & Model	Honda CR-V EX	Honda CR-V EX	Honda CR-V EX
Manufacture date	May 2010	June 2010	April 2010
Vehicle mileage	101,116	94,524	95,156
Drive Type	All wheel drive	All wheel drive	All wheel drive
Vehicle test mass	1,710 kg	1,716 kg	1,713 kg
Vehicle ID Number	5J6RE4H56AL073772	5J6RE4H54AL076167	5J6RE4H5XAL061981

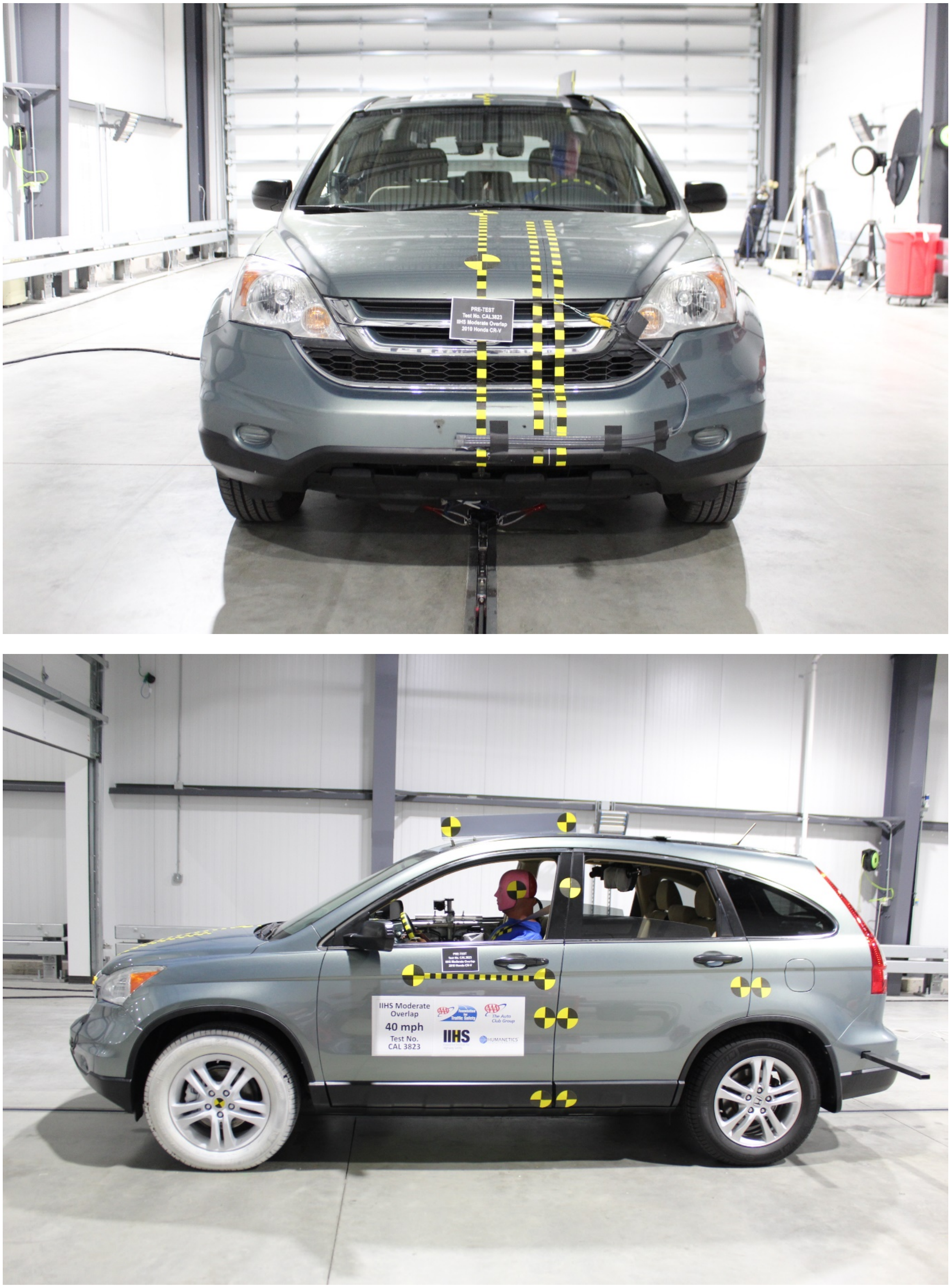

Figure 2. Front and side views of the vehicle for Test 1

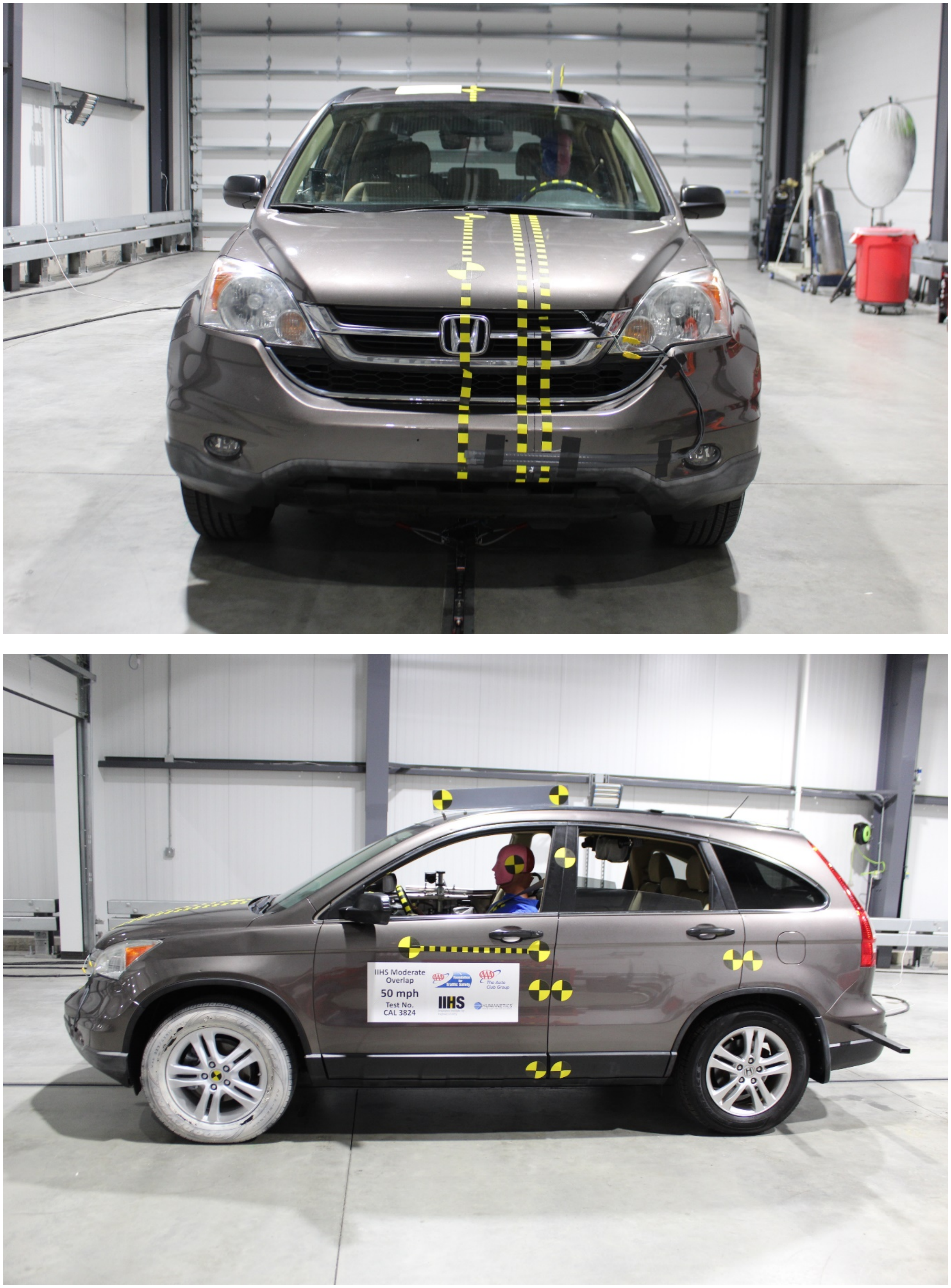

Figure 3. Front and side views of the vehicle for Test 2

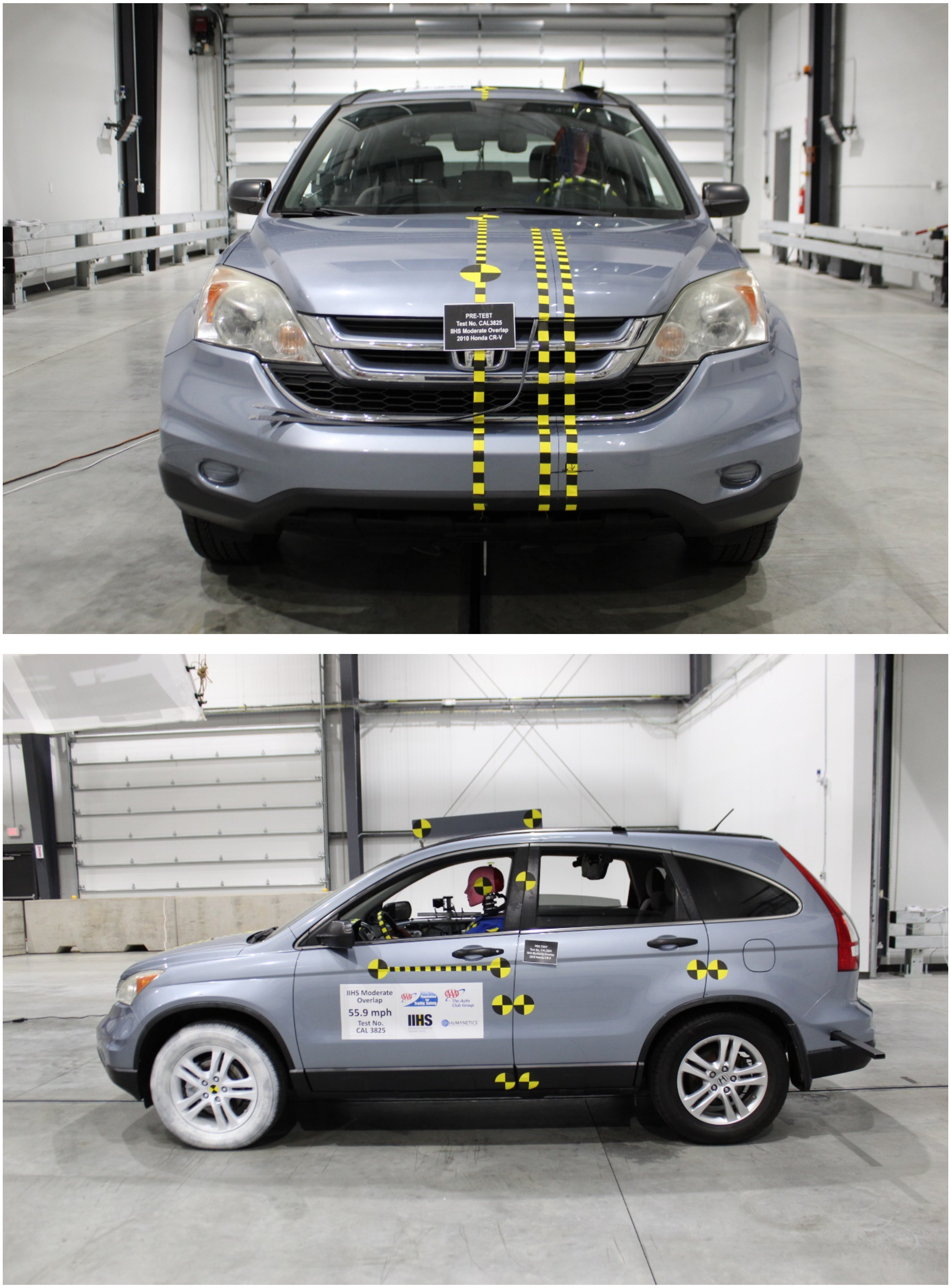

Figure 4. Front and side views of the vehicle for Test 3

Barrier Type

The barrier that the test vehicles collided with consisted of three components: base unit, extension, and deformable face. Figure 5 illustrates the barrier composition. The base unit is made of laminated steel and reinforced concrete, while the main body of the extension is composed of structural steel. The deformable face is 1 m wide and attached to the extension at a height of 20 cm from the ground. The face is composed of a bumper attached to a base constructed of different aluminum honeycomb materials. Figure 6 presents pre-test views for the actual barrier used for this study.

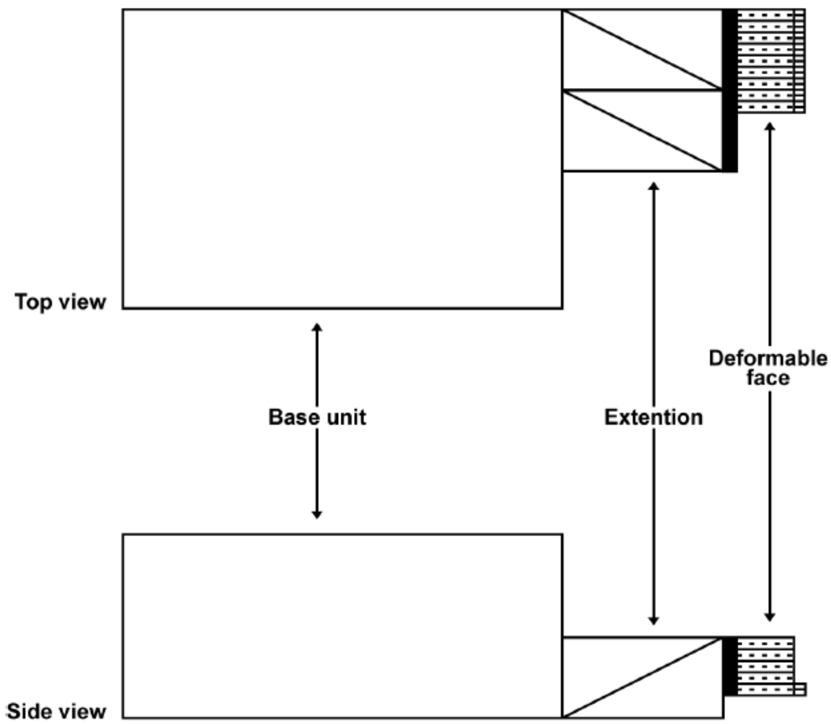

Figure 5. Deformable barrier composition
Source: IIHS crash test protocol (IIHS, 2017)

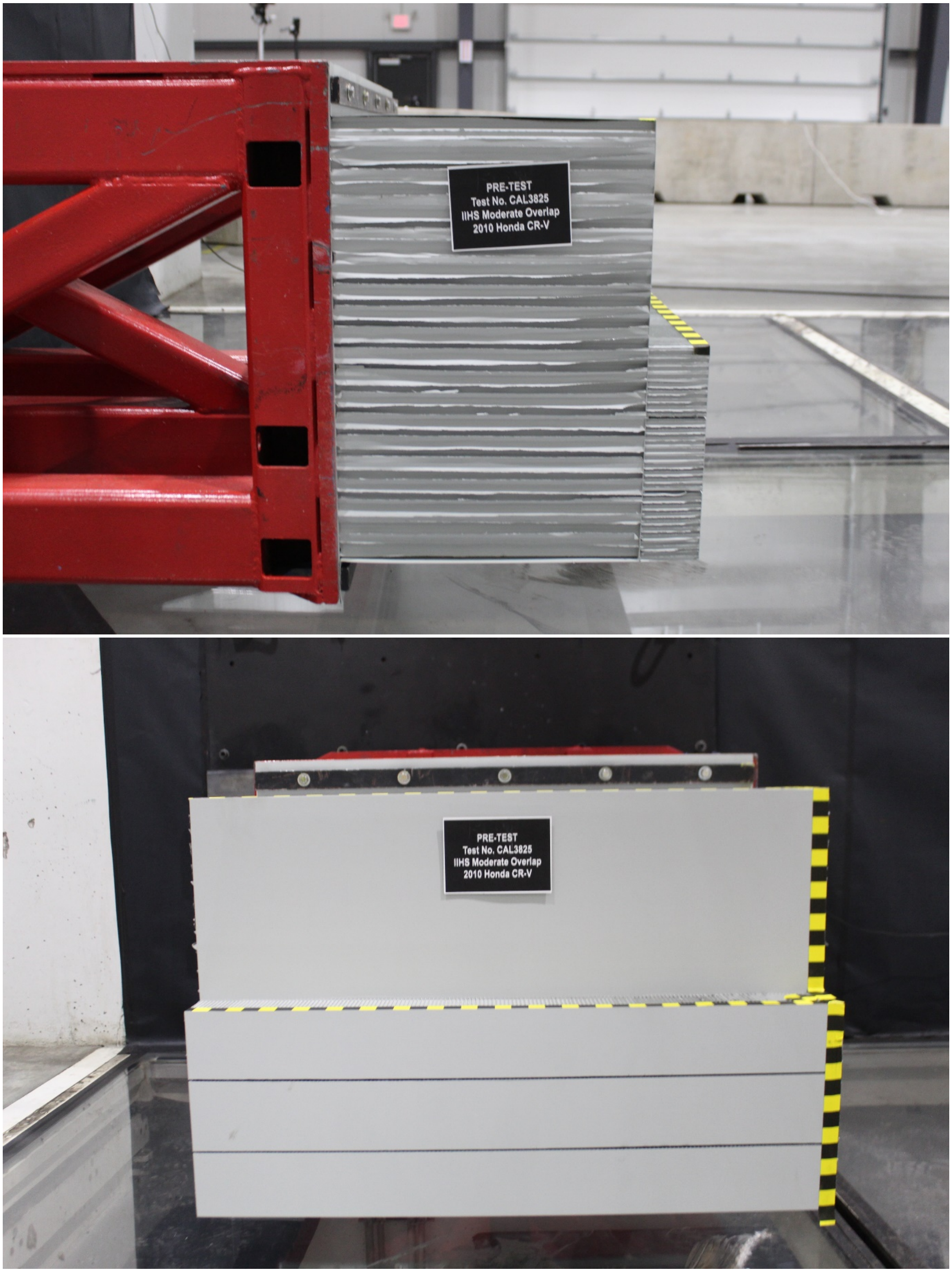

Figure 6. Side and front views of deformable barrier used for this study

Crash Test Dummy Type

Crash tests use a full-scale anthropomorphic test device (ATD) or crash test dummy. Data collected from ATDs are analyzed to assess the risk to a human in a given test.

One standard ATD family used for frontal crash tests is the Hybrid III family that includes a 50th percentile male, 95th percentile male, 5th percentile female, and three child dummies (ten-, six- and three-year olds). This study used a Hybrid III 50th percentile male dummy positioned in the driver seat, as shown in Figure 7, to represent an average-sized male driver. The seat adjustment and dummy positioning were performed according to the *Guidelines for Using the UMTRI ATD Positioning Procedure for ATD and Seat Positioning Version V* (IIHS, 2004). Following dummy positioning, pre-crash coordinates of various dummy locations and dummy-to-vehicle clearance measures were recorded to ensure repeatable pre-crash conditions for each test (Appendix A). Pre-crash locations of key dummy locations (head center of gravity and hip reference point) were within a 5 – 10 mm range between tests.

The dummy in each test was instrumented to record measures from the head, neck, chest, femur, and lower legs. In addition to dummy instrumentation, vehicle onboard and offboard high-speed cameras (500 frames per second) were used to document deployment times for airbags and belt tensioners as well as kinematic events involving the dummy, including interaction times with the airbag and components within the vehicle.

In addition to comparing differences in dummy injury outcomes and dummy kinematics throughout the crash, deformation of the occupant compartment caused by the crash test was also assessed. Pre- and post-crash measures of vehicle controls (steering wheel and brake pedal), toe pan region, and closure of the door opening were recorded, following the IIHS test protocol.

Figure 7. Side and front views of deformable barrier used for this study

Figure 8 depicts the full setup of the crash test prior to running each of the tests. All tests were conducted by Calspan Corporation in its crash laboratory in Buffalo, New York. We chose Calspan, an independent crash-testing facility serving the auto industry, because they could conduct tests at the higher crash test speeds required for this study.

Figure 8. Overview of pre-test setup

Study Results

Vehicle Response

Changes in vehicle metrics

Table 2 summarizes peak vehicle longitudinal accelerations and velocity change (delta-V). For each crash test, the delta-V is greater than the impact velocity due to the additional velocity change resulting from the vehicle rebounding off the fixed barrier (i.e. rearward vehicle motion). Figures 9 and 10 show vehicle acceleration and delta-V during each test. The onset of increased vehicle accelerations in Tests 2 and 3 was caused by the left front wheel being pushed back into the hinge-pillar and lower sill areas. The increased impact velocities in Tests 2 and 3 of 15.6 km/h and 25.6 km/h, respectively, equate to an increase in kinetic energy of 54% and 95% relative to Test 1.

Table 2. Summary of vehicle metrics for each test

	Test 1	**Test 2**	**Test 3**
Target velocity (km/h)	64.4	80.5	90.0
Actual impact velocity (km/h)	64.4	80.5	89.8
Peak longitudinal acceleration (g)	–36.9	–46.8	–55.5
Delta-V (km/h)	72.9	87.7	99.0

Figure 9. Vehicle longitudinal accelerations
Note: The abbreviation *ms* stands for millisecond (a thousandth of a second).

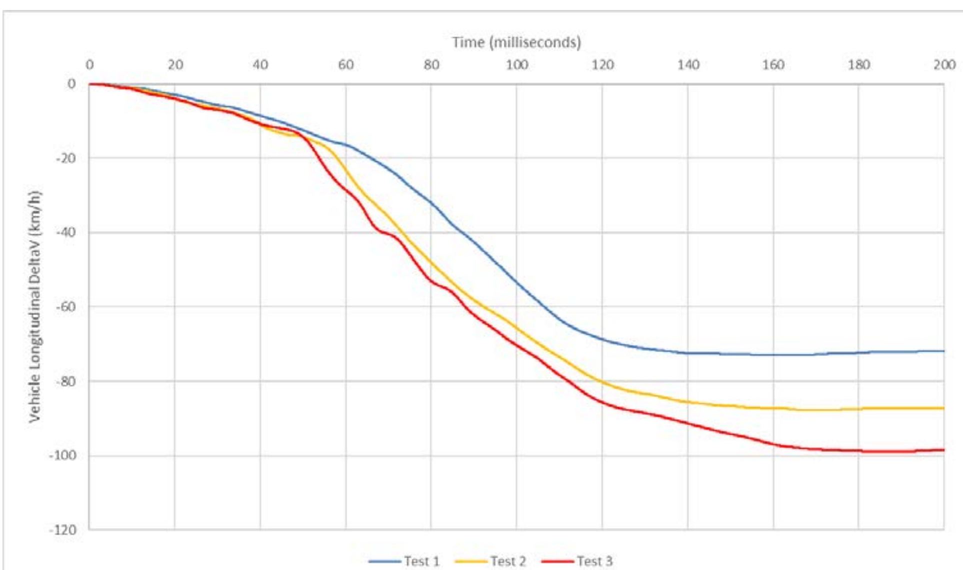

Figure 10. Vehicle longitudinal delta-V

Occupant compartment deformation

Table 3 summarizes the occupant compartment intrusion measures and Figures 11 – 13 provide a visual of the major observations for vehicle and occupant compartment deformation. As shown, the increased crash energy resulted in higher levels of occupant compartment deformation across all compartment measures with each test. Vehicles are typically designed so that the engine compartment crushes, absorbing energy and enabling the occupant compartment to remain intact. Although the baseline test (Test 1) had some occupant compartment intrusion, it was minimal. Test 2 resulted in some deformation of the driver side door opening (A-B-pillar closure increased from 0 cm to 1 cm) and instrument panel and footwell deformations (brake pedal) that were 4 cm – 18 cm greater than the baseline test. The occupant compartment was significantly compromised in Test 3, with a narrowing of the driver door opening by 11 cm and with interior intrusion measures that were 13 cm – 40 cm greater than those in the baseline test.

In Test 1, the steering column's energy-absorbing mechanism allowed it to compress, which resulted in post-crash measures of the center of the steering wheel that were 3 cm forward (away from the occupant) and 3 cm higher than the pre-crash position. The movement away from the dummy is due to the dummy loading the steering wheel through the airbag. The steering column is designed as an energy-absorbing feature of the overall occupant restraint system. In Tests 2 and 3, there was some rearward movement (2 cm and 8 cm, respectively) and a large upward movement (11 cm and 18 cm, respectively) of the steering wheel while the dummy was moving forward into the inflated airbag. Large upward movement of the steering column is not desirable for ideal occupant restraint because it places the airbag in a suboptimal position.

Table 3. Summary of occupant compartment intrusion

Intrusion Measurement Location	Test 1	Test 2	Test 3
Steering Wheel (x-axis)	-3 cm	2 cm	8 cm
Steering Wheel (z-axis)	3 cm	11 cm	18 cm
A-B Pillar Closure (x-axis)	0 cm	1 cm	11 cm
Footrest	3 cm	11 cm	31 cm
Left Toepan	7 cm	12 cm	43 cm
Center Toepan	6 cm	14 cm	45 cm
Right Toepan	5 cm	16 cm	45 cm
Brake Pedal	4 cm	18 cm	36 cm
Left Instrument Panel	0 cm	4 cm	13 cm
Right Instrument Panel	0 cm	4 cm	13 cm

Note: Positive measurement values indicate rearward (x-axis) and upward (z-axis) movement of the center of the steering wheel. Positive A-B Pillar closure indicates a narrowing of the door opening. Values for all other measurement locations indicate resultant movement.

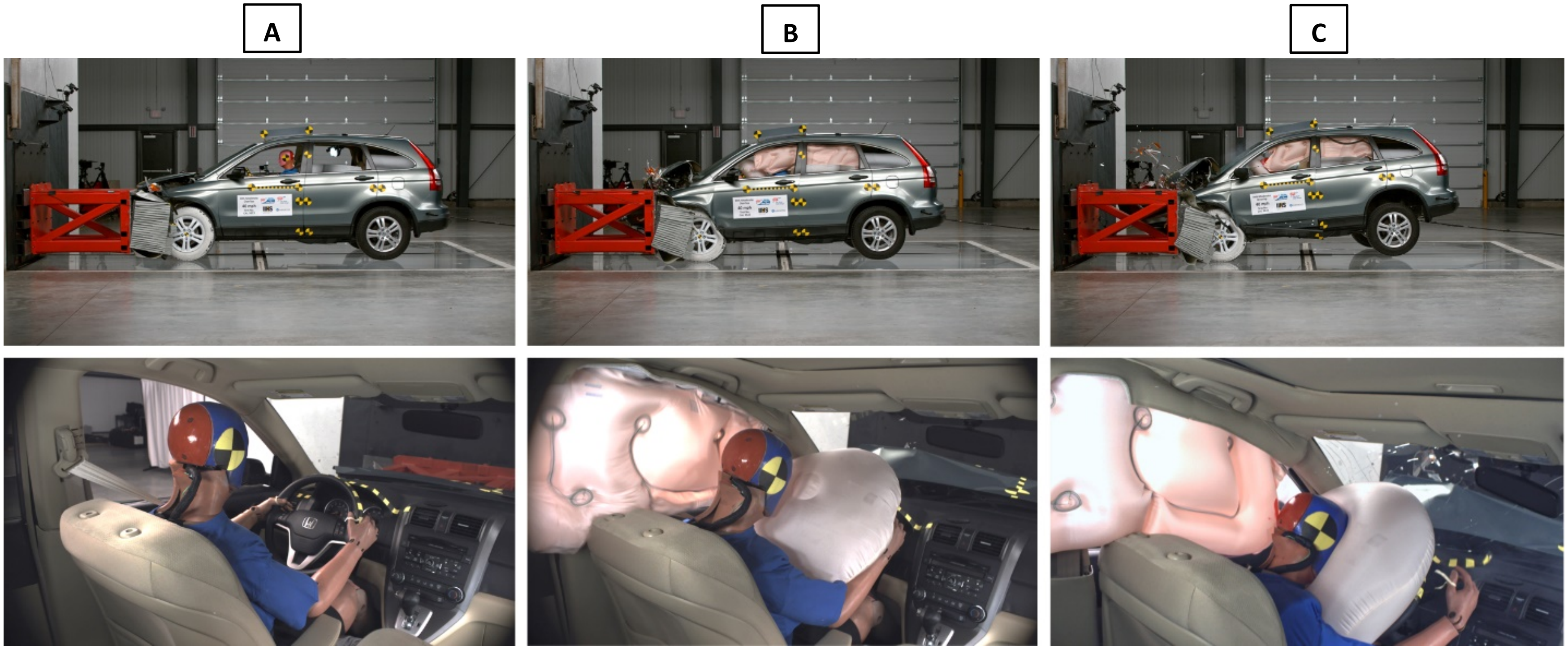

Figure 11. Vehicle and onboard views from Test 1 (64.4 km/h) at 50 ms (column A), 82 ms (column B) when peak vehicle longitudinal acceleration occurs, and 120 ms (column C)

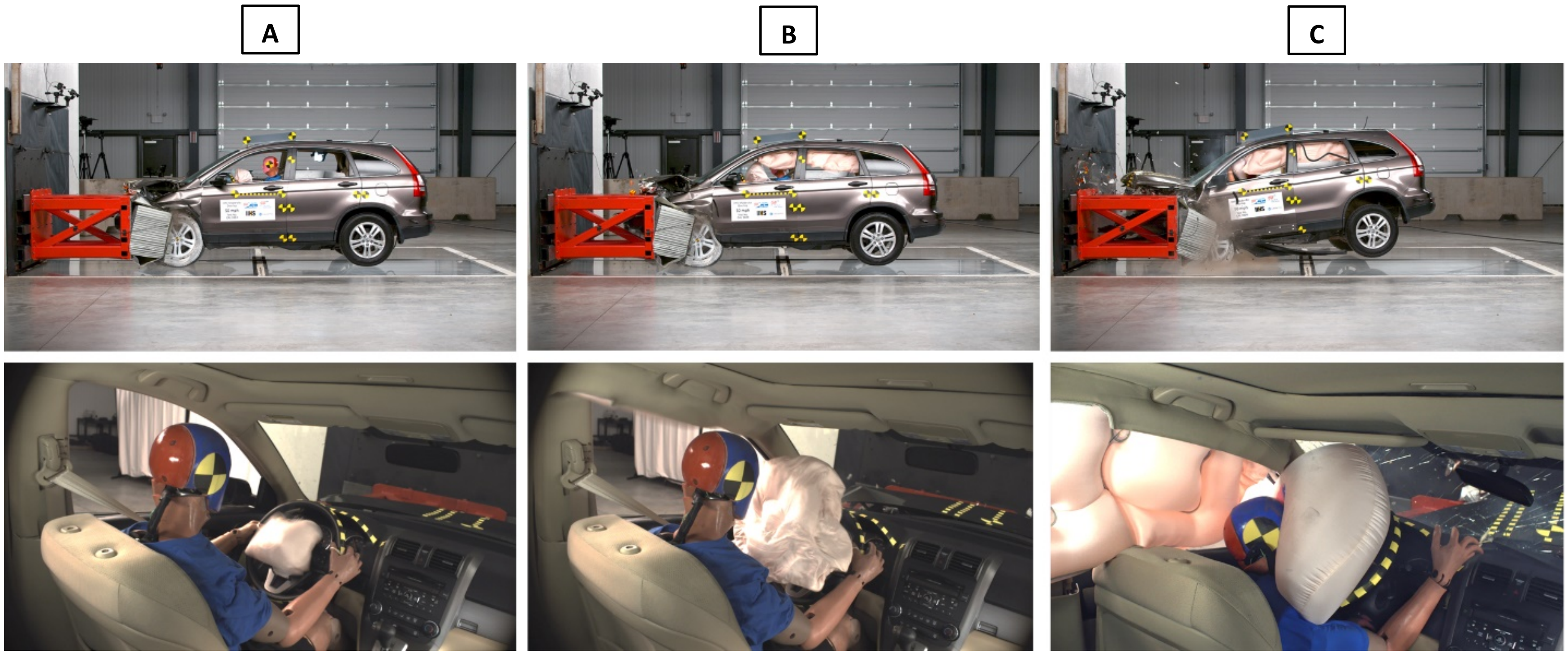

Figure 12. Vehicle and onboard views from Test 2 (80 km/h) at 50 ms (column A), 60 ms (column B) when peak vehicle longitudinal acceleration occurs, and 120 ms (column C)

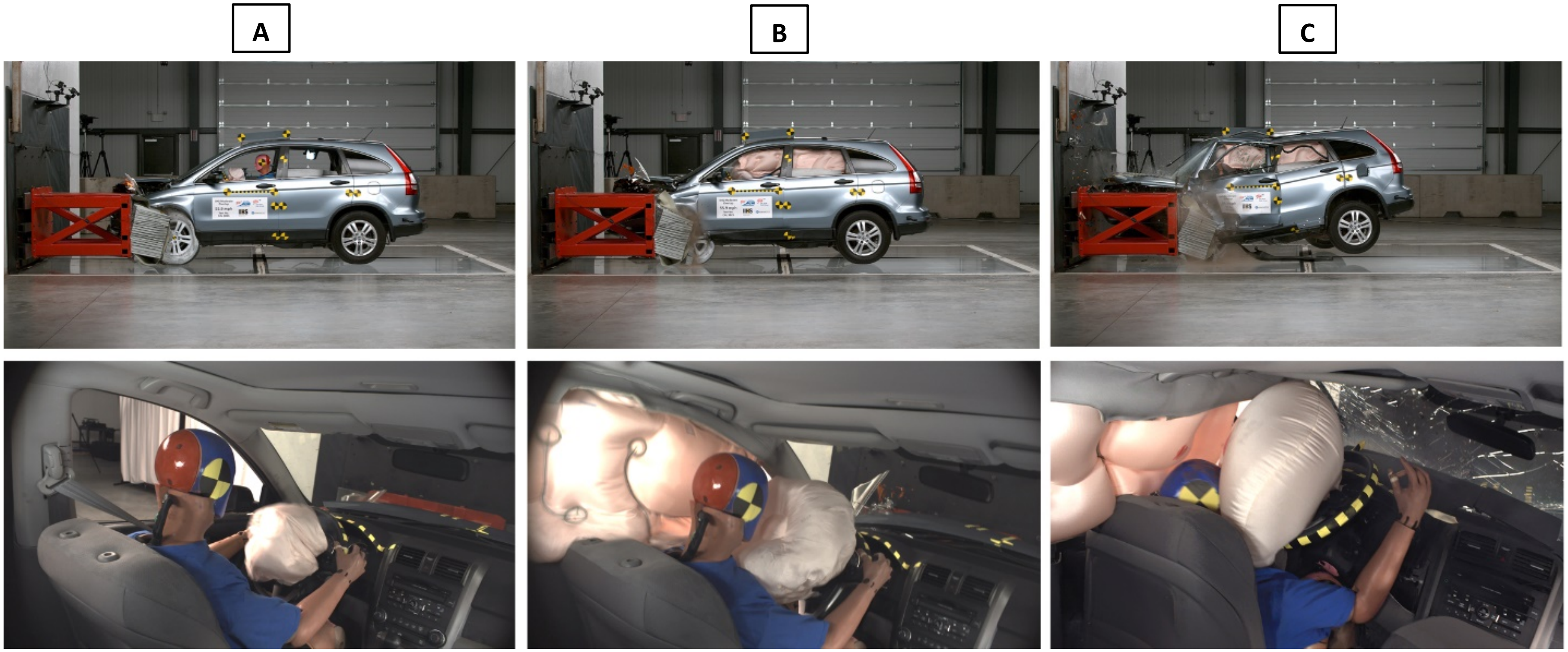

Figure 13. Vehicle and onboard views from Test 3 (90 km/h) at 50 ms (column A), 64 ms (column B) when peak vehicle longitudinal acceleration occurs, and 120 ms (column C)

Dummy Kinematic Evaluation and Injury Measures

Restraint system performance and dummy kinematic observations

Table 4 summarizes the timing of the restraint system's key performance and associated dummy kinematic observations. Figure 14 shows video frames from onboard high-speed cameras that correspond to notable kinematic events for Test 1. In Test 1, the occupant restraint system successfully controlled the dummy's forward excursion limiting loads to the head, neck, chest, and lower extremities. The seat belt tensioner deployed at 24 ms (Table 4) and the frontal airbag deployed at 54 ms into the crash (Figure 14-A). The dummy's face began loading the inflated airbag at 88 ms (Figure 14-B). The dummy's head and torso continued rotating forward until the dummy started to rebound rearward at approximately 150 ms (Figure 14-C). During the forward excursion, both knees contacted the bottom of the steering column and the lower legs contacted the knee bolster.

Table 4. Restraint system performance and dummy kinematics

Event	Test 1 Time (ms)	Test 2 Time (ms)	Test 3 Time (ms)
Activation of seat belt crash tensioner	24	26	22
Deployment of driver frontal airbag	54	46	44
Deployment of roof-mounted side curtain airbag	70	56	52
Deployment of seat-mounted side thorax airbag	70	56	52
Frontal airbag fully inflated	82	78	74
Face begins loading frontal airbag	88	80	78
Head contacts steering wheel rim through frontal airbag	n/a	99	90

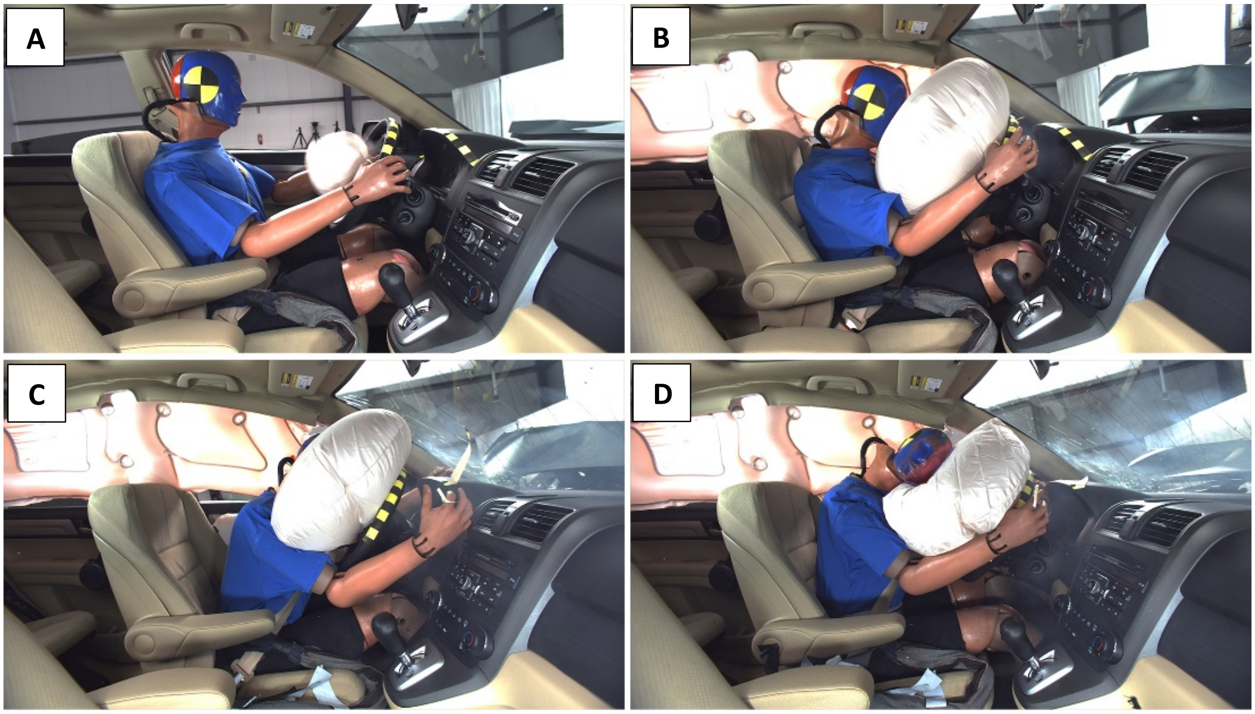

Figure 14. Test 1 dummy kinematics during forward loading (A at 54 ms and B at 88 ms) and rebound (C at 150 ms and D at 200 ms)

In Tests 2 and 3, the belt tensioner deployed at approximately the same time as in Test 1 (26 and 22 ms, respectively, see Table 4). However, the frontal airbag deployment time was approximately 10 ms earlier (Figure 15 – A for Test 2 and Figure 16 – A for Test 3) and the loading of the dummy face occurred 8 ms – 10 ms earlier (Figure 15 – B for Test 2 and Figure 16 – B for Test 3).

As the dummy continued to move forward into the airbag, the steering wheel rim rotated upward. The upward steering-wheel motion resulted in little airbag surface area loading the dummy's chest, with the airbag primarily loading the head/neck region (the airbag deployed at optimal position covers the head, neck, and chest). The higher energy in Tests 2 and 3 combined with the steering wheel upward movement resulted in the dummy's head bottoming out the airbag (i.e., going through the deployed airbag). This, consequently, resulted in a hard contact between the face and the steering wheel rim, hub or both at 99 ms in Test 2 (Figure 15 – C & D) and 90 ms in Test 3 (Figure 16 – C & D).

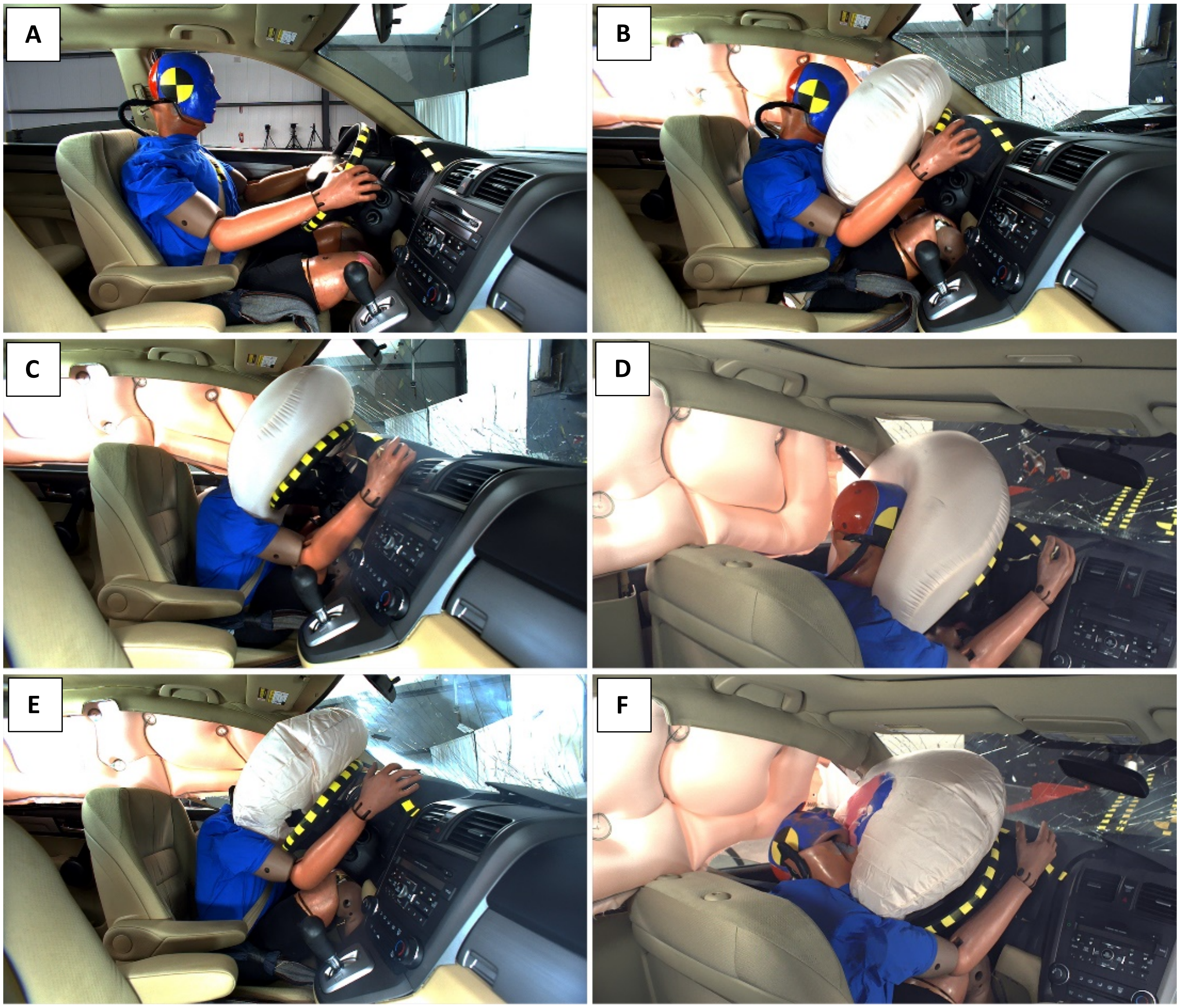

Figure 15. Test 2 dummy kinematics at airbag deployment (A at 46 ms), face loading the airbag (B at 80ms), bottoming of the steering wheel (C & D at 100 ms), and rebound (E & F at 150 ms)

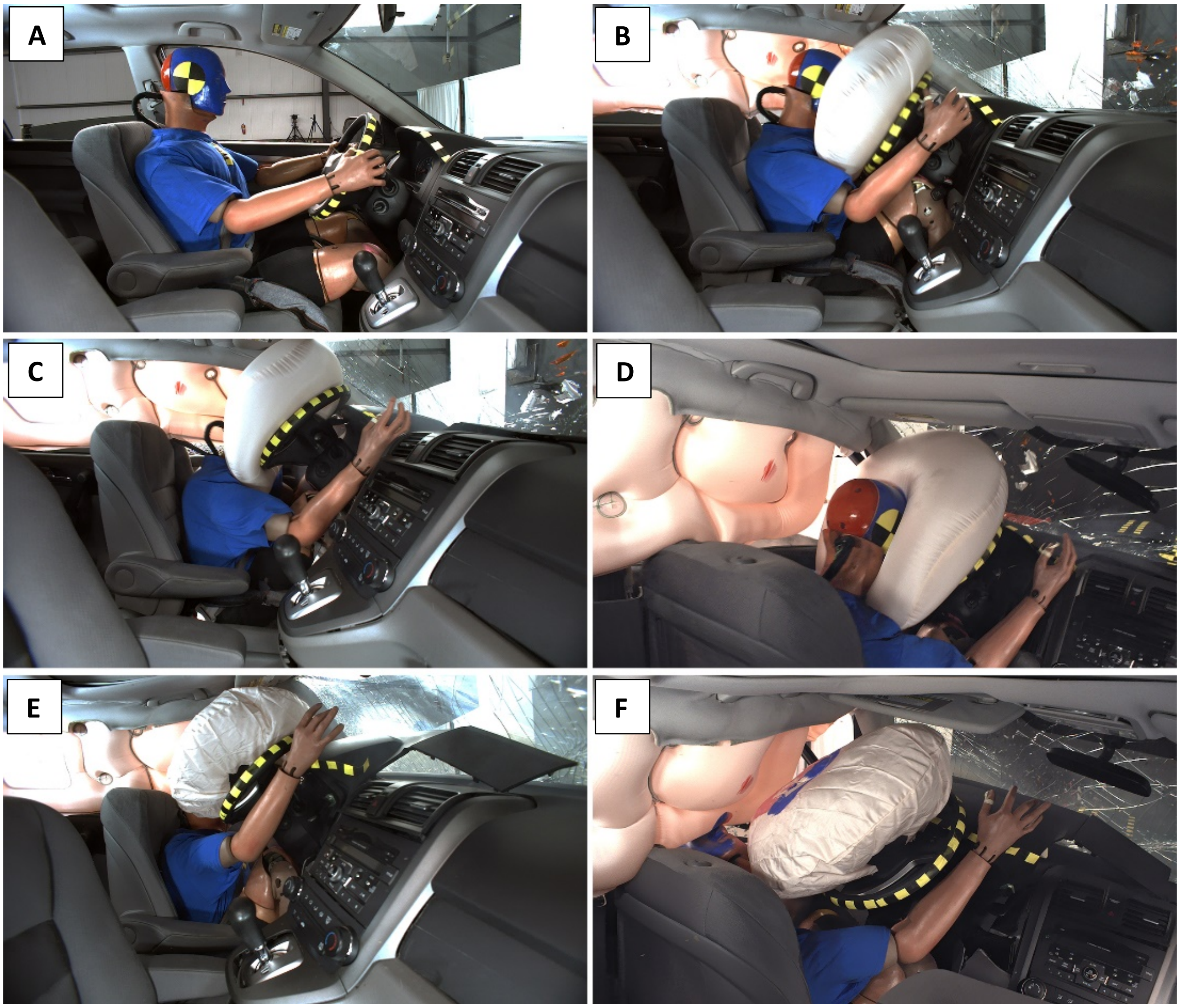

Figure 16. Test 3 dummy kinematics at airbag deployment (A at 44 ms), face loading the airbag (B at 78ms), bottoming of the steering wheel (C & D at 90 ms), and rebound (E & F at 150 ms)

Injury measures

Appendices B1, B2, and B3 list peak dummy injury measures and timing for each test. Figures 17 – 19 show peak injury measures normalized by Injury Assessment Reference Values (IARV) (i.e., dividing the peak recorded values by IARV) for each body region. In Test 1, injury measures for the dummy were below published IARVs for each body region (i.e., below 100% in Figures 13 – 15), which indicates no severe injuries over the entire body.

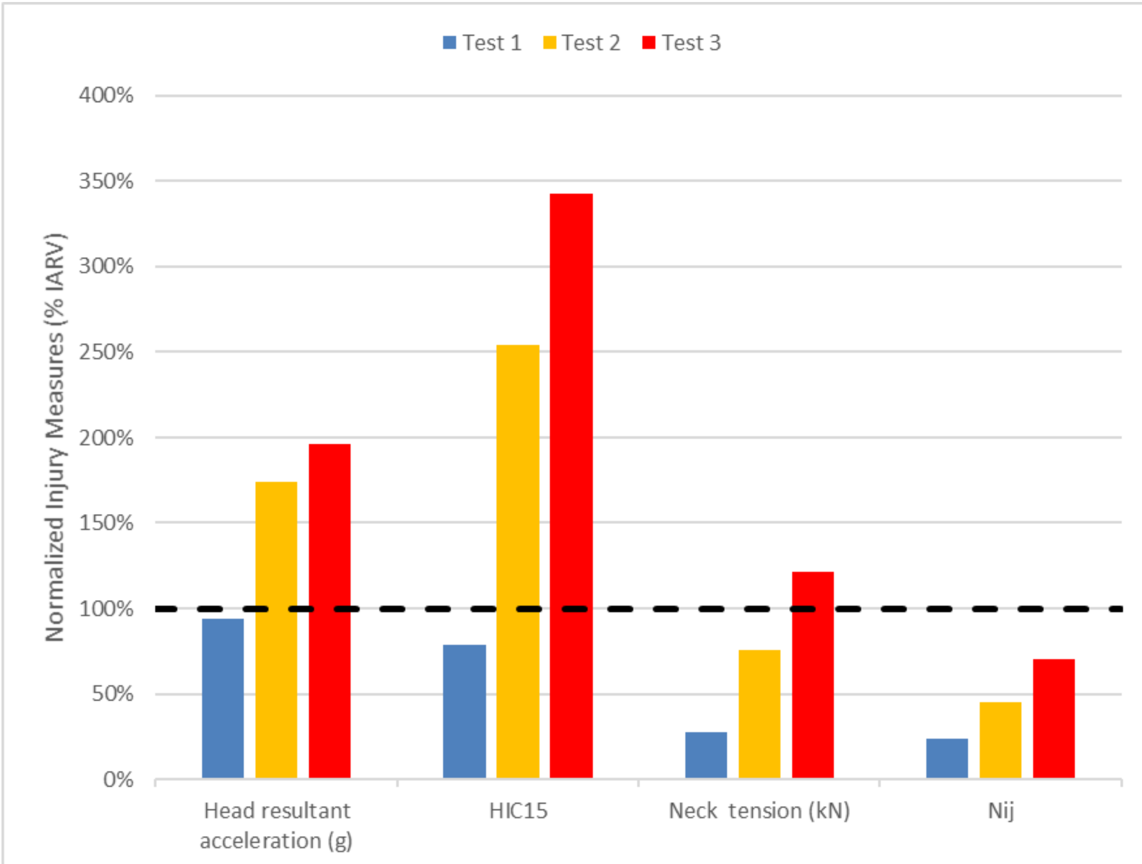

Figure 17. Head and neck injury measures normalized by IARV

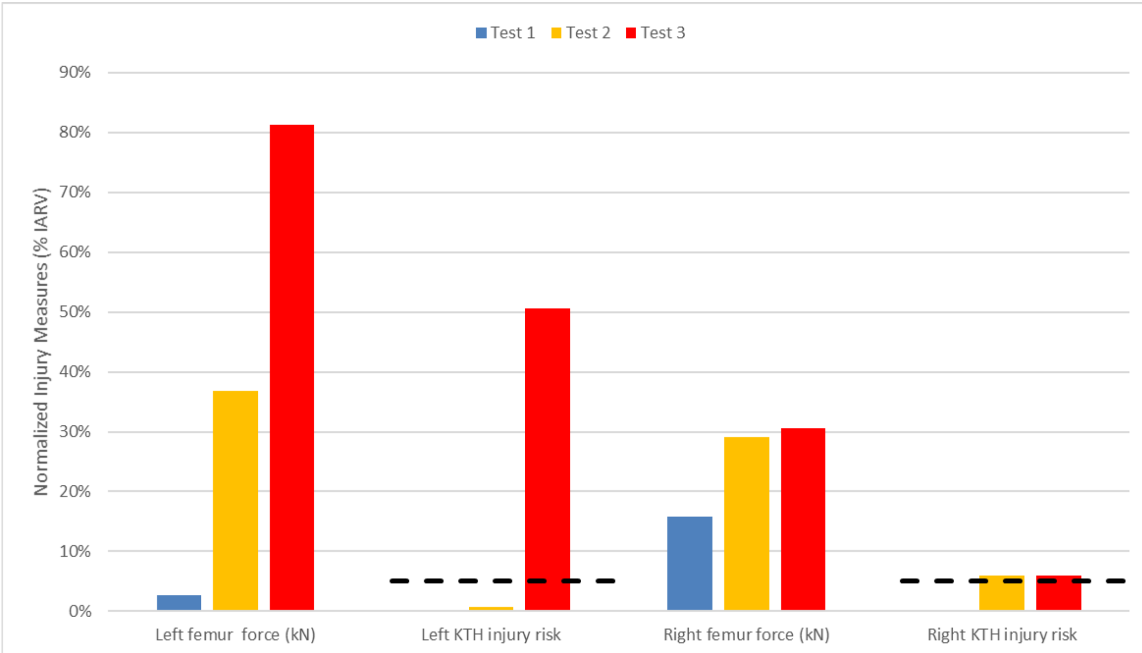

Figure 18. Femur injury measures

Notes: Femur force is shown normalized by IARV and values for knee-thigh-hip (KTH) injuries are shown as absolute risk of fracture.

The dashed line for KTH injury risk is shown at 5%, which is the IIHS boundary for downgrading KTH injury measures.

The injury risk for both left and right KTH in Test 1 is 0%.

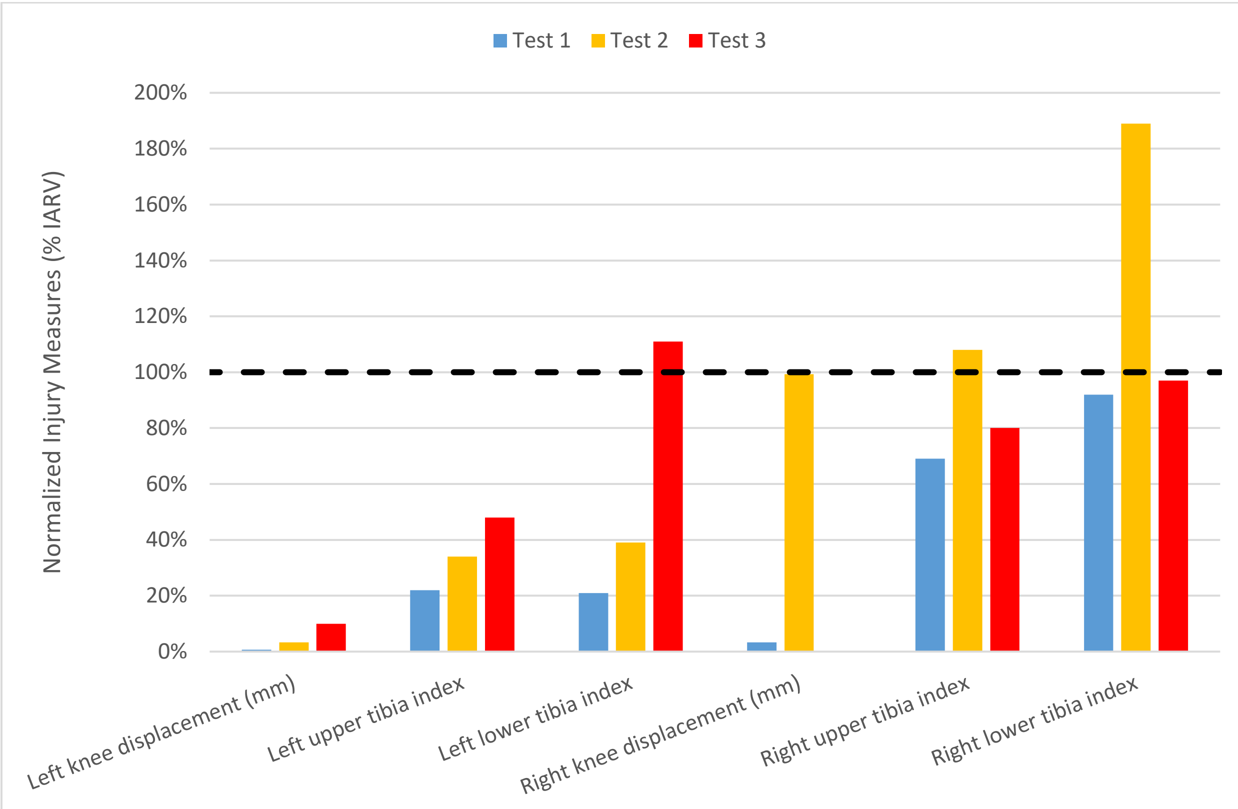

Figure 19. Lower leg injury measures normalized by IARV

In Tests 2 and 3, the contact through the airbag to the steering wheel rim/hub produced head accelerations and as a result Head Injury Criterion (HIC15) values greatly exceeded IARVs (i.e., greater than 100% in Figure 13). These high HIC15 values are indicative of a high risk (52% – 67%) of facial fracture and severe brain injury (Consumer Information; New Car Assessment Program, 2008). The peak neck tension seen in Test 3 (4.0 kN of neck axial tension in Appendix B3) corresponds to a 19% risk of a serious neck injury (Consumer Information; New Car Assessment Program, 2008).

Peak accelerations to the chest increased with test severity, but the maximum chest compression was similar between the three tests (27 mm – 30 mm of chest displacement in Appendices B1, B2, and B3). This was because of the increased loads to the head/neck region in Tests 2 and 3, which resulted in lower relative loads to the center of the dummy's chest, where the sternum deflection sensor is located.

As with other body regions, loads to the lower extremities increased with test severity as well. Femur force increased in Tests 2 and 3 as shown in Figure 18. Especially in Test 3, very high peak left femur compressive force and impulse (load duration) indicates a 50% risk of a hip fracture (femoral neck fracture) (Rupp et al., 2009). The tests with higher impact speed also produced higher axial forces and bending moments to the lower legs, which resulted in Tibia

Index values that correspond to a higher likelihood of fracture to the long bones in the lower leg (tibia, fibula, or both).

Overall Result and Crashworthiness Rating

Figures 20 and 21 show postcrash photos of the vehicle exterior and occupant compartment, respectively. Overall, as the impact speed of the test increased, the additional occupant compartment deformations and higher crash energy resulted in higher peak injury measures recorded by dummy sensors over the entire body region. The increased risks to vital body regions, such as the head, neck, and chest, are more relevant than those to the lower extremities in understanding the overall occupant fatality risk.

According to National Highway Traffic Safety Administration (Consumer Information; New Car Assessment Program, 2008), the injury measures from the baseline test represent a 15% risk of serious or worse *overall* injury. Here, a “serious or worse” injury indicates one with a score of 3 or higher on the Abbreviated Injury Scale (AIS) (Associate for the Advancement of Automotive Medicine, 1990). In contrast, the result from Test 2 indicates a 59% risk, while the result from Test 3 indicates a 78% risk of serious or worse *overall* injury.

Figure 20. Visual comparison of vehicle exterior between the three tests

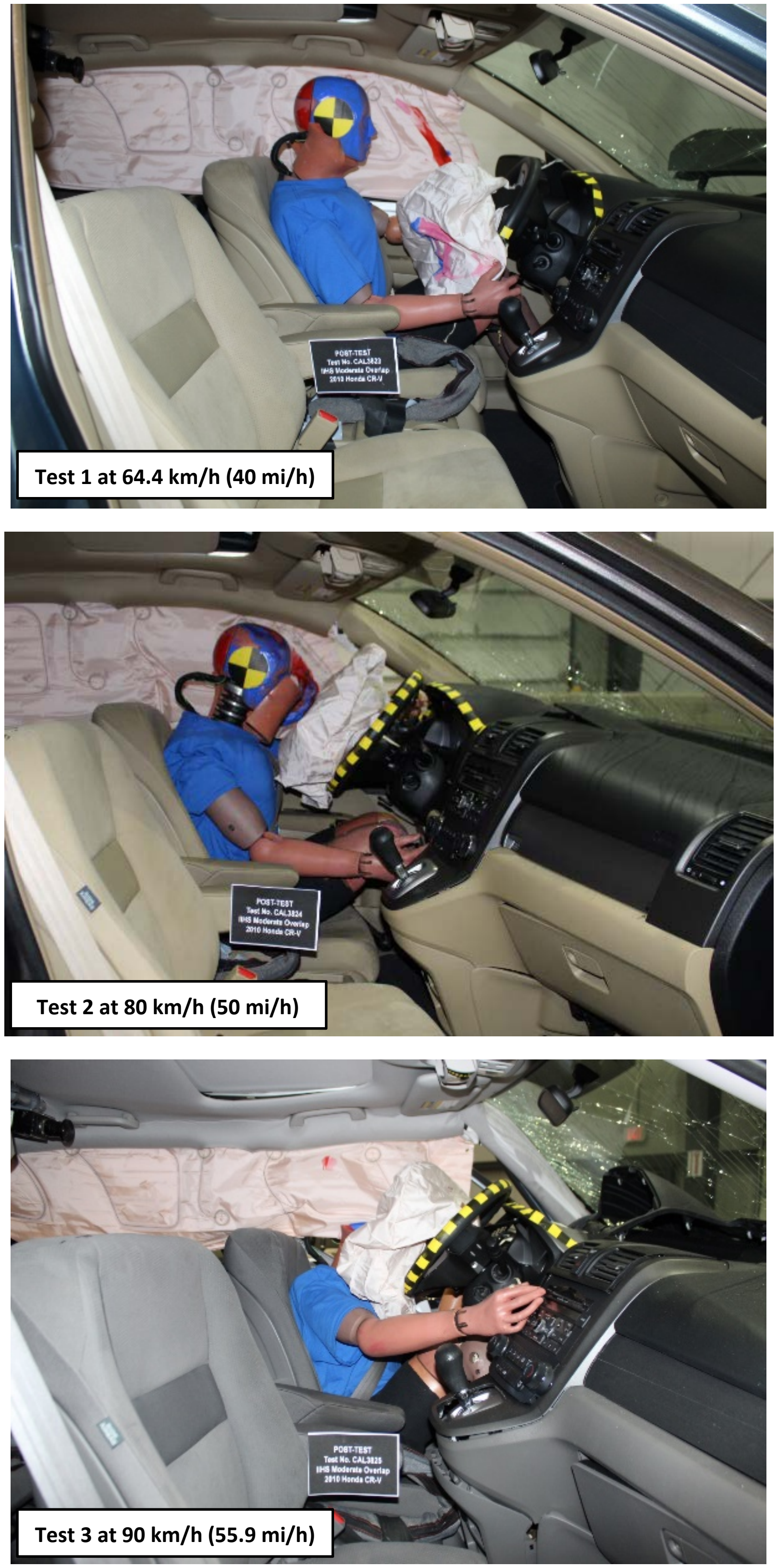

Figure 21. Visual comparison of occupant compartment between the three tests

If each test vehicle were rated per IIHS protocols (IIHS, 2006, 2007, 2014, and 2017), only the baseline test would earn a rating of Good, with Good ratings for the injury, structure, and restraint and kinematics components that make up the overall rating (Table 5). Tests 2 and 3 would earn a poor overall score, with Test 2 results heavily influenced by the elevated head injury measures, and Test 3 by elevated injury measures to vital body regions and the heavily compromised occupant compartment.

Table 5. IIHS Crashworthiness Ratings

	Test 1 64.4 km/h (40 mi/h)	**Test 2** 80 km/h (50 mi/h)	**Test 3** 90 km/h (55.9 mi/h)
Overall evaluation	G	P	P
Structure	G	G	P
Restraints & Kinematics	G	A	P
Driver injury measures			
Head/neck	G	P	P
Chest	G	A	P
Left leg	G	G	A
Right leg	G	P	P

Note: The overall rating and each measurement for a vehicle's crashworthiness can be good (G; the highest rating), acceptable (A), marginal (M), or poor (P; the lowest rating).

Discussion

This study examined the effects of increasing impact velocity in a frontal offset crash test on a vehicle with state-of-the-art crashworthiness design that earned a good rating from IIHS. Three tests were conducted; one at the standard crashworthiness test speed of 64.4 km/h (40 mi/h: Test 1) and two higher energy tests, one at 80 km/h (50 mi/h: Test 2) and one at 90 km/h (55.9 mi/h: Test 3). The results showed that impact velocities in Tests 2 and 3 increased the kinetic energy to levels that exceeded the capacity of the vehicle's energy-absorbing structures. The remaining crash energy transferred to the occupant compartment resulted in increased injury severity on the test dummies. This was especially the case for the test vehicle crashed at the highest test speed (Test 3), which was rated poor for not protecting the driver from severe injury over all vital body regions including head, neck, and chest. The injury measures from the baseline test (Test 1) represent a 15% risk of serious or worse *overall* injury; this risk increased to 59% for Test 2 and to 78% for Test 3, a 4 and 5 fold increase in serious or worse overall injury due to fairly modest speed increases.

Several studies have discussed how the crash and injury severities of these tests compare with real-world crashes. A 1998 study by IIHS showed that the frontal 40% offset crash test at 40 mi/h (the baseline test in the present study) represented approximately 80% of all real-world crashes with serious (or greater) injuries and one third of all fatal crashes (Nolan et al., 1998). However, a more recent analysis with only good-rated vehicles suggested the same type of crash test represents just over 50% of serious injury crashes in the United States (Brumbelow, 2019).

Speeding is prevalent and socially acceptable. Speeding is viewed as less dangerous than other aggressive driving behaviors, such as red-light running or tailgating. A national survey conducted by the AAAFTS in 2019 revealed that 64% of respondents perceived switching lanes aggressively or tailgating as extremely dangerous. Among them, 16% admitted to having done so at least once in past 30 days before the survey (AAAFTS, 2020). In contrast, only 29% perceived driving 15 mi/h over the speed limit on freeways as extremely dangerous. Among them, over 30% admitted to having done so at least once in past 30 days before the survey. Speeds in the field are, therefore, often significantly higher than posted speed limits and those used in crash tests. Even after accounting for braking or other factors that decrease impact speed, some portion of serious injury crashes occur at severities higher than those from these crash tests.

Nevertheless, speed limits have trended up because more state and local transportation authorities have increased their posted speed limits to the average travel speeds of vehicles. These decisions are based on traffic studies that have reviewed prevailing speed profiles, crash history, roadway geometric designs, pedestrian/bicyclist volumes, etc. Also, the advanced technology in the automobile industry has proven to contribute to manufacturing good-rated vehicles that can withstand and protect occupants from severe or fatal injuries during high-energy impacts. However, this study clearly shows that a relatively small increase in absolute speed (5 and 10 mi/h) not only results in more energy to overwhelm the crash energy management designs of state-of-the-art vehicles significantly, but also proportionally increases injury risk, raising the likelihood of fatality drastically.

Results from the first phase of this project found that traffic engineers do not necessarily prioritize safety when changing posted speed limits (Kim et al., 2019). Further, this study showed that increased vehicle speed would increase drivers' injury risk. In an era focusing on efficiency, economy, and mobility, demonstrating the dangers of excessive speeds, educating about the importance of speed limit compliance, and advocating for the development of safe driving environments are critical to saving lives on roadways. Therefore, it is recommended that policy/law makers continue discussing speed limit policies towards improving roadway safety and practitioners have more safety consideration when setting maximum speed limits.

To continue contributing efforts to mitigating speed-related traffic safety issues, the research team will further explore how a variety of factors, such as vehicle type, passenger age, size and location, among others affect the occupants' injury severity.

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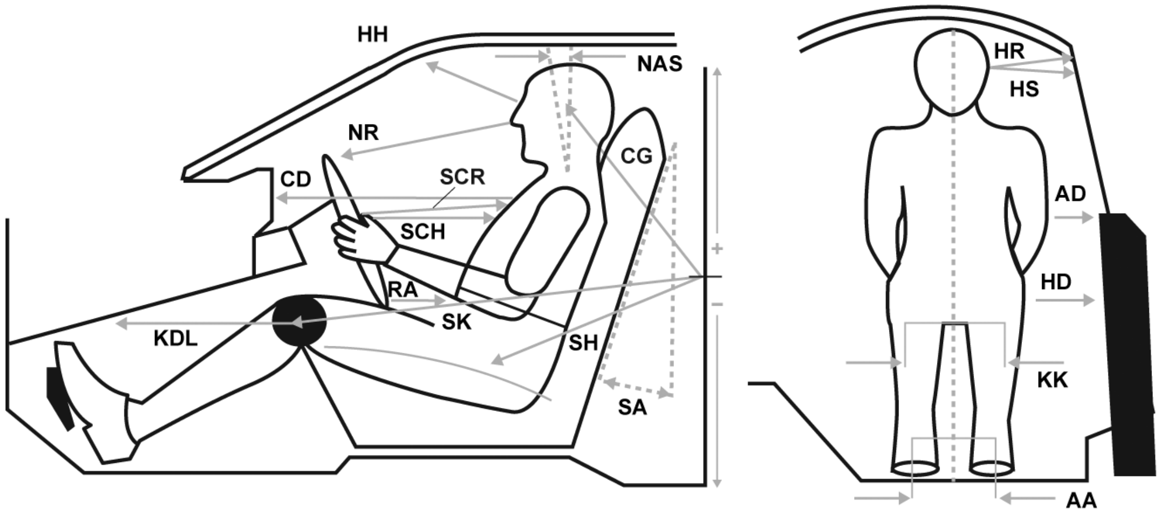
Appendix A. Crash Test Dummy Clearance Measures

Manual Measures	Notation	**Units**	**Test 1**	**Test 2**	**Test 3**
Head to header	HH	mm	442	447	452
Nose to rim	NR	mm	483	478	482
Chest to dash	CD	mm	603	610	608
Rim to abdomen	RA	mm	241	254	246
Steering wheel to chest, horizontal	SCH	mm	353	361	361
Steering wheel to chest, reference	SCR	mm	436	441	444
Hub to chest, minimum	HCM	mm	338	345	346
Knee to dash, left	KDL	mm	214	223	224
Knee to dash, right	KDR	mm	174	215	193
Knee to knee	KK	mm	298	290	302
Ankle to ankle	AA	mm	352	355	351
Arm to door	AD	mm	101	105	100
H-point to door	HD	mm	155	151	152
Head to A-pillar	HA	mm	549	545	560
Head to roof	HR	mm	189	192	183
Head to side window	HS	mm	256	250	260
Pelvic angle	PA	degrees	24.5	23.9	24.2
Seat back angle	SA	degrees	10.5	8.7	10.2
Neck bracket angle	NBA	degrees	0	0	0
Neck angle, seated	NAS	degrees	4.2	4.8	4.9
Coordinate Measurement Machine Measures					
Striker to head CG, horizontal	CGH	mm	-2195	-2189	-2193
Striker to head CG, lateral	CGL	mm	-450	-447	-447
Striker to head CG, vertical	CGV	mm	842	843	840
Striker to H-point, horizontal	SHH	mm	-2331	-2326	-2322
Striker to H-point, vertical	SHV	mm	191	198	188
Striker to knee	SK	mm	580	569	574
Torso recline angle	TRA	degrees	11.8	12	11.2
Striker to knee angle	SKA	degrees	0.3	0.7	0.5



Depicted Crash Test Dummy Clearance Measures with Notations

Appendix B1. Summary of Peak Dummy Injury Measures and Timing for Test 1

		Injury Assessment Reference Value	Measured Value	t1 (ms)	t2 (ms)
Head	Resultant acceleration (g)	80	75	113	
	Resultant acceleration (3ms clip, g)	80	73	110	113
	HIC	1000	677	98	125
	HIC15	700	548	105	120
Neck	X shear force (kN)	±3.1	0.8	115	
	Axial compression (kN)	4.0	0.0	-100	
	Axial tension (kN)	3.3	0.9	119	
	Nij - Tension-Extension	1.0	0.17	163	
	Nij - Tension-Flexion	1.0	0.24	117	
	Nij - Compression-Extension	1.0	0.01	27	
	Nij - Compression-Flexion	1.0	0.00	17	
Chest	Resultant acceleration (3ms clip, g)	60	39	115	119
	X displacement (mm)	-50	-27	115	
	V*C (m/s)	1.0	0.1	33	
	Sternum deflection rate (m/s)	-8.2	-2.1	29	
Left Leg	Left femur maximum force (kN)		-0.25	229	
	Left femur impulse (Ns)		0.0		
	Left KTH injury risk		0.0%		
	Left KTH injury location		n/a		
	Left knee displacement (mm)	-15	0	260	
	Left upper tibia X moment (Nm)	±225	-23	95	
	Left upper tibia Y moment (Nm)	±225	-40	95	
	Left upper tibia resultant moment (Nm)	225	46	95	
	Left upper tibia index	1.00	0.22		
	Left lower tibia X moment (Nm)	±225	-26	88	
	Left lower tibia Y moment (Nm)	±225	-34	81	
	Left lower tibia resultant moment (Nm)	225	34	81	
	Left lower tibia axial force (kN)	-8.0	-2.1	80	
	Left lower tibia index	1.00	0.21		
	Left foot X acceleration (g)		-47	80	
	Left foot Z acceleration (g)		-49	81	
	Left foot resultant acceleration (g)	150	66	80	
Right Leg	Right femur maximum force (kN)		-1.44	86	
	Right femur impulse (Ns)		0.0		
	Right KTH injury risk		0.0%		
	Right KTH injury location		n/a		
	Right knee displacement (mm)	-15	-1	85	
	Right upper tibia X moment (Nm)	±225	-106	87	
	Right upper tibia Y moment (Nm)	±225	76	84	
	Right upper tibia resultant moment (Nm)	225	123	87	
	Right upper tibia index	1.00	0.69		
	Right lower tibia X moment (Nm)	±225	-176	86	
	Right lower tibia Y moment (Nm)	±225	-32	76	
	Right lower tibia resultant moment (Nm)	225	176	86	
	Right lower tibia axial force (kN)	-8.0	-5.1	87	
	Right lower tibia index	1.00	0.92		
	Right foot X acceleration (g)		-96	77	
	Right foot Z acceleration (g)		-66	83	
	Right foot resultant acceleration (g)	150	101	77	

Appendix B2. Summary of Peak Dummy Injury Measures and Timing for Test 2

		Injury Assessment Reference Value	Measured Value	t1 (ms)	t2 (ms)
Head	Resultant acceleration (g)	80	**139**	101	
	Resultant acceleration (3ms clip, g)	80	125	100	103
	HIC	1000	**1805**	90	107
	HIC15	700	**1780**	92	107
Neck	X shear force (kN)	±3.1	1.2	103	
	Axial compression (kN)	4.0	0.1	368	
	Axial tension (kN)	3.3	2.5	105	
	Nij - Tension-Extension	1.0	0.28	134	
	Nij - Tension-Flexion	1.0	0.45	105	
	Nij - Compression-Extension	1.0	0.12	237	
	Nij - Compression-Flexion	1.0	0.00	19	
Chest	Resultant acceleration (3ms clip, g)	60	**69**	105	109
	X displacement (mm)	-50	-30	112	
	V*C (m/s)	1.0	0.2	102	
	Sternum deflection rate (m/s)	-8.2	-1.9	28	
Left Leg	Left femur maximum force (kN)		-3.35	92	
	Left femur impulse (Ns)		0.0		
	Left KTH injury risk		0.7%		
	Left KTH injury location		femur/knee		
	Left knee displacement (mm)	-15	-1	85	
	Left upper tibia X moment (Nm)	±225	-61	113	
	Left upper tibia Y moment (Nm)	±225	-74	90	
	Left upper tibia resultant moment (Nm)	225	76		
	Left upper tibia index	1.00	0.34		
	Left lower tibia X moment (Nm)	±225	-34	82	
	Left lower tibia Y moment (Nm)	±225	-67	62	
	Left lower tibia resultant moment (Nm)	225	67	62	
	Left lower tibia axial force (kN)	-8.0	-3.6	63	
	Left lower tibia index	1.00	0.39		
	Left foot X acceleration (g)		-104	63	
	Left foot Z acceleration (g)		-105	62	
	Left foot resultant acceleration (g)	150	138	62	
Right Leg	Right femur maximum force (kN)		-2.65	82	
	Right femur impulse (Ns)		0.0		
	Right KTH injury risk		0.3%		
	Right KTH injury location		femur/knee		
	Right knee displacement (mm)	-15	-15	113	
	Right upper tibia X moment (Nm)	±225	-184	71	
	Right upper tibia Y moment (Nm)	±225	-69	80	
	Right upper tibia resultant moment (Nm)	225	190	71	
	Right upper tibia index	1.00	**1.08**		
	Right lower tibia X moment (Nm)	±225	-358	71	
	Right lower tibia Y moment (Nm)	±225	-128	69	
	Right lower tibia resultant moment (Nm)	225	370	71	
	Right lower tibia axial force (kN)	-8.0	**-8.9**	71	
	Right lower tibia index	1.00	**1.89**		
	Right foot X acceleration (g)		-244	69	
	Right foot Z acceleration (g)		-147	68	
	Right foot resultant acceleration (g)	150	**277**	68	

Note: Values that exceed the IARV are in bold.

Appendix B3. Summary of Peak Dummy Injury Measures and Timing for Test 3

		Injury Assessment Reference Value	Measured Value	t1 (ms)	t2 (ms)
Head	Resultant acceleration (g)	80	**157**	92	
	Resultant acceleration (3ms clip, g)	80	**147**	91	94
	HIC	1000	**2415**	83	101
	HIC15	700	**2399**	85	100
Neck	X shear force (kN)	±3.1	1.3	95	
	Axial compression (kN)	4.0	0.5	160	
	Axial tension (kN)	3.3	**4.0**	97	
	Nij - Tension-Extension	1.0	0.52	117	
	Nij - Tension-Flexion	1.0	0.70	98	
	Nij - Compression-Extension	1.0	0.38	169	
	Nij - Compression-Flexion	1.0	0.03	242	
Chest	Resultant acceleration (3ms clip, g)	60	**92**	99	102
	X displacement (mm)	-50	-29	104	
	V*C (m/s)	1.0	0.2	100	
	Sternum deflection rate (m/s)	-8.2	-2.1	24	
Left Leg	Left femur maximum force (kN)		-7.39	81	
	Left femur impulse (Ns)		186.0		
	Left KTH injury risk		**50.6%**		
	Left KTH injury location		hip		
	Left knee displacement (mm)	-15	-2	88	
	Left upper tibia X moment (Nm)	±225	-97	94	
	Left upper tibia Y moment (Nm)	±225	-81	107	
	Left upper tibia resultant moment (Nm)	225	108	117	
	Left upper tibia index	1.00	0.48		
	Left lower tibia X moment (Nm)	±225	-115	73	
	Left lower tibia Y moment (Nm)	±225	**233**	84	
	Left lower tibia resultant moment (Nm)	225	**250**	84	
	Left lower tibia axial force (kN)	-8.0	-4.3	55	
	Left lower tibia index	1.00	**1.11**		
	Left foot X acceleration (g)		-111	54	
	Left foot Z acceleration (g)		-106	54	
	Left foot resultant acceleration (g)	150	**150**	54	
Right Leg	Right femur maximum force (kN)		-2.78	61	
	Right femur impulse (Ns)		0.0		
	Right KTH injury risk		0.3%		
	Right KTH injury location		femur/knee		
	Right knee displacement (mm)	-15	0	-5	
	Right upper tibia X moment (Nm)	±225	-157	99	
	Right upper tibia Y moment (Nm)	±225	-85	64	
	Right upper tibia resultant moment (Nm)	225	167	100	
	Right upper tibia index	1.00	0.80		
	Right lower tibia X moment (Nm)	±225	-63	61	
	Right lower tibia Y moment (Nm)	±225	-142	64	
	Right lower tibia resultant moment (Nm)	225	150	64	
	Right lower tibia axial force (kN)	-8.0	-11.1	64	
	Right lower tibia index	1.00	0.97		
	Right foot X acceleration (g)		-290	62	
	Right foot Z acceleration (g)		-318	62	
	Right foot resultant acceleration (g)	150	427	62	

Note: Values that exceed the IARV are in bold.

Appendix C1. Postcrash Views from Test 1

Overview after Test 1

Test vehicle after Test 1

Front view of deformed test vehicle

Driver side view of deformed test vehicle

Front view of driver seat after the crash test

Passenger side view of driver seat after the crash test

Dummy on the driver seat after the crash test

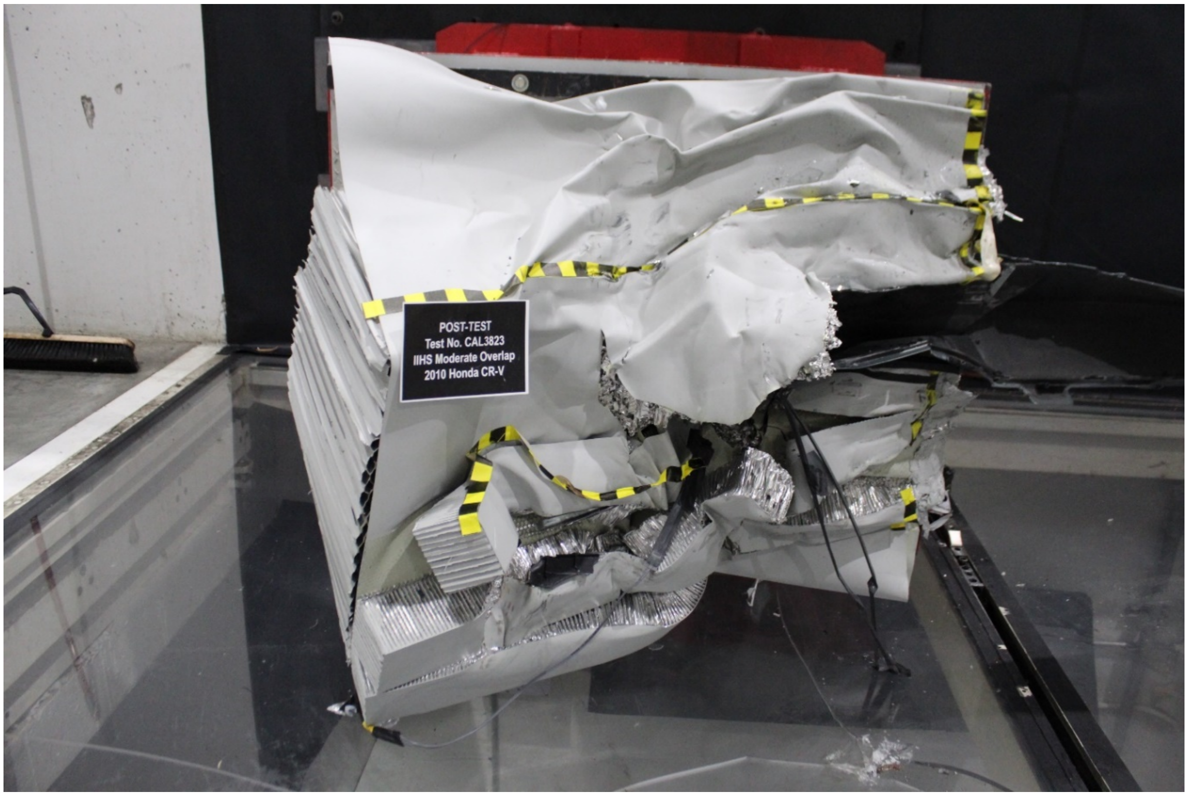
Lower and upper left leg of dummy after the crash test

Deployed curtain airbag with paint mark applied to the dummy's head before test

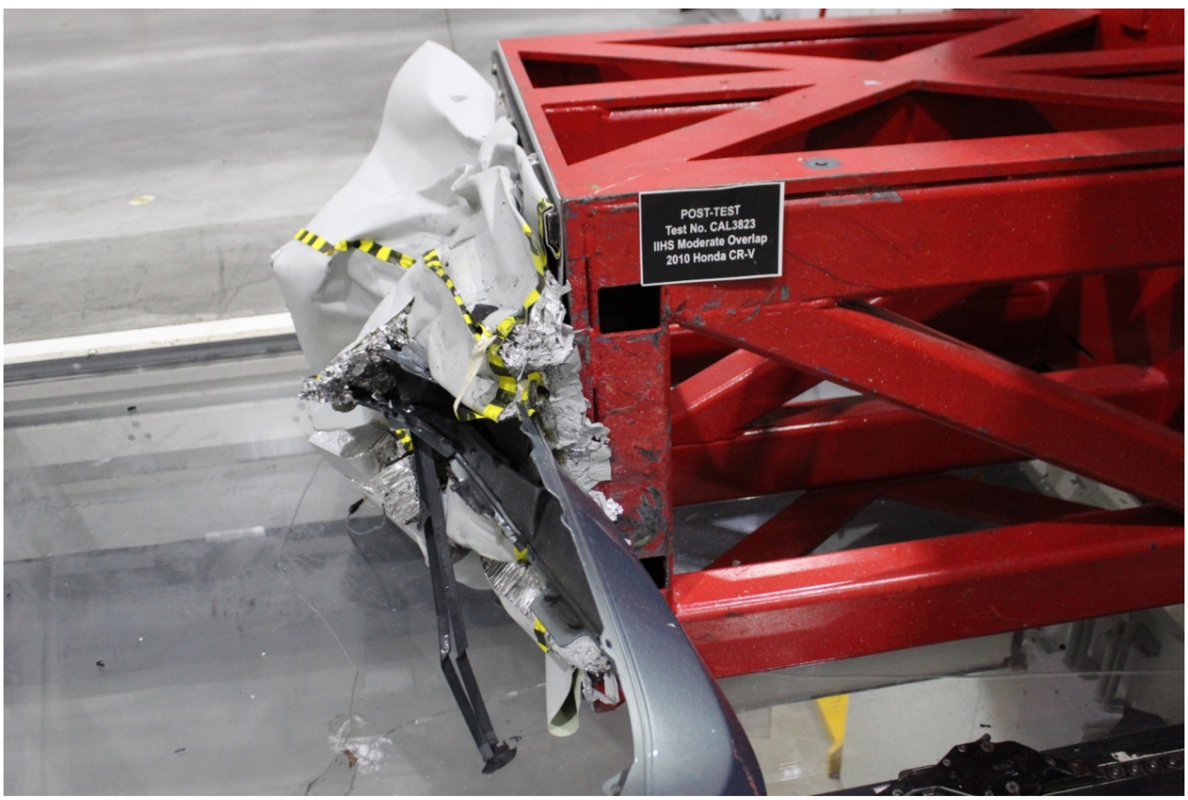
Deployed airbag with paint mark from dummy's head

Footwell intrusion and paint mark from dummy's body

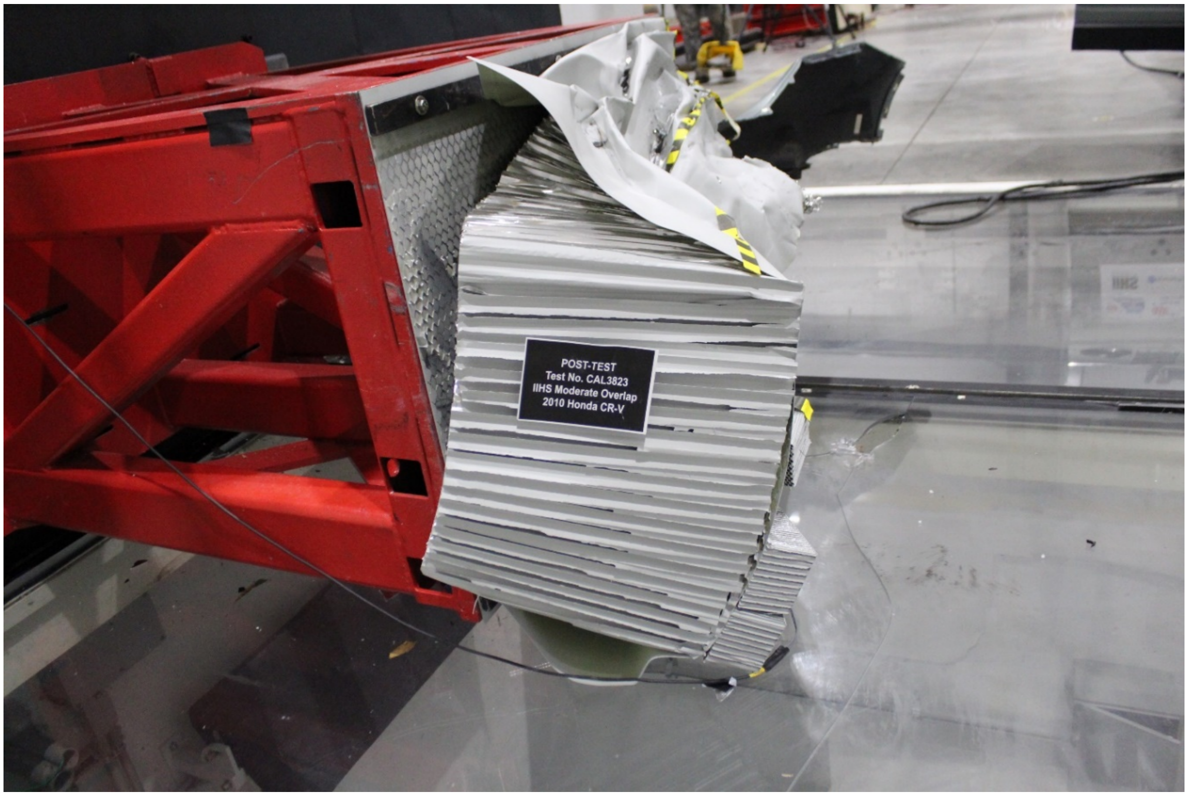
Footwell intrusion and paint mark from dummy's body after displacing the dummy



Front view of deformed barrier



Right side view of deformed barrier



Left side view of deformed barrier

Appendix C2. Postcrash Views from Test 2

Overview after Test 2

Test vehicle after Test 2

Front view of deformed test vehicle

Driver side view of deformed test vehicle

Front view of driver seat after the crash test

Passenger side view of driver seat after the crash test

Deployed airbag with paint mark from the dummy's head

Dummy on the driver seat after the crash test

Deployed airbag with paint mark from the dummy's head

Left leg of dummy after the crash test

Left lower leg and footwell intrusion after the crash test

Vehicle intrusion and paint mark from dummy after displacing the dummy

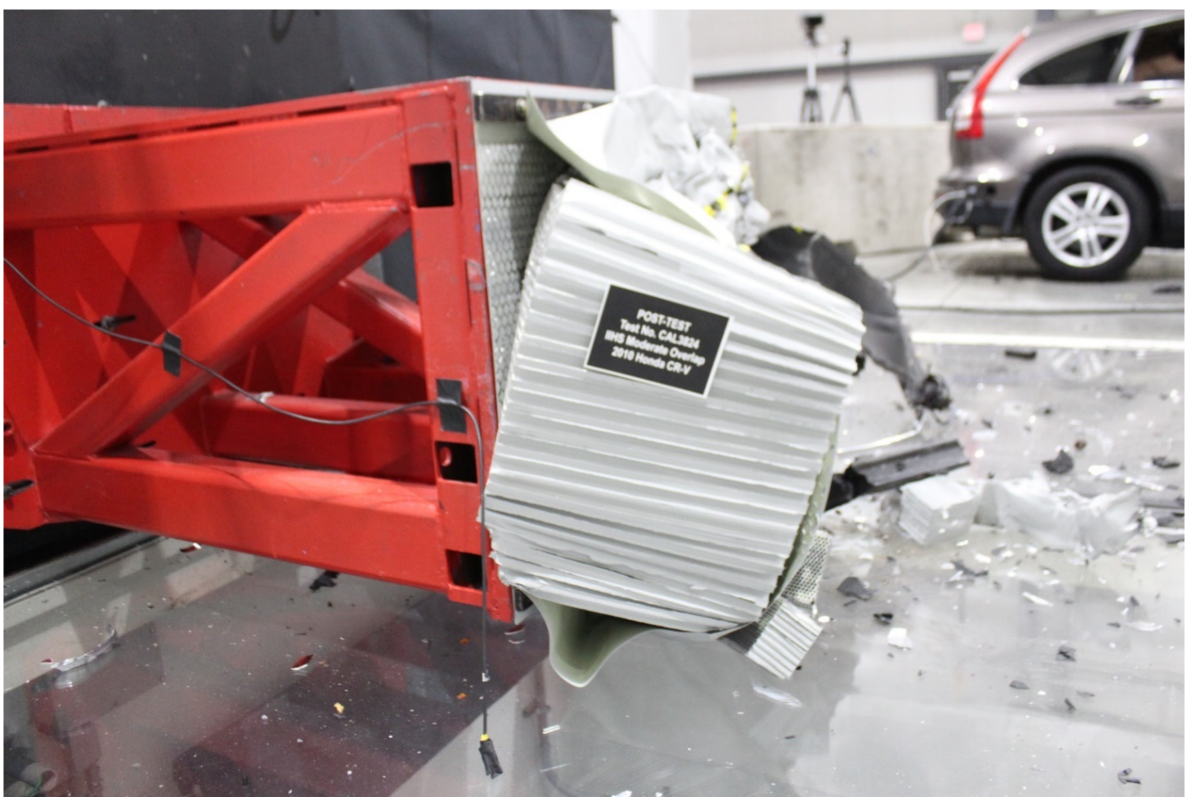
Footwell intrusion after displacing the dummy

Inside view of vehicle after the crash test

Shattered windshield

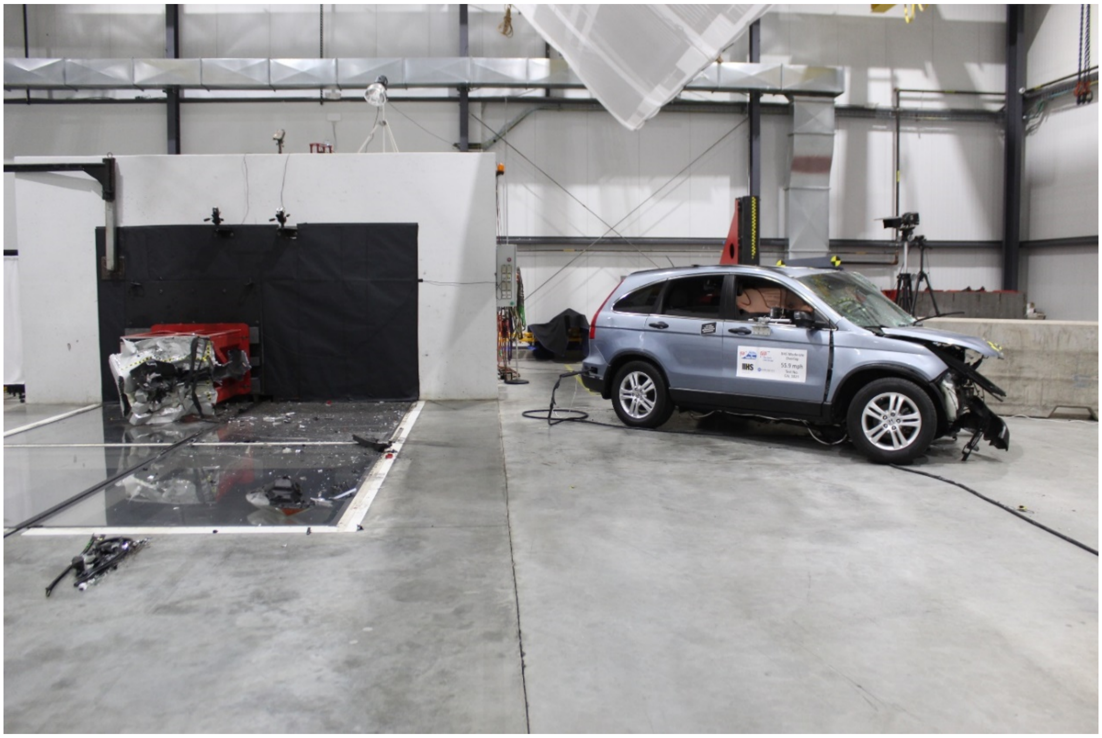
Front view of deformed barrier

Right side view of deformed barrier



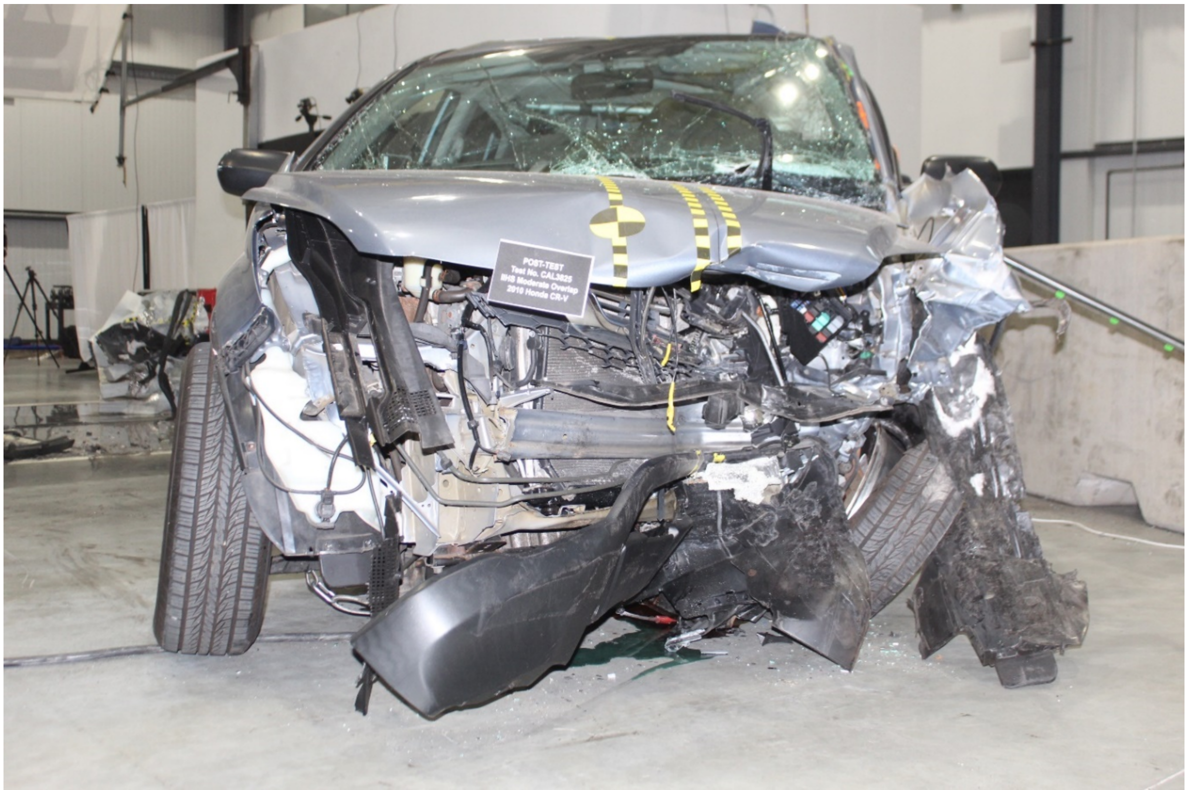
Left side view of deformed barrier

Appendix C3. Postcrash Views from Test 3



Overview after Test 3

Test vehicle after Test 3



Front view of deformed test vehicle

Driver side view of deformed test vehicle

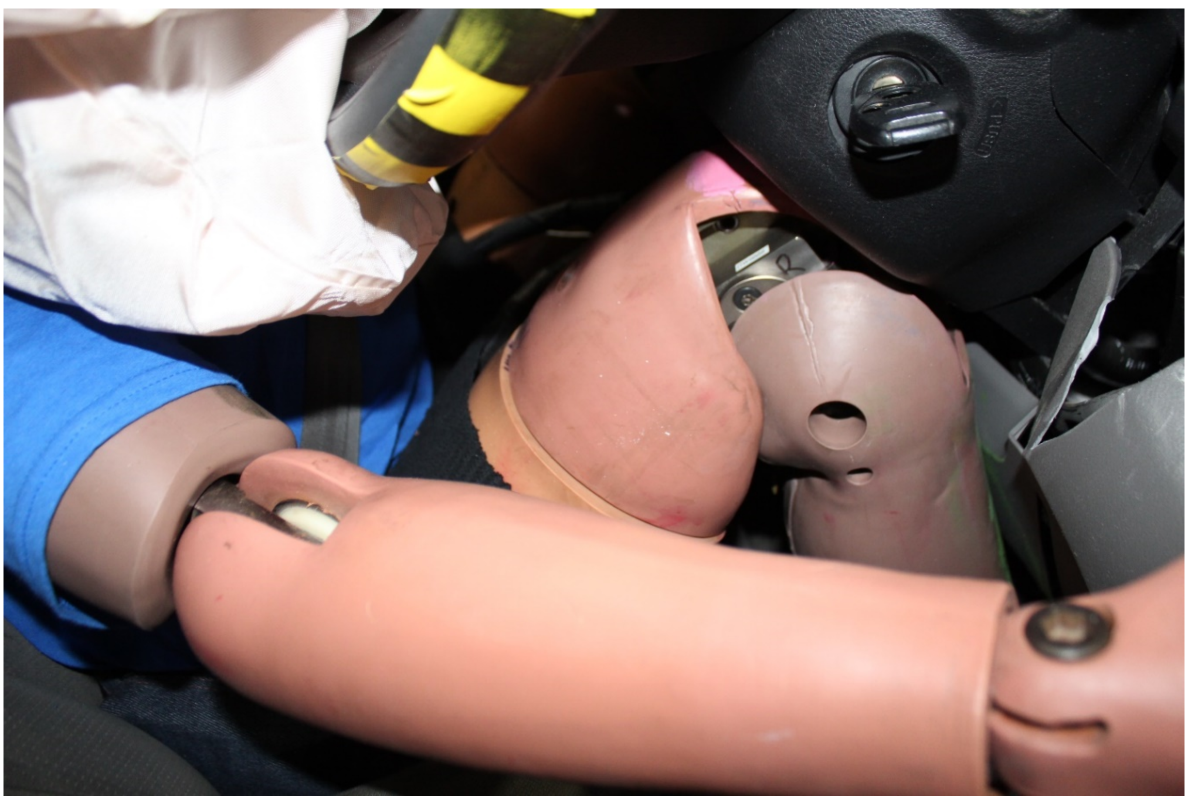
Front view of driver seat after the crash test

Dummy sticking out of the window and deformed driver door

Deformed vehicles and dummy on driver seat

Deployed airbag with paint mark from dummy's head

Dummy on the driver seat

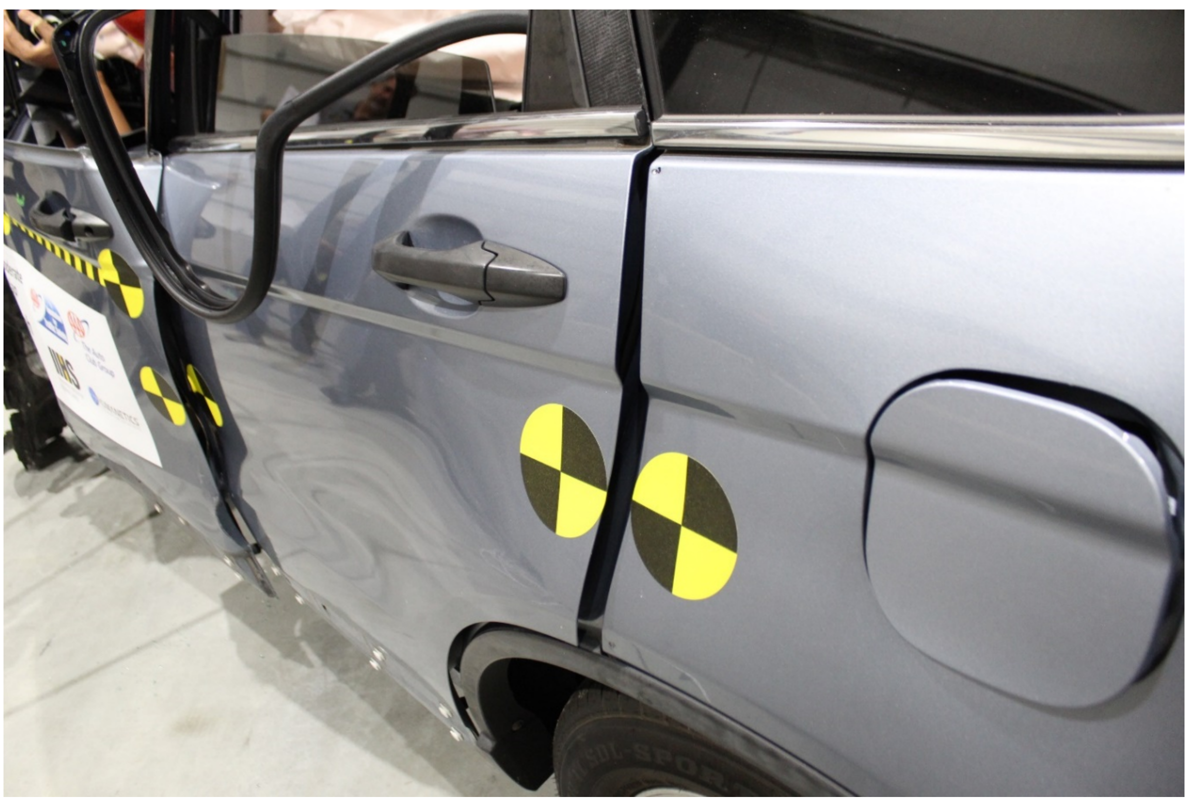


Dummy's right knee contacting the steering wheel column

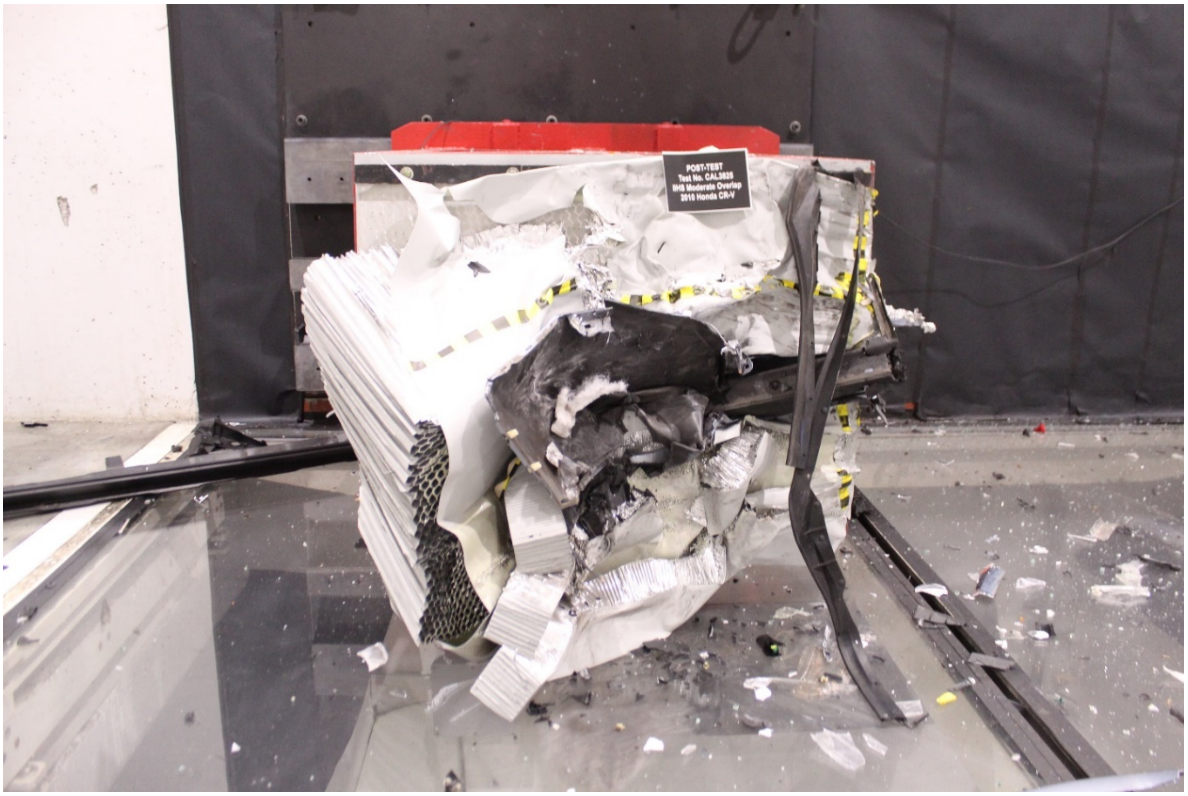
Left lower leg of dummy after the crash test

Significant footwell intrusion

Inside view of vehicle with deployed side airbag and significant intrusion



Driver side's rear door and fuel door



Front view of deformed barrier

Right side view of deformed barrier

Left side view of deformed barrier