

Alternative Approaches to Occupant Response Evaluation in Frontal Impact Crash Testing

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ABSTRACT

The National Highway Traffic Safety Administration has performed research investigating the Test Device for Human Occupant Restraint 50th male (THOR-50M) response in Oblique crash tests. This research is being expanded to investigate THOR-50M in the driver position in a 56 km/h frontal impact crash. Hybrid III 5th percentile adult female (AF05) anthropomorphic test devices (ATDs) were used in this testing to evaluate the RibEye Deflection Measurement System. The AF05 ATDs were positioned in the right front passenger and right rear passenger seating positions. For the right front passenger, the New Car Assessment Procedure (NCAP) seating procedure was used, except the seat fore-aft position was set to mid-track. For the right rear passenger, the seating followed the FMVSS No. 214 Side Impact Compliance Test Procedure. The NCAP frontal impact test procedure was followed with additional vehicle instrumentation and pre/post-test measurements. Results from this test series were compared with previous NCAP crash tests. The THOR-50M showed similar kinematics to the Hybrid III 50th but predicted a higher risk of chest and femur injury. The mid-track seat position of the right front passenger AF05 led to lower levels of femur compression loading due to additional distance to the dash. BrIC for the driver and front passenger showed higher injury risk than HIC₁₅. In all vehicles, the rear seat AF05 predicted a substantially higher risk of head, neck and chest injury than the right front passenger. The AF05 RibEye output showed a higher peak deflection (x-axis) than the chest potentiometer.

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INTRODUCTION

The National Highway Traffic Safety Administration's (NHTSA's) New Car Assessment Program (NCAP) has been conducting frontal impact tests at 56 km/h (35mph) into a rigid barrier to provide the public with a simple rating system on the safety of new automobiles and to aid with purchasing decisions. Currently, a large number of new vehicles have NCAP star ratings of 4 and 5 stars.

This frontal crash test typifies vehicle crash inputs that are a major source of injuries and fatalities in the field. Recent Fatality Analysis Reporting System data indicated that, despite improvements in seat belts and air bag technology, restrained occupant fatalities persist in frontal impacts.

This NHTSA Crashworthiness research study presents results and compares anthropomorphic test device's (ATD's) response to that of the most recent NCAP testing. This study utilized new ATDs to evaluate occupant protection in NCAP's frontal impact crash test. Test Device for Human Occupant Restraint 50th percentile male (THOR-50M) were used to determine if current vehicle safety systems can be improved [1]. The THOR-50M was positioned in the driver's seat.

The Hybrid III 5th percentile adult female (AF05) was positioned in the right front passenger's seat as it is in current NCAP frontal impact tests. Since not all passengers sit in the full-forward position, the seat was positioned at mid-track to investigate the implications for occupant kinematics and injury risk for smaller occupants.

This study also evaluated the rear seat position because it has been shown to be less protective for some occupants than the front [2]. An AF05 was used to evaluate the restraint effectiveness for a rear seat passenger.

Additional instrumentation was added to both AF05 ATDs used in this study. The RibEye Multi-point Deflection Measurement System [3] was installed into both AF05s in the hope of enabling improved resolution for chest deflection. The RibEye system can record up to twelve chest locations and measure deflections in the local x and y axes.

METHODOLOGY

Frontal Impact Crash Testing

In the NCAP frontal impact test setup, a test vehicle is directed into a rigid barrier at a speed of 56 km/h perpendicular to the barrier face. Vehicle instrumentation is comprised of accelerometers positioned

about the vehicle. Based on the response of the ATDs positioned within the vehicle, an injury risk is calculated for each occupant and those results are combined to generate the joint probability of injury.

In this study, each AF05s was equipped with the RibEye Measurement Deflection System to provide greater detail on chest deflection for the crash events. The instrumentation allows the recording of x and y positions of LEDs mounted bi-laterally on all six ribs of the AF05. The LED sensor heads are placed on each rib 6 cm from the center of the sternum. Rib #1 is at the top of the chest and rib #6 is at the bottom.

In the current research study, six vehicles were instrumented with additional accelerometers and angular rate sensors to record vehicle kinematics. In addition, string potentiometers were positioned inside the vehicle to record the deformation of the left and right side toe pan. Two Chevrolet Malibu models were tested in sequence to compare ATD and vehicle response repeatability.

Due to the additional ATD and data acquisition equipment, five of the six vehicles had test weights that were greater than the NCAP vehicle weights. The single vehicle weighing less was the F-150 SuperCrew which was tested without the 4X4 drivetrain that was present on the NCAP test vehicle. To assist in bringing two of the test vehicles (Mazda3, Fit) closer to the NCAP weights, the amount of Stoddard fluid was reduced to approximately 1/3 of the fuel tank's capacity. [Table 1](#) shows the list of test vehicles and corresponding NCAP vehicle tests.

Table 1. Research / NCAP frontal impact test vehicles

NHTSA Test Number	Make	Model	Year	Weight (kg)
9332/7856	Chevrolet	Malibu	2015/2013	1870/1844
9333/7856	Chevrolet	Malibu	2015/2013	1867/1844
9334/8531	Toyota	Highlander	2015/2014	2335/2250
9335/9097	Ford	F-150 Super Crew	2015/2015	2474/2577
9336/8539	Mazda	Mazda3	2015/2014	1599/1470
9337/9033	Honda	Fit	2015/2015	1427/1329

RESULTS

Injury Criteria and Associated Injury Risk - THOR-50M

Occupant injury risk was assessed by determining the probability of a given severity of injury based on the Abbreviated Injury Scale (AIS) [4] [5]. For the head, neck, and chest, the probability of an AIS score of three or higher ($AIS \geq 3$) was calculated. For the femur, the probability of an AIS score of two or higher ($AIS \geq 2$) was calculated. The injury criteria and associated risk functions used to predict injury risk for the THOR-50M in the driver's seat were used in the assessment of THOR-50M injury in oblique moving deformable barrier crash tests described by Saunders, et al [6].

Injury Criteria and Associated Injury Risk - AF05

The injury criteria and associated risk functions used to assess injury for the AF05 in this right front passenger seat were those used in frontal NCAP testing [7], with one addition. In this testing, the front AF05 was equipped with angular rate sensors to allow the calculation of Brain Injury Criterion (BrIC) [8]. Injury risk assessment for the rear seat occupant utilized the frontal NCAP risk functions for the AF05 [7].

Occupant Injury Assessment

Driver

The driver's seat in NCAP tests is positioned at mid-track. The THOR-50M in this study was seated using a new procedure developed to achieve reproducible position and posture by accounting for the adjustability, flexibility, and measurement capabilities of the THOR-50M [9].

During the tests, seat belt pretensioners and frontal air bags deployed for the driver. Force limiting seat belts were noted in all tests at the driver position. However, the Toyota Highlander lap belt force also showed a rise and peak that is more characteristic of a seat belt without force limiting. The initial lap belt force indicated force limiting behavior until approximately 40 milliseconds after impact. The belt force then steadily increases up to a 6000 lb peak. Seat belt loads for the driver are shown in [Figure 1](#) and [Figure 2](#).

Curtain air bags deployed in both of the Chevrolet Malibu tests and in the Toyota Highlander test. Curtain air bag deployment was not considered to affect ATD response in these test events because occupant motion was directed primarily forward. In the three tests with curtain air bag deployment there was no observed contact with the driver's head.

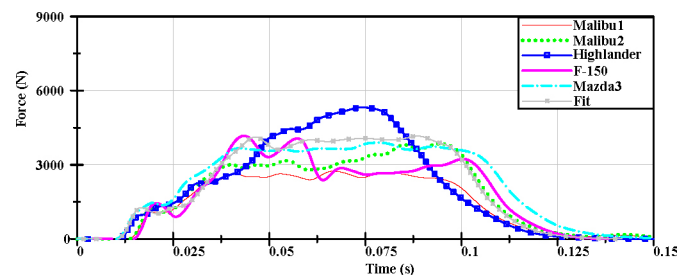


Figure 1. Driver, shoulder belt force

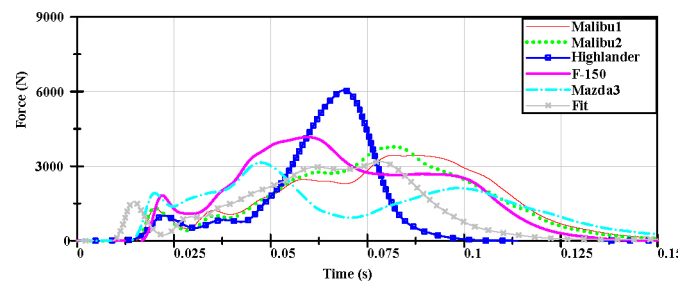


Figure 2. Driver, lap belt force

For all crashes in this study, the THOR-50M HIC₁₅ was higher than the 50th percentile male Hybrid III (AM50) response seen in the NCAP testing (Table 2). The highest increase over the NCAP results was seen in the first Malibu test with an increase in risk of 1.1%. This was also the highest Driver HIC₁₅ injury risk for this study.

Table 2. Driver, HIC₁₅ values and injury risk

	Research						
	THOR-50M						
	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
HIC ₁₅	317	265	261	205	238	298	
Injury probability (AIS 3+)	1.1%	0.6%	0.5%	0.2%	0.4%	0.9%	
	NCAP						
	AM50						
HIC ₁₅	134	195	199	192	251		
Injury probability (AIS 3+)	0.0%	0.2%	0.2%	0.1%	0.5%		

The THOR-50M clearance measurements were compared with the AM50 driver values from similar NCAP tests. In the same seat position, there was increased clearance between the THOR-50M head and the steering wheel (Table 3). This additional clearance allowed the THOR-50M head greater free travel prior to contact with a fully deployed air bag.

Table 3. Driver, clearance distance comparison

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Increase in clearance - nose to steering wheel rim (mm, X-axis)	127	136	93	89	64	76

With the inclusion of angular rate sensors within the THOR-50M head, BrIC was also calculated for each test. Table 4 provides the BrIC value and the injury risk (AIS3+). In all cases, BrIC predicts AIS 3+ head injury risk that is 23 to 47 times greater than that calculated using HIC₁₅. While BrIC significantly elevates the head injury risk in the frontal, these BrIC values are lower than the THOR-50M response seen in oblique testing [6].

Table 4. Driver, BrIC values and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
BrIC	0.71	0.68	0.59	0.58	0.56	0.60
Injury probability (AIS 3+)	31.6%	28.4%	19.8%	18.9%	17.2%	20.7%

The THOR-50M response showed higher Nij values for the Mazda3 and Honda Fit test, with minimally increased injury risk ($\leq 0.2\%$) (Table 5).

Table 5. Driver, Nij values and injury risk

	Research						
	THOR-50M						
	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Nij	0.21	0.22	0.38	0.26	0.22	0.29	
Injury probability (AIS 3+)	5.7%	5.7%	7.7%	6.2%	5.7%	6.6%	
	NCAP						
	AM50						
Nij	0.29	0.29	0.47	0.28	0.20	0.28	
Injury probability (AIS 3+)	6.6%	6.6%	9.1%	6.4%	5.6%	6.4%	

The higher biofidelity of the THOR-50M chest resulted in greater chest deflection (Table 6). The maximum IR-TRACC resultant deflection within the THOR-50M chest was greater than the maximum chest potentiometer (chest pot) deflection for the AM50 in NCAP testing. For each test in this study the THOR's upper right chest quadrant, opposite the shoulder belt path, showed the greatest deflection.

Injury risk for the THOR-50M was calculated using the Multi-point Thoracic Injury risk function [6]. The age used in the risk function was 35 years old, which is the age NCAP considers the average for the driving population for the chest pot risk function [7]. The THOR's injury risk from chest deflection was at least 10 times greater than the AM50's risk in similar test events.

Table 6. Driver, maximum chest deflections and injury risk

	Research						
	THOR-50M IR-TRACC (upper right)						
	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Chest deflection (mm)	-41.3	-44.3	-65.5	-39.3	-51.1	-50.4	
Injury probability (AIS 3+)	14.5%	20.0%	79.7%	11.4%	36.6%	34.6%	
	NCAP						
	AM50 CHEST POT						
Chest deflection (mm)	-20.6	-18.7	-14.9	-24.7	-23.8		
Injury probability (AIS 3+)	1.5%	1.1%	0.6%	2.5%	2.2%		

The maximum compressive force measured along the z-axis of the THOR's femur was greater than that of the AM50 test events, yet the force level did not correlate to high injury risks. Knee air bags were present in the Malibu and Highlander vehicles.

Table 7. Driver, maximum femur force and injury risk

		Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Research THOR-50M	Peak femur force (N)	-2696	-1857	-3867	-2973	-3891	-2933
	Injury probability (AIS 2+)	1.2%	0.8%	2.2%	1.4%	2.2%	1.4%
NCAP AM50	Peak femur force (N)	-1353	-2299	-2011	-1115	-242	
	Injury probability (AIS 2+)	0.6%	1.0%	0.9%	0.5%	0.3%	

The difference in knee to dash clearance between the THOR-50M and AM50 is provided in Table 8 and Table 9. The values within the tables are the x and z axis differences between the KDL (left knee to dash), KDR (right knee to dash) measurements from the test setup. Negative value indicates less clearance for the THOR-50M. The small knee to dash clearance is also due to the longer THOR-50M femur as well as closer ATD positioning clearance.

Mazda3 pre-test photos demonstrate the noticeable change in dash to knee clearance between the two ATDs (Figure 3). The THOR-50M knees are considerably closer to the knee bolster than the AM50. The z-axis response of the femur load cell confirms that close proximity of the THOR-50M knee lead to compressive loading early in the test event. Output from the femur load cell is initially positive indicating a tensile force. Knee contact with the dash compressively loads the femur and results in a negative output value.

Table 8. Driver, clearance distance comparison, (THOR-50M - AM50)

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Left knee to dash (mm, x-axis)	-22	-2	-22	-35	-54	-35
Right knee to dash (mm, x-axis)	-20	-30	2	-20	-30	-20

Table 9. Driver, clearance distance comparison, (THOR-50M - AM50)

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Left knee to dash (mm, z-axis)	-22	-6	-15	-22	-44	14
Right knee to dash (mm, z-axis)	5	16	-53	-56	-55	-37

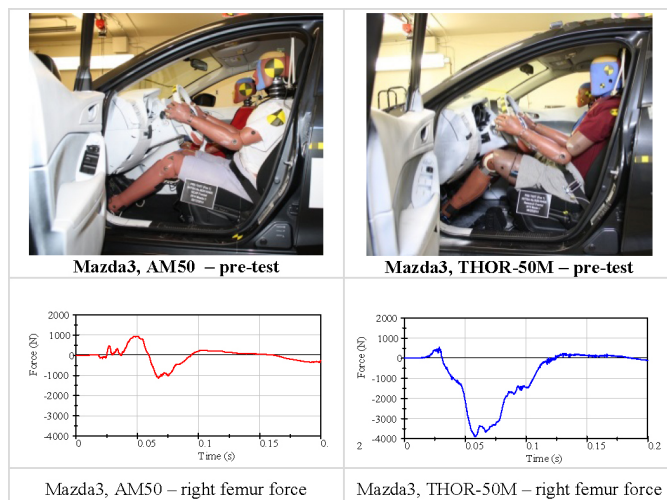


Figure 3. Mazda3, driver, knee position, femur loading

Right Front Passenger

The seat position for the right front AF05 in NCAP testing is full forward. For this study, the right front seat was positioned at mid-track. Other than this modification, the NCAP frontal impact seating procedure was used to seat the right front AF05. Compared to NCAP test data, the clearance between the AF05 chest and the dash increased in all cases, as did the AF05 nasion to windshield clearance (Table 10).

Table 10. Right front passenger, clearance distances comparison, (research - NCAP)

	Increase in clearance (mm), chest to dash (CD)	Increase in clearance (mm), nasion to windshield (HW)
Chevrolet Malibu	116	70
Chevrolet Malibu	111	92
Toyota Highlander	140	146
Ford F-150	153	200
Mazda3	139	107
Honda Fit	108	149

In all of the tests, seat belt pretensioners and frontal air bags deployed for the right front passenger. This study's seat belt load cells indicated seat belt load limiters for the right front passenger. Shoulder belt load cells showed force limiting behavior at approximately 3,000 N (Figure 4). Lap belt load cell output for all vehicles is seen as similar except for the Toyota Highlander (Figure 5). In this vehicle, lap belt force appears to be more similar to the right rear seat position in the Highlander which does not have a force limiting seat belt (Figure 12). There was no instrumentation for the right front passenger belt force in the prior Highlander NCAP test available for comparison.

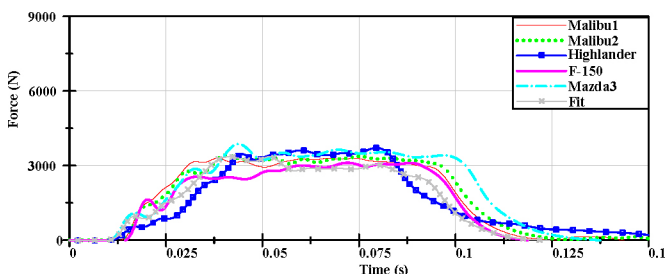


Figure 4. Right front passenger, shoulder belt force

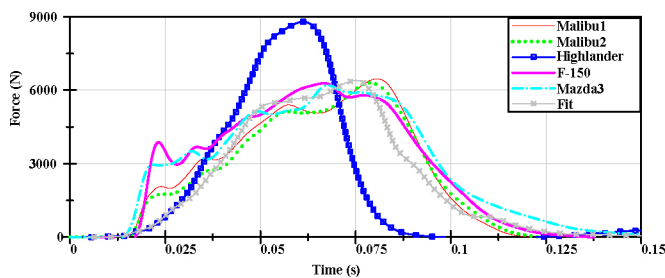


Figure 5. Right front passenger, lap belt force

Images from test videos showing the right front passenger to air bag clearance is included in Appendix A. In NCAP tests, frame captures are collected when the right front passenger contacts the frontal air bag. A frame capture from the current study at the same event time was paired to demonstrate the clearance due to the mid-track seat position. In all cases, the NCAP tests show right front passenger contact with the air bag occurring earlier than this study due to the seat’s full forward-track position. Vehicle air bags appear to be tuned for the AF05 seated at the full forward-track position.

For the majority of this study’s tests, the right front AF05 HIC₁₅ head injury risk was low (< 1.1%) as in the NCAP testing (Table 11). The single test showing higher head injury risk was with the Ford F-150, with AIS 3+ injury probability increasing from 0.2% to 4.5%.

Table 11. Right front passenger, HIC₁₅ values and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Research						
	HIC ₁₅	218	188	238	490	258
	Injury probability (AIS 3+)	0.3%	0.1%	0.4%	4.5%	0.5%
NCAP						
	HIC ₁₅	315	291	203	218	267
	Injury probability (AIS 3+)	1.1%	0.8%	0.2%	0.3%	0.6%

To investigate the higher HIC₁₅ value, video and data was reviewed from the Ford F-150 crash tests. Head position and timing of air bag contact is shown in Figure 6 along with the resultant head acceleration. For the AF05 seated full forward (NCAP), the head fully contacts the air bag at 48 milliseconds with a resultant head acceleration of 20 g. For the AF05 positioned at mid-track in the current study, there is head to air bag clearance at 48 milliseconds (left image) and head contact with the air bag at 66 milliseconds

(right image). Head acceleration is greater than 40 g at that time point. The additional clearance to the dash panel due to the mid-track seat position allows the AF05 head greater free travel prior to air bag contact, which results in a higher head acceleration value.

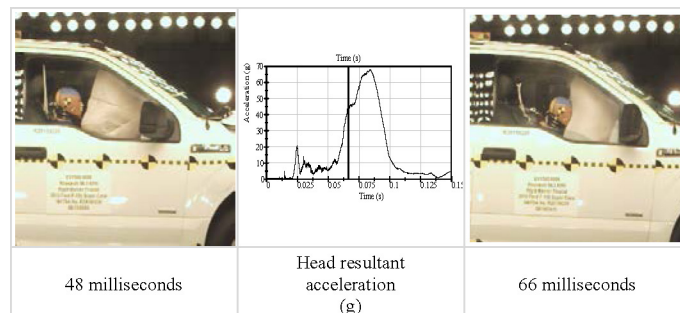


Figure 6. Right front passenger, Ford F-150 air bag deployment in research test

The current study’s right front AF05 was equipped with head angular rate sensors which allowed for the calculation of BrIC. The injury risk calculated for the BrIC measurements is considerably higher than that calculated from HIC₁₅ (Table 12).

NCAP testing performed with a Ford F-150 Super Crew 4X4 pickup (Test Number 9097) had the right front AF05 instrumented with angular rate sensors. With the right front seat positioned full forward, a BrIC value of 0.78 and a 39.4% injury risk was recorded. This risk was over three times greater than that seen for the AF05 seated at mid-track in the current study.

Table 12. Right front passenger, BrIC values and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Research						
	BrIC	0.48	0.48	0.58	0.49	0.52
	Injury probability (AIS 3+)	11.3%	11.3%	18.9%	12.0%	14.1%
NCAP						
	BrIC	n/a	n/a	n/a	0.78	n/a
	Injury probability (AIS 3+)				39.4%	

The AF05 response showed higher Nij values than NCAP in all but one test. The largest increase was seen with the Honda Fit with an injury risk increasing from 6.7 to 11.9% (Table 13).

Table 13. Right front passenger, Nij values and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Research	Nij	0.44	0.49	0.51	0.47	0.45	0.62
	Injury probability (AIS 3+)	8.6%	9.4%	9.8%	9.1%	8.8%	11.9%
NCAP	Nij	0.42	0.32	0.32	0.48	0.30	
	Injury probability (AIS 3+)	8.3%	6.9%	6.9%	9.3%	6.7%	

AF05 chest deflection for NCAP testing is recorded through the use of a chest pot. The injury risks using maximum chest pot deflection for the current research study and NCAP tests are given in Table 14. Chest deflection measured with the AF05 in the mid-track position was higher in every case than in full forward-track match. However, the percentage increase in chest deflection was not uniform between tests. Chest deflection approximately doubled for the Highlander, F-150 and second Malibu test, while increasing by approximately 50% for the Mazda3 and the first Malibu test. The Honda Fit test showed a 70% increase in chest deflection.

Table 14. Right front passenger, maximum chest pot deflection and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Research	Chest deflection (mm)	13.9	17.6	22.6	20.7	17.7	24.4
	Injury probability (AIS 3+)	0.9%	1.7%	3.6%	2.7%	1.7%	4.6%
NCAP	Chest deflection (mm)	9.0	9.2	7.9	12.2	14.5	
	Injury probability (AIS 3+)	0.3%	0.3%	0.2%	0.6%	1.0%	

In this study, additional right front AF05 chest deflection was provided by the RibEye Deflection Measurement System (Table 15). Compared to the chest pot, the maximum RibEye deflection was 7 to 22% greater in each test. The location of the maximum rib deflection was consistently at the upper left rib. Appendix B contains tables showing the maximum rib displacements for the right front passenger in all tests as well as the maximum chest pot deflection measured.

Table 15. Right front passenger, maximum chest deflection

	Chest pot deflection (mm)	RibEye deflection (mm)	(RibEye – Chest pot) chest deflection (mm)	% increase
Chevrolet Malibu	13.9	16.5	2.6	19
Chevrolet Malibu	17.6	19.5	1.9	11
Toyota Highlander	22.6	25.2	2.6	11
Ford F-150	20.7	22.2	1.5	7
Mazda3	17.7	21.7	4.0	22
Honda Fit	24.4	26.1	1.7	7

The compressive femur forces of the current test were markedly lower than NCAP due to the mid-track seat position and reduced amount of contact between knees and the lower dash. In this study, the highest z-axis femur loading was in tension due to inertial loading. Tensile loading is not used in evaluating injury risk. Table 16 shows the compressive loading in the current study and the NCAP tests. Compressive loading is denoted as negative in the femur's coordinate system.

Table 16. Right front passenger, compressive femur force and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Research	Peak femur force (N)	-113	-93	-625	-449	-167	-64
	Injury probability (AIS 2+)	0.3%	0.3%	0.5%	0.4%	0.3%	0.3%
NCAP	Peak femur force (N)	-610	-1745	-1813	-1582	-1449	
	Injury probability (AIS 2+)	0.5%	1.1%	1.2%	1.0%	0.9%	

Right Rear Passenger

For this study, an AF05 was positioned in the right rear seat using the FMVSS No. 214 Side Impact Protection seating procedure. No supplemental restraint devices (e.g. air bag, seat belt load limiter, seat belt pretensioner) were present at this seat location in any of the tested vehicles. In the six crash events there was no significant contact between the AF05 and the seatback or interior components in front of the AF05.

The HIC₁₅ was calculated for five of the six crash events (Table 17). Questionable data from the x-axis head accelerometer during the F-150 test did not allow calculation of HIC₁₅. Head injury risk ranged from 16.7 to 42.9%.

Table 17. Right rear passenger, HIC₁₅ and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
HIC ₁₅	844	939	1510	n/a	1099	738
Injury probability (AIS 3+)	16.7%	20.6%	42.9%		27.1%	12.6%

Chin to chest contact was judged to have occurred in the Highlander, Mazda3 and Fit tests. In addition to high x-axis head acceleration peaks (> 70 g) which corresponded with substantial neck flexion, post-test photos document chalk transfer indicating chin to chest contact. In the case of the Mazda3, video showed that the right rear AF05 had the lap belt slide over the top of both iliac crests (submarining) which induced twisting of the torso with chin to chest contact. Similar chalk transfer was recorded with post-test photos of the F-150 right rear AF05; however the head CG accelerometer output was deemed faulty and is not included as a figure. No indication of chin to chest contact was noted in either Malibu test. Images from the test videos for each test showing right rear AF05 torso flexion are included in Appendix C.

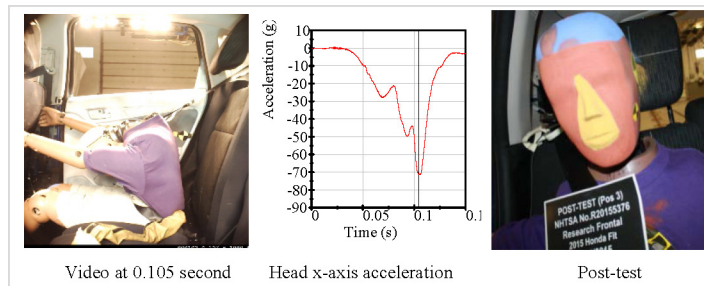


Figure 9. Fit, right rear passenger, chin to chest contact

Nij was calculated for each test with a calculated injury risk range from 21.8 to 36.2% (Table 18).

Table 18. Right rear passenger, Nij and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Nij	0.99	1.08	1.35	1.33	1.29	1.05
Injury probability (AIS 3+)	21.8%	25.0%	36.2%	35.2%	33.5%	23.9%

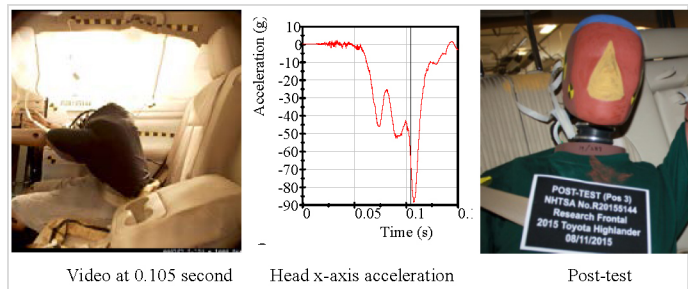


Figure 7. Highlander, right rear passenger, chin to chest contact

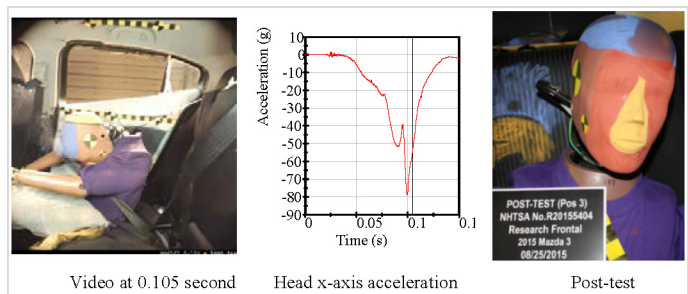


Figure 8. Mazda3, right rear passenger, chin to chest contact

Chest pot data was collected for each test and presented in Table 19 along with injury risk. The maximum chest deflection and injury risk was seen in the Toyota Highlander test which had the chest pot bottom out.

Table 19. Right rear passenger, maximum chest pot deflection and injury risk

	Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit
Chest deflection (mm)	-41.1	-42.7	-55.9	-51.6	-39.1	-48.0
Injury probability (AIS 3+)	27.0%	30.4%	61.3%	51.6%	23.0%	42.9%

Like the right front AF05, the right rear AF05 had a RibEye Deflection Measurement System installed. In the Toyota Highlander and Ford F-150 crash events, the RibEye did not collect data. In each test, the maximum deformation (x-axis) recorded by the RibEye was greater than that recorded by the chest pot (Figure 10). The maximum chest deflection was observed on the ATD's left side but the rib that sustained the maximum deflection was not consistent. There is not an injury risk function for RibEye deflections at this time.

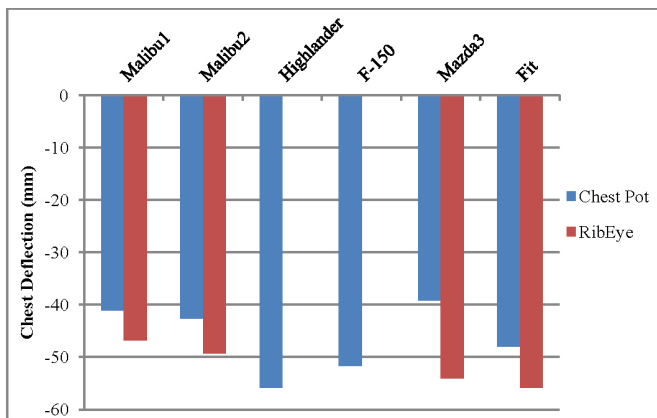


Figure 10. Right rear passenger, chest pot versus maximum RibEye deflection (x-axis)

The following tables demonstrate the behavior of the RibEye during the four tests in which the system was functional. Signal drop-out was noted in each test, with the majority of drop-outs occurring at the left upper rib (#1), and at the right lower ribs (#5 & #6). The maximum deflection for each crash test is indicated in bold. If a RibEye signal drop-out is noted below, the rib deflection prior to signal loss is provided.

Table 20. Right rear passenger, RibEye maximum individual rib deflection (x-axis)

Chevrolet Malibu, test #9332

Rib #	Rib deflection (mm)	
	Left	Right
1	-44 ¹	-26.7
2	-43.7	-24.4
3	-45.4	-23.1
4	-45.7	-20.2
5	-46.8	-13 ¹
6	-45.2	-13 ¹

¹ drop-out occurred
maximum chest pot deflection: -41.1 mm

Chevrolet Malibu, test #9333

Rib #	Rib deflection (mm)	
	Left	Right
1	-44 ¹	-28.4
2	-45.5	-26.1
3	-47.3	-24.6
4	-47.9	-21.9
5	-49.3	-13 ¹
6	-48.4	-4 ¹

¹ drop-out occurred
maximum chest pot deflection: -42.7 mm

Mazda3, test #9336

Rib #	Rib deflection (mm)	
	Left	Right
1	-46 ¹	-22.1
2	-52.8	-20.7
3	-54.1	-17.8
4	-52.5	-14.6
5	-50.6	-14 ¹
6	-47.9	-3 ¹

¹ dropout occurred
maximum chest pot deflection: -39.1 mm

Honda Fit, test #9337

Rib #	Rib deflection (mm)	
	Left	Right
1	-43 ¹	-29.2
2	-49.3	-29.4
3	-52.8	-28.3
4	-55.8	-19 ¹
5	-56 ¹	-12 ¹
6	-56 ¹	-2 ¹

¹ dropout occurred
maximum chest pot deflection: -48.0 mm

As demonstrated in Figure 8, video of the Mazda3 crash event showed the lap belt sliding over the top of both iliac crests (submarining) of the right rear AF05. This explains the belt force behavior for the Mazda3 shown in Figure 11 and Figure 12.

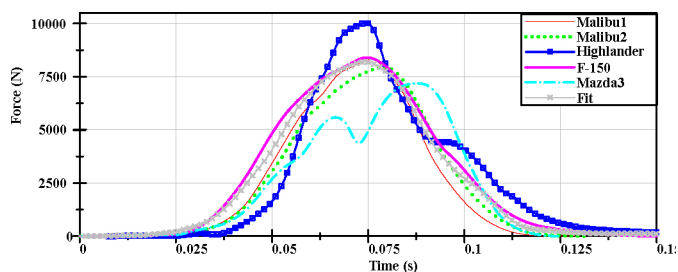


Figure 11. Right rear passenger, shoulder belt force

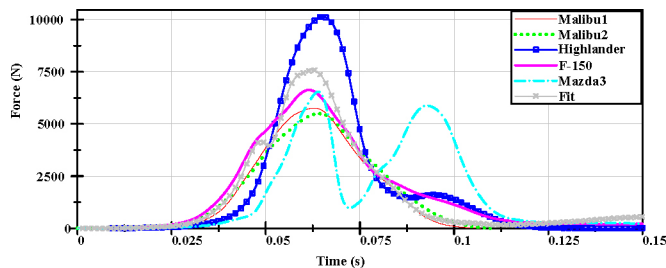


Figure 12. Right rear passenger, lap belt force

The anterior superior iliac spine (A.S.I.S.) load cell in the AF05 also provided confirmation of the submarining event. Review of the A.S.I.S. load cell data which showed a decreasing rate of ilium bone force of 1,000,000 N/second or more (Figure 13). This instrumentation response rate was considered by the Japanese New Car Assessment Program (JNCAP) to indicate a potential abdominal injury caused by the lap belt sliding off the ilium bone of the pelvis. Such an event would have reduced the JNCAP abdomen weighed score from a maximum of 3.2 points to 0 points [10]. Currently there is no NCAP injury criterion for abdominal injury in the frontal impact test.

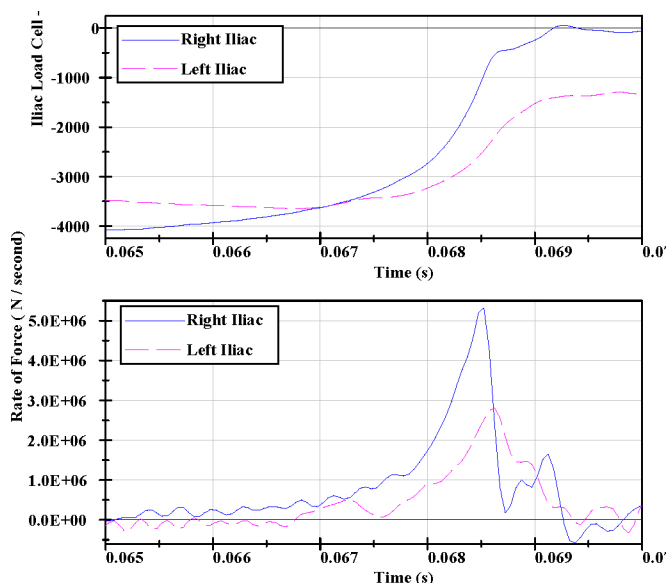


Figure 13. Mazda3, right rear passenger, iliac load cell

NCAP Frontal Impact Rating

The NCAP star rating system is based on the combined injury risk to selected body regions for a series of tests. For the frontal impact test, the selected body regions are the head, neck, chest and femur. Individual body region injury risks determined from the ATD response during the crash test are combined into a joint probability of injury.

$$P_{joint} = 1 - (1 - P_{head}) \times (1 - P_{neck}) \times (1 - P_{chest}) \times (1 - P_{femur})$$

The analysis that follows looks at frontal impact test results from the current study and compares injury risk to prior NCAP tests. These individual ATD calculations do not take into account the additional NCAP tests used to generate the Combined Crashworthiness Rating Vehicle Safety Score.

Joint Probability of Injury, Driver

Table 21 contains the joint probability of injury calculated for the AM50 in NCAP crash tests. The injury risk was calculated by using HIC_{15} , N_{ij} , and peak resultant chest deflection and peak femur load in the joint probability of injury equation.

Table 21. Driver - AM50, NCAP testing, joint probability of injury

Test Number	7856	8531	9097	8539	9033
Year	2013	2014	2015	2014	2015
Make	Chevrolet	Toyota	Ford	Mazda	Honda
Model	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	8.5%	11.1%	8.0%	8.5%	9.2%

Table 22 provides the joint probability of injury based on the response of the THOR-50M seated at mid-track in this study. The joint probability of injury for the THOR-50M is higher compared to the NCAP tests primarily due to chest deflection recorded by the IRTRACC instrumentation. Chest deflection is notable for the Highlander, Mazda3, and Fit leading to a four to seven times greater joint probability of injury than NCAP tests.

Table 22. Driver - THOR-50M, research testing, joint probability of injury

Test Number	9332	9333	9334	9335	9336	9337
Year	2015	2015	2015	2015	2015	2015
Make	Chevrolet	Chevrolet	Toyota	Ford	Mazda	Honda
Model	Malibu	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	21.2%	25.6%	81.8%	18.2%	41.8%	40.3%

Table 23 is generated for the THOR-50M driver with BrIC substituted for HIC_{15} for head injury risk in the joint probability calculation. The head injury risk from BrIC was greater than HIC_{15}

injury risk for each test and contributes to an increase in all joint probability values. All vehicles show a minimum four times increase in joint probability of injury over NCAP tests.

Table 23. Driver - THOR-50M, research testing, joint probability of injury (with BrIC)

Test Number	9332	9333	9334	9335	9336	9337
Model	Malibu	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	45.5%	46.4%	85.3%	33.5%	51.6%	52.2%

Joint Probability of Injury, Right Front Passenger

Table 24 is the joint probability of injury calculated for the AF05 seated full forward in NCAP crash tests.

Table 24. Right front passenger - AF05, NCAP testing, joint probability of injury

Test Number	7856	8531	9097	8539	9033
Year	2013	2014	2015	2014	2015
Make	Chevrolet	Toyota	Ford	Mazda	Honda
Model	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	10.0%	9.0%	8.4%	11.0%	8.9%

Table 25 provides the joint probability of injury based on the response of the AF05 right front passenger seated at mid-track in this study. The maximum deflection of the chest pot was used for probability calculations. The Highlander's risk increased by 52% due to an increase in HIC_{15} , N_{ij} , and chest deflection, while the F-150 and Fit both showed over 80% increase in joint probability of injury primarily due to an increase in N_{ij} and chest deflection.

Table 25. Right front passenger - AF05, research testing, joint probability of injury

Test Number	9332	9333	9334	9335	9336	9337
Year	2015	2015	2015	2015	2015	2015
Make	Chevrolet	Chevrolet	Toyota	Ford	Mazda	Honda
Model	Malibu	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	9.9%	11.3%	13.8%	15.8%	11.1%	16.2%

Table 26 values were generated for the AF05 right front passenger with BrIC substituted for HIC_{15} for head injury risk. The head injury risk from BrIC was greater than HIC_{15} injury risk for each test and more than doubles the joint probability of injury in the first Malibu, Highlander, Mazda3, and Fit tests.

If BrIC in the NCAP Ford F-150 test (Test Number 9097) was used to calculate joint probability of injury for the right front passenger in that test (Table 24), joint probability of injury increases from 8.4 to 44.4%.

Table 26. Right front passenger - AF05, research testing, joint probability of injury (with BrIC)

Test Number	9332	9333	9334	9335	9336	9337
Model	Malibu	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	19.9%	21.3%	29.8%	22.5%	23.2%	40.9%

Joint Probability of Injury, Right Rear Passenger

Table 27 provides the joint probability of injury calculated for the AF05 rear seat passenger. The maximum deflection of the chest pot was used for probability calculations. High injury risk was noted for the head, neck and chest leading to a joint probability of injury from 52.6% up to maximum of 86%. The joint probability of injury for the rear passenger was 3.8 to 6.2 times greater than the front passenger when not considering BrIC values.

Table 27. Right rear passenger - AF05, research testing, joint probability of injury

Test Number	9332	9333	9334	9335	9336	9337
Year	2015	2015	2015	2015	2015	2015
Make	Chevrolet	Chevrolet	Toyota	Ford	Mazda	Honda
Model	Malibu	Malibu	Highlander	F-150	Mazda3	Fit
Joint probability of injury	52.6%	58.7%	86.0%	68.8%	62.9%	62.2%

Repeatability of Test Procedure

The repeatability of vehicle response within the current research study was evaluated by performing two crash tests with the 2015 Chevrolet Malibu. The left and right vehicle frame x-axis accelerometer data were compared using CORA [11]. CORA software uses two methods to evaluate the correlation of a signal. The corridor method compares the deviation between curves while the cross correlation method compares curve characteristics such as shape, phase shift and size. The CORA rating in Table 28 compares data from the two 2015 Malibu vehicles in the current study. The high CORA rating indicates a very high correlation for vehicle frame acceleration in the two crash tests.

Table 28. CORA evaluation of research frontal impact crash tests

Experiment	Rating	Weight
2015 Chevrolet Malibu, Test #9332	0.945	0.50
2015 Chevrolet Malibu, Test #9333	0.946	0.50
Total rating:	0.946	1.00

As an additional measure of repeatability, CORA was also used to compare the current study's two Malibu crash tests to an earlier 2013 Chevrolet Malibu NCAP test (Table 29). The inclusion of a third test changed the basis for evaluation (corridor, cross-correlation reference curve) and accounts for the change in rating for the two tests from Table 28. This evaluation also resulted in a high total CORA rating.

Table 29. CORA evaluation of NCAP and research frontal impact crash tests

Experiment	Rating	Weight
2015 Chevrolet Malibu, Test #9332	0.882	0.333
2015 Chevrolet Malibu, Test #9333	0.911	0.333
2013 Chevrolet Malibu, Test #7856	0.839	0.333
Total rating:	0.877	1.000

DISCUSSION

The introduction of the THOR-50M to the NCAP frontal impact test resulted in an accompanying increase in joint probability of injury for the driver. While the increase in HIC_{15} was negligible, the increase in head injury risk was evidenced by the BrIC injury criterion and associated risk function. The THOR-50M high chest deflections and greater injury risk was demonstrated using the Multi-point Thoracic risk function. The maximum resultant deflection was in the upper right chest quadrant which was opposite the shoulder belt path. The increase in femur loads was low and did not increase injury risk above 2.2%.

For the front passenger AF05, the joint probability of injury nearly doubled when BrIC is used for head injury risk for all but one test. The one exception was the F-150 which increased slightly less than 50%.

The maximum RibEye measurements were greater than those provided by the chest pot. In the case of the right front AF05, the maximum deflection was seen at the same rib for each test. This was left rib #1, in the upper left chest quadrant, opposite the belt path. RibEye channel drop-outs occurred at the lower right rib for each test event. This was due to an interruption of the light from the LED unit and has been reported as due to interference by the abdominal insert or the chest potentiometer structure [11]. A chest potentiometer was installed in each AF05 to allow comparison to the RibEye.

The right rear passenger's injury risk was considerably higher than that measured for the right front passenger where supplemental restraints, such as pretensioners, load limiters and air bags are available. A HIC_{15} value in excess of 700 was seen in all tests. The calculated N_{ij} value was greater than 1.0 for five of the six tests. Chest pot deflection was double that of the right front passenger. These three criteria all contributed to a 4 to 6 times greater joint probability of injury over the right front passenger. Peak shoulder belt loads for the right rear passenger were nearly double or higher than the right front passenger. In addition, lap belt submarining of the right rear passenger was recorded through video and A.S.I.S. load cell output in the Mazda3 test.

CORA evaluation of vehicle crash pulse for the two Malibu tests run in series indicated repeatability of the tests. ATD instrumentation response and injury risks calculated for each seating position were also similar between tests. For the driver, the greatest difference in injury risk (5.5%) between the two tests was due to the difference in chest deflection (3mm). For the right front passenger, the greatest difference in injury risk (0.8%) between the two tests was chest deflection and Nij. For the right rear passenger, the greatest difference in injury risk (3.9%) between the two tests was HIC₁₅ (844 vs. 939).

SUMMARY

The THOR-50M in the driver's position for the frontal impact research tests showed a higher injury risk than the AM50 used in NCAP tests. The HIC₁₅ and femur loads were higher, but the most significant change to the joint probability of injury was driven by the chest injury risk and BrIC head injury risk. Chest injury risk and BrIC more than quadruple the joint probability of injury over NCAP tests.

The repositioning of the AF05 in the right front passenger seat to mid-track resulted in a notable increase in joint probability of injury for three vehicles. For the right front passenger, the F-150's risk increased by 50%, while the Highlander and Fit showed an 80% increase in joint probability of injury. Maximum deflection of the AF05 chest potentiometer in this study was greater than NCAP testing. RibEye deflection was even greater but the percentage increase over the chest pot was not uniform among the test vehicles. For all of the vehicles, the inclusion of BrIC head risk at least doubles the joint probability of injury over NCAP tests.

The AF05 positioned in the right rear seat had higher injury risk calculated from HIC₁₅, Nij and chest compression than the right front passenger. The joint probability of injury ranged from 3.8 to 6.2 times greater than the front passenger. The maximum RibEye deflection was greater than the chest pot and there were some RibEye signal drop-outs during tests. In the Mazda3 test event, video and ASIS load cell output confirmed the AF05 lap belt slid over both iliac crests and led to a submarining event.

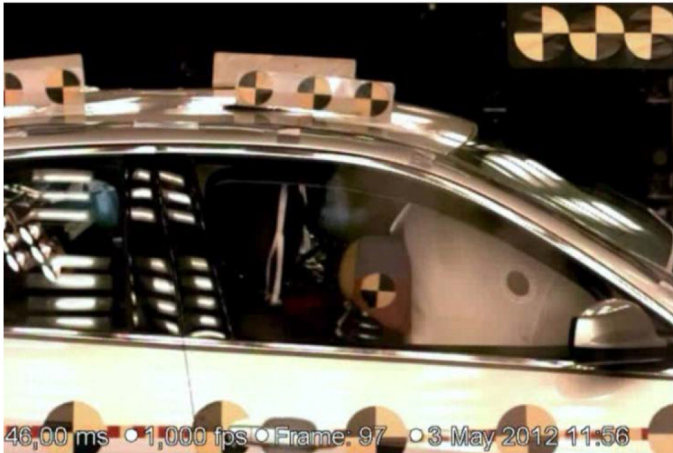
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APPENDIX

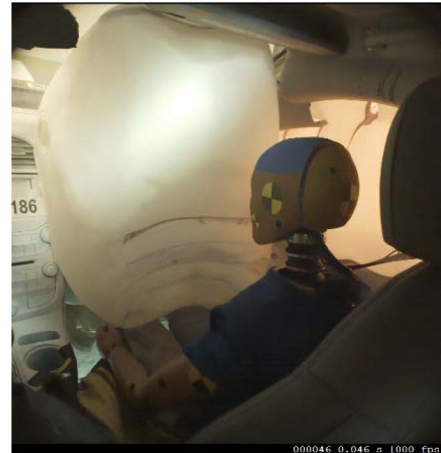
APPENDIX A

NCAP (full forward)

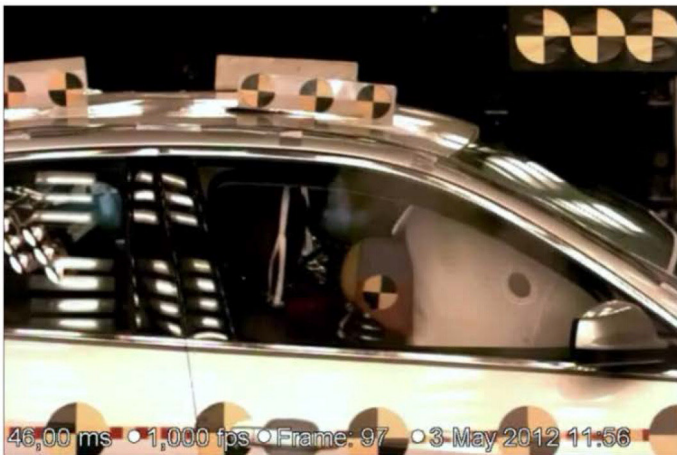


Chevrolet Malibu, test #9332, air bag deployment at 0.046 seconds

Research (mid-track)



NCAP (full forward)

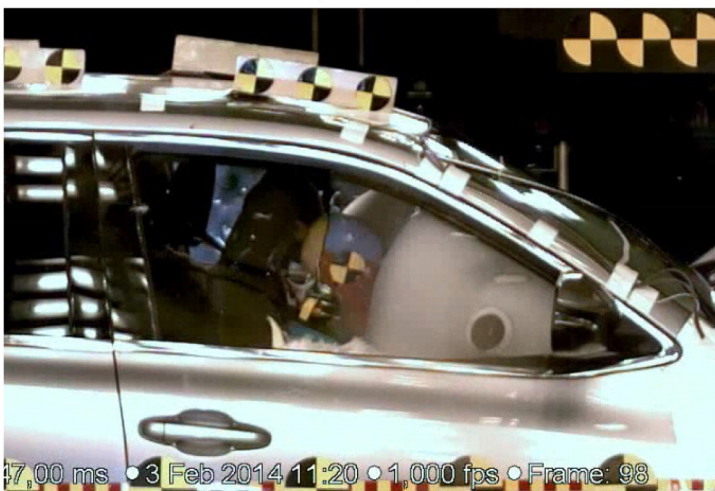


Chevrolet Malibu, test #9333, air bag deployment at 0.046 seconds

Research (mid-track)



NCAP (full forward)



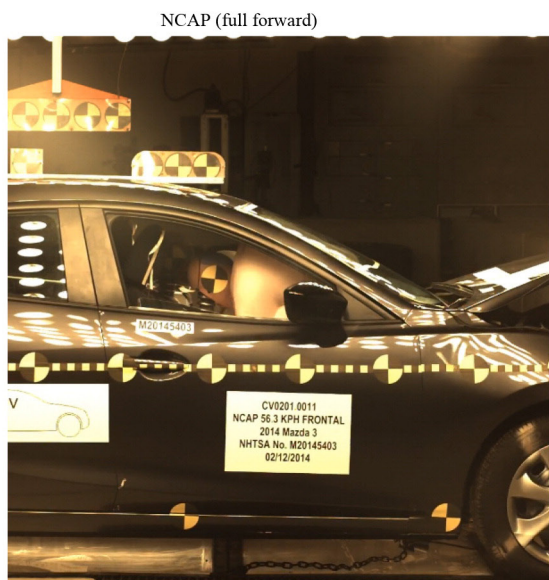
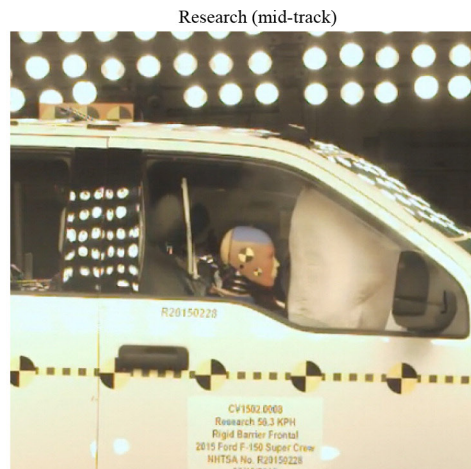
Toyota Highlander, test #9334, air bag deployment at 0.047 seconds

Research (mid-track)

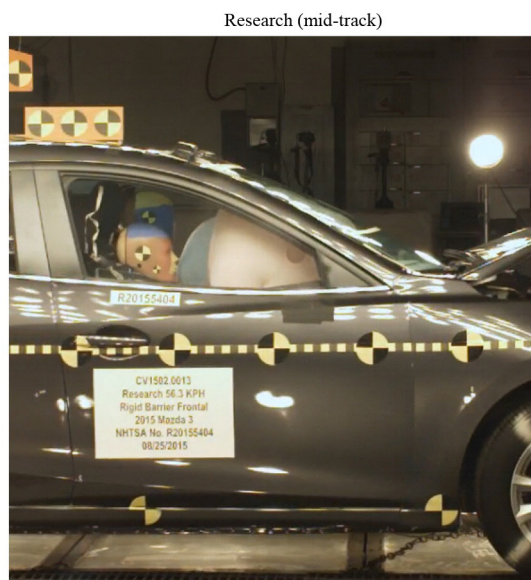




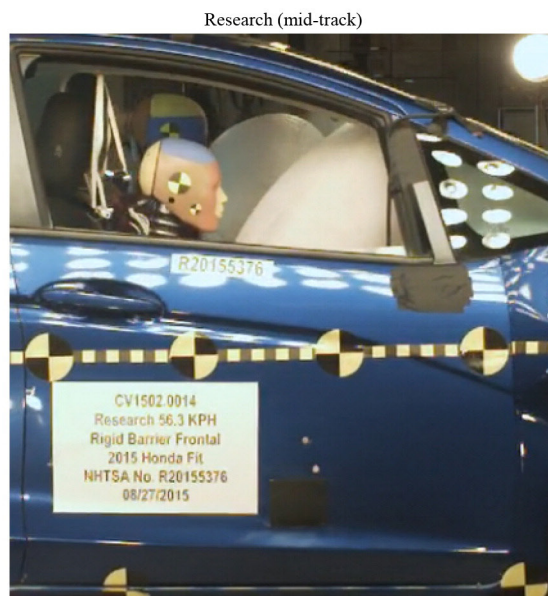
Ford F-150, test #9335, air bag deployment at 0.052 seconds



Mazda3, test #9336, air bag deployment at 0.039 seconds



Honda Fit, test #9337, air bag deployment at 0.046 seconds



APPENDIX B

Note: Maximum chest deflection is **bolded**.

When a signal drop-out is noted, the rib deflection prior to signal loss is provided.

Chevrolet Malibu, test #9332

Rib deflection (mm)

Rib #	Left	Right
1	-16.5	-11.2
2	-15.2	-9.3
3	-14.2	-8.2
4	-12.9	-6.8
5	-11.8	-5.8
6	-10.4	-3 ¹

¹ signal drop-out occurred

maximum chest pot deflection: -13.9 mm

Chevrolet Malibu, test #9333

Rib deflection (mm)

Rib #	Left	Right
1	-19.5	-13.3
2	-18.4	-11.3
3	-17.5	-10.3
4	-16.1	-8.7
5	-15.1	-7.6
6	-13.9	-3 ¹

¹ signal drop-out occurred

maximum chest pot deflection: -17.6 mm

Toyota Highlander, test #9334

Rib deflection (mm)

Rib #	Left	Right
1	-25.0	-16.4
2	-24.0	-13.9
3	-23.1	-12.3
4	-22.0	-10.7
5	-21.4	-9.4
6	-19.9	-3 ¹

¹ signal drop-out occurred

maximum chest pot deflection: -22.6 mm

Ford F-150, test #9335

Rib deflection (mm)

Rib #	Left	Right
1	-22.0	-16.2
2	-20.7	-13.6
3	-19.8	-12.4
4	-18.4	-10.7
5	-17.4	-9.7
6	-15.6	-6 ¹

¹ signal drop-out occurred

maximum chest pot deflection: -20.7 mm

Mazda3, test #9336

Rib deflection (mm)

Rib #	Left	Right
1	-21.7	-12.5
2	-20.4	-10.6
3	-19.5	-9.4
4	-18.3	-8.3
5	-17.2	-7.5
6	-16.2	-3 ¹

¹ signal drop-out occurred

maximum chest pot deflection: -17.7 mm

Honda Fit, test #9337

Rib deflection (mm)

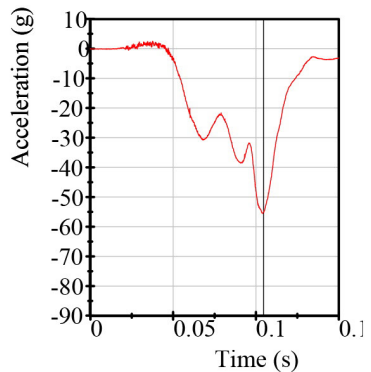
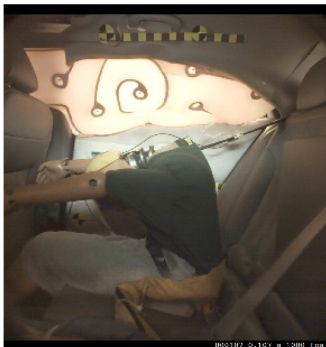
Rib #	Left	Right
1	-26.1	-16.9
2	-25.5	-14.8
3	-25.1	-13.7
4	-24.5	-12.4
5	-23.9	-11.8
6	-22.5	-5 ¹

¹ signal drop-out occurred

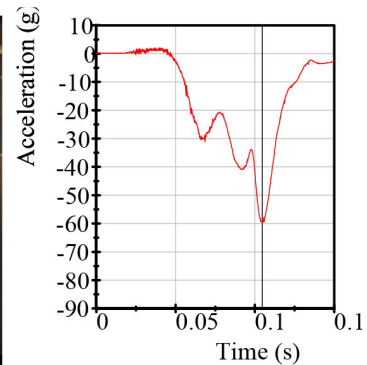
maximum chest pot deflection: -24.4 mm

APPENDIX C

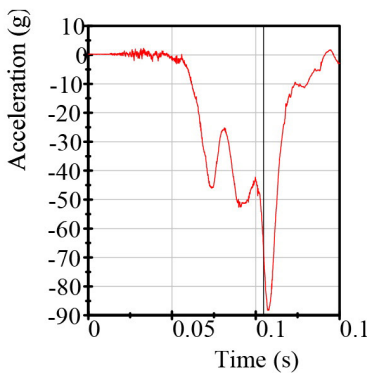
Right rear AF05 position at 105 milliseconds, head x-axis accelerometer



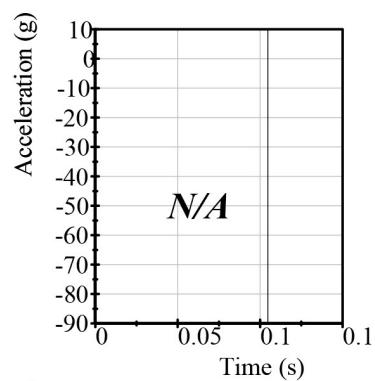
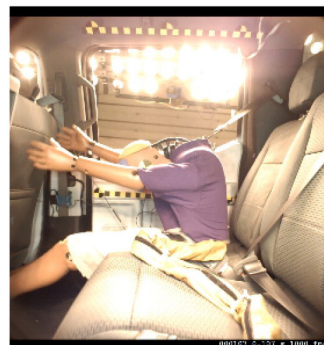
Chevrolet Malibu, test #9332



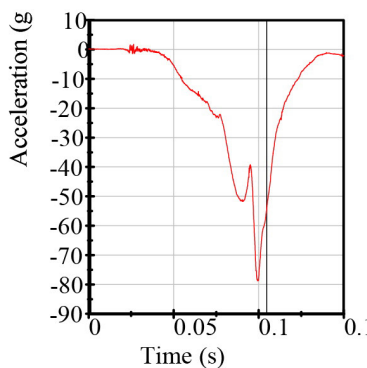
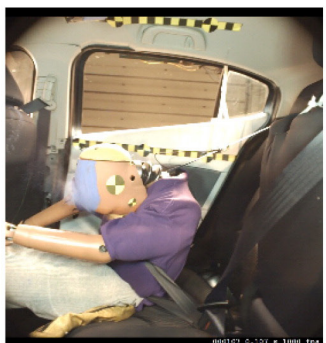
Chevrolet Malibu, test #9333



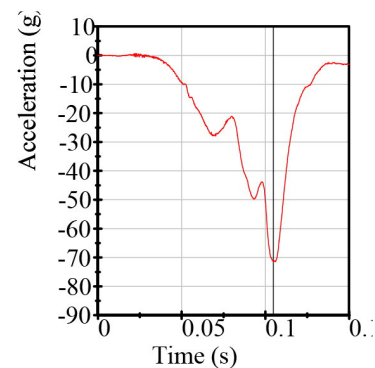
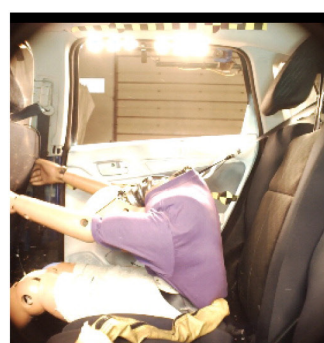
Toyota Highlander, test #9334



Ford F-150, test #9335



Mazda3, test #9336



Honda Fit, test #9337

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