

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.

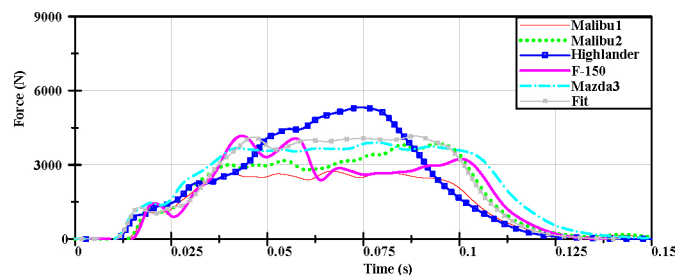


Figure 1. Driver, shoulder belt force

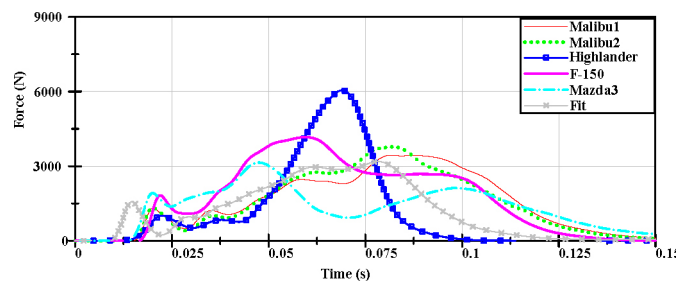


Figure 2. Driver, lap belt force

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

		Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Research	THOR-50M	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

		Vehicle						
		Chevrolet Malibu	Chevrolet Malibu	Toyota Highlander	Ford F-150	Mazda3	Honda Fit	
Research	THOR-50M IR-TRACC (upper right)	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

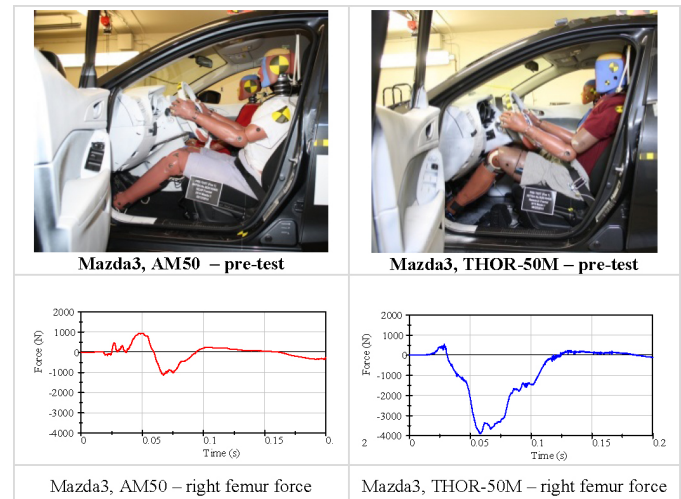


Figure 3. Mazda3, driver, knee position, femur loading

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.

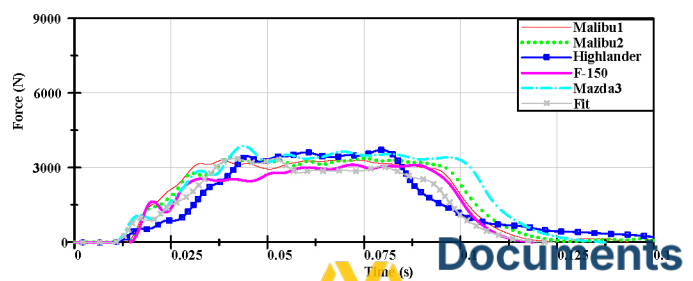


Figure 4. Right front passenger, shoulder belt force

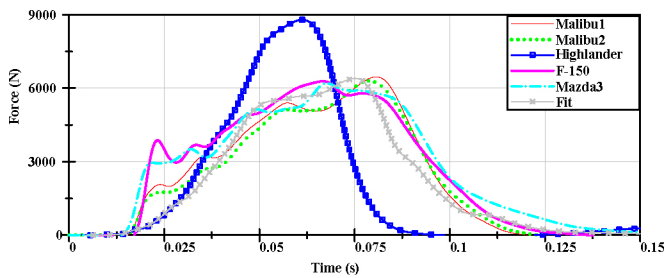


Figure 5. Right front passenger, lap belt force

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	149
Injury probability (AIS 3+)	0.3%	0.1%	0.4%	4.5%	0.5%	0.0%
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.

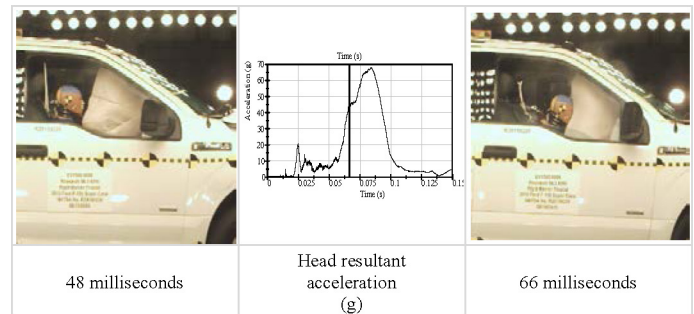


Figure 6. Right front passenger, Ford F-150 air bag deployment in research test

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	0.69
Injury probability (AIS 3+)	11.3%	11.3%	18.9%	12.0%	14.1%	29.5%
NCAP						
BrIC	n/a	n/a	n/a	0.78	n/a	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](#)).