

Comparison of the THOR and Hybrid III Responses in Oblique Impacts

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ABSTRACT

NHTSA has been investigating a new test mode in which a research moving deformable barrier (RMDb) impacts a stationary vehicle at 90.1 kph, a 15 degree angle, and a 35% vehicle overlap. The test utilizes the THOR NT with modification kit (THOR) dummy positioned in both the driver and passenger seats. This paper compares the behavior of the THOR and Hybrid III dummies during this oblique research test mode.

A series of four full vehicle oblique impact crash tests were performed. Two tests were equipped with THOR dummies and two tests were equipped with Hybrid III dummies. All dummies represent 50th percentile males and were positioned in the vehicle according to the FMVSS208 procedure. The Hybrid III dummies were instrumented with the Nine Accelerometer Package (NAP) to calculate brain injury criteria (BrIC) as well as THOR-Lx lower legs. Injury responses were recorded for each dummy during the event. High speed cameras were used to capture vehicle and dummy kinematics. The vehicle restraint devices and their associated deployment times remained the same for each test. Post test analysis investigated each dummy injury response, kinematics, and vehicle structural performance. The results of the current study show that during an oblique impact, where significant lateral motion of the vehicle is observed, there are differences between the THOR and Hybrid III dummies.

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INTRODUCTION

To improve occupant protection and reduce the number of injuries and fatalities during real world crash events, new tests modes are currently being developed. The following field data studies have been conducted in order to investigate the reasons behind the increase in injuries in the field despite the increase of seatbelt usage rate and more vehicles being equipped with airbags. Rudd et al. (2009) concluded that frontal oblique crashes is one of the main factors in which fatalities occur. Since the principle direction of force (PDOF) acts at an angle, the motion of the occupant does not entirely move in a longitudinal X-direction as seen in full frontal crashes. The restraint provided by the airbag is less effective because the occupant's trajectory caused it to interact outboard from the airbag's centerline.

In a separate study, Rudd et al. (2011) concluded that an oblique impact, coupled with a small overlap, increased the occupant's chance of injury by coming into contact with the vehicle's interior components. Sherwood et al. (2009) defined the small overlap crash as a collision in which the front end side (longitudinal) member of the vehicle does not get entirely engaged causing severe intrusion to the occupant compartment. The authors concluded that there was a high

correlation between intrusion and injury severity. Crashes that caused higher injuries included collinear collisions with narrow fixed objects and vehicle to vehicle oblique crashes.

Recent efforts by NHTSA to address the findings mentioned above have led to its development of a small overlap oblique frontal test mode. During this test mode NHTSA is seeking to replicate both vehicle and occupant kinematics experienced in the field by impacting a stationary vehicle with a research moveable deformable barrier (RMDb) at a certain velocity, angle, and overlap [Saunders et al. 2011].

During this small overlap oblique test mode, it is important to have an anthropometric test device (ATD) that is able to capture real world occupant kinematics. It has been known in the industry that the Hybrid III dummy is sometimes limited and does not produce desired kinematic results during certain crash test modes. The THOR dummy was first introduced in 1996 and has undergone several design changes which included the THOR Alpha in 2001 and the THOR NT in 2005 [Martin et al. 2007]. In 2011 NHTSA updated the THOR NT to improve its durability, usability, and biofidelity [Ridella et al. 2011]. Along with its added biofidelity, the THOR dummy is equipped with additional instrumentation. These include angular rate sensors to measure head rotational velocities in order to calculate rotational brain injury criterion (BrIC) as well

as the Infrared Telescoping Rod for Assessment of Chest Compression (IR-TRACC) in order to measure chest displacement (four locations) and abdomen displacement (two locations). To help monitor hip injuries, additional load cells are found on the THOR hip to measure acetabulum forces. The THOR Lx lower leg also has several enhancements that include rotational potentiometers to measure ankle rotations.

Several studies have been performed comparing kinematics and injury severity risks between the THOR and Hybrid III dummies. [Yaguchi et al. \(2009\)](#) compared these kinematics and injury severity risks between the two dummies during two 64 kph 40% offset frontal crash tests. Differences were seen in the final dummy seating postures despite following the same ECE R94 seating procedure. The authors concluded that the kinematic behaviors were fairly similar between the two dummies. Equivalent injury response values were also seen.

[Mueller et al. \(2011\)](#) compared Hybrid III, THOR FT, and THOR NT during small overlap frontal offset tests. Minor differences were seen in head rotation where the THOR FT tended to twist more than the Hybrid III and THOR NT. Differences occurred in the lower extremities where earlier loading times of both THOR dummies was seen due to their longer femurs. The authors concluded that similar performances were seen between Hybrid III and THOR dummies during a frontal offset small overlap type test.

METHODS

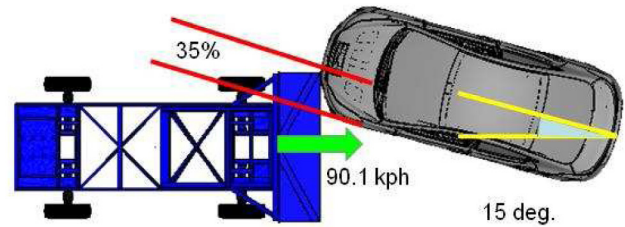
[Table 1](#) shows a series of four NHTSA oblique crash tests that were performed representing two sets of comparisons. Comparison 1 consists of Vehicle A and compares the THOR to Hybrid III. Comparison 2 consists of Vehicle B and will have the same dummy comparison. Vehicles A and B were of the small car class with differences in structural makeup between the two vehicles.

[Table 1. Vehicle and dummy test matrix.](#)

Test #	Test Mode	Target Vehicle		Dummy	
		Vehicle A	Vehicle B	THOR	H3
1	NHTSA Oblique	X		X	
2	NHTSA Oblique	X			X
3	NHTSA Oblique		X	X	
4	NHTSA Oblique		X		X

Test Mode Description

The NHTSA oblique test mode used for this analysis consists of a research moving deformable barrier (RMDB) impacting the target stationary vehicle at a velocity of 90.1 kph, a 15 degree angle, and a 35% vehicle overlap ([Figure 1](#)). The RMDB was a modified FMVSS 214 barrier with a test weight of 2490.7 Kg.



[Figure 1. NHTSA Oblique test setup.](#)

Onboard and off board cameras were positioned accordingly in order to obtain the necessary camera views needed for video analysis of the vehicle and dummies. Accelerometers were placed on various positions along the vehicle body in which acceleration characteristics of the vehicle could be monitored. For the RMDB, accelerometers were placed on the front portion of the barrier as well as its center of gravity (CG).

During the test series each vehicle was equipped with a driver airbag, curtain airbag, anchor pretensioner, and retractor pretensioner on the driver side. On the passenger side, the restraint system consisted of a passenger airbag, anchor pretensioner, and a retractor pretensioner. During the first test, a live fire for the restraint system was utilized. After reviewing the restraint system time to fires (TTF's) of the first test, a remote trigger with the same fire times was used for the remaining three tests in order to ensure consistency between all tests. [Table 2](#) shows the TTF's of the restraint system.

[Table 2. Restraint system time to fire.](#)

Restraint	Time to fire (TTF)
DAB 1 st Stage	12
DAB 2 nd Stage	22
CAB (Driver)	32
Anchor PT (Driver and Passenger)	12
Retractor PT (Driver and Passenger)	12
PAB 1 st Stage	12
PAB 2 nd Stage	22

Accelerometers were placed on the left and right side sills behind the front driver and passenger seats in order to obtain vehicle acceleration in both the longitudinal (X) and lateral (Y) directions. Intrusion measurements were taken on the driver and passenger side floor pan, cross car beam, driver door opening, and vehicle exterior profile.

Dummy Description

For each test, two dummies were seated on both the front driver and passenger positions with either two 50th percentile male THOR dummies or two 50th percentile Hybrid III dummies. Each dummy was positioned into the seat according to the FMVSS 208 seating procedure. It is important to note that although the THOR and Hybrid III were positioned according to the same procedure, pre-test coordinate measurements showed a difference in final seating posture. In particular, the head of the THOR was positioned above the Hybrid III and the knees of the THOR were positioned forward of the Hybrid III ([Figure 2](#)).

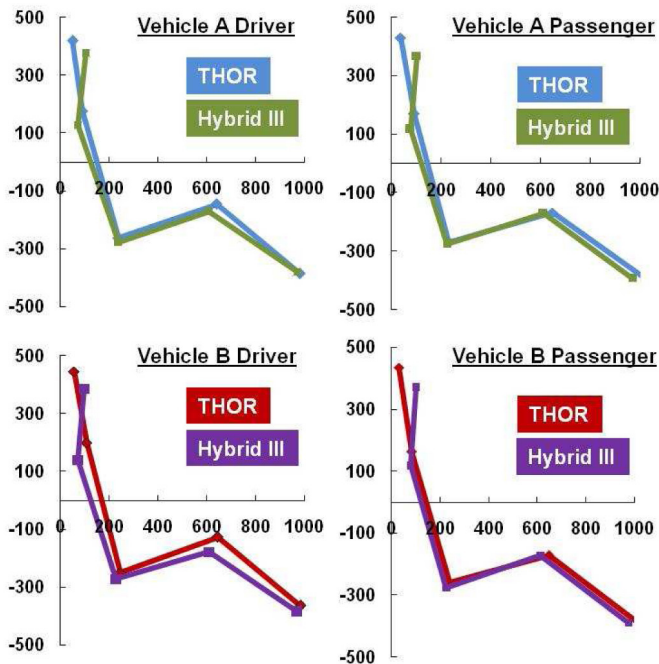


Figure 2. Dummy coordinate measurements.

The latest version of the THOR dummy was used for this analysis which consists of the modification kit as described by [Ridella et al. \(2011\)](#). All Hybrid III dummies were instrumented with the Nine Accelerometer Package (NAP) to obtain angular acceleration and velocity measurements for calculating the rotational brain injury criterion (BrIC). THOR-Lx lower legs were also installed onto each Hybrid III dummy.

The injury criteria and reference values used for this analysis can be found on [Table 3](#). Since injury assessment values have yet to be determined for the THOR, interim reference values were used. These interim reference values for the THOR can also be referenced from NHTSA's study [[Saunders et al. 2013](#)] regarding small overlap oblique moving deformable barrier testing. Reference injury values pertaining to the Hybrid III were referenced from the FMVSS 208 standard [[Eppinger et al. 1999](#)]. The body regions that will be focused on during this comparison will be the head, neck, chest, femurs, and tibias. HIC_{15} and BrIC values were calculated to assess the head injuries for both dummies. The BrIC calculation used for this assessment is shown in [equation 1](#) where rotational velocity is taken into account in all three directions (X-, Y-, and Z-axis) [[Takhounts et al. 2013](#)]. The BrIC critical values are shown in [Table 4](#) where the average of the Cumulative Strain Damage Measure (CSDM) and Maximum Principal Strain (MPS) values were used when calculating BrIC during this study. These critical values are the same for all ATD's, therefore the BrIC reference value was set to a limit of 1.0 for both the THOR and Hybrid III. Neck force will be used to compare neck response where the reference limit for the THOR was 2520 Newtons (N) in tension and 3640 N in compression [[Saunders et al. 2013](#)]. The Hybrid III neck force reference limit was 4170 N in tension and 4000 N in compression as documented by [Eppinger et al. \(1999\)](#). THOR reference injury values for chest deflection and

chest acceleration (3ms clip) were set to be the same as the Hybrid III where the reference injury value for all four THOR chest locations (upper left, upper right, lower left, and lower right) was set to 63 mm and chest acceleration was set to 60 g's [[Saunders et al. 2013](#)]. Since the Hybrid III was instrumented with THOR-Lx lower legs, the same femur load of 9040 N and the revised tibia index of 1.16 was set as injury reference values for both the THOR and Hybrid III.

Table 3. Injury criteria reference values

Body Region	Injury Criteria	THOR Reference Value	Hybrid III Reference Value
Head	HIC_{15}	700	700
	BrIC	1	1
Neck	Tension (N)	2,520	4,170
	Compression (N)	3,600	4,000
Chest	UPR LH (mm)	63	-
	UPR RH (mm)	63	-
	LWR LH (mm)	63	-
	LWR RH (mm)	63	-
	Chest Displacement (m)	-	63
	Chest (g's)	60	60
Abdomen	LH (mm)	111	-
	RH (mm)	111	-
Hip	Acetabulum LH (N)	3,500	-
	Acetabulum RH (N)	3,500	-
Femur	LH (N)	9,040	9,040
	RH (N)	9,040	9040
Tibia	LH UPR (Revised)	1.16	1.16
	LH LWR (Revised)	1.16	1.16
	RH UPR (Revised)	1.16	1.16
	RH LWR (Revised)	1.16	1.16
Ankle	LH Inversion/Eversion (deg)	35	35
	LH Dorsiflexion/Plantarflexion (deg)	35	35
	RH Inversion/Eversion (deg)	35	35
	RH Dorsiflexion/Plantarflexion (deg)	35	35

$$BrIC = \sqrt{\frac{\omega_x^2}{\omega_{xc}} + \frac{\omega_y^2}{\omega_{yc}} + \frac{\omega_z^2}{\omega_{zc}}}$$

(1)

Table 4. BrIC critical values.

Critical Max Angular Velocity	Rad/s (CSDM based)	Rad/s (MPS based)	Rad/s (Average of CSDM and MPS)
ω_x	66.20	66.30	66.25
ω_y	59.10	53.80	56.45
ω_z	44.25	41.50	42.87

RESULTS

Vehicle A Driver

Figure 3 shows dummy injury measurement comparisons for the Vehicle A driver. This figure summarizes certain injury criteria from the main body regions (head, neck, chest, femurs, and tibias) of each dummy.

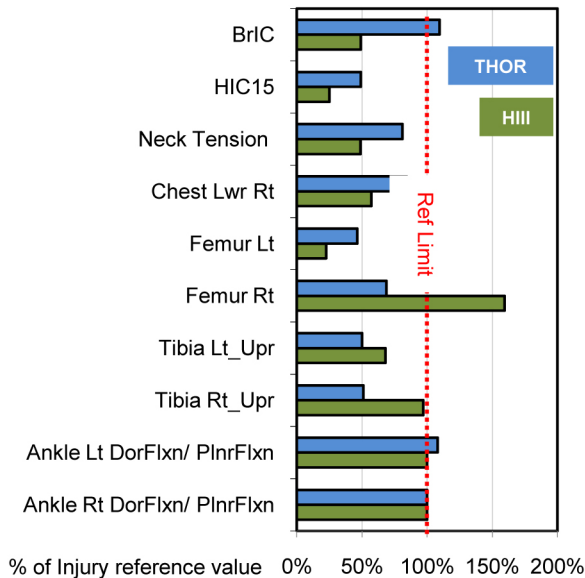


Figure 3. Vehicle A driver injury results.

Vehicle A Driver Head and Neck Response

Head center of gravity {CG} translational accelerations (X-, Y-, and Z-directions) are shown in Figure 4. When comparing the translational accelerations of both dummies, differences can be seen in the Y and Z-directions. Most notably, the Y-acceleration of the THOR experiences a sudden peak of 100 g's at 108 ms due to the left side of its head coming into contact with the upper door trim. A difference in acceleration in the Z-direction can also be seen where Hybrid III peaks at 35 g's at 61ms and the THOR peaks at 44 g's at 87 ms. The acceleration in the Z-direction of the Hybrid III and THOR begin to diverge from each other at 74 ms where the acceleration of the Hybrid III starts to decrease and the THOR continues to increase. Due to the THOR's spike in acceleration in the Y-direction, it experienced a higher HIC_{15} value of 344 while the Hybrid III experienced a lower HIC_{15} value of 173. Both values did not exceed the HIC_{15} injury reference limit of 700.

In order to evaluate how angular velocities about each axis (ω_x , ω_y , ω_z) influence BrIC, individual BrIC components relative to time are shown in Figures 5 (THOR) and 6 (Hybrid III). $BrIC_{\omega_x}$, $BrIC_{\omega_y}$, and $BrIC_{\omega_z}$ were obtained through equations 2, 3, and 4. The head rotational velocity of the THOR produced a BrIC value of 1.095 which exceeded the reference limit of 1.00, while Hybrid III produced a lower BrIC value of 0.491. For the THOR, head rotations about the X, Y, and Z-axis all contributed to its overall BrIC value. The peak BrIC component about the Y-axis ($BrIC_{\omega_y}$) occurs at 84 ms, followed by $BrIC_{\omega_z}$ at 98 ms and $BrIC_{\omega_x}$ at 105 ms. Note: The BrIC calculation only takes into account the maximum values for head angular velocities while time of these maximum values is not considered [Takhounts et al. 2013]. The BrIC value of the Hybrid III was mostly influenced by $BrIC_{\omega_x}$ and $BrIC_{\omega_z}$. The Hybrid III experienced minimal head rotation about its Y-axis.

$$BrIC_{\omega_x} = \left(\frac{\omega_x}{\omega_{xc}} \right)^2$$

(2)

$$BrIC_{\omega_y} = \left(\frac{\omega_y}{\omega_{yc}} \right)^2 \quad (3)$$

$$BrIC_{\omega_z} = \left(\frac{\omega_z}{\omega_{zc}} \right)^2 \quad (4)$$

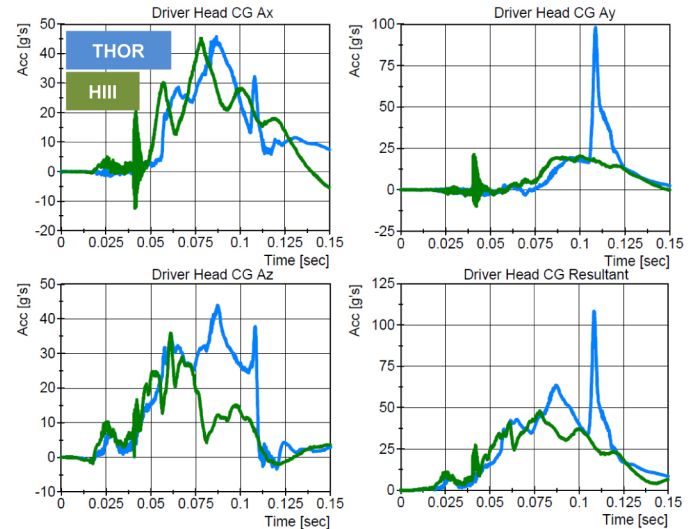


Figure 4. Vehicle A driver head CG translational acceleration.

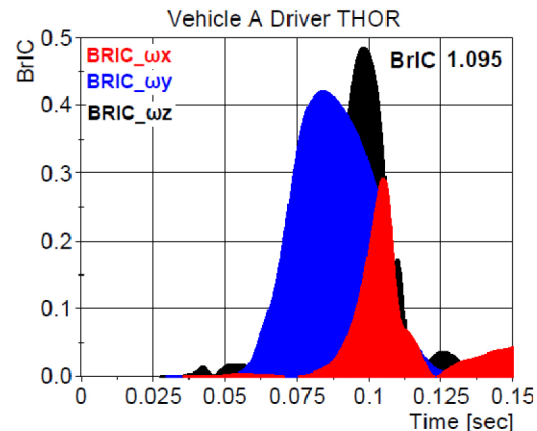


Figure 5. Vehicle A driver THOR BrIC component values.

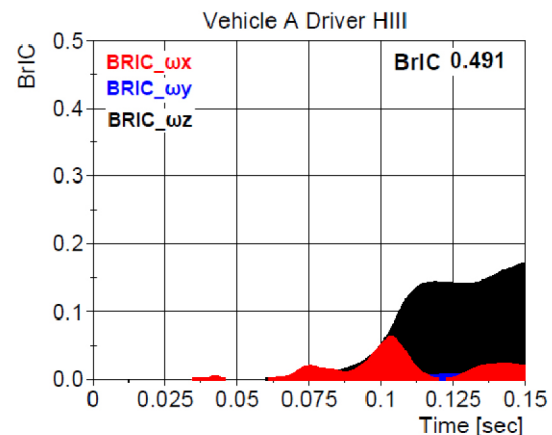


Figure 6. Vehicle A driver Hybrid III BrIC component values.

Neck tension and compression forces (Fz) of the THOR and Hybrid III are shown in Figure 7. Neck Fz showed similar peak (tension) values between the two dummies with the Hybrid III peaking 25ms earlier.

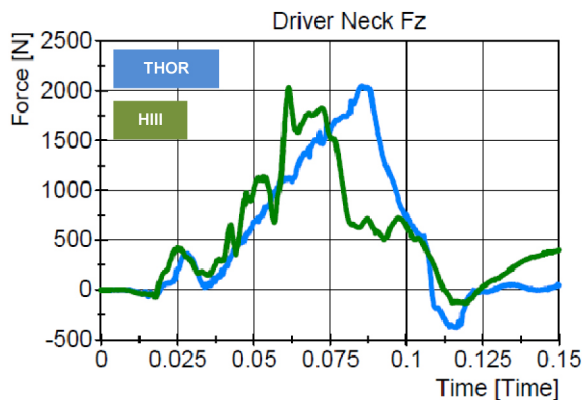


Figure 7. Vehicle A driver neck Fz.

Vehicle A Driver Chest Response

Figure 8 shows the chest deflection measurements for both Vehicle A THOR and Hybrid III driver dummies. Note that the same Hybrid III sternum chest deflection is overlaid on all four THOR chest displacement graphs. Of the four THOR chest locations, the deflection recorded from the lower right chest IR-TRACC gave the highest result. The chest deflection of the Hybrid III gave a similar result as the THOR's upper right location.

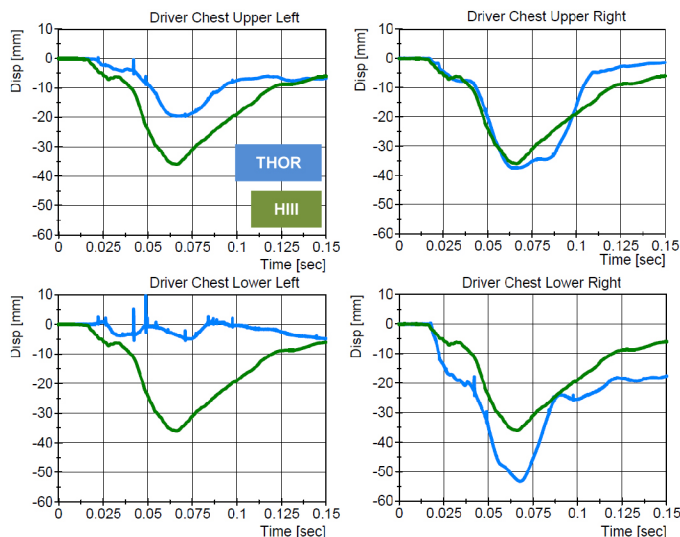


Figure 8. Vehicle A driver chest deflection.

Vehicle A Driver Lower Extremity Response

Figure 9 shows the femur loads of the Vehicle A driver dummies. The final seated position of the Hybrid III dummy caused a delayed contact with its knees to the driver side knee bolster. The elevated right femur load of the Hybrid III was due to the seat belt anchor pretensioner restraining the dummy's left side of the pelvis which caused the dummy's legs to rotate outboard. The contact point for the Hybrid III's right knee then

contacted the bottom center of the steering column shroud. Figure 10 shows the differences between contact points of the Hybrid III and THOR right knees.

Figure 11 shows vehicle A driver tibia index. Elevated right tibia index values for the Hybrid III were seen due to the same reasons that caused its elevated right femur loads.

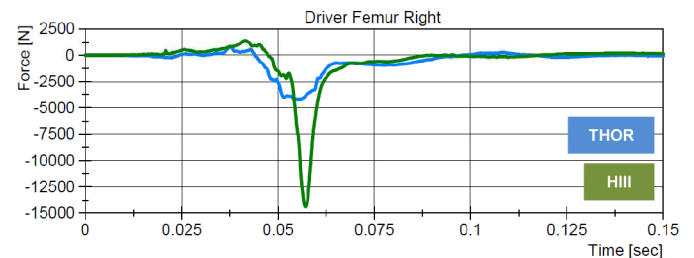
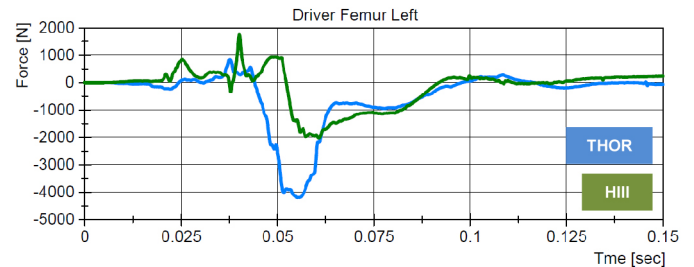


Figure 9. Vehicle A driver femur loads.



Figure 10. Vehicle A driver right femur contacts.

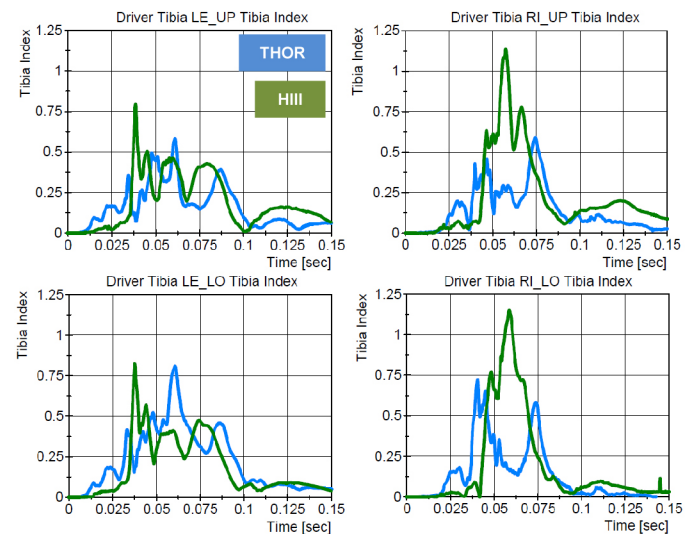


Figure 11. Vehicle A driver tibia index.

Vehicle A Passenger

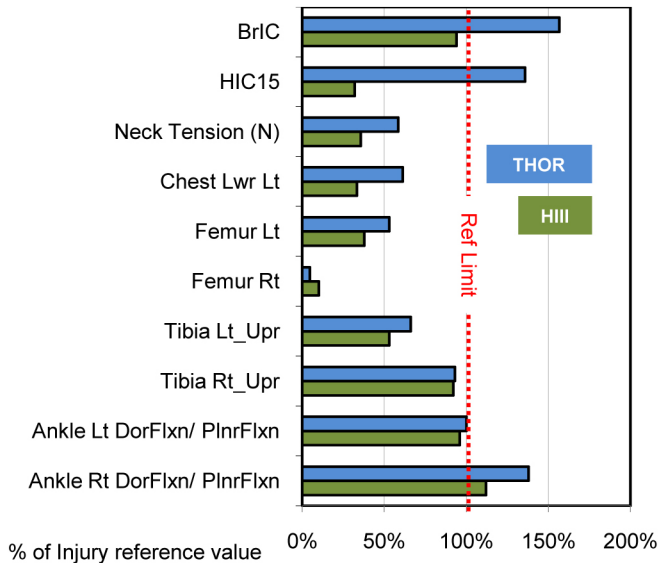


Figure 12. Vehicle A passenger injury results.

Vehicle A Passenger Head and Neck Response

Contrasting HIC_{15} values were seen between the THOR and Hybrid III Vehicle A passenger occupants where the THOR produced an elevated HIC_{15} value of 951 (136% of the reference value) while the Hybrid III produced a lower HIC_{15} value of 222 (32% of the reference value). The cause for the THOR's elevated HIC_{15} can be seen when evaluating its head CG translational accelerations (Figure 13) where a spike in peak g's is seen at 108 ms in both X and Y-directions. At this time, the left rear side of the THOR's head comes into contact with the vehicle's center section of the instrument panel causing the spike in acceleration. The Hybrid III showed no evidence of hard contact with the instrument panel.

BrIC component ($BrIC_{\omega_x}$, $BrIC_{\omega_y}$, $BrIC_{\omega_z}$) time history plots are shown in Figures 14 and 15. The BrIC value for the THOR was 1.567, which exceeded the reference value limit of 1.0 (157%), while the BrIC value for the Hybrid III was 0.939. Unlike the THOR on the driver side, the major component contributing to the overall BrIC value of the THOR passenger was its head rotation about the Z-axis ($BrIC_{\omega_z}$). The THOR's head rotation about the Z-axis occurs as the dummy loads the passenger airbag (PAB) from 52 ms to its peak at 94 ms. During this time, the THOR's torso moves inboard towards the center console and instrument panel while its head is restrained in the opposite direction by the PAB causing $BrIC_{\omega_z}$ to increase. The THOR's maximum $BrIC_{\omega_z}$ occurs right before its head contacts the instrument panel. Figure 15 shows that the Hybrid III's BrIC value is mostly influenced by its rotation about the X-axis which occurs from 68 ms to 99 ms. Refer to Figures B1 and B2 of Appendix B for illustrations regarding head kinematics.

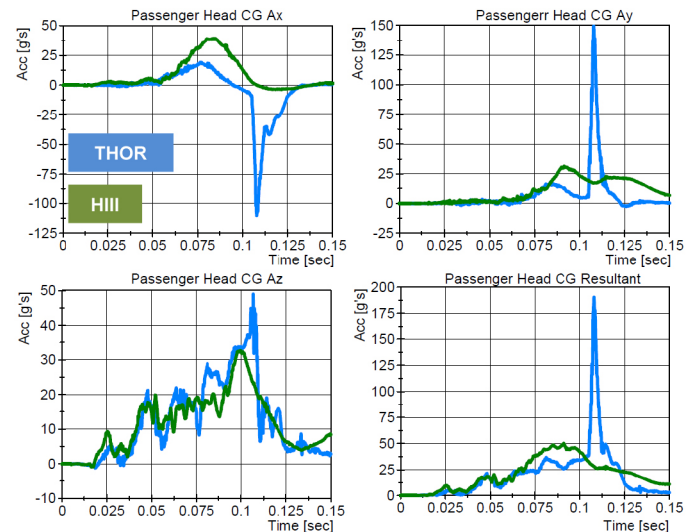


Figure 13. Vehicle A passenger head CG translational acceleration.

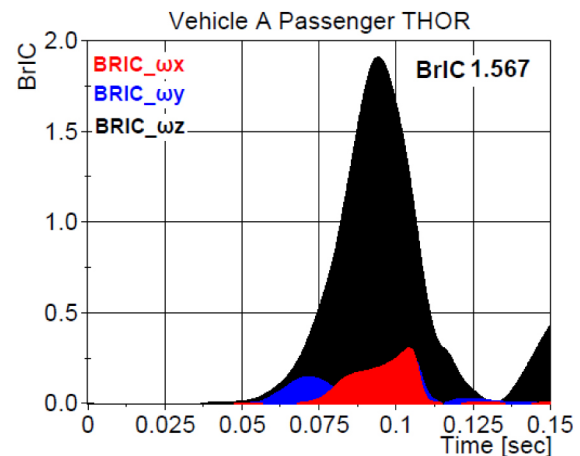


Figure 14. Vehicle A passenger THOR BrIC component values.

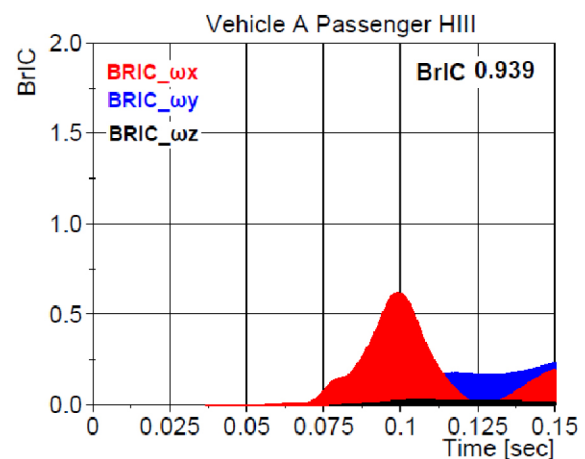


Figure 15. Vehicle A passenger Hybrid III BrIC component values.

Figure 16 shows neck tension and compression forces (F_z) for both of the Vehicle A passenger dummies. A similar trend in neck loads can be seen with their peak values occurring at approximately the same time.

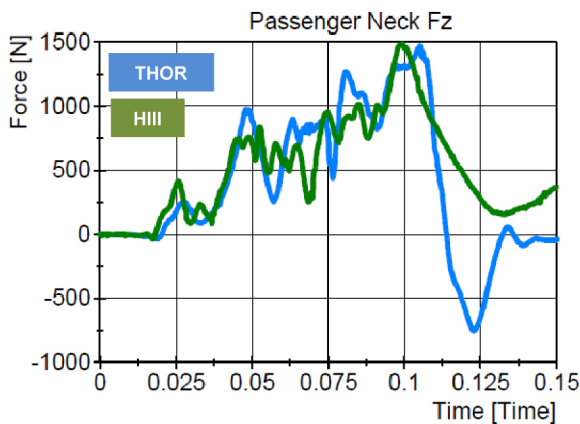


Figure 16. Vehicle A passenger neck Fz.

Vehicle A Passenger Chest Response

Figure 17 shows Vehicle A passenger chest deflection results. The THOR passenger's lower left chest deflection yielded the highest value. The THOR's chest deflections were greater than the Hybrid III's except for the THOR's lower right location.

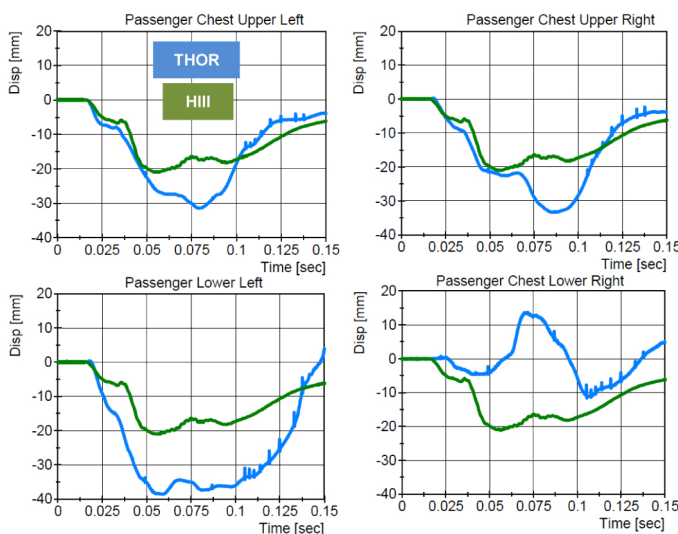


Figure 17. Vehicle A passenger chest deflection.

Vehicle A Passenger Lower Extremity Response

Figures 18 and 19 shows Vehicle A passenger femur loads and tibia index values. The delayed femur response of the Hybrid III was due to its final seating position where its knees were located 35mm rearward of the THOR's knees. A similar effect can be seen when looking at the right tibia index of the THOR where an early spike is seen due the THOR's knees positioned 35mm closer to the instrument panel than the Hybrid III.

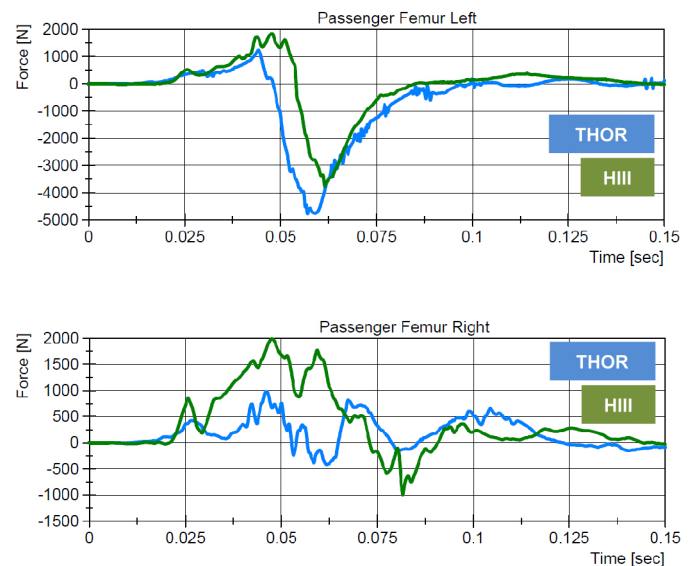


Figure 18. Vehicle A passenger femur loads.

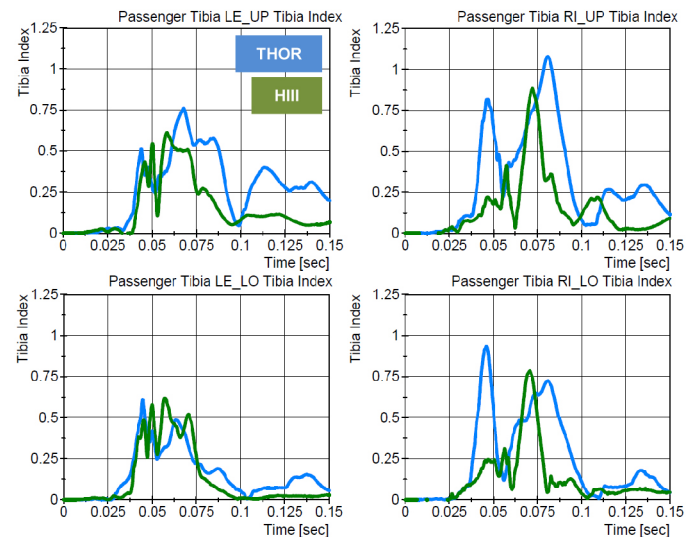
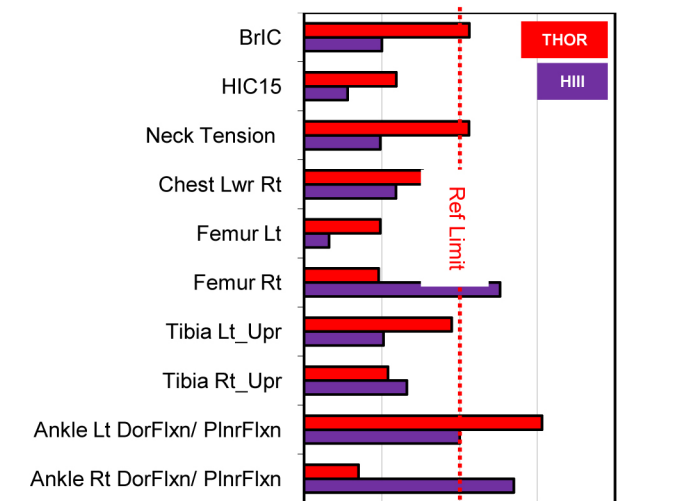


Figure 19. Vehicle A passenger tibia index.

Vehicle B Driver



% of Injury reference value 0% 50% 100% 150% 200%

Figure 20. Vehicle B driver injury results.