

# NHTSA'S TEST PROCEDURE EVALUATIONS FOR SMALL OVERLAP/OBLIQUE CRASHES

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## ABSTRACT

In September 2009, the National Highway Traffic Safety Administration (NHTSA) published a report that investigated the question “why, despite seat belt use, air bags, and the crashworthy structures of late-model vehicles, occupant fatalities continue to occur in frontal crashes.” The report concluded that aside from a substantial proportion of these crashes that are just exceedingly severe, the primary cause was poor structural engagement between the vehicle and its collision partner: corner impacts, oblique crashes, impacts with narrow objects, and heavy vehicle underrides. By contrast, few if any of these the 122 fatal crashes examined in the report were full-frontal or offset-frontal impacts with good structural engagement, unless the crashes were of extreme severity or the occupants were exceptionally vulnerable. As a result of the NHTSA study, the agency stated its intent to further analyze small overlap and oblique frontal crashes in its Vehicle Safety Rulemaking & Research Priority Plan 2009-2011 published in November 2009 [NHTSA, 2009].

As part of the study the agency initiated a research program is to investigate crash test protocols that replicates real-world injury potentials in small overlap (SOI) and oblique frontal offset impacts (OI). The test program compared the results from vehicle-to-vehicle (VtV) tests to tests conducted with a moving deformable barrier-to-vehicle (MDBtV) and pole using the same baseline vehicles. The first part of the analysis of the results compared the vehicle crash metrics (pulse, change in velocity, and interior intrusion) of the MDBtV/Pole test procedure to the VtV test procedure. The second part of the analysis

compared injury assessment of the MDBtV/Pole test procedure to the VtV test procedure.

## INTRODUCTION

Previous research has been performed to define and study small overlap impacts (SOI). Lindquist et al. (2004) investigated 91 fatal frontal crashes in Sweden and found that SOI's, impacts with no longitudinal engagement, account for 48% of the fatalities of belted front row occupants in frontal collisions. Grosch et al. (1989) defined a partial overlap as a 20% overlap with no longitudinal engagement while Hill et al. (1993) defined a small overlap as one longitudinal engagement. Longitudinal engagement can be described as having part of the load path through a main longitudinal structural member or frame rail, with no longitudinal engagement referring to the load path missing both main longitudinal structural members (frame rails). Furthermore, Pintar et al. (2008) studied the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) and the Crash Injury Research and Engineering Network (CIREN) and concluded that trauma and injury pattern differed between small-offset and wider-offset crashes, and that countermeasures designed for wider-offset crashes may not be effective in small-offset crashes. Brumelow et al. (2009) studied crashes that involved vehicles that were rated good for frontal crash protection. This study concluded that asymmetry in the loading of the vehicle will often cause intrusion into the occupant compartment leading to intrusion based injuries. Furthermore, this study stated that the most common crash modes leading to significant intrusion in frontal crashes are

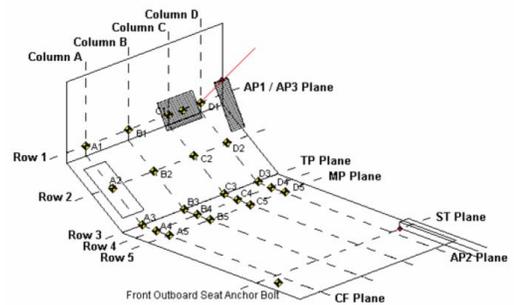
“asymmetric of concentrated loading across the vehicles front often resulted in occupant compartment intrusion and associated injury” and “small overlap, underride, and high-velocity moderate overlap crashes are the most common configurations producing substantial amounts of intrusion in frontal crashes.” Kullgren et al. (1998) studied real world collisions and found that “the percentage of moderately and severely injured drivers was higher in impacts with an overlap below 30%.” Sherwood et al. (2009) assessed the characteristics of “small-overlap” frontal crashes and concluded that “despite structural improvements prompted by offset crash tests, vehicle structures must improve if they are to prevent occupant compartment intrusion when a vehicle is loaded outboard of longitudinal structural members.” Eichberger et al. (2007) investigated the accident statistics using GIDAS and Austrian databases and concluded that, in SOI, the longitudinal beams are not involved and the “rim locking effect” provides a load path into the occupant compartment, which endangers the safety cage. The rim locking effect is when two vehicle’s wheels contact which drives the wheels back into the occupant compartment providing a load path to the toe pan and the side sill. This effect can be seen by any structure forcing the wheels rearward into the occupant compartment. The authors Eichberger et al. (2007) proposed a car-to-car test method to address the SOI scenario. This proposed test method was a 17% overlap collinear impact with a closing speed of 112 kmph. The intent of this test program is to develop a test protocol that replicates real-world injury potentials in SOI and oblique impacts (OI).

To develop a baseline understanding of vehicle interaction and occupant safety a series of vehicle-to-vehicle (VtV) test results were conducted and the results compared to a series of moving deformable barrier-to-vehicle (MDBtV) tests with the same vehicle. The first part of the analysis of the results compared the vehicle crash characteristics of the MDBtV/Pole to VtV. The details of each test procedure are described below. The second part compared measured occupant injury assessment of the MDBtV/Pole to VtV. The objective is to develop test procedures that replicate real-world crash conditions and injury outcomes such that a fleet study can be conducted.

## VEHICLE CRASH CHARACTERISTICS

### Vehicle Crash Metrics

The following is a list of vehicle crash metrics used to compare the target vehicle of the MDBtV test procedure to the target vehicle of the VtV test procedure. The first criterion is how well the acceleration pulses match (peak Gs, peak Gs timing, and duration). The second criterion is the velocity time history. The third criterion is the interior intrusion. The following are a list of interior intrusion measurements: four points across the middle of the toe pan (row 2, Figure 1), the contact point where the left and where the right knee would hit the knee bolster in a full frontal test, the center of the steering wheel, the A-pillar. The A-pillar bottom intrusion was measured at the intersection of the top of the window sill and the A-pillar.



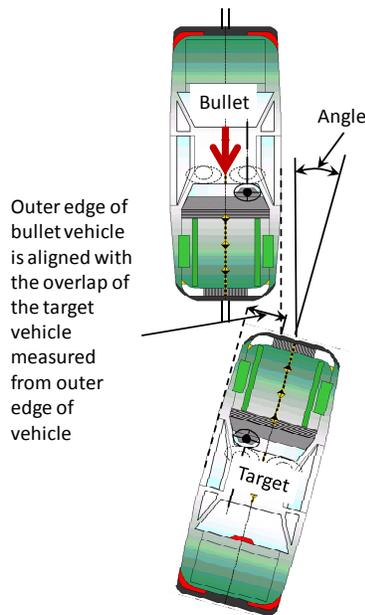
**Figure 1: Toe pan intrusion measurements points**

### Oblique Offset

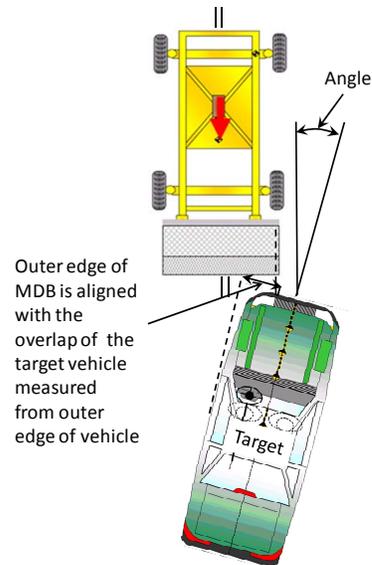
**Test Setup-** Figure 2 shows the test setup for the VtV OI test procedure. The overlap is marked on the target vehicle (width excludes mirrors and door handles) and the stationary target vehicle is positioned at the desired angle. Once this is achieved, the outer edge of the bullet vehicle is aligned with the overlap mark on the target vehicle. The MDB OI setup is similar to the VtV OI setup except the edge of the honeycomb face is aligned with the overlap mark on the target vehicle (Figure 3). To achieve the same change in velocity (DV) for the target vehicle in the MDBtV OI test as in the VtV OI test, the closing speed was calculated using conservation of momentum.

A THOR-NT 50th percentile male test dummy was positioned in the driver’s seat of all target vehicles in

this study. The THOR-NT, as described by Shams et al. (2005), has advanced biofidelity and instrumentation features that were thought to be useful for the current study. From a biofidelity perspective, the THOR-NT has a more flexible spine and improved neck biofidelity compared to other 50th percentile dummies, allowing for kinematics that may better represent those of a human. The real-world analysis of the crash data (Bean et al., 2009) indicated that the occupant kinematics are a concern because of the oblique nature of the impact and it was thought that the improved flexibility of the THOR-NT's spine would better simulate the real world occupants motion. Among other instrumentation advantages of the THOR-NT, it has the capability of measuring multi-point (four locations) chest deflection and bi-lateral, tri-axial acetabular loads.



**Figure 2: VtV OI test setup**



**Figure 3: MDBtV OI test setup**

**Results 214MDB OI-** The logical choice as a surrogate for the bullet vehicle in the VtV OI test procedure was the MDB specified in Federal Motor Vehicle Safety Standard (FMVSS) No. 214 (214MDB), since it is readily available. Computer simulations with the 214MDB in different test configurations were run with the Ford Taurus (model year vintage 2000-2006) to verify its suitability and the final test setup for the crash test. Based upon the VtV computer simulation results and comparing the results with real-world crash investigation data and damage patterns, a crash test delta-v (DV) of 35 mph and an overlap of 50 percent was selected.

Table 1 shows the test conditions for comparing the VtV OI test to the 214MDBtV OI test for the Ford Taurus and Ford Five Hundred (model year vintage 2005-2007). Figure 4 and Figure 5 show the x-axis accelerations for the left rear sill of the Ford Taurus and Ford Five Hundred, respectively. From these figures it can be seen that the acceleration has a spike early in the event, 40 ms for the Taurus and 25 ms for the Ford Five Hundred, for both vehicle comparisons. After that early spike in the acceleration the Taurus peak Gs and timing of the peak Gs are approximately the same, but the duration of pulse is shorter for the 214MDBtV OI test. For the Ford Five Hundred the acceleration was generally higher than the VtV OI acceleration up to the time peak Gs occurred. The peak Gs for the Ford Five Hundred occurred about

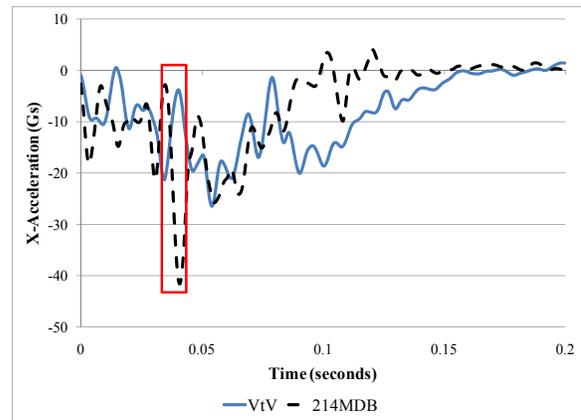
**Table 1: Test matrix for oblique testing with the 214MDB**

Vehicle / Mode	NHTSA Test No.	Bullet	Target	Closing Speed (kph)	Crabbed Angle (degrees)	Overlap (%)
Taurus Oblique	6830	2007 Taurus	2007 Taurus	113	15	50
	6852	214MDB	2007 Taurus	126	15	50
Ford Five Hundred Oblique	6831	2007 Five Hundred	2007 Five Hundred	113	15	50
	6937	214MDB	2007 Five Hundred	116	15	50

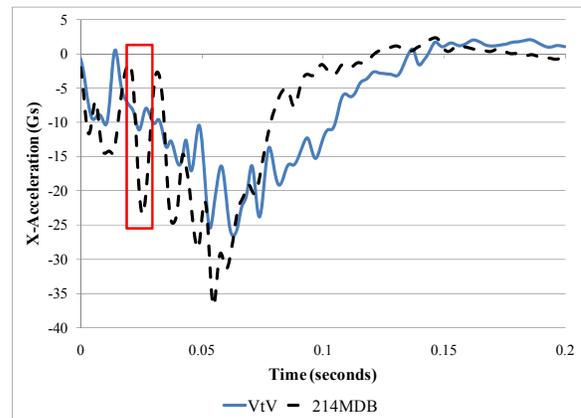
the same time, but was 10 Gs higher than the VtV OI test. The pulse duration was also shorter for the 214MDBtV OI Ford Five Hundred test.

Figure 6 and Figure 7 show the interior intrusion comparison of the 214MDBtV OI test and the VtV OI test for the Ford Taurus and Ford Five Hundred, respectively. The results present in the figure show that the toepan intrusions from the 214MDBtV OI matched the toepan intrusions of the VtV OI. However, the instrument panel and the A-pillar bottom intrusion did not correlate.

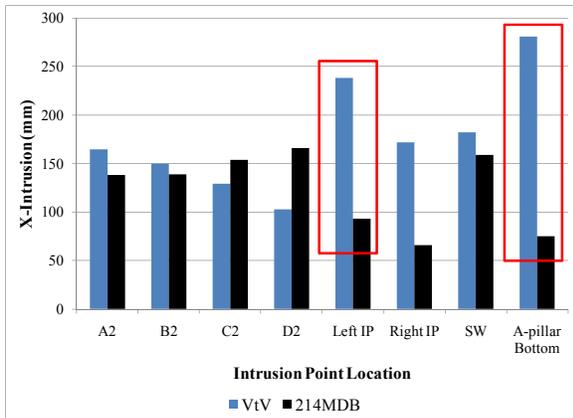
A number of issues were noted during the 214MDBtV OI tests. First, the front wheel of the 214MDB was damaged when it interacted with the target vehicle, since it was placed outside the face plate. Second, the 214MDB had the potential of bouncing down the track at these high speeds, since there was no suspension on the 214MDB. Finally, from film analysis it was observed that these spikes in vehicle acceleration early in the event for the 214MDBtV OI tests were caused by the 214MDB honeycomb bottoming out (at 40 ms for the Taurus and 25 ms for the Five Hundred) (Figure 4 and Figure 5). This anomaly was not detected in the computer simulations. Bottoming out during an MDBtV OI test procedure can represent the engine to engine contact, but these acceleration pulses are unrealistic and not representative of a VtV crash. With these results and the issue with the 214MDB, it was determined that modifications to the MDB design would be necessary to achieve results consistent with the VtV tests.



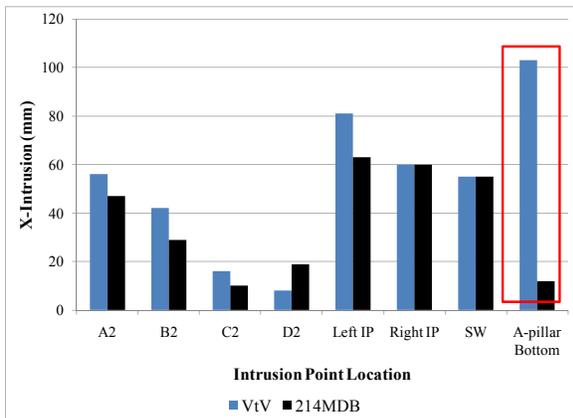
**Figure 4: X-acceleration of the left rear sill for the target vehicle for the Taurus 214MDBtV OI comparisons**



**Figure 5: X-acceleration of the left rear sill for the target vehicle for the Ford Five Hundred 214MDBtV OI comparisons**



**Figure 6: Interior intrusions for the target vehicle for the Taurus 214MDBtV OI comparisons**



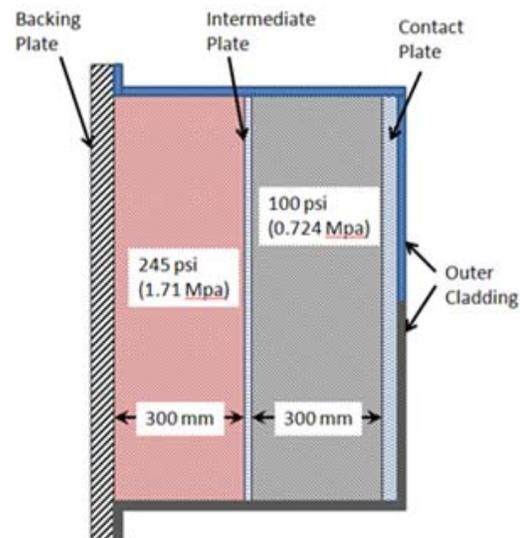
**Figure 7: Interior intrusions for the target vehicle for the Ford Five Hundred 214MDBtV OI comparisons**

**Results Research Moving Deformable Barrier (RMDB) OI-**

To address some of the issues with using the 214MDB as a surrogate for the bullet vehicle, modifications were made to the MDB face and cart. This new barrier name is called “RMDB” throughout the rest of the paper. To prevent wheel damage, the barrier face plate was widened to be outside of the track width of the barrier. To minimize bouncing while traveling at high speeds, a suspension system was added to the cart. And finally, to prevent bottoming out of the barrier face too soon, finite element modeling of different barrier stiffnesses and thicknesses was performed. There was no attempt to match any certain vehicle characteristics in the design of the barrier (i.e. frontal stiffness) but only to address the issues raised in the previous series of tests. Figure 8 shows the RMDB final barrier face

used as a surrogate for the bullet vehicle. To prevent a spike in the acceleration at the beginning of the test, a soft honeycomb was used in the front (0.724 MPa), and to prevent bottoming out, a second stiffer honeycomb was added against the backing plate (1.71 MPa). The final weight of the RMDB was 2,385 kg.

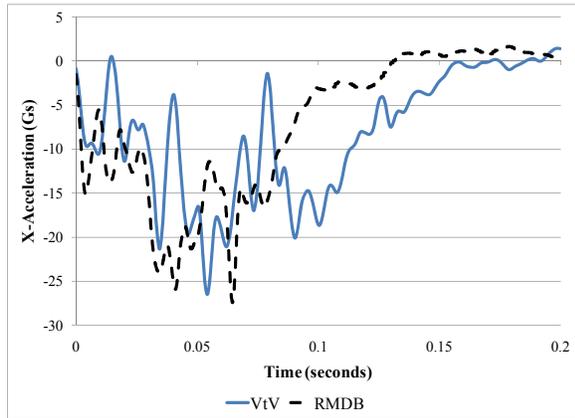
The overlap used in the test setup was decreased from 50 percent (as used in the 214MDBtV tests) to 35 percent in an attempt to achieve A-pillar bottom and IP intrusions. It appeared since the MDB is homogenous the barrier more evenly distributed the crash load on the struck vehicle where an actual vehicle produced more localized loading due to the longitudinal frame rails. It was believed the change in overlap would allow the RMDB to interact more like an actual bullet vehicle as it could better expose the A-pillar and IP to more of the crash forces.



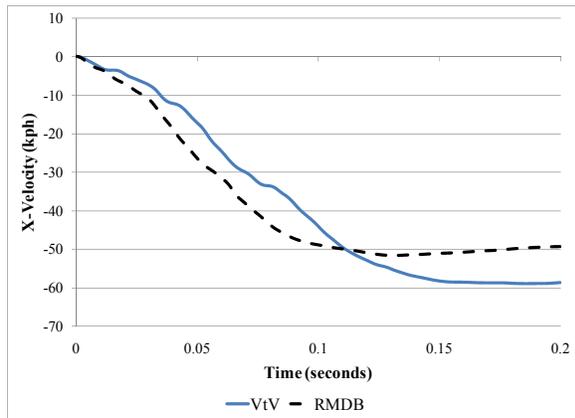
**Figure 8: Final properties and thickness of the RMDB honeycomb face**

Figure 9 show the x-acceleration of the Taurus in the RMDBtV OI test (NHTSA test number 7366). The general shape of the RMDBtV OI acceleration is similar to the VtV OI acceleration, except for the duration. The RMDBtV OI generally follows the VtV OI acceleration up to 40 ms and then the first peak in the acceleration is slightly higher and later in the event and the second peak is also slightly higher and later in the event. Figure 10 shows the RMDBtV

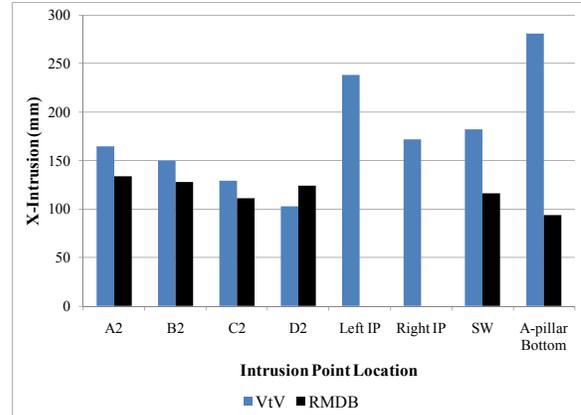
OI test had a steeper change in velocity than the VtV OI test and the RMDBtV OI test did not achieve the same total Delta V (DV) as the VtV OI test. Figure 11 shows that the toepan intrusions matched very well, but the instrument panel and the A-pillar bottom intrusion did not match.



**Figure 9: Left rear sill x-acceleration of the Taurus in the RMDBtV OI comparison**



**Figure 10: Left rear sill x-velocity of the Taurus in the RMDBtV OI comparison**



**Figure 11: Interior intrusions for the target vehicle for the Taurus RMDBtV OI comparisons**

### Small Overlap

**Test Setup-** Some preliminary collinear pole crash tests were performed at the Medical College of Wisconsin (MCW). These tests showed that the vehicle started at the original offset and then pushed the vehicle laterally and the vehicle ended up sliding off the pole before it engaged the occupant compartment. The angle used in the OI procedure was used in the next set of tests, as a means to produce better engagement in attempt to achieve the intrusion levels observed in the field data. During these tests it was observed the pole did not tear down the side of the vehicle, but went toward the center of the vehicle. To keep engagement and the ability of the bullet vehicle to tear down the side of the target vehicle, an angle of 7 degrees was chosen for all SOI tests.

The VtV SOI test setup is the same as the VtV OI test setup described previously, with the exception of overlap. The overlap is determined by aligning the outside of the left longitudinal rail of the bullet and target vehicle (Figure 12). Again, the desired total DV of the target vehicle for the RMDBtV SOI test was calculated using conservation of momentum.

The second type of simplified test setup to represent the VtV SOI test is a target vehicle into a pole (VtPole SOI). In this setup the vehicle is positioned on a floating floor at the desired angle and then positioned such that the center of the tire is aligned with the edge of the 10 inch pole (Figure 13). The floating floor brings the target vehicle into the pole at

the desired closing speed. Table 2 shows the test matrix for the SOI comparison of VtV SOI to RMDBtV SOI and VtP SOI tests.

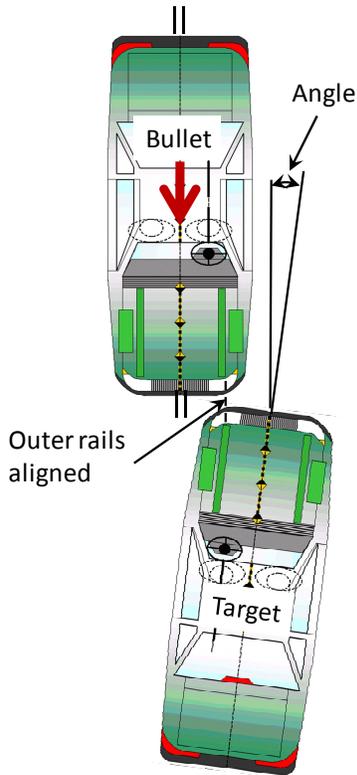


Figure 12: VtV SOI test setup

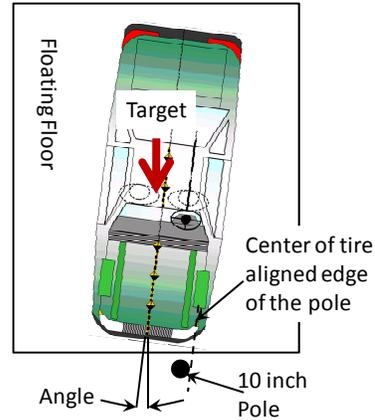


Figure 13: VtP SOI test setup

Table 2: Test matrix for small overlap tests

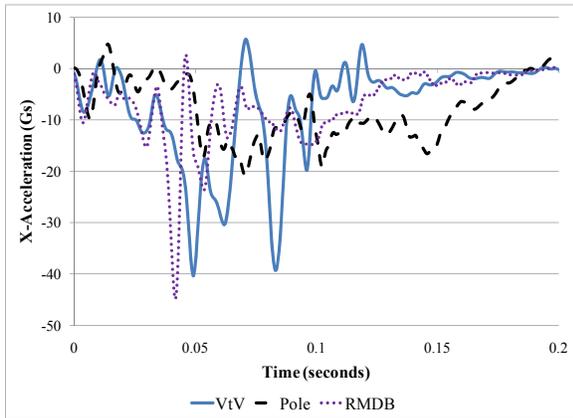
Vehicle / Mode	NHTSA Test No.	Bullet	Target	Closing Speed (kph)	Crabbed Angle (degrees)
Taurus SOI	7292	2007 Taurus	2007 Taurus	113	7
	7366	RMDB	2007 Taurus	97	7
	7144	10 inch Pole	2007 Taurus	56	7

1. Floating floor velocity

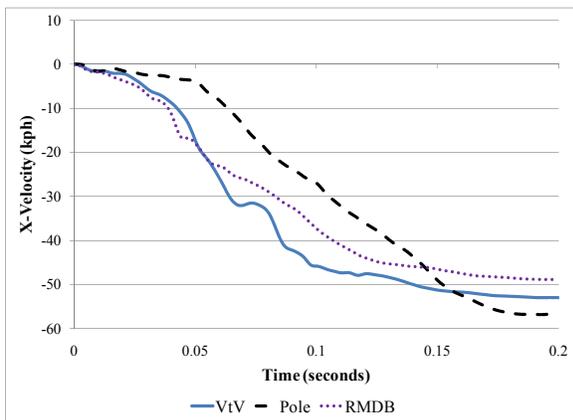
**Results of RMDBtV and VtP SOI-** Figure 14 shows the x-acceleration of the left rear sill of the target Taurus for the VtV SOI test procedure compared to the RMDBtV and VtP SOI test procedures. The acceleration pulse for the VtP SOI resulted in a lower peak Gs which occurred much later in the event than the other two test procedures. The RMDBtV SOI acceleration peaked about 10 ms before the VtV SOI test, but the peak Gs are similar in magnitude. The duration of the acceleration pulse

is shorter than the VtV acceleration duration. Figure 15 shows the DV of the three test procedures. The VtP SOI shows the DV does not start to change until 50 ms and the total DV is slightly higher than the VtV SOI total DV. The RMDBtV SOI DV matched the VtV SOI DV up to 50 ms, then diverges resulting in a slightly lower total DV than the VtV SOI total DV.

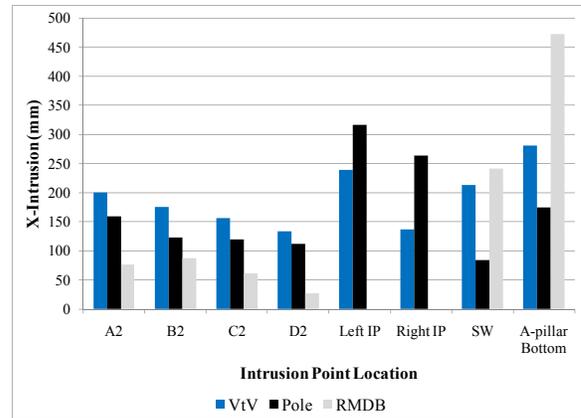
Figure 16 shows the interior intrusion comparison of the VtV SOI test procedure to both the RMDBtV and VtP SOI test procedure. It should be noted that the IP intrusion for the RMDBtV SOI were not collected due to the IP separation. The VtP SOI test had higher IP intrusions than the VtV SOI test, but the toepan intrusions were lower. Also, the A-pillar bottom was lower for the VtP SOI test when compared to VtV SOI test. The RMDBtV SOI had more A-pillar bottom and SW intrusion.



**Figure 14: Left rear sill x-acceleration of the Taurus in the small overlap comparisons**



**Figure 15: Left rear sill x-velocity of the Taurus in the small overlap comparisons**



**Figure 16: Interior intrusions for the target vehicle for the small overlap comparison**

### INJURY ASSESSMENT

In addition to the crash-based comparison metrics described earlier, the test results also were evaluated based on differences in anthropomorphic test device (ATD) kinematics and response. Table 3 summarizes the peak injury assessment values (IAVs) measured by the THOR-NT ATD in the driver’s seat of the target vehicle for the Ford Taurus (model year vintage 2000 – 2006) and the Ford Five Hundred (model year vintage 2005-2007) tests. Many of the injury assessment reference values (IARVs) listed in Table 3 are provisional and are for reference only (i.e., final published versions have not been established). Others, such as those for the lower leg (Kuppa et al., 2001a,b), are more well established. The primary aim in this analysis was to compare the MDB and pole results to the baseline vehicle to vehicle results. The primary body regions that will be compared are head, chest, knee/thigh/hip, and lower leg. Three sets of comparisons are made: 1) Taurus oblique impacts (test numbers 6830, 6852 and 7366); 2) Five Hundred oblique impacts (test numbers 6831 and 6937); and 3) Taurus narrow overlap impacts (test numbers 7292, 7368 and 7144).

**Table 3: Target vehicle driver THOR-NT 50th Injury Assessment Values**

Body Region	Injury Metric	IARV	Taurus - Oblique			Five Hundred - Oblique		Taurus - Narrow Overlap			
			50%		35% Overlap	50% Overlap		18% Overlap			
			50% Overlap	Overlap 214	RMDB to	50% Overlap	214 MDB to	18% Overlap	RMDB to		
			Veh to Veh	MDB to Veh	Veh	Veh to Veh	Veh	Veh to Veh	Veh	Veh to Pole	
			NHTSA 6830	NHTSA 6852	NHTSA 7366	NHTSA 6831	NHTSA 6937	NHTSA 7292	NHTSA 7368	NHTSA 7144	
			IAV	IAV	IAV	IAV	IAV	IAV	IAV	IAV	
Head	BRIC	1	0.99	1.04	0.73	0.84	1.06	1.57	0.75	1.08	
	HIC <sub>15</sub>	700	594.0	233.6	290.1	363.0	576.0	216.7	504.5	535.3	
	Resultant 3 ms clip (g)	80	89.2	49.6	53.0	59.4	74.5	47.9	78.8	90.3	
Neck	Neck Tension (N)	2520	2767.2	1887.1	2311.3	1807.6	2157.0	2029.5	1287.6	1211.6	
	Neck Compression (N)	3600	352.6	527.1	336.2	277.4	1215.7	234.6	713.8	254.8	
	Flexion at OC (Nm)	48	18.0	6.2	23.1	21.1	4.3	15.1	12.8	17.5	
	Extension at OC (Nm)	72	7.6	15.1	14.6	8.9	28.0	9.4	23.4	5.0	
Chest	Upr Rt - Disp (mm)	NA <sup>2</sup>	30.4	33.5	35.8	41.7	44.4	IM <sup>3</sup>	27.9	31.6	
	Upr Lt - Disp (mm)	NA <sup>2</sup>	17.7	15.5	20.2	23.7	31.6	8.9	9.1	8.0	
	Lwr Rt - Disp (mm)	NA <sup>2</sup>	25.7	29.1	3.1	35.1	45.2	26.0	2.5	21.5	
	Lwr Lt - Disp (mm) <sup>1</sup>	NA <sup>2</sup>	21.5	14.9	14.1	14.9	14.2	8.6	15.0	5.3	
	Displacement Max (mm)	NA <sup>2</sup>	30.4	33.5	35.8	41.7	45.2	26.0	27.9	31.6	
	3ms Chest Gs (g)	60	36.2	39.6	48.6	31.8	41.8	42.4	43.2	32.6	
Abdomen	Displacement (mm)	111	37.0	31.3	38.2	43.7	36.4	29.0	24.6	33.1	
Acetabulum	Rt Resultant Force (N)	3500	1267	3988	4474	1466	2060	2591	2794	2168	
	Lt Resultant Force (N)	3500	6236	3650	4298	3376	1727	4184	5962	3169	
Femur	Rt - Fz (N)	10000	3910	6768	7555	3472	4708	5167	4528	4148	
	Lt - Fz (N)	10000	5755	6547	3538	4171	3091	6055	4805	4026	
Tibia	Rt Upr Tibia Index	1.16	0.37	1.05	1.2	0.61	0.76	0.41	0.92	IM <sup>3</sup>	
	Rt Lwr Tibia Index	1.16	0.59	1.37	1.41	0.87	0.51	0.37	0.69	IM <sup>3</sup>	
	Lt Upr Tibia Index	1.16	0.45	0.44	1.34	0.33	0.58	0.56	3.19	IM <sup>3</sup>	
	Lt Lwr Tibia Index	1.16	0.31	0.54	0.84	0.43	0.38	0.6	1.57	IM <sup>3</sup>	
Ankle	Rt Inversion/Eversion	35 / 35	34.9	46.3	36.1	31.1	38.1	27.7	28.8	34.0	
	Rt Dorsiflexion/Plantarflexion	35 / 35	40.4	36.7	45.2	34.3	32.5	17.9	31.7	11.6	
	Lt Inversion/Eversion	35 / 35	16.4	30.9	IM <sup>3</sup>	23.7	25.7	7.6	IM <sup>3</sup>	30.2	
	Lt Dorsiflexion/Plantarflexion	35 / 35	35.5	37.2	60.9	29.0	26.7	26.3	55.9	31.0	

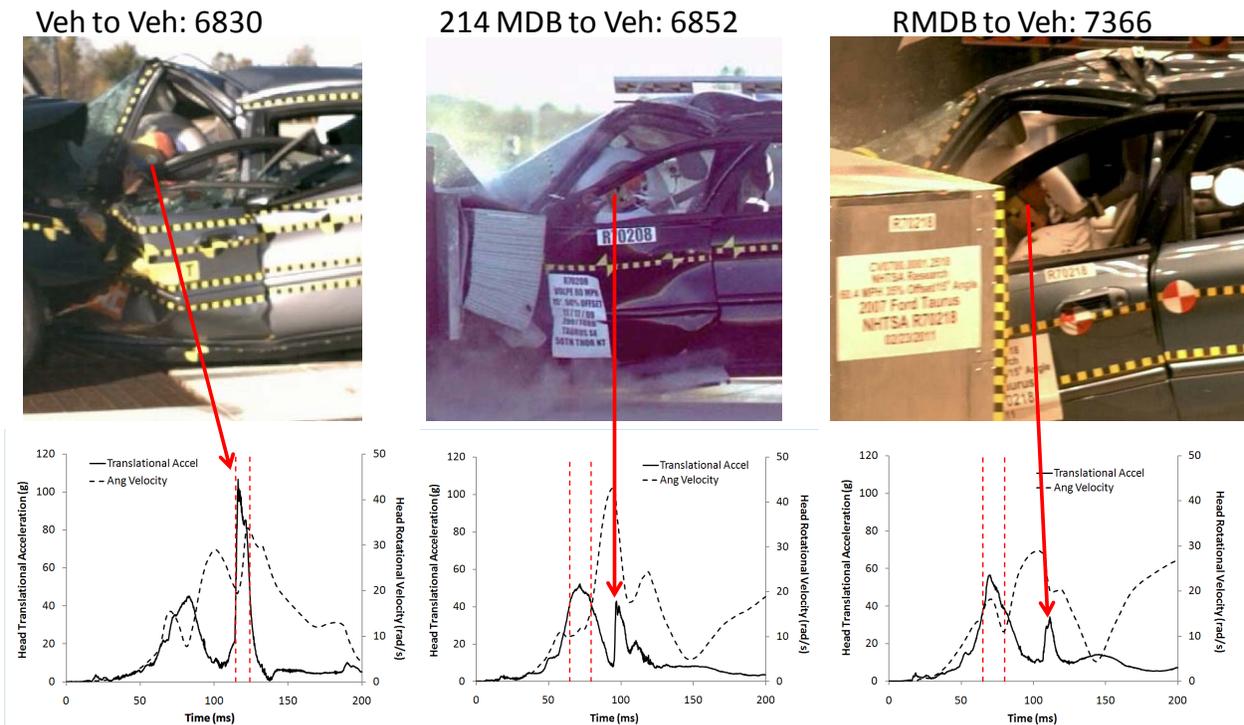
1. Shaded values represent points where deflection was positive (chest expansion)
2. There isn't currently a provisional IARV for chest deflection
3. Instrumentation malfunction

### Head Injury Comparison

Comparisons to the VtV oblique and small overlap impacts start with an assessment of the head kinematics, contacts and injury measures. The three main injury measures summarized in Table 3 are BRIC, HIC<sub>15</sub> and 3 ms peak acceleration. BRIC or brain injury criterion has been proposed by Takhounts et al. (2011) for the Hybrid III 50th, WorldSID and ES-2re test dummies. BRIC takes the peak head center of gravity (cg) rotational velocity and acceleration and divides them by their respective critical intercepts that were developed for the Hybrid III. The two numbers are then added. For the purposes of this study, it is assumed that the critical intercepts (46.4 rad/s and 39,477.9 rad/s<sup>2</sup>) for the THOR-NT are the same as the Hybrid III. The IARV of 1.0 represents a 30% probability of diffuse axonal injury (DAI).

Figure 17 shows the head CG resultant linear acceleration, rotational velocity time-history, and an image at the time of contact to the vehicle interior / door for the oblique Taurus tests. The head CG

resultant acceleration shows a similar two-peak pattern in all three tests. The first peak occurs during head interaction with the air bag. The second peak results from head contact with the door frame or A-pillar. The Taurus to Taurus oblique test (6830) resulted in the THOR-NT ATD's head contacting the A-pillar/door frame. This contact produced the peak head CG resultant acceleration and HIC<sub>15</sub> value for this test both of which were higher than the peaks observed in the Taurus MDBtV oblique tests. The two MDB tests (6852 and 7366) experienced steering wheel intrusion that, coupled with the occupant kinematics, resulted in greater shoulder and thorax interaction of the THOR-NT dummy with the steering wheel than what was observed in the vehicle to vehicle test. This steering wheel interaction limited the forward and outboard excursion observed in the VtV test. As a result, the peak head acceleration in both MDB tests occurred at roughly 70 ms during head interaction with the air bag, while the subsequent second peaks from head contact to door frame in both tests were smaller and were note within the HIC<sub>15</sub> window.



**Figure 17: Head excursion for time history data for Taurus oblique tests (HIC<sub>15</sub> time interval shown as vertical dashed lines)**

Figure 18 shows the images and head response data for the oblique tests on the Ford Five Hundred. These tests had comparable kinematics, and did not have the same variable kinematics due to steering wheel interaction that was seen in the Taurus tests. The stiffer crash pulse in the 214MDBtV (Figure 4 and Figure 5) test resulted in higher peak translational acceleration and rotational velocity than the VtV test. Higher HIC<sub>15</sub> and BRIC values were seen as a result. In the case of the VtV test, the THOR-NT ATD's head contacted the beltline, resulting in the peak translational acceleration. In the 214MDBtV test the ATD's head contacted its left lower arm, which was against the instrument panel at the time, resulting the peak acceleration.

Figure 19 shows a similar set of pictures and head response time histories for the Taurus SOI impacts. Each test again resulted in head contact to the vehicle interior/door. However, given the differences in pulse (Figure 9) and intrusion (Figure 11), the head contacts and resulting IAVs were significantly

different between the three tests. The vehicle-to-vehicle test resulted in a head contact to the door frame. However, that contact did not contribute to the peak HIC value. HIC<sub>15</sub> and resultant translational head acceleration in this test were the lowest of all eight tests summarized in this study. However, the peak rotational velocity and BRIC values were the highest of all eight vehicles studied. The RMDB (head contact to the a-pillar) and pole (head contact to steering wheel) had higher resultant accelerations due to their respective contacts, but rotation and thus

### Chest Injury Comparison

The THOR-NT measures chest deflection in four locations that correspond to the anatomical 4th and 8th anatomical ribs. There is no provisional criterion in place for the use of the multipoint data. Separate research funded by NHTSA is slated to develop multi-point thoracic deflection injury criteria for the THOR-NT. Starting with the oblique tests of the Taurus (Table 3), it can be seen that the maximum chest deflection ranged from 30.4 mm in the vehicle

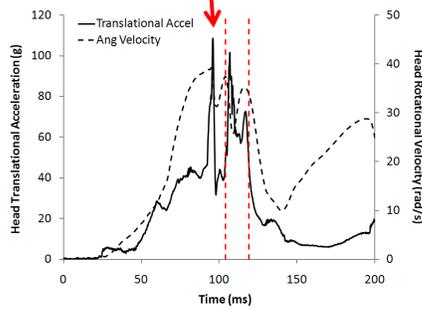
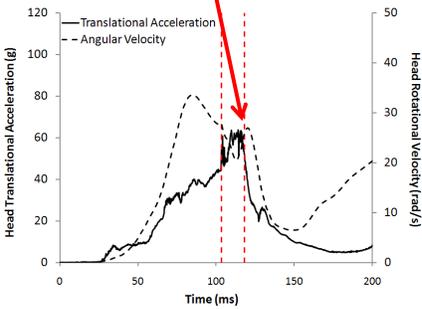
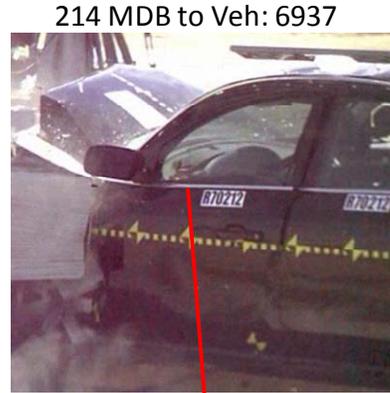


Figure 18: Head excursion and time history data for Five Hundred oblique tests (HIC<sub>15</sub> time interval shown as vertical dashed lines)

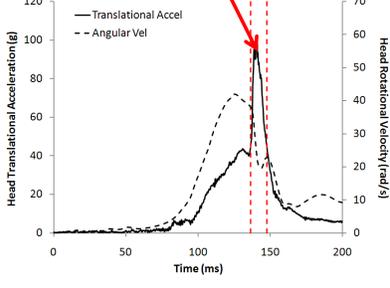
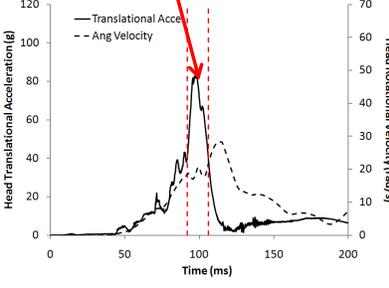
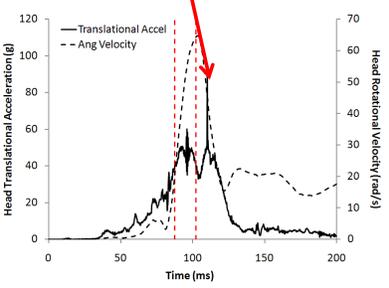


Figure 19: Head excursion and time history data for Taurus narrow overlap tests (HIC<sub>15</sub> time interval shown as vertical dashed lines)

to vehicle test to 35.8 mm in the RMDB test. All peak deflections were measured at the upper right chest. While the differences in deflections were small, the associated peak shoulder belt loads did follow a typical trend where the case with lowest chest deflection had the lowest shoulder belt load (3.8 kN), while the case with the highest deflection had the highest shoulder belt load (5.3 kN). There was limited steering wheel interaction with the chest in any of these oblique tests on the Taurus. The oblique Five Hundred results showed comparable peak deflections for the VtV and 214MDBtV test. Similar to the oblique Taurus tests, there was limited interaction between the chest and the steering wheel.

It was not possible to compare the chest deflection results in the SOI tests due to an instrumentation malfunction related to the upper right THOR-NT chest deflection in the Taurus VtV SOI test (test no. 7292). The upper right chest deflection as documented in this study was typically the point of maximum deflection. However, in absence of valid upper right chest deflection data in the Taurus VtV test, it would be expected that the chest displacement measures in the SOI VtV test would have differed from those measured in the RMDBtV and VtP tests given differences in crash pulse and chest interaction with the steering wheel observed in the VtV test. While the VtV test did have a moderately stiffer pulse as compared to the RMDB test (Figure Figure 14), it was also notable as observed in analysis of the video that the THOR-NT in the VtV test had significant interaction with the steering wheel, while in the RMDB and pole tests of the Taurus there was limited or no interaction between the thorax and the steering wheel.

### **Knee / Thigh / Hip Comparison**

Martin and Scarboro (2011) have looked at a selection of tests from NHTSA's frontal oblique / narrow overlap program. They have proposed a provisional IARV of 3,500 N for the resultant acetabular load. Looking at the three oblique Ford Taurus tests, it can be seen that all three tests exceeded the proposed IARV. However, the magnitudes and observed patterns differed from test to test. These differences, which are also notable in the differences seen in femur loads (especially when comparing the vehicle to vehicle test – 6830 and the

RMDB to vehicle – 7366) are likely the product of differences in crash pulses and intrusions seen in these tests. It is noteworthy that none of the femur loads exceeded the 10 kN IARV in the oblique tests while all exceeded the provisional acetabulum load limit. In the Taurus SOI tests, right and left femur loads were highest in the VtV test, while the left acetabulum load was highest in the RMDB test. Differences in intrusion may have contributed to the measured differences in acetabular and femur loads between the VtV and RMDB tests. The pole test, which had more IP intrusion than the VtV test, had lower femur and acetabular loads. The softer crash pulse in the pole test (Figure 14) may have contributed to the lower loads.

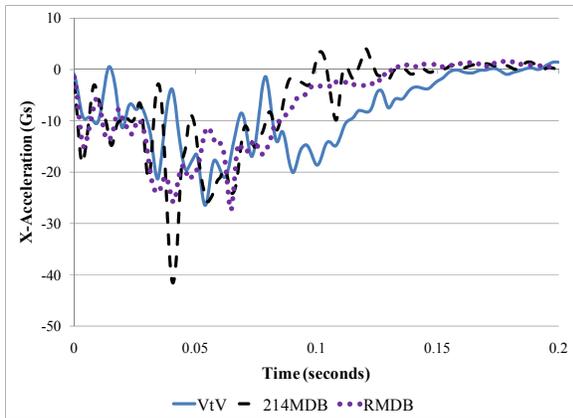
### **Lower Leg Comparison**

The lower leg IAVs in Table 3 include the respective upper and lower revised tibia indices and the ankle rotations for the right and left leg. Of the body regions evaluated, the results for the lower leg showed the greatest differences in performance in the MDB tests versus the VtV tests that they were designed to duplicate. All MDB or pole tests had at least one lower leg IAV that was at least 50% higher or lower than the corresponding value in the respective VtV tests. Differences in intrusion, initial foot/ankle placement, and crash pulse likely contributed to these highly variable values.

## **DISCUSSION**

### **Vehicle Crash Characteristics**

The change in the honeycomb from the 214MDB honeycomb to the RMDB honeycomb eliminated the high spike in the acceleration early in the event (Figure 20) and matched the pulse shape, but not the duration. The RMDB did not reproduce the desired DV and A-pillar bottom intrusion seen in the VtV OI test. This may be because the RMDB starts rotating sooner in the RMDBtV OI test than the VtV OI test, and part of the energy from the RMBD is released into the rotation of the barrier. This rotation may be caused by the center of gravity of the RMDB not being aligned with the vehicle center of gravity. The rotation may also be caused by the RMDB having no structure to stay engaged with the target vehicle.



**Figure 20: Comparison of x-acceleration of the left rear sill of the VtV OI test to the 214MDBtV and RMDBtV OI tests**

The drop in the RMDBtV SOI acceleration and difference in the DV may be because of how the RMDB interacts with the vehicle during the test (Figure 15 (a) and (b)). As the RMDB moved down the side of the target vehicle and pushed the target vehicle wheel back into the occupant compartment, the RMDB started to ride up the tire, causing the barrier to override the vehicle and pushing the A-pillar back (see Figure 21). This was inconsistent with the baseline VtV test and likely explains the differences in the crash pulse and sharp drop off in the accelerations after the peak is reached.



**Figure 21: Barrier override during Taurus SOI test**

### Injury Assessment

The main purpose of the IAV comparison in this paper was not to evaluate the IAVs against provisional IARVs, but as metrics for comparison of MDB and pole tests to the respective vehicle-to-

vehicle tests in oblique and small overlap impacts. Simply looking at the peak values in Table 3 does not help one understand the source of those differences. The kinematics, head contact points, and thorax and lower extremity interactions were all dependent on vehicle crash characteristics, most notably the crash pulse and intrusion measures. For both the head and chest, it was observed in tests on the Taurus that steering column / wheel motion and intrusion affects both head and chest IAVs. It is possible that with more modern vehicles (the vintage Taurus evaluated in this study started in model year 2000), the motion and intrusion of the steering column will be more controlled. The two tests on the Five Hundred, which did not include the RMDB test at the time of this paper being submitted, had roughly 100 mm less steering wheel movement than the Taurus.

Current regulatory and consumer metric frontal crash evaluations with restrained occupants produce kinematics that result in sustained head interaction with the air bag and limited or no contact with interior components. The exception to this is the occasional bottoming-out of the ATD's head through the air bag to the steering wheel. The head kinematics and contacts described in this study span from the door, to the a-pillar and steering wheel. The oblique nature of the studied crash conditions, the limited overlap and other factors, such as steering column motion, affected the kinematics and resulting injury measures. As seen in the results of the current study, it is unreasonable to expect that a single MDB will be able to replicate the occupant response observed in a vehicle-to-vehicle test. Instead, it will be necessary to complete such paired analyses on multiple vehicles and vehicle types to see if the MDB can grossly replicate the occupant responses observed in vehicle to vehicle tests and at the very least the observed injury trends from real-world small overlap and oblique cases.

While it was not the paper's focus, it is notable to look at a few trends in IAVs versus IARVs for several body regions. First, concerning observed head injury measures, it is noteworthy that  $HIC_{15}$  values did not exceed the IARV of 700 in any test, while the rotational injury measure, BRIC, was exceeded in four of seven tests. The study of rotationally-induced brain injuries and associated

injury metrics is an area of continuing study at NHTSA. While the use of BRIC or other rotational brain injury-related measures to assess occupant performance in crash testing is a relatively new concept, the results of this study do indicate a potential area for future emphasis regarding restraint system design. However, real-world analysis of crash data with respect to brain injury risk should be compared against the predicted risk based on BRIC prior to drawing broad assumptions related to its potential use in restraint system development. Finally, it was observed that none of the femur loads exceeded the 10 kN limit. However, in all of the tests on the Ford Taurus, the provisional acetabular resultant load IARV of 3,500 N was exceeded. While this may seem counter-intuitive, in studies of NASS-CDS and CIREN cases (Rudd et al., 2011), acetabular fractures are frequently observed in the absence of femur fractures.

The use of the THOR-NT in this research provides the opportunity for a more detailed look at the kinematics and injury measures that are appropriate for small overlap and oblique crashes. The advanced capabilities of the THOR-NT allow for injury risk evaluations that are not currently possible in other frontal ATDs. Most notably, the addition of multi-point thoracic deflection instrumentation provides the future opportunity to develop an advanced injury criteria. Also, as discussed by Martin and Scarborough (2011), the acetabular load measure presents an opportunity to study injury potential and countermeasures for addressing hip and pelvis fractures, which are prevalent in oblique and narrow overlap crashes.

## LIMITATIONS

The RMDB developed for this test procedure was not designed to represent the exact characteristics of a vehicle, but to try to recreate the crash conditions (pulse, intrusion) that lead to injuries in oblique and small overlap crashes in the real-world. This paper only examines one vehicle (Taurus) for these different oblique and small overlap test procedures. The RMDB performance may be different for different classes of vehicles. Thus, it is not appropriate to draw conclusions from the evaluations of the RMDB on a single vehicle model.

Though it is interesting to compare the relative magnitudes and possible factors leading to the observed injury values within this test program, a future step will be to compare the predicted injury risk by body region and injury type in a more extensive set of fleet tests to the observed injury risks seen in field data.

## CONCLUSIONS

Based upon the limited data, the following conclusions were made:

- The RMDBtV OI barrier face design prevented the spike in the acceleration early in the event due to bottoming out of the 214MDB and provided a similar acceleration pulse as the VtV OI test.
- The RMDBtV OI did not achieve the A-pillar bottom intrusion and total DV when compared to the VtV OI test.
- Vehicle-to-vehicle, MDB-to-vehicle and vehicle to pole tests, in their respective oblique conditions, produced head excursions that resulted in limited interaction with the driver air bag, allowing head contact with a variety of interior components. These observations are unique as compared to current belted consumer metric and regulatory frontal crash modes where ATD heads are generally well restrained by the air bag, but are consistent with case analysis of frontal oblique and narrow overlap real-world cases.
- Injury measures such as BRIC and resultant acetabular loads showed promise in being able to identify the potential for serious injuries that current instrumentation and/or injury measures may not have detected. While not available at the time of this study, it is expected that other advanced injury measures, such as a multi-point thoracic deflection injury criteria, could provide similar benefits.
- The THOR-NT has provided occupant kinematics and injury evaluation capabilities that will continue to assist in NHTSA's efforts to develop and evaluate small overlap and oblique test procedures.

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