

Moving Deformable Barrier Test Procedure for Evaluating 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 incidence of fatalities to belted non-ejected occupants in frontal crashes involving late-model vehicles. The report concluded that after exceedingly severe crashes, the largest number of fatalities occurred in crashes involving poor structural engagement between the vehicle and its collision partner, present in crashes characterized as corner impacts, oblique crashes, impacts with narrow objects, and heavy vehicle underrides. By contrast, few if any of these 122 fatal crashes were full-frontal or offset-frontal impacts with good structural engagement, excepting crashes that were of extreme severity or the occupants that were exceptionally vulnerable.

The intent of this research program is to develop a test protocol that replicates real-world injury potential in small overlap impacts (SOI) and oblique offset impacts (Oblique) in motor vehicle crashes. Previous work towards this goal has led to the development of a Research Moving Deformable Barrier-to-Vehicle (RMDBtV) test protocol, which is further evaluated in this paper. While there were some inherent differences in the Vehicle-to-Vehicle (VtV) and RMDBtV test results, the overall agreement of vehicle and occupant responses proved promising enough to perform another VtV to RMDBtV comparison. As in the previous study, the first step is to compare the RMDBtV to VtV test for the same vehicle. This comparison focuses on the target vehicle crash metrics (pulse shape, average deceleration, slope of the velocity time-history, total change in velocity, exterior crush profile, and interior intrusion) as well as occupant kinematics and injury assessment values.

The second step of this research program is to assess the performance of new vehicles in the SOI RMDBtV and the Oblique RMDBtV test procedures. This research will provide insight on the ability of these two test procedures to replicate vehicle and occupant response as seen in the field. This paper presents the results of 7 different 2010-2011 model year vehicles tested in both the SOI and the Oblique test procedures. In these tests the overlap and RMDB closing speed was held constant for both procedures. The vehicle response demonstrated a decreasing trend of delta-V and longitudinal acceleration with increasing vehicle mass, but the trend did not hold for lateral acceleration. Aside from the lightest vehicle showing the largest magnitude of intrusion, there was no apparent trend of vehicle mass with intrusion. The occupant kinematics demonstrated head contact locations that are common in the field, torso loading of the restraint system and steering wheel, and a distribution of injury assessment values that is representative of the field injury risk.

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INTRODUCTION

According to a study conducted by Bean et al. in 2009 [1], poor structural engagement between the vehicle and its collision partner resulted in the largest number of fatalities to belted non-ejected occupants in frontal crashes involving late-model vehicles, excluding exceedingly severe crashes and/or anomalies. Motor vehicle crashes that demonstrate such poor structural engagement include corner impacts, oblique crashes, impacts with narrow objects, and heavy vehicle underrides. By contrast, few if any of these 122 fatal

crashes 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 [2].

To better understand the injuries, injury source, and occupant kinematics in these small overlap impacts (SOI) and oblique offset impacts (Oblique), NHTSA performed a review of motor vehicle crashes included in the Crash Injury



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Research and Engineering Network (CIREN) and National Automotive Sampling System Crashworthiness Data System (NASS-CDS) databases [3]. In this study, a total of 276 drivers were identified to be involved in crashes that were characterized as either left offset or SOI. Left offset was defined as having only the left longitudinal being engaged during the crash. SOI was defined as engagement outside the left longitudinal, as defined by Halloway et al. in 2011 [4]. Drivers sustained AIS 3+ injuries to the knee-thigh-hip (KTH) complex in 65% of the cases, AIS 3+ chest injuries in ~45% of the cases, AIS 2+ leg and foot injuries in ~38% of the cases, and AIS 3+ head injuries in ~19% of the cases. There was no consistent and significant difference in the injury distribution between left offset and SOI. The most frequent source of KTH injury was contact to the instrument panel, responsible for 80% of the AIS 3+ KTH injuries sustained in left offset and SOI. The attribution of chest injury source varied noticeably by crash mode, and was divided between interaction with the safety belt (47% left offset, 39% SOI), steering wheel (34% left offset, 16% SOI), and door (9% left offset, 31% SOI). Sources for AIS 3+ head injuries were distributed over a wide range of contact surfaces, including the steering wheel (32%), A-pillar (~17%), and air bag (~9%).

NHTSA initiated a research program to investigate crash test protocols that replicates real-world injury potentials in small overlap (SOI) and oblique frontal offset impacts. The main objective of this research program was to develop a test procedure involving a moving deformable barrier (MDB) in order to a) allow comparisons of vehicles across classes, b) reduce the costs that would be associated with vehicle-to-vehicle test procedures, and c) create a feasible test procedure that could be reproduced a wide number of crash test facilities.

The first step in this program was to conduct VtV tests in both SOI and Oblique conditions, which could subsequently be used as surrogates to evaluate the utility of MDB-to-vehicle crash tests. Paired VtV and MDBtV tests in the oblique condition were carried out for three passenger cars (PC): PC weighing 1731 kg (PCa), PC weighing 1892 kg (PCb), and a smaller PC weighing 1345 kg (PCc). Additionally, paired VtV and moving deformable barrier-to-vehicle (MDBtV) tests were carried out in the SOI condition for the PCa and the PCc. Evaluation of these tests led to improvements to the Federal Motor Vehicle Safety Standards (FMVSS) No. 214 Side Impact Protection MDB that was originally implemented, resulting in the Research Moving Deformable Barrier (RMDB). The previous study by Saunders et al. in 2011 [5] presented the results of VtV, MDBtV, and RMDBtV tests of a PCa in the SOI and oblique condition, as well as VtV and MDBtV tests of a PCb in the oblique condition. The current study contributes an additional RMDBtV test of a PCb in the oblique condition. Since the RMDB overrode all the vehicles in the SOI test configurations intended to replicate VtV SOI tests, no

comparisons of the RMDBtV SOI will be presented in this paper.

Additionally, a series of 15 RMDBtV tests (8 SOI and 7 Oblique) were conducted to assess the performance of 2010 and 2011 model year vehicles. In this paper this test series is referred to as "New Model Tests." This test series included different classes of vehicles, including a sub-compact car on the light end and full-size truck on the heavy end. This test series was performed to provide insight into the ability of these two test procedures to represent the vehicle crash characteristics and occupant injury risk seen in the field. In order to compare vehicles across classes, the New Model Tests used a constant-energy test configuration with a constant impact speed for the RMDB.

TEST PROCEDURE DEVELOPMENT

From the Rudd analysis [3] of real world cases, it was suggested that the steering wheel-mounted air bag did not properly restrain the occupant, and the head often moved outboard of the air bag to contact the A-pillar or upper portion of the door. Therefore, NHTSA chose the Test Device for Human Occupant Restraint (THOR) anthropomorphic test device (ATD) for this crash test program. The THOR-NT, as described by Shams et al. in 2005 [8], 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. 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. For all target vehicles in this study, the THOR-NT 50th percentile male test dummy was positioned the driver's seat according to FMVSS No. 208 seating procedure.

In order to determine the test setup for Oblique test procedure, Saunders used the 2009 analysis from Eigen and Najm [7]. They studied 389 NASS CDS vehicles in frontal crashes that had an occupant who sustained a MAIS 3+ injury. The results of this study showed that 95 percent of the cases had a change in velocity or delta V (DV) below 60 kph, and 67 percent had an overlap of 50 percent or less. They also performed an analysis of 1998-2005 NASS-CDS cases which showed that 73 percent of vehicles with frontal damage were VtV. In a related non-published analysis of this data, it was found that while the highest percentage of MAIS 3+ cases involved a principal direction of force (PDOF) equal to 0 degrees, a significant percentage of MAIS 3+ cases involved a PDOF between 340 and 350 degrees. Using this information and additional computer modeling, Saunders [5] used the following test parameters for the Oblique VtV test procedure: (1) to simplify the test procedure since few crash test facilities that can perform an angled VtV crash test with both vehicles moving, the target vehicle was held stationary; (2) the bullet vehicle impacted the target vehicle at 113 kph

(70 mph); (3) the overlap of 50 percent was used to produce occupant compartment intrusion; and (4) the target vehicle was angled 15 degrees relative to the track to produce oblique kinematics of the dummy. To further simplify the test procedure, an Oblique MDBtV test condition was developed, where conservation of momentum was used to calculate an estimated DV in the target vehicle of 56 kph (35 mph) in a full frontal crash.

To determine the SOI test procedure, a collinear pole crash test was performed at the Medical College of Wisconsin (MCW). The NHTSA test number for this test is 7490 and can be downloaded from the NHTSA's Vehicle Crash Test Database¹. In this test, the outside of the pole was aligned with the outside of the longitudinal of the target vehicle, with no initial vehicle rotation. The vehicle displaced laterally during the test to the point that it slid off of the pole before the occupant compartment was engaged. A subsequent test used an angle of 15 degrees (as used in the oblique procedure) as a means to produce better engagement in an attempt to match the intrusion patterns observed in the field data (NHTSA Test Number 7491). During this test, it was observed that the pole did not engage the structure of the vehicle outboard of the longitudinal rail as seen in the field, it instead penetrated toward the center of the vehicle. The conditions of these two tests were interpolated to arrive at an angle of 7 degrees for the SOI condition, in order to keep engagement while allowing the pole to penetrate outboard of the longitudinal rail. Using this information, the SOI test procedure was the same as the oblique procedure, with the exception of the target vehicle angle (7 degrees) and the amount of overlap, as the outsides of the left longitudinal rails of the target and bullet vehicles were aligned. To reproduce this SOI test in an MDB procedure, the following parameters were developed: (1) MDB aligned outside the rail; (2) closing speed of the MDB calculated using conservation of momentum to achieve a 56 kph (35 mph) DV in the target vehicle; and (3) the target vehicle rotated 7 degrees relative to the track.

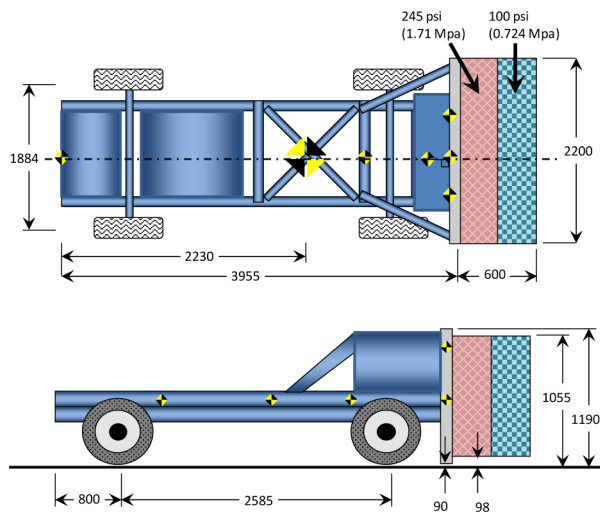
The first set of tests using the FMVSS No. 214 MDB demonstrated several undesirable issues, as described by Saunders et al. in 2011 [5]. First, the 214 MDB honeycomb bottomed out too soon, causing a spike in the acceleration early in the event. Second, the tires of the 214 MDB were not protected by the face plate, causing unforeseen damage to the barrier. Finally, the use of 50 percent overlap procedure did not produce the same A-pillar intrusion as the VtV test. For these reasons, the moving deformable barrier was replaced by an instrumented barrier designed and developed by Trella et al., (2000) [9], which was originally developed for use in research crash testing to address vehicle aggressivity and compatibility issues. The instrumented MDB (iMDB) design is an adaptation of the current FMVSS No. 214 MDB design and duplicates as closely as possible its physical and dynamic

specifications. This MDB also had the following features: (1) a suspension system to prevent bouncing of the cart during approach, (2) ability to ballast up to 2722 kg (6000 lbs), (3) adjustable ride height, (4) ability to adjust wheel base, and (5) can be used in both side and frontal impacts.

NHTSA further modified the MDB to widen the face plate to be outside of the track width of the barrier in order to protect the wheels of the barrier. Also, the face plate was lowered in an attempt to prevent override, and raised such that it was as high as the window sill for most vehicles. The honeycomb was modified to prevent bottoming out of the barrier too soon in the event. Using computer modeling, a two-layered barrier honeycomb face was developed. The first layer was 300 mm thick and had a stiffness of 0.724 MPa (100 psi) and the second layer was also 300 mm thick and the stiffness was increased to 1.71 MPa (245 psi) to prevent bottoming out of the barrier during the event. The resulting barrier is referred to as the Research Moving Deformable Barrier (RMDB). It should be noted that the design characteristics (i.e. frontal stiffness) of the RMDB were not developed to match a specific or even an average passenger car, but were developed to address the issues observed in testing with the FMVSS No. 214 MDB. Since the RMDB is homogenous, the barrier would more evenly distribute the crash load on the struck vehicle where an actual vehicle produced more localized loading due to the longitudinal frame rails and engine. It was believed that changing the overlap from 50 percent to 35 percent would allow the RMDB to interact more like an actual bullet vehicle as it could better expose the A-pillar and instrument panel to more of the crash forces.

From the previously-published tests [5], it was demonstrated that compared to the oblique FMVSS No. 214 MDB, the Oblique RMDBtV improved the qualitative and quantitative agreement of the target vehicle acceleration pulse compared to its VtV counterpart in the case of a PCa. While there were some differences in the A-pillar intrusion and resulting occupant response, the comparison was promising. However, when implemented in the SOI condition, the RMDB overrode the PCa. NHTSA also performed SOI VtV (NHTSA Test Number 7293) and Oblique VtV (NHTSA Test Number 7371) tests with the PCc to have a comparison of a compact car when using the RMDB. However, when these tests were repeated with the RMDB in both the Oblique (NHTSA Test Number 7434) and SOI (NHTSA Test Number 7433) configurations, the RMDB overrode the target vehicle in both cases. Therefore, the face plate was lowered to its lowest position possible. Figure 1 shows the final dimensions of the RMDB used in this paper.

¹<http://www-nrd.nhtsa.dot.gov/database/aspx/vehdb/querytesttable.aspx>



All dimensions are in mm

Figure 1. Dimensions of the RMDB

RMDBTV TO VTV COMPARISON

VEHICLE RESPONSE METHODOLOGY

The vehicle characteristics used for evaluation of the RMDBTV test relative to the VTV test, are listed below.

1. The acceleration pulses (shape, peak Gs, peak Gs timing, average deceleration, and duration). Since the target vehicle is stationary, there is not always a point where the acceleration crosses zero during the main part of the event. For this paper, the duration is defined as the time it takes the acceleration pulse to go above -10 Gs after peak Gs is reached (duration_{-10Gs}). Sometimes there are oscillations in the acceleration when the acceleration was around -10 Gs. In this case, the latest part of the acceleration was used for analysis. Saunders et al. (2007) [6] showed that average deceleration (AvgGs) is a good predictor of probability of injury and was defined as the closing speed divided by the time it takes for the velocity to cross zero. Again, since the vehicle is stationary and time to zero crossing of the velocity trace cannot be determined, duration_{-10Gs} replaces the time to zero crossing of the velocity. Also, the closing speed is replaced by the change in velocity at duration_{-10Gs} (DV_{-10Gs}). Equation 1 was used to calculate AvgGs_X in the longitudinal direction. Since the magnitude of the lateral acceleration is less than the longitudinal acceleration the AvgGs_Y is calculated when the acceleration goes below 5 Gs.

$$\text{AvgGs}_X = \frac{1000 \cdot 1000 \cdot \text{DV}_{-10\text{Gs}}}{3600 \cdot 9.81 \cdot \text{duration}_{-10\text{Gs}}} \quad (1)$$

2. The slope of the velocity time history and total DV.

3. Interior intrusion. A 4 by 5 matrix was placed on the toe pan and floorpan and four points across the middle of the

toe pan (row 2, Figure 2) were used for the comparison analysis and all points are used later in this paper. The procedure is as followed:

1. Locate and mark point D1 (column D row 1): Project a line 45 degrees (from the horizontal) down and forward from the center of the top accelerometer pedal in the x-z plane until the line intersects the interior of the vehicle. Mark this point by cutting a small "v" in the carpet and underlying padding and peeling back and exposing the floor. The carpet and padding are then refitted prior to crash.
2. ST plane: The ST plane is a y-z plane that passes through the front edge of the right seat track.
3. AP1 plane: The AP1 plane is a y-z plane that passes through point D1.
4. AP2 plane: The AP2 plane is an x-z plane that passes through point D1.
5. AP3 plane: The AP3 plane is an x-y plane that passes through point D1.
6. MP plane: The MP plane is a y-z plane located halfway between the ST plane and AP1 plane.
7. CF plane: The CF plane is an x-z plane that passes through the center of the footrest. If there is no visible footrest, locate the x-z plane to pass through a point located 64 mm measured along the MP plane in the y-direction from the intersection of the door sill and floorboard.
8. BP plane: The BP plane is an x-z plane that passes through the center of the brake pedal.
9. TP plane: The TP plane is a y-z plane at the intersection of the BP plane and the intersection of the toe pan and floorboard.
10. Column A is at the intersection of the vehicle and the CF plane.
11. Column D is at the intersection of the vehicle and the AP2 plane.
12. Row 1 is at the intersection of the vehicle and the AP3 plane.
13. Row 3 is at the intersection of the vehicle and the TP plane.
14. Row 5 is at the intersection of the vehicle and MP plane.
15. Columns B and C are evenly spaced between Columns A and D.
16. Row 2 is evenly spaced between Row 1 and Row 3.
17. Row 4 is evenly spaced between Row 3 and Row 5.
18. Map and mark additional driver points:

- a. Mark the center of the brake pedal.
 - b. Mark the left upper IP located above where dummy's knees contact the dash.
 - c. Mark the right upper IP located above where dummy's knees contact the dash.
 - d. Mark the center of the steering wheel.
4. Mark the front outboard seat attachment point A-pillar bottom: A-pillar bottom intrusion is point 1 in the door profile measurements (Figure 3). The door profile and 4 by 5 matrix measurements will be used later in the paper and the procedures for obtaining these points are as followed:

- a. Put steering wheel in center position. Create a horizontal plane (plane 1) that passes through the center of the steering wheel.
- b. Point 1: Mark the sheet metal at the intersection of plane 1 and the outer edge of rubber part of the door sill running down the A-pillar.
- c. Point 22: Mark the sheet metal at the intersection of plane 1 and the outer edge of rubber part of the door sill running down the B-pillar.
- d. Mark 20 evenly spaced points between points 1 and 22 along the outer edge of the rubber door sill on the sheet metal.
- e. Mark 20 evenly spaced points between points 22 and 1 along the outer edge of the rubber door sill on the sheet metal.

5. Exterior profile of the target vehicle. To obtain the exterior profile, the vehicle was placed at the proper attitude and a vehicle coordinate system was created at the rear bumper. The target vehicle is measured around the circumference of the vehicle at the height of the center of the bumper (d1) (Figure 4a). After the test, the vehicle was put back into its original vehicle coordinate and re-measured at the same height (d1) after the test (Figure 4b).



Figure 3. Door profile measurements

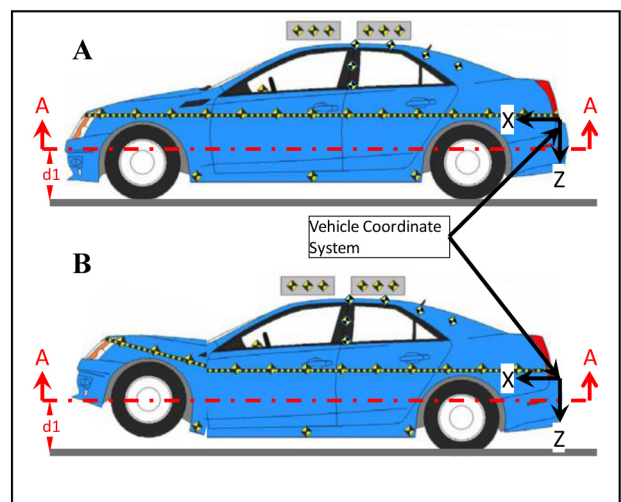


Figure 4. External crush profiles

OCCUPANT RESPONSE METHODOLOGY

For all of the tests presented in the current study, a THOR 50th percentile male anthropomorphic test device (ATD) was positioned in the driver's seat of the target vehicle. For the VtV and RMDBtV comparison tests, a standard THOR-NT ATD as described by Shams et al [8] was used. The THOR-NT ATD was instrumented with a nine-accelerometer array in the head to record six-degree-of-freedom kinematics, upper and lower neck loads and moments, accelerations of the thoracic spine and pelvis, three-dimensional displacements of four anterior rib cage locations measured using systems of rotational potentiometers and rigid links known as CRUX units, three-dimensional displacements of two anterior abdominal locations measured using double-gimballed string potentiometer (DGSP) systems, bi-lateral acetabulum loads, bi-lateral femur loads and moments, bi-lateral upper and lower tibia loads and accelerations, and ankle rotations.

While injury risk functions specific to the THOR hardware have not yet been developed [15], provisional

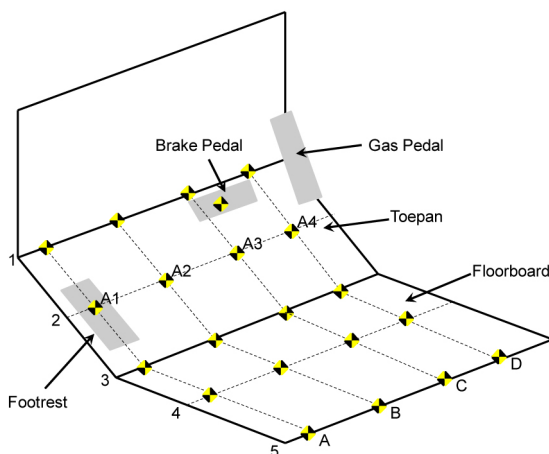


Figure 2. Toe pan measurements

injury assessment reference values have been developed for several body regions. To assess head injury risk, the head injury criterion (HIC) is assumed to be applicable to THOR, since the design requirements for the mass, moment of inertia, and biomechanical response characteristics mirror that of the Hybrid III for which HIC is traditionally applied. Additionally, a rotational brain injury criterion (BRIC) has been developed to estimate the risk of brain injury due to rotation of the skull [9]. Further test data are necessary to fully develop the relationship between BRIC and cumulative strain damage measure (CSDM) specific to THOR, but for the purpose of this analysis all of the THOR tests in the small overlap and oblique test program have been used to develop the intercepts (63.5 rad/s and 19,501 rad/s²) for the calculation of BRIC for the tests presented in this paper (See [Appendix B](#)). The BRIC Injury Assessment Reference Value (IARV) is 0.89, which corresponds to a 30% risk of AIS 3+ traumatic brain injury (TBI). For the neck, cervical spine load tolerance values, which would represent a conservative estimate of tolerance values when applied to the stiffer THOR neck, have been proposed: tension force of 2520 Newtons (N), compression force of 3640 N, flexion moment of 48 Newton-meters (Nm), and extension moment of 72 Nm [11]. Injury assessment reference values have not yet been determined for the THOR chest, though research has been planned to develop an injury risk function that leverages the ability of the THOR to measure deflection at four points on the anterior rib cage. The fracture tolerance of a human hip under neutral loading through the knee was determined to be 4560 N [12]; adjusting for the difference in load transfer between the THOR dummy and human subjects, the associated load measured at the THOR acetabulum would be 3500 N [13]. Lower extremity injury risk was assessed using the Revised Tibia Index, for which the IARV of 1.16 represents a 50% risk of an AIS 2+ leg shaft injury [14].

RESULTS RMDBTV TO VTV OBLIQUE COMPARISON

Vehicle Response: *VtV* vs. *RMDBtV*

The PCb was used for this *RMDBtV* to *VtV* comparison. [Figure 5](#) shows the shape of the left rear sill acceleration of the PCb in the *RMDBtV* test has a similar shape to the *VtV* left rear sill acceleration in both the x and y direction. The only difference in the *RMDBtV* X-acceleration compared to the *VtV* X-acceleration is that the *RMDBtV* X-acceleration is slightly higher, the peaks occur earlier, and the duration-10Gs of the pulse is shorter. The effect of this earlier acceleration can be seen in both the AvgGs_x and the velocity trace ([Figure 6](#)) The AvgGs_x are higher for the *RMDBtV* tests (≈ 4 Gs) and the change in velocity starts sooner for the *RMDBtV* test. But it should be noted that *RMDBtV* velocity slope is similar to the *VtV* velocity slope. The Y-direction *RMDBtV* vehicle characteristics were similar in the Y-direction. [Table A 1](#) and

[Table A 2](#) in the [Appendix](#) show all of the calculated vehicle characteristics in both the X- and Y-directions.

[Figure 7](#) shows that the interior intrusions of the PCb *RMDBtV* compared to the *VtV* test. This figure shows the *RMDBtV* test has a similar toepan intrusion pattern, but at slightly different magnitudes. For the IP and Steering Wheel intrusions the *RMDBtV* intrusions were slightly higher compared to the *VtV* test. Also, in this figure it can be seen that the A-pillar bottom intrusion was higher in the *VtV* test when compared to the *RMDBtV* test.

[Figure 8](#) shows the post-test exterior profiles for the *RMDBtV* and *VtV* tests. From this figure it can be seen that the exterior profiles are similar, except at the left side longitudinal. [Figure 9](#) shows the deformation of the left side longitudinal. It can be seen from this figure that the left side longitudinal did not deform during the *RMDBtV* test.

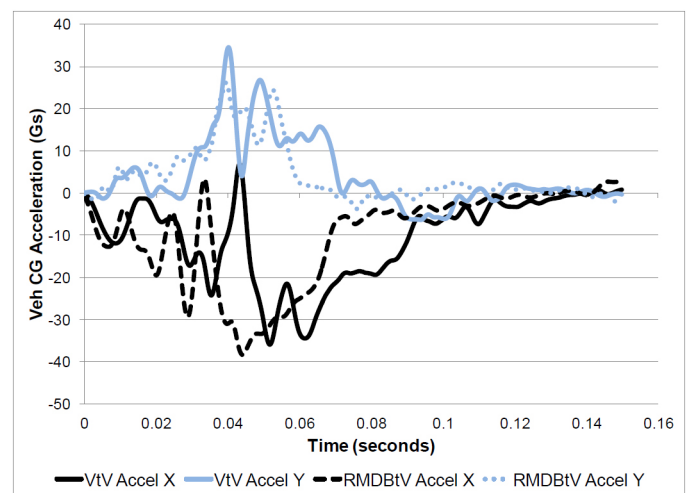


Figure 5. X and Y acceleration of the Oblique PCb

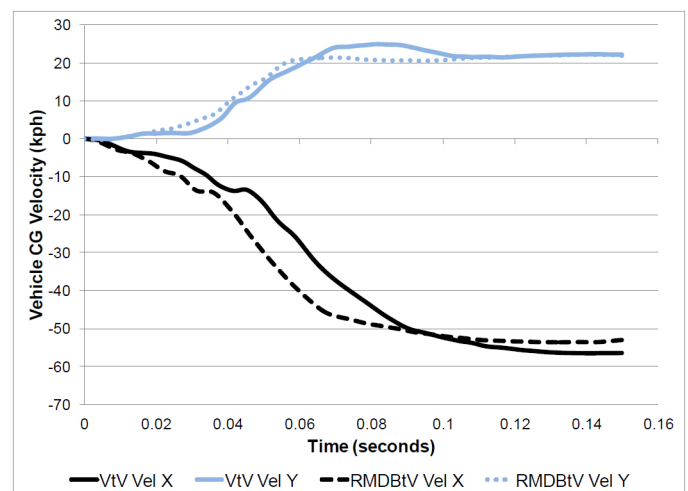


Figure 6. X and Y velocity of the Oblique PCb

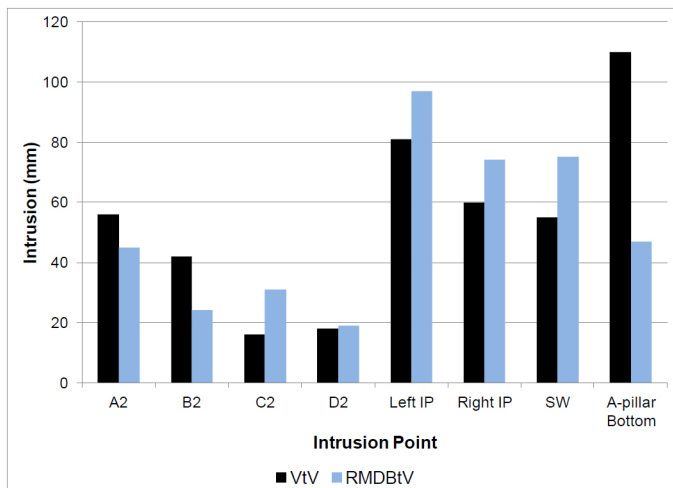


Figure 7. Interior intrusions of the Oblique PCb

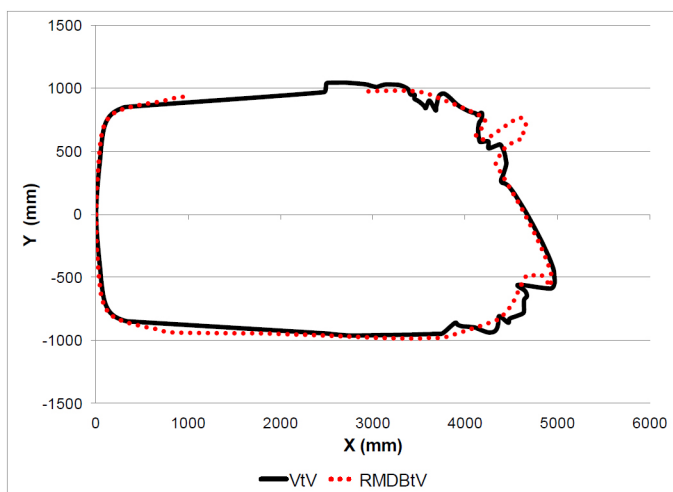


Figure 8. Exterior profile of the Oblique PCb

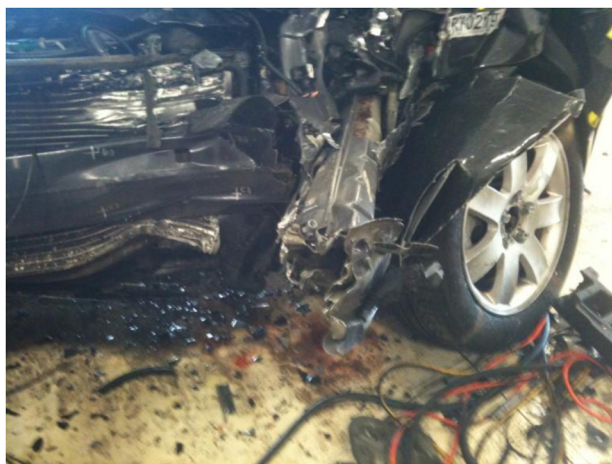


Figure 9. Oblique PCb main longitudinal structure not deformed

Occupant Response: VtV vs. Oblique RMBDtV

As reported by Saunders et al in 2011 [5], a comparison of VtV and RMBDtV Oblique tests was carried out using an exemplar mid-sized sedan (PCa) (NHTSA test numbers 6830 and 7366). The occupant kinematics in both test procedures were qualitatively similar, where the lateral acceleration pulse coupled with inboard deformation of the steering column resulted in the head slipping outboard of the air bag and translating towards the A-pillar. Due to differences in intrusion of the A-pillar as well as differences in the interaction of the torso with the restraint system, contact of the head with the A-pillar and door frame resulted in higher head accelerations in the VtV test than in the RMBDtV test. Differences in restraint interaction with the torso were also theorized to have contributed to differences in chest deflection and the magnitude and distribution of femur and acetabulum loads.

An additional RMBDtV test was performed using PCb (NHTSA test numbers 6831 and 7429) to allow further comparison to the VtV test procedure, which was carried out using PCb and presented by Saunders et al in 2011 [5].

The occupant kinematics in the PCb RMBDtV test were similar to those of the VtV test. The occupant initially translates forward parallel to the longitudinal axis of the vehicle, with an increasing outboard lateral component that begins to contribute about 50 milliseconds after the impact. The frontal air bag triggers at 22 milliseconds after initial bumper contact with the barrier, and the head of the occupant contacts left-of-center on the deployed air bag. After this initial air bag interaction, the steering assembly intrudes rearward (towards the occupant) and translates inboard. Since the occupant is moving outboard while the steering assembly is moving inboard, the occupant receives minimal restraint from the air bag and the head translates outboard towards the A-pillar and door frame. The head of the occupant contacts a similar location on the door panel in the vehicle-to-vehicle test (Figure 10) and RMBDtV test (Figure 11), though there are differences in the resulting head acceleration due to the structural deformation of the door. In the vehicle-to-vehicle test, deformation at the hinges causes the door to translate rearward and buckle outward (Figure 12), while in the RMBDtV test, the door frame approximately retains its original position and shape (Figure 13). This difference may have resulted in the elevated HIC_{15} measured in the RMBDtV test, as there was more structure immediately behind the door panel. Aside from the spike at the time of contact of the head with the door frame in the RMBDtV test, the resultant head accelerations are similar (Figure 14).

As with the comparison between the vehicle-to-vehicle and RMBDtV tests with the PCa, there were notable differences in the injury assessment metrics measured using the THOR dummy positioned in the driver's seat. The relevant injury assessment values (IAVs) are shown in Table 1, along with those from the previously-conducted relevant tests. Generally, the PCb RMBDtV test demonstrates higher

values for all of the measured quantities compared to the vehicle-to-vehicle test, with the exception of abdominal deflection. While none of the provisional IARVs are exceeded in the vehicle-to-vehicle test, several are exceeded in the RMBDtV test (HIC15, BRIC, neck tension, left acetabulum resultant force, Tibia Index, and ankle rotation). However, the loading pattern appears to be similar, as the peak chest deflection occurs in the upper right quadrant in both tests, and the left aspect of the knee/thigh/hip (as measured at the acetabulum and femur) shows higher peak loads than the right aspect.

Comparing the thoracic response between vehicle-to-vehicle and RMBDtV, the magnitudes of the chest deflections are on average 15% higher in the RMBDtV tests. Correspondingly, belt loads are higher in each RMBDtV test compared to its paired vehicle-to-vehicle test (Figure 15). However, the trend in chest deflection among vehicles remains the same, as the peak occurred in the upper right quadrant for all four tests, and the peak chest deflection is higher in PCb than the PCa for both test conditions.

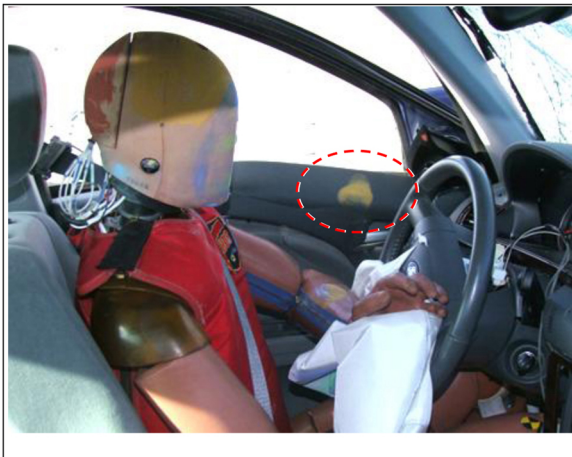


Figure 10. Head contact with door panel in PCb ViV test



Figure 11. Head contact with door panel in PCb RMBDtV test



Figure 12. Door frame deformation in PCb ViV test

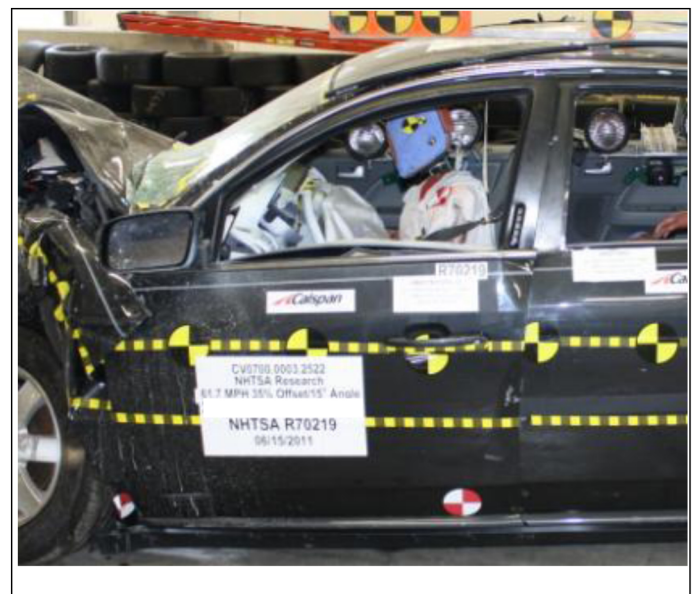


Figure 13. Door frame deformation in PCb RMBDtV test