

ANALYSIS OF THE PROPOSED FRONTAL OBLIQUE CRASH TEST

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ABSTRACT

On December 2015, The National Highway Traffic Safety Administration (NHTSA) published a Request for Comments (RFC) and proposal to implement U.S New Car Assessment Program (NCAP) changes covering three categories of crashworthiness, crash avoidance and pedestrian protection, beginning with the 2019 model year. The crashworthiness included a new frontal oblique impact (OI) test protocol. The test comprises of a new Oblique Moving Deformable Barrier (OMDB), new THOR 50th percentile male (THOR-50M) anthropomorphic test device, and a new test configuration. An OMDB of 2,486 kg (5,480 lb) impacts a stationary target vehicle at a speed of 90 kph (56 mph) at an angle of 15 degrees with a 35% barrier overlap with the front end of the vehicle. This paper describes the analyses of a 31 OI tests conducted by NHTSA, in which the target vehicles used were of different sizes and weight distribution ranging between 1034 Kg (SMART)-2624 Kg (Silverado).

Target vehicle Deformation Energy (DE) in each of the 31 OI test was determined and compared to its 56 kph (35 mph) dummy responses for each test were plotted against Velocity Change (Delta V) calculated from momentum equation and from test's velocity time histories. In addition, Barrier Equivalent Velocity (BEV) of target vehicles was calculated and the THOR M50 dummy responses were plotted against BEV and presented in this paper. Results indicated that target vehicles absorb more DE in the proposed OI compared to a 56 kph (35 mph) full frontal barrier impact. Lighter weight vehicles, in particular, have to manage approximately 50-60% more DE in the proposed OI. Larger vehicles (i.e., similar weight to the OMDB) manage approximately same DE as in the 56 kph (35 mph) full frontal barrier impact. Therefore lighter vehicles will require significant structural stiffening which may have negative impacts on other attributes such as Fuel Economy, vehicle compatibility and stiffer crash pulse or restraint system in small light weight vehicles, which may lead to safety degradation for rear seat occupant, elderly in particular. Biomechanics injury risk indicates that occupant's injury risk increases with the velocity change experienced by the occupant during a crash. Injury risk associated with THOR-M50 dummy responses in NHTSA's OI tests showed weak or no correlations with velocity change. The same responses were plotted against BEV and showed similar results and observation. The proposed OI mode did not demonstrate the expected injury trend with velocity change and/or BEV. Other issues may exist with the barrier mass, stiffness, THOR or test configuration. Further research is needed to develop appropriate OI test parameters, OMDB, and dummy type and/or criteria.

INTRODUCTION

Regulatory and Public Domain (PD) frontal impact test protocols continue to evolve globally in order to address injuries and fatalities associated with various real world crash modes. Among the existing test protocols issued by The National Highway Traffic Safety Administration (NHTSA), The Insurance Institute of Highway Safety (IIHS) and the European New Car Assessment Program (Euro-NCAP) are: Fixed Full Rigid Barrier (FRB) impact, fixed Offset Deformable Barrier (ODB) impact with moderate overlap, and fixed Small Overlap Rigid Barrier (SORB) impact. The crash barriers are fixed and the vehicle, which carries initial kinetic energy, runs into the barriers in a collinear fashion of impact with either full, moderate, or small overlaps [1, 2, 3]. These test protocols are designed to assess self-protection in terms of structural intrusions and Hybrid-III 50th% male and 5th% female Anthropomorphic Test Device (ATD) responses.

In June 2015 Euro-NCAP introduced a new frontal impact protocol as part of the 2020 Euro-NCAP roadmap to be implemented in 2020 [4, 5]. This test protocol is using new Moving Progressive Deformable Barrier (MPDB) and new THOR ATD and is designed to assess self and partner protection. It is a 50% overlap co-linear frontal impact in which both the MPDB and the vehicle are moving against each other with a fixed initial speed of 50 kph (31 mph). Self-protection is assessed through structural deformation and THOR dummy responses and the partner protection is assessed through the aggressivity metric, calculated from the MPDB deformation map. On December 2015, NHTSA published its proposal to implement new U.S NCAP changes beginning with the 2019 model year [1]. The crashworthiness category included a new frontal Oblique Impact (OI) test protocol. The test comprises of a new Oblique Moving Deformable Barrier (OMDB), new THOR ATD, and a new test configuration. An OMDB of 2,486 kg (5,480 lb) impacts a stationary target vehicle at a speed of 90 kph (56 mph) at an angle of 15 degrees with a 35% barrier overlap with the front end of the vehicle. As a result of the NHTSA study published by Bean *et al.* [5], NHTSA initiated a vehicle crash research program with the intent to develop a test protocol that replicates real-world vehicle kinematics and injury potential in a small overlap impacts and oblique offset impacts [6]. This research led to the development of a Research Moving Deformable Barrier (RMDB) and an opportunity for improved

ATD to be used in a RMDB-to-Vehicle impact test protocol. The RMDB was a modified FMVSS 214 barrier with a test weight of approximately 2500 kg [7]. Since then NHTSA has been investigating a new frontal OI test mode in which a RMDB impacts a stationary vehicle at 90 kph, a 15 degree angle, and a 35% vehicle overlap. The test utilizes The Test Device for Human Occupant Restraint (THOR) dummy positioned in both the driver and passenger seat. The dummy has been developed to provide enhanced bio-fidelity compared to the Hybrid III which is currently used in frontal crash tests.

In this paper a series of 31 OI tests conducted by NHTSA was selected and analyzed to better understand the feasibility and validity of the proposed OI test protocol. The DE for both the impacted vehicle and the OMDB were calculated and compared to their respective DE in the 56 kph (35 mph) NCAP test. The measured THOR dummy responses in the test series were plotted against (Δv) to better understand the THOR dummy suitability in injury assessment to replicate the injury outcome and injury trends observed in real-world crashes [8, 10, 11]. Similar analysis for THOR suitability in injury assessment was performed by plotting the dummy responses against the calculated Barrier Equivalent Velocity (BEV) for all the vehicles in the selected test series. The following sections provide the description and the analyses for the selected NHTSA's OI, in which the target vehicles used were of different sizes and weight distribution ranging between 1034 Kg (Smart) to 2624 Kg (Silverado).

DESCRIPTION AND ANALYSIS OF FRONTAL OBLIQUE IMPACT TEST

Oblique Impact Set Up

The selected OI test series conducted by NHTSA included different classes of vehicles consisting of a sub-compact car on the light end and full-size truck on the heavy end as shown in Figure 1. All tests were performed according to the OI test protocol shown in Figure 2. The THOR dummy was positioned at the driver's seat according to the Federal Motor Safety Standard FMVSS 208 seating procedure. The OMDB impacted a stationary vehicle at a speed of 90 kph (56 mph) while the target vehicle was placed at a 15-degree angle and a 35 percent initial overlap of the struck vehicle front-end width with the OMDB (see Figure 2). The total weight of the OMDB was 2,486

kg (5,480 lb) in which the barrier honeycomb consisted of two layers with different stiffness [7]. The stiffness of the first 300 mm thick honeycomb layer was 0.724 Mpa (100 psi) and that of the second 300 mm thick honeycomb layer was 1.71 Mpa (245 psi).

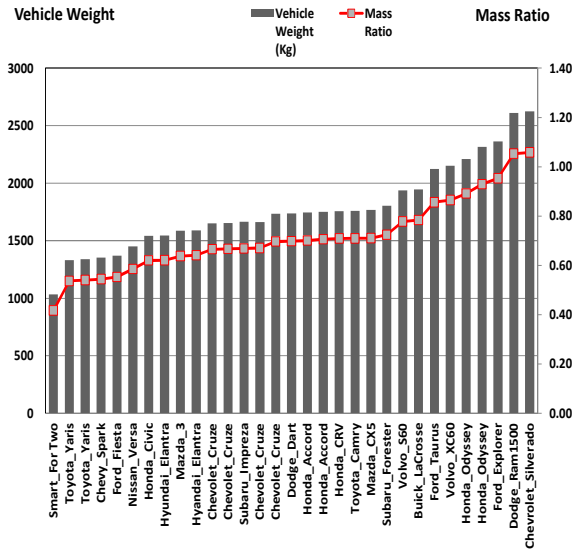


Figure 1. Vehicle mass and mass ratio in the NHTSA's OI tests

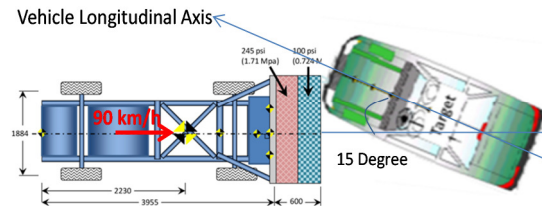


Figure 2. NHTSA's OI Schematic and test-setup

The OMDB centerline makes an angle of 15 degrees with the vehicle longitude center line, according to the initial test configuration. At time zero, at the first

point of the contact of the barrier with the vehicle, the OMDB imposes both longitudinal and lateral components of impact velocities of 87 kph (54.1 mph) and 23.3 kph (14.5 mph), respectively and a 35% initial overlap with the vehicle. The initial percentage of overlap generates an initial contact zone between the barrier and the impacted front end of the vehicle. During the crash, both the barrier and vehicle continue to rotate causing the contact area and the impact force acting on it to change. An example of this behavior is shown in Figure 3: between time zero and 80 ms, the angle between the barrier and the target vehicle centerlines changed from 15 degrees to 30 degrees and the impact contact zone between the barrier and the vehicle increased from 35 % to 50 % overlap. The progressive change in the Principle Direction of Impact Force (PDIF) and the progressive increase in the contact area during the crash cause different kinematics of the occupants compared to co-linear impacts (Figure 4). The changes in the PDIF and contact area necessitate the need of struck target vehicles to manage increased DE than what is designed for in their 56 kph (35 mph) NCAP test.

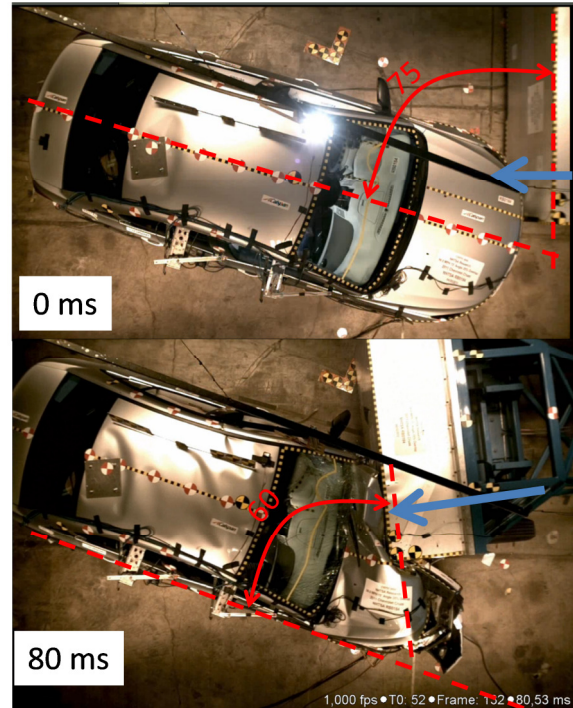


Figure 3. Changes in initial impact angle, direction of the impact force, and contact area between the OMDB and target vehicle at 80 ms.



Figure 4. Examples of OI dummy kinematics shown at rebound time 116 ms

The Target Vehicle Crash Pulse in OI

The resulting crash pulse signatures in target vehicles in frontal OI are distinguishably different than those obtained in any other existing frontal impact collinear modes, for the same vehicles. Investigating the difference may help with the understanding of the unique occupant kinematics and the excessive DE needs in OI. In the frontal OI, the lateral component has a significant contribution to the deformation energy absorbed by the target vehicle. This also confirms the fact that although the OI is a frontal impact at time zero, the PDIF continues to change towards the lateral direction during the crash.

Figures 5 and 6 show eight longitudinal X and lateral Y acceleration time-history curves of the 31 NHTSA's OI tests. As shown in Figure 6, the lateral Y accelerations tend to peak around 40 ms reaching values close to peak accelerations in the longitudinal X direction. This demonstrates the unique behavior of the vehicle kinematics in OI that is not observed in other frontal impact configurations.

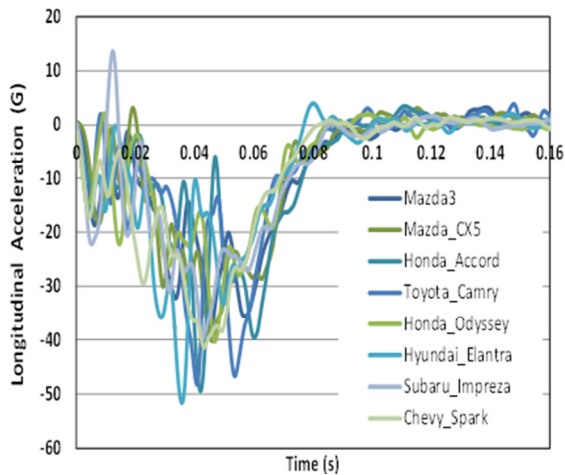


Figure 5. Longitudinal X-accelerations in target vehicles

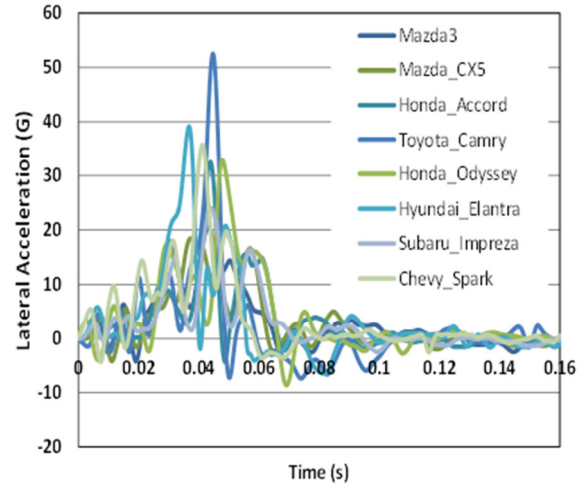


Figure 6. Lateral Y-accelerations in target vehicles

The Hyundai Elantra OI test is one of the NHTSA's tests shown in Figures 5 and 6 and was randomly selected to be analyzed against the IIHS 64 kph (40 mph), 40% ODB frontal impact test. The X and Y pulse components of the Hyundai Elantra from the NHTSA OI and IIHS ODB tests are compared in Figures 7 and 8 respectively. Figure 7 shows that the dominant longitudinal acceleration pulse continues to rise and peaks towards the end of the ODB crash around 90 ms. At this time the lateral acceleration is almost diminished. The lateral acceleration is very low throughout the ODB crash event, Figure 8. The earlier observation of the lateral contributions of impact forces to the DE sustained by the target vehicle and the unique occupant kinematics in OI should be thoroughly investigated to assess the validity of the test configuration.

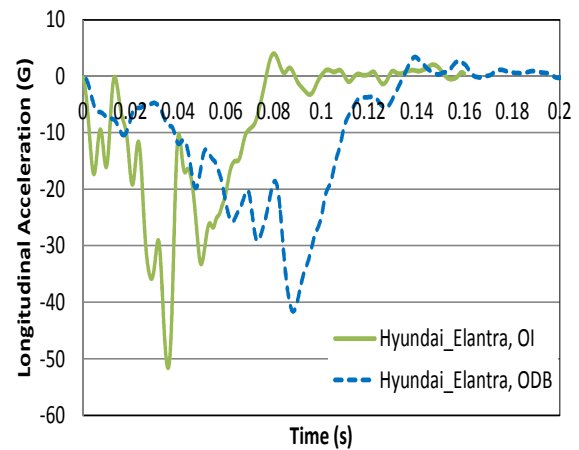


Figure 7. Longitudinal acceleration comparison of Hyundai-Elantra in OI and ODB

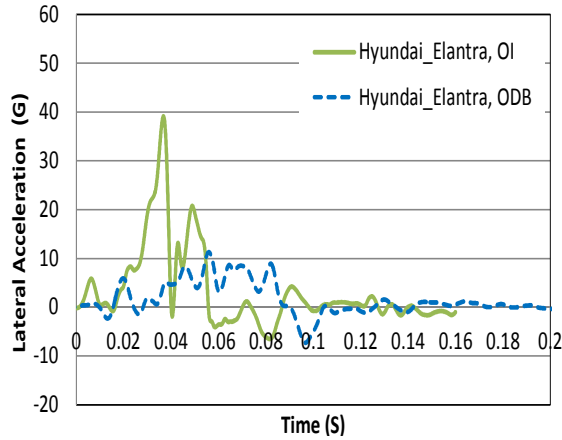


Figure 8. Lateral Acceleration comparison of Hyundai-Elantra in OI and ODB

The velocity Change in the Target Vehicle

Target vehicle's velocity change is an important measure influencing the vehicle occupant's responses, represented by THOR crash dummy. At the rebound both the OMDB and the impacted target vehicle reach a common velocity (v_c). Let the mass of the OMDB defined by (m_1), the mass of the target vehicle be defined by (m_2), and the mass ratio of the target vehicle to the barrier be defined by (R), $R = m_2/m_1$, (range 0.5 ~ 1.2). Using momentum equation the common velocity (v_c) is expressed by Equation 1.

$$v_c = \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2} = \frac{v_1 + R v_2}{1 + R} \quad \text{(Equation 1)}$$

The velocity changes in the OMDB (Δv_1) and in the target vehicle (Δv_2) can be calculated by subtracting the common velocity (v_c) from their initial velocities.

$$\Delta v_1 = v_1 - v_c = v_1 - \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2} = \frac{R(v_1 - v_2)}{1 + R} \quad \text{(Equation 2)}$$

$$\Delta v_2 = v_2 - v_c = v_2 - \frac{m_1 v_1 + m_2 v_2}{m_1 + m_2} = \frac{-(v_1 - v_2)}{1 + R} \quad \text{(Equation 3)}$$

$$\frac{\Delta v_1}{\Delta v_2} = R = \frac{m_2}{m_1} \quad \text{(Equation 4)}$$

The Mass Ratio for the most vehicles investigated in this study is less than 1 (i.e. $R < 1$), due to the high mass of the OMDB. This resulted in the velocity

change of target vehicles to be higher than those of the OMDB. Equations 2 and 3 indicate that the velocity changes experienced by the impacted bodies depend on mass ratio and the relative speed ($v_1 - v_2$). In a two-cars collision, the lighter vehicle always experiences a higher velocity change. In the NHTSA's OI test the relative speed is always constant and equal to 90 kph (56 mph) and the velocity change in target vehicles only depends on the function of the mass ratio R . Figure 9 shows that the velocity change of target vehicle calculated from equation 3 is a non-linear function with R . Figures 10 and 11 show the velocity time histories of the target vehicle and the OMDB in the 31 NHTSA's OI tests, respectively. The (Δv) of the target vehicle can be calculated from Figure 10.

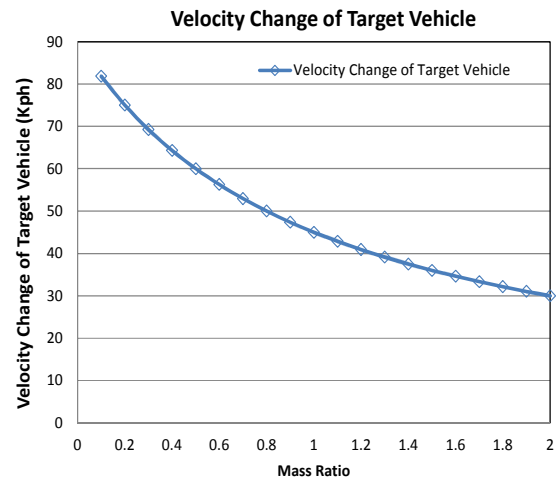


Figure 9. Velocity change of the target vehicle (Δv_2) vs. the Mass Ratio

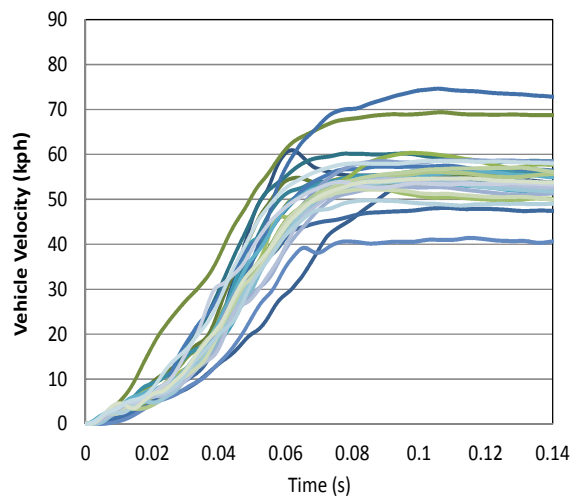


Figure 10. Target vehicle velocity change (Δv_2)

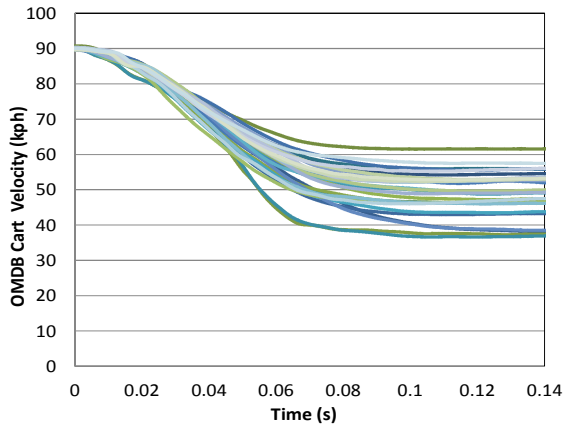


Figure 11. OMDB velocity change (Δv)

The velocity change (Δv_2) of the target vehicles versus mass ratio of the vehicle to the barrier in the selected test series is shown in Figure 12. The target velocity change shown in the Blue “Diamond” legend were calculated from Equation 3, and those shown with the Red “Stars” legend were calculated from the test velocity curves shown in Figures 10 and 11. There is a strong correlation ($R^2 = 0.7056$) between the velocity change and target vehicle to barrier mass ratio, indicating that the lighter vehicle experience higher velocity change in the OMDB-to-vehicle impact.

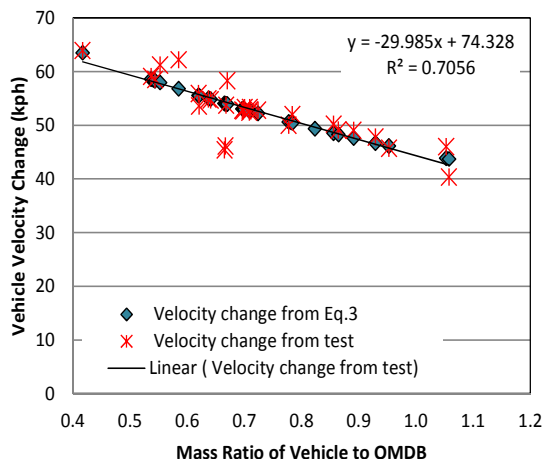


Figure 12. Target vehicle change (Δv_2) vs. vehicle to OMDB mass ratio

VEHICLE BARRIER EQUIVALENT VELOCITY

Delta V and Barrier Equivalent Velocity (BEV) are terms that have been used for many years to describe aspects of what happened to a vehicle when an impact occurs [14]. That is, they are used to describe some physical change in the vehicle state

before and after impact. Specifically, the (Delta V) describes the change in the vehicle velocity vector from just before the impact until just after the impact. The BEV attempts to quantify the energy required to cause the damage associated with an impact. The Barrier Equivalent Velocity (BEV) of a crashed vehicle is the speed with which the vehicle would have to strike a rigid barrier in order for it to absorb the same amount of crush energy as it did in the actual impact [15].

In a vehicle-to-rigid barrier impact, the total deformation energy absorbed by the vehicle is almost equal to the initial kinetic energy if the rebound, heat and friction energies are neglected. While in the OMDB-to-vehicle OI test, the change of the kinetic energy (ΔKE) is equal to the total system deformation energy (DE_{total}), assuming no heat or friction energy loss. The total deformation energy can be expressed by Equation 5,

$$DE_{total} = \Delta KE = \frac{1}{2} \frac{m_1 m_2}{m_1 + m_2} (v_1 - v_2)^2 \quad \text{(Equation 5)}$$

The Contact force between any two non rigid impacting bodies is the same at all time during the impact. The total deformation energy of the two impacting bodies, assuming no heat or friction losses, is equal to the sum of the deformation energies absorbed by body 1 (DE_1) and by body 2 (DE_2). However, the deformation energy in each colliding body can be expressed by the area under the curve of the contact force vs. body deformation. In the OMDB-to-vehicle impact, it is assumed that the relation between the contact force and vehicle/barrier deformations is linear, for the purpose of the BEV calculation. Figure 13 shows the linear assumption between the vehicle/barrier contact force and vehicle/barrier deformations.

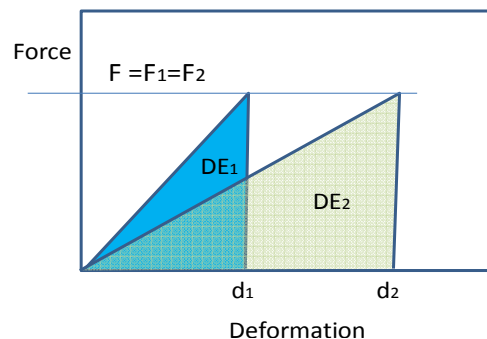


Figure 13. Assumption deformation energies and linearity between contact force and deformation,

The total deformation energy in the NHTSA's OMDB-to-vehicle impact is equal to the sum of the deformation energy of the OMDB (DE₁) and of the target vehicle (DE₂), assuming no friction or heat loss

$$DE_{total} = DE_1 + DE_2 \quad (\text{Equation 6})$$

Using the linear assumption shown in Figure 13, DE₁ and DE₂, can be expressed by:

$$DE_1 = \frac{1}{2} F_1 d_1 \quad (\text{Equation 7})$$

$$DE_2 = \frac{1}{2} F_2 d_2 \quad (\text{Equation 8})$$

F₁ and d₁ represent the contact force and the deformation associated with the OMDB while F₂ and d₂ represent the contact force and deformation associated with the target vehicle. Since the contact force between the vehicle and barrier is the same then F₁ = F₂ = F.

$$DE_{total} = \frac{1}{2} F (d_1 + d_2) \quad (\text{Equation 9})$$

Equating Equation 5 to Equation 9 results

$$F = \frac{1}{(d_1 + d_2)} \left(\frac{m_1 m_2}{m_1 + m_2} \right) (v_1 - v_2)^2 \quad (\text{Equation 10})$$

Substituting Equation 10 into Equations 7 and 8 will results in:

$$DE_1 = \frac{1}{2} \left(\frac{d_1}{d_1 + d_2} \right) \left(\frac{m_1 m_2}{m_1 + m_2} \right) (v_1 - v_2)^2 \quad (\text{Equation 11})$$

$$DE_2 = \frac{1}{2} \left(\frac{d_2}{d_1 + d_2} \right) \left(\frac{m_1 m_2}{m_1 + m_2} \right) (v_1 - v_2)^2 \quad (\text{Equation 12})$$

The BEV of the OMDB (V_{1_BEV}) and of the target vehicle (V_{2_BEV}) are the speeds with which the OMDB and the target vehicle would have to strike a rigid barrier in order to absorb the same amount of crush energy, DE₁ and DE₂, as it did in the actual oblique impact test.

$$DE_1 = \frac{1}{2} m_1 v_{1_BEV}^2 \quad (\text{Equation 13})$$

$$DE_2 = \frac{1}{2} m_2 v_{2_BEV}^2 \quad (\text{Equation 14})$$

Equating equation 13 to Equation 11, and Equation 14 to Equation 12, will result into

$$v_{1_BEV} = (v_1 - v_2) \sqrt{\frac{d_1}{d_1 + d_2} \cdot \frac{m_2}{m_1 + m_2}} \quad (\text{Equation 15})$$

$$v_{2_BEV} = (v_1 - v_2) \sqrt{\frac{d_2}{d_1 + d_2} \cdot \frac{m_1}{m_1 + m_2}} \quad (\text{Equation 16})$$

d₁ (the maximum measured crush in the OMDB), and d₂ (the maximum measured crush in the vehicle) are the two parameters introduced in Equations 15 and 16 for the BEV calculations compared to Equation 2 and 3 used for the (Delta V) calculations. The OMDB and target vehicle stiffness, represented by d₁ and d₂ respectively, are introduced in the analysis by calculating their respectively BEV.

Figure 14 shows a comparison between the velocity change measured from tests and the calculated barrier equivalent velocity for the entire 31 vehicle in the test series analyzed in this paper.

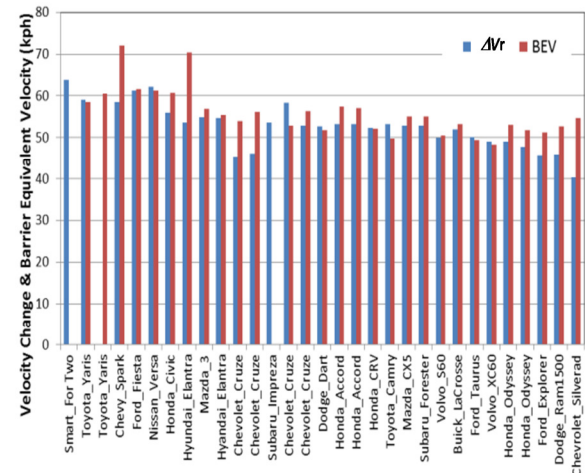


Figure 14. Comparison of vehicles velocity change and BEV

DUMMY RESPONSES WITH VEHICLE VELOCITY CHANGE AND VEHICLE BARRIER EQUIVALENT VELOCITY

NHTSA introduced THOR as a new crash test dummy representing a mid-size male in their OI test. The driver was to promote further development and enhancement of car crash safety and restraint technologies to help address and mitigate injuries seen in the field and reduce fatalities. It is assumed that this dummy, compared to the current 50th% Hybrid III used in the current regulations and NCAP, is a more advanced dummy with higher measurement capability and biofidelity. The dummy used in NHTSA's selected OI tests was instrumented to measure responses for the head, neck, chest, abdomen, and lower extremity including ankle rotations. The head was instrumented with a nine-accelerometer array in the head to record six-degree-of-freedom kinematics. To assess head injury risk, the head injury criterion (HIC) was 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 [3]. The dummy was also instrumented for measurements of the upper and lower neck loads and moments, accelerations of the thoracic spine and pelvis, chest deflections through three-dimensional displacements at four anterior rib cage locations, acetabulum loads, femur loads and moments, upper and lower tibia loads and moments, and ankle rotations.

The velocity change (Δv) was calculated solely based on initial velocity and mass of the impacted bodies. It was used to plot injury indices measured on the THOR dummy versus the velocity change of the target vehicles in the NHTSA's 31 OI tests. Figure 15 shows the injury risk versus (Delta V) curve for frontal crashes (NASS-CDS 1996-2007) [12]. It is a well-established fact that occupant injury risk increases as the (Delta V) increases [12, 13]. Nine of the THOR dummy responses were plotted against the target vehicle velocity change (Δv_2) and Barrier Equivalent Velocity (BEV) arranged from the lightest to heaviest weighted vehicle and are shown in Figure

16 and 17. In general, the plots for all the injury measurements showed weak correlations and no correlations in some cases between the injury risk and both of the velocity change and BEV. In Figure 16 the dummy responses are cross plotted with target vehicle velocity change, the R^2 for the nine injury measurements ranged between 0.011, for the HIC, to 0.442, for the Tibia Index. It appears from the regression analysis that there is a negative correlation for the head response (HIC) and the abdominal deflection responses. In Figure 17 the dummy responses are cross plotted with target vehicle BEV. Similar trends and conclusions to those seen in Figure 16 conclusion were observed. These results contradict the basic biomechanics principles and understanding of injury risk, as the injury risk increases as vehicle velocity change increases. This has raised some concerns that there are other issues attributed to this trend that are may be related to the current test configuration, the OMDB specifications, or may even be the THOR dummy characteristics.

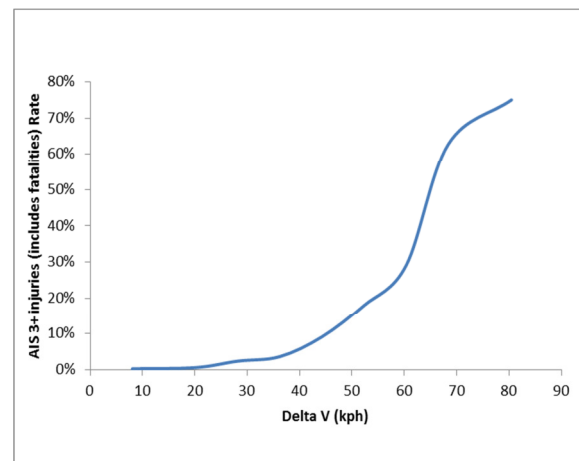


Figure 15. Injury risk in frontal crashes as function Delta V

The authors decided to further analyze the OI test protocol to better understand the barrier mass and stiffness characteristics and the selected oblique angle to determine if they were appropriately chosen to capture real-world field injury and deformation observations in frontal impact crashes. The further analysis is described in the following sections based on barrier deformation and stiffness and target vehicle deformation energy management.

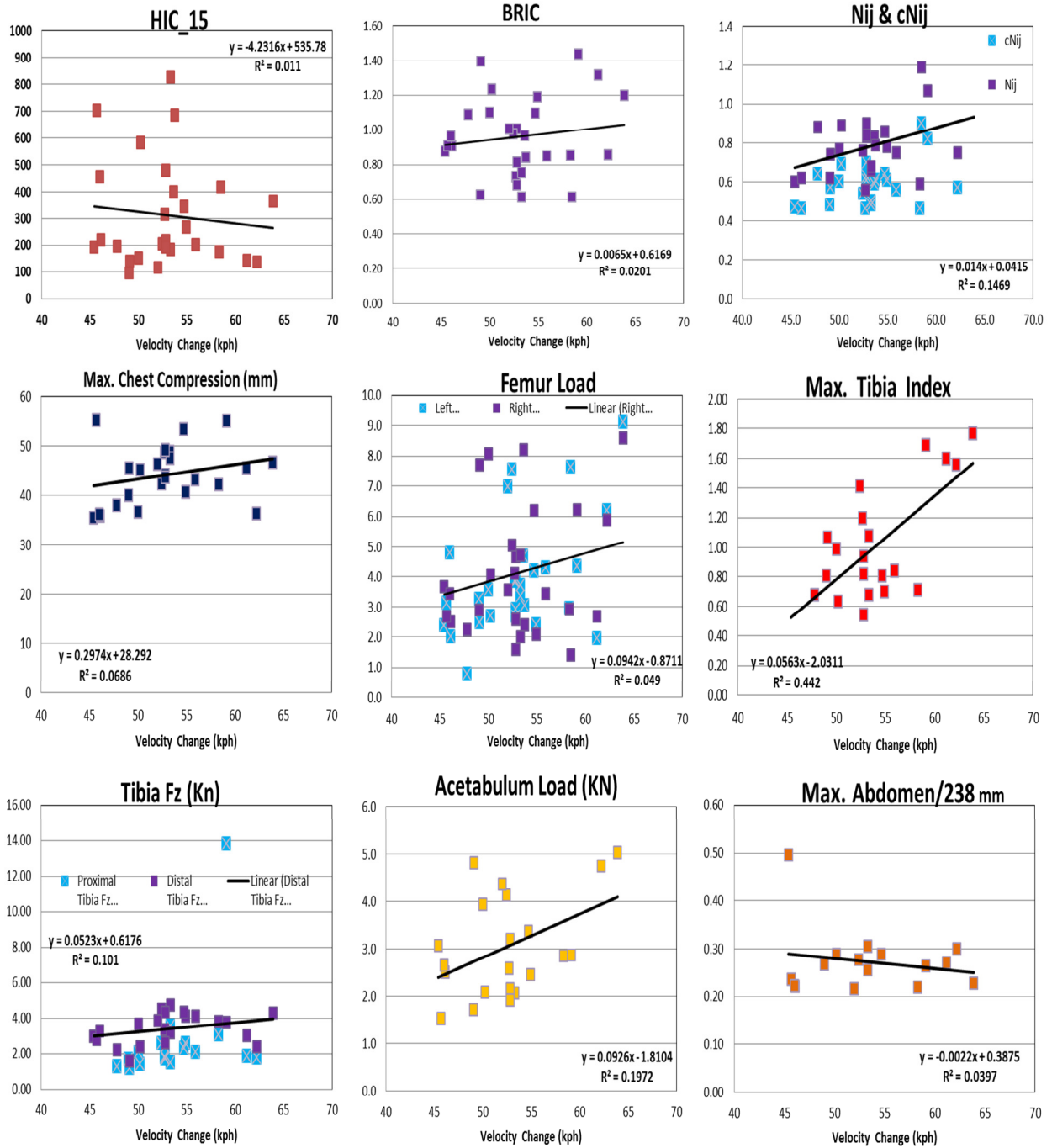


Figure 16. Dummy responses vs. velocity change (Δv_2)

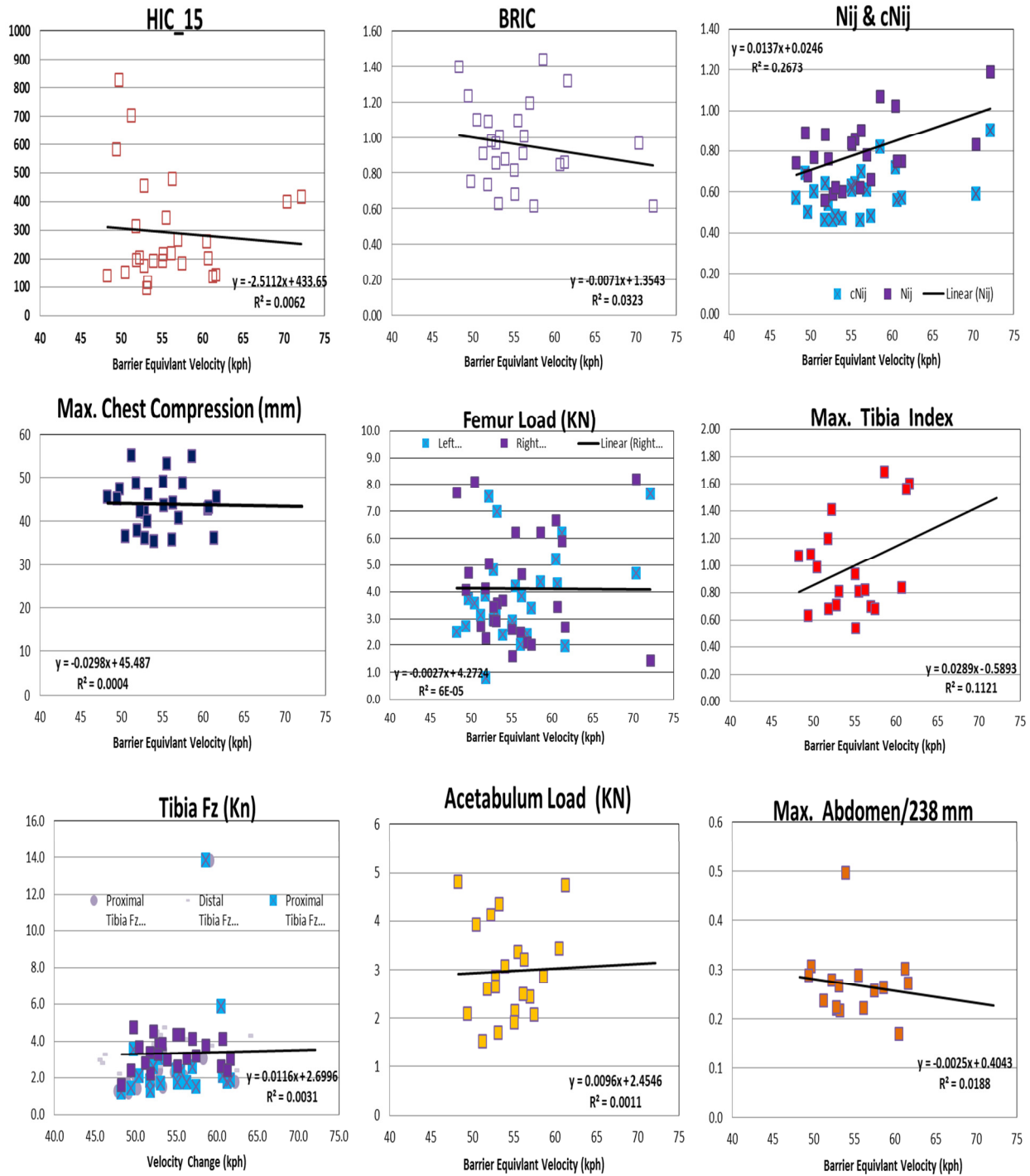


Figure 17. Dummy responses vs. barrier equivalent velocity (BEV)

FURTHER OI PROTOCOL ANALYSIS: DEFORMATION ENERGY

OMDB Specifications Background

The FMVSS 214 moving deformable barrier (MDB) for side impact was the basis for the current NHTSA's OMDB development. The FMVSS 214 MDB demonstrated several undesirable issues when it was used in the first set of NHTSA's tests, as reported by Saunders et al. in 2011 [7]. Among these issues were the bottoming out of the honeycomb causing a spike in the acceleration early in the crash event and the tires were not protected by the face plate causing unforeseen damage to the barrier. Initially NHTSA was conducting the OMDB-to-vehicle impact with 50% overlap. Those tests, per NHTSA, failed to produce the same and/or similar A-Pillar deformations seen in vehicle-to-vehicle crash tests. NHTSA then moved to another instrumented OMDB that was used in vehicle compatibility research and developed by Trella et al. [13]. NHTSA further modified the OMDB by making changes to the face plate in terms of the width, the height above the ground to prevent override, and the full height of the barrier to be around the beltline (window sill) height. To prevent the bottoming out of the honeycomb, NHTSA used computer simulations and developed a two-layer barrier honeycomb face. The front layer has a stiffness of 0.74 MPa (100 psi), and the back layer stiffness was increased to 1.71 MPa (245 psi) to help prevent the bottoming out phenomena. Both honeycomb layers have a thickness of 300 mm. The resulting barrier was referred to as the Research Moving Deformable Barrier (RMDB), which is currently proposed for the new OI NCAP update. It should be noted that the frontal stiffness characteristics of this barrier 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 214 OMDB

Maximum Crush in the OMDB and Vehicle

Grid points were placed on the OMDB face prior to impact along 11 Rows (R1-R11) and 11 Columns (C1-C11) matrix. Crush measurements along the deformable face of the barrier after the impact at each of these grid points were made. Figure 18 shows an example of the deformed barrier with the grid points imposed on the barrier face. Table 2 shows the post-test crush measurements at each

grid point of the C11xR11 matrix. The deformation is concentrated in the overlap contact area with the impacted vehicle. The crush measurements of this particular example were taken from NHTSA's test report. Figure 19 shows a schematic diagram of the points C1 – C6 across the bumper width in which the static crush measurements were made by taking the difference between the pre-crash and post-crash measurements relative to a reference point.



Figure 18. Post-crash photo of the OMDB deformation

Table 2. The OMDB Post-Crash Measurements at the R11 x C11 Matrix Points

		BARRIER X-CRUSH										
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
		50 mm	260 mm	470 mm	680 mm	890 mm	1100 mm	1310 mm	1520 mm	1730 mm	1940 mm	2150 mm
R11	910mm	3.6	5.3	4.0	4.7	4.9	5.0	4.8	5.0	8.3	5.0	6.5
R10	824mm	3.2	3.0	2.7	2.2	2.3	2.4	11.7	4.6	4.0	4.7	17.4
R9	738mm	2.8	2.3	2.0	1.7	1.6	1.7	6.7	13.8	9.1	6.5	39.6
R8	652mm	2.5	1.7	1.4	1.3	1.1	1.2	2.6	24.2	27.7	13.4	73.4
R7	566mm	1.1	0.6	0.5	0.3	0.7	0.8	1.0	14.4	34.4	23.9	106.7
R6	480mm	0.8	0.1	0.1	0.1	0.3	0.4	0.7	9.9	61.9	76.6	139.5
R5	384mm	-0.4	-0.8	-0.6	-0.4	0.1	0.1	0.6	40.4	53.8	203.4	252.0
R4	308mm	-1.0	-1.0	-1.1	-0.7	-0.4	-0.1	0.8	79.3	37.9	201.7	243.4
R3	222mm	-1.6	-1.2	-1.1	-0.8	-0.6	-0.4	1.2	119.6	16.8	139.9	205.0
R2	136mm	-2.1	-1.7	-1.2	-0.8	-0.6	-0.3	20.1	142.1	15.0	87.6	155.8
R1	50mm	-2.2	-1.9	-1.1	-0.6	-	-	31.8	165.6	30.0	31.3	111.8

*Barrier was cut to clear rail and defined points were unmeasurable

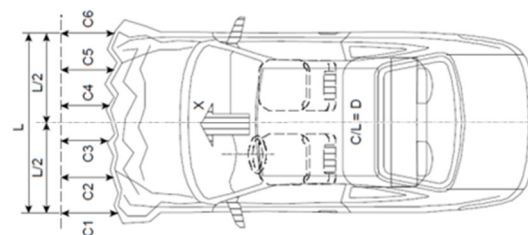


Figure 19. Schematic diagram of vehicle static crush measurement points

Maximum values of the static crush measured on the vehicle and the OMDB matrix points of OI crash tests are presented in Figure 21. It is evident that the majority of the grid points on the OMDB crushed less than or around 300 mm. That means in the majority of the tests, regardless of the impacted vehicle type and weight, only the first honeycomb layer was

crushed. In a few tests, the second layer was crushed. The maximum static crush in small and light vehicle groups is higher than those observed in mid-size or full-size vehicle groups. There are some outlier points as it appears in the SUV and Pickup groups (see Figure 21). The general observed trend is lighter and smaller vehicles experienced higher crush compared to heavier vehicles.



Figure 20. Post-crash vehicle static crush measurements

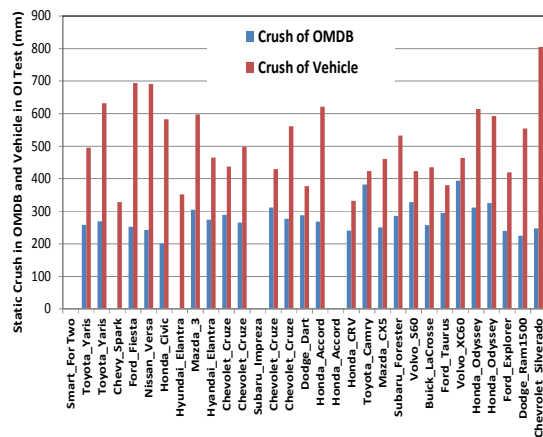


Figure 21. OMDB and target vehicles maximum static crush

Vehicle Deformation Energy

In the fixed rigid wall barrier test (FRB), vehicle deformation energy is almost equal to the initial kinetic energy, $\frac{1}{2} m_2 v^2$. While in the OMDB-to-vehicle OI test the change of the kinetic energy (ΔKE) is equal to the total system deformation energy, (DE_{total}), assuming no heat or friction energy loss. Total deformation energy can be expressed by Equation 5.

Total system deformation energy is the energy absorbed by the OMDB and the target vehicle, as expressed by Equation 17.

$$DE_{Total} = DE_{Vehicle} + DE_{OMDB} \quad \text{(Equation 17)}$$

Estimated Deformation Energy in the OMDB

Post-crash maximum static intrusion measurements at the grid points along an 11 Row (R1-R11) and 11 Column (C1-C11) cell matrix were conducted. An example of an OMDB deformation contour map, based on the intrusions of the barrier face at each cell after the crash, is shown in Figure 22. Each color level represents intrusion in 50 mm increments. The cell size on the barrier face was 210 mm x 86 mm, providing a total area of 18060 mm². The energy absorbed by each deformed cell can be calculated as a product of the cell area, cell maximum static intrusion, and the barrier honeycomb stiffness. Summing the absorbed energy across all the cells on the barrier deformed face can provide a reasonable estimate of the OMDB deformation energy (DE). If the cell intrusion is less than 300 mm then the honeycomb stiffness is taken as 0.74 Mpa for the DE calculations. But, if the intrusion is larger than 300 mm the cell DE consists of two parts, one is the cell's area times 300 mm times 0.74 Mpa. The second part is the cell's area times the intrusion of the second layer (max. intrusion – 300 mm) times 1.71 Mpa. The total absorbed energy into the OMDB can be obtained by summing all the energy absorbed by each cell.

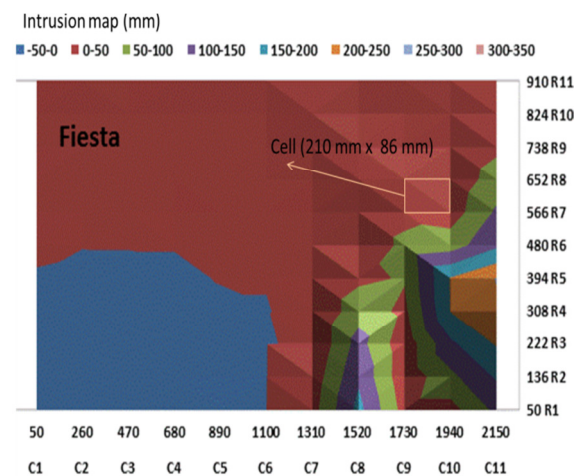


Figure 22. An example of the intrusion contour map of the OMDB

A total of seven out of the 31 NHTSA's OI tests in the series had barrier intrusion data available on NHTSA's website at the time of this research. The DE of the OMDB for the seven tests was calculated, as described in the previous section, and plotted against the corresponding mass ratio of the target vehicle to OMDB in Figure 23. A linear regression to fit the seven points was performed to estimate the DE of the OMDB for the rest of the test series. A good fit with a R^2 of 0.7033 was obtained, as shown in Figure 23. It is consistent with physics that the heavier the target vehicle is the more DE is induced in the OMDB.

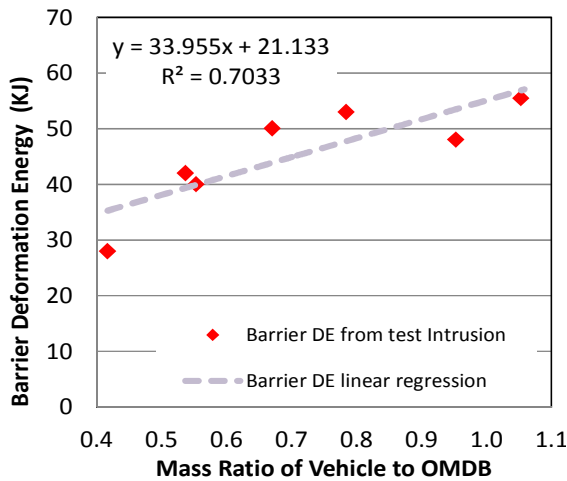


Figure 23. Estimated DE in the OMDB

Vehicle Deformation Energy

Equation 17 can be used to calculate the DE of the target vehicle in OI test by subtracting the absorbed energy in the OMDB from the total deformed energy. The total DE in each test is represented by the change in kinetic energy before and after the impact and is calculated using Equation 5. Target vehicles front-end structure and the restraint systems are designed to manage the current 56 kph (35 mph) NCAP crash test against a FRB and provide good star ratings. The DE of target vehicles in the current NCAP test can be calculated from the vehicle kinetic energy Equation 18, assuming rebound energy is ignored. The initial velocity is constant, so the kinetic energy or deformation energy only depends on the vehicle mass.

$$DE_{NCAP} = \frac{1}{2} m_2 (56)^2 \quad \text{(Equation 18)}$$

Figure 24 shows the total system DE energy, the DE of the OMDB, the target vehicle DE, and the vehicle current NCAP DE, for the 31 NHTSA's OI tests in the selected series. For all the target vehicles considered in these analyses, it is quite clear that in OI the vehicle absorbs more DE compared to that in NCAP test. Figure 25 shows the normalized vehicle DE in OI by that of the NCAP plotted against target vehicle to OMDB mass ratio. It is very clear from Figures 24 and 25 that the structural deformation generated in target vehicles subjected to NHTSA's OI is significantly higher compared to the structural deformation in their NCAP test.

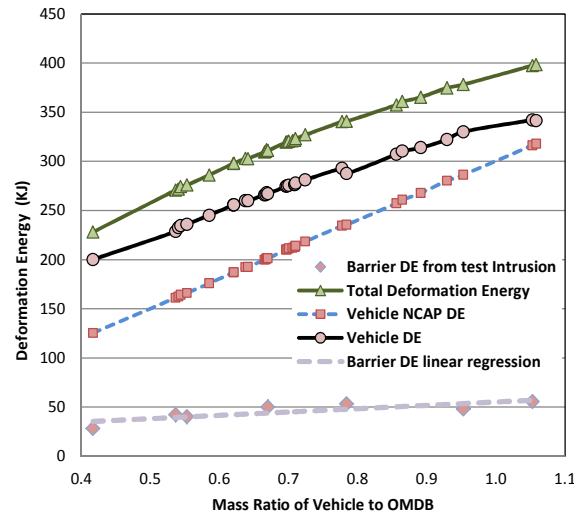


Figure 24. Vehicle deformation energy vs. mass ratio

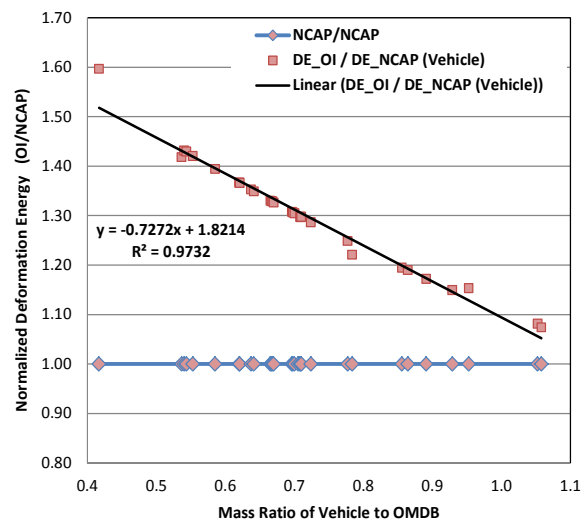


Figure 25. Normalized deformation energy (OI to NCAP) vs. mass ratio

Figure 26 show the DE analysis for randomly selected pairs of small light vehicles and heavy weight vehicles for comparison. Current vehicles are structurally designed to manage impact energy of a 56 kph (35mph) full frontal barrier for self-protection. The OI crash condition is significantly more severe than the 56 kph (35 mph) full frontal barrier impact. Lighter vehicles get penalized much more than heavy vehicles in managing the impact energy and require to manage significantly higher deformation energy than their current NCAP capacity. Target vehicles with similar weight to the OMDB manage approximately same DE as in the 56 kph (35 mph) full frontal barrier impact.

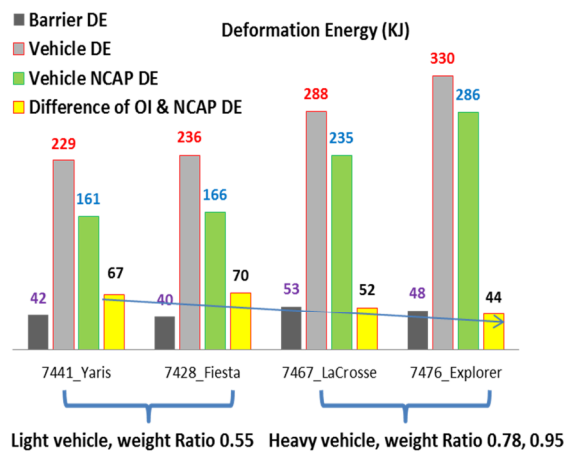


Figure 26. DE comparison for light and heavy target vehicle in NHTSA's OI

DISCUSSION

All 31 target vehicles considered in this analysis had to manage more DE energy in OI than their structural capacity (NCAP structural capacity). Small and light vehicles in particular, as shown in Figures 24 and 26, get significantly penalized in the OI because they require to manage 50% ~ 60% more DE compared to their intended NCAP design. This may lead to an ill-defined need of significant front-end stiffening or reinforcement.

The OI protocol calls for a 15 degrees oblique angle which produces a 23.3 kph (14.5 mph) lateral initial impact velocity. There is a significant initial lateral KE energy coming into the target vehicle which needs to be managed through structural deformation energy, $[1/2 m_2 * (23.3 \text{ kph})^2]$. This lateral impact energy produces a lateral acceleration component in the target vehicle which may peak close to or at a similar level to that of the longitudinal component during

the impact. (See Figures 5-8). Today's vehicles are designed for side impact resulting in a good structural performance. The 15 degree oblique angle in OI is specified for frontal impact which may falsely lead the structural engineers to add unnecessary structural frontal reinforcements to manage lateral impact energy. The 15 degree angle produces occupant kinematics different than those observed in other frontal impact crash modes and that may drive development for new restraint systems or enhancing the current ones.

Other contributions to the added DE in the struck vehicles in the OI test are the barrier mass, velocity, and stiffness. The initial kinetic energy in OI is higher than those in other frontal impact modes due to a heavier barrier mass and a higher initial impact speed. In most of the 31 tests, considered in this paper with the exception of a few, the first honeycomb layer of OMDB was penetrated and deformed in the contact overlap area due to its low stiffness of 0.74 MPa (100 psi). However, the second layer has a stiffer honeycomb of 1.71 MPa (245 Psi) and it was hardly penetrated after the first layer completely deformed or bottomed out. To balance the total system energy between the impacting OMDB and the impacted vehicle, the remaining kinetic energy, after the first layer completely deformed, would have to be transferred to the impacted vehicle and managed through more structural deformation and possibly rotation. These observations in addition to the weak correlation of the THOR dummy responses with the vehicle velocity change (Delta V) or with the vehicle BEV suggest further research may be warranted to develop a more feasible and viable new frontal impact protocol to further enhance real world safety.

CONCLUSION

The final conclusions of this study are summarized below:

- The proposed OI crash condition is significantly more severe than the 56 kph (35 mph) full frontal barrier impact.
- In vehicle-to-vehicle collisions, the lighter weight vehicle experiences a higher velocity change and higher acceleration levels, and therefore, occupants in the lighter vehicle experience higher injury risk.

- The THOR dummy responses in NHTSA’s OI tests showed weak or no correlation (sometimes negative correlations) with the velocity change or with the BEV of the target vehicle. This contradicts the general basic biomechanics understanding that occupant injury risk increases as velocity change increases.
- Lighter vehicles have to manage approximately 50-60% more DE in the OI than in their corresponding 56 kph (35 mph) full frontal barrier impact.
- Even larger vehicles (i.e. similar mass to the OMDB) need to manage more DE but approximately same as in their 56 kph (35 mph) full frontal barrier impact.
- Lighter vehicles will require significant structural stiffening and potentially stiffer restraint systems. This may lead to other potential issues and conflict with other requirements such as fuel economy.
 - Stiffening front-end structure of small and lighter weight vehicles for the proposed OI may lead to stiffer crash pulses which may have negative impact on rear seat occupant safety and the likelihood to increase mass and stiffness incompatibility in front-to-front and front-to-side impacts.
 - Stiffer restraint systems may have an adverse effect on elderly.
 - 2017-2025 fuel economy regulations may lead to downsizing of vehicles and/or mass reduction and higher penetration of small vehicles in the fleet.
- In general, the proposed OI mode did not demonstrate the expected injury trend with velocity change. Other issues may exist with the barrier mass, stiffness, THOR dummy or test oblique angle.

- Further research is suggested to develop the appropriate OI test parameters, OMDB, and dummy type and or injury criteria.

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