Frontal Pole Impacts

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Abstract Based on past findings that the between-rail frontal crash has a higher trauma risk than either the full-engagement or 40% offset crash, this study investigated those three crashes with laboratory tests and finite element simulations. The focus was on these three test types as undergone by four sedans that had been rated *good* by IIHS: (1) 2006 Volkswagen Passat, (2) 2007 Toyota Camry, (3) 2007 Chevrolet Malibu and (4) 2007 Subaru Legacy. Using the 50th percentile male Hybrid III dummy in the driver and right front passenger seats, injury risks were calculated for five body regions: head, neck, thorax, knee-thigh-hip (KTH), and foot/ankle. Comparisons were made for the injury risk in the center pole test to the injury risk for the NCAP frontal test and the IIHS frontal test. The driver compartment intrusion in the center pole test was compared to the intrusion in the NCAP frontal test and the IIHS frontal test. Assuming that the center pole test is a satisfactory laboratory test representing the between-rail crash, a concept for a between-rail countermeasure was designed for a finite element model of a 2001 Ford Taurus. Safety performance and mass increase of the between-rail redesign of the Ford Taurus were evaluated.

Keywords FRONTAL IMPACT, CRASHWORTHINESS, INJURY SEVERITY, CENTER POLE CRASH, FINITE ELEMENT

I. INTRODUCTION

Arbelaez et al. [1] analyzed real-world crash data and found that frontal collisions with narrow objects contribute significantly to occupant fatalities and injuries. Arbelaez proposed that safety professionals for government regulation and consumer information should study the frontal collision with narrow objects with more concern.

Sullivan et al. [2] of Ford Motor Company developed a methodology for defining the post-crash damage profile of vehicles in a frontal impact collision, using both vehicle crush measurements and elements of the CDC (National Automotive Sampling System - Crashworthiness Data System or NASS-CDS). This classification method is based on the concept of identifying the location of the direct damage relative to the estimated location of the underlying vehicle structure and the likely engagement of these primary structures during the crash.

Using US field data, Padmanaban and Okabe [3] examined belted drivers of passenger vehicles in frontal crashes with narrow objects. Padmanaban and Okabe suggested that (1) frontal crashes with poles, posts or trees are relatively infrequent and (2) the fatality rate is lower in narrow-object collisions than in other frontal crashes.

Hong et al. [4] investigated the dynamic response of the structure of a passenger vehicle impacting (1) a full-frontal rigid barrier, (2) an offset frontal deformable barrier and (3) a center pole. A finite element model of the vehicle was used for the study. It was found that the passenger vehicle managed the full-frontal crash and 40% offset frontal crash well by absorbing crash energy in the frame rails. In the center rigid pole impact, the pole avoided the side rails and caused detrimental intrusion into the occupant compartment.

The researchers of the Insurance Institute for Highway Safety [5] analyzed case files from NASS. They found frontal crashes in which 116 drivers and right-front passengers were seriously traumatized or died despite using safety belts. Nineteen percent of the crashes were center impacts into a tree, pole or post. IIHS noted that neither the government nor IIHS uses a frontal pole crash in their consumer information program. In the crash laboratory, IIHS had conducted center pole impacts with a 25.4 mm diameter, rigid pole.

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In 2010, Scullion et al. [6] applied the Ford taxonomy to classify real-world, frontal-impact crashes based on the NASS. Frontally-impacted vehicles were identified for 1985 – 2008 model year passenger vehicles with Collision Deformation Classification (CDC) data from the 1995 – 2008 years of NASS. Using the CDC-based information in NASS and using the methodology identifying the location of the longitudinal rail, he successfully grouped together the frontal impact crashes with common damage patterns. As shown in Figure 1 and Figure 2, Scullion's findings suggested that the *Between-Rail* crash—where the direct damage is between the two longitudinal rails—accounts for 6.1% of all frontal crashes and has a higher injury risk than any other crash type studied. For completeness, Scullion's grouping of frontal crashes is illustrated in Figure 3.

The conclusions of the Padmanaban and Okabe [3] paper and the Scullion [6] paper seem to be in agreement. Looking at Figure 1, the frequency of between-rail crashes is about 6.1%, and it follows that frontal crashes with poles, posts or trees (a subset of between-rail collisions) are relatively infrequent compared to all frontal crashes. While between-rail crashes have a high injury risk of AIS ≥ 3 as shown in Figure 2, it would follow that narrow-object crashes would have a lower fatality rate (i.e., risk multiplied times frequency) because other frontal crashes occur with more frequency.

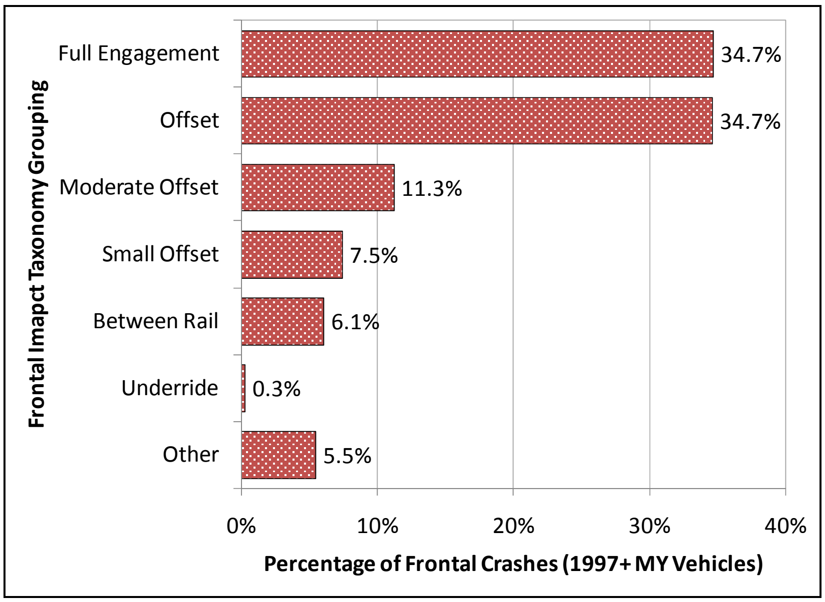


Figure 1. Distribution of 1997 and later model year frontal crashes for NASS-CDS 1997-2009 [6]

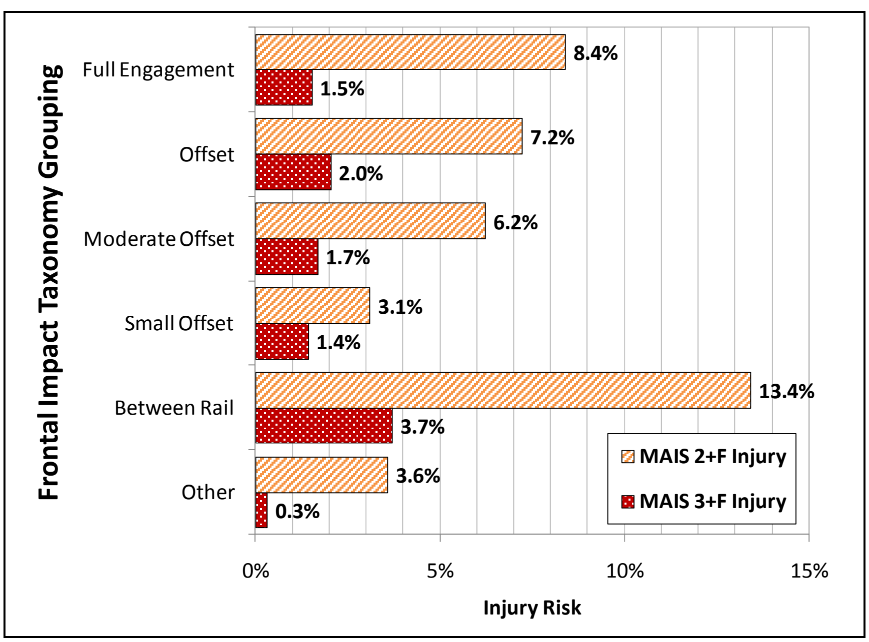


Figure 2. Front-row occupant injury risk in frontal crashes to 1997 and later model year vehicles for NASS-CDS

1997-2009 [6]

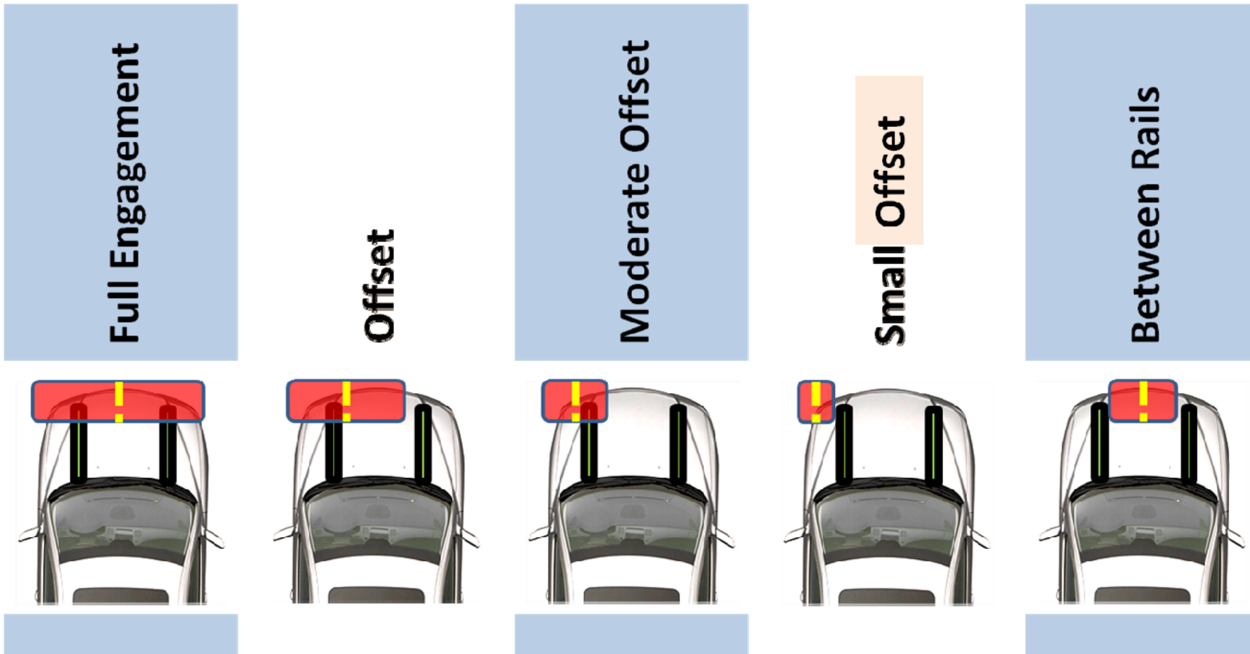


Figure 3 – Illustration of grouping of frontal crashes used by Scullion and based on direct damage recorded in NASS-CDS data [6]

Berg and Ahlgrimm [7] found that tree impacts are still one of the most important struck objects for road-way deaths in Germany. They observed that the federal statistics for 2008 in Germany reported that out of the total of 4,117 crashes with fatalities, 838 crashes (38%) were vehicle-to-tree impacts alongside the roadway. For impact of a tree into the side of a vehicle, they pointed out that EuroNCAP does a 29 km/h test into a fixed rigid pole of 254 mm diameter. Similarly, USA NCAP, ANCAP, and KNCAP do a test of a rigid pole into the side of a vehicle. Currently there is no consumer-information test for driving a pole into the front of a vehicle [8].

Greater intrusion into the occupant compartment has been used by the Insurance Institute for Highway Safety as an indicator of greater risk to the vehicle occupant. [9]–[10] In side impact crashes with children on the struck side, Scullion et al. [11] showed that larger intrusion into the occupant compartment was directly correlated with greater injury. Austin [12] examined frontal crashes for the NASS crash database from 1997 through 2009. He found that intrusion predicts lower extremity injuries for drivers even when controlling for crash severity.

For frontal crashes in which the struck object loads a smaller area of the vehicle, the ΔV estimate in NASS may be lower than the actual ΔV. Neihoff and Gabler found that WinSmash underestimated longitudinal ΔV by 29% for frontal overlap lower than 50% [13].

II. METHODS

US field data suggest that the between-rail frontal crash has a higher injury risk than either the full-engagement crash or the offset crash (see Figure 2). Assuming the field data are approximately correct, does a between-rail laboratory test exhibit a higher trauma risk than either the USA NCAP frontal laboratory test or the IIHS 40% offset frontal laboratory test? The first objective of this study will be to compare these three frontal impact tests based on (1) the injury risk predicted by the 50th percentile male Hybrid III dummy and (2) occupant compartment intrusion.

This study analyzed laboratory-based data for four different cars crashed in (1) NCAP frontal, (2) IIHS frontal and (3) between-rail frontal tests. The four sedans were the (1) 2006 Volkswagen Passat, (2) 2007 Toyota Camry, (3) 2007 Chevrolet Malibu and (4) 2007 Subaru Legacy. [14]–[15] Previously, these four sedans were all rated *good* by IIHS in the 40% offset frontal test. The set-up procedures for the NCAP rigid wall frontal test and the IIHS 40% offset frontal test are well described in the literature.

For their between-rail frontal test, IIHS tows a vehicle at high speed into a rigid pole. Based on NASS-CDS data, the entity struck in the between-rail frontal crash varies over many different objects. The struck object could involve a large tree, pole, or post (≥ 10 cm in diameter); another vehicle; a small tree, pole, or post (≤ 10 cm in diameter); a guardrail; a culvert; an animal; a building; and so on. The NASS-CDS data upholds that a large tree or post is the struck object in approximately 39 percent of all between-rail collisions.

To briefly describe the IIHS center pole test, the passenger vehicle is towed into a rigid steel pole of 25.4 cm (10 inch) diameter at 64 km/h (40 mph) with no offset from the vehicle centerline. Hybrid III 50th percentile male dummies are positioned in the driver seat and in the right-front-passenger seat. (While not discussed herein, IIHS also tested with a Hybrid III 5th percentile female dummy.) Both the driver and right-front-passenger dummy are restrained with the lap/shoulder belts fastened. Measures of intrusion into the driver and right-front-passenger compartment are taken after the crash. The dummies have standard crashworthiness instrumentation in the head, neck, chest, femur and ankle.

Experimental Testing

During the execution of twelve frontal crash tests (three types of tests times four different sedans), dynamic measurements were recorded in the Hybrid III 50th percentile male dummy. The purpose of the dynamic measurements is to be used in approximating the risk of trauma to the occupant. The dynamic signals from the dummies were used in five injury risk curves [16]-[17]-[18]-[19]. The equations for the injury risk curves used for this study are presented in the Appendix. The risk was calculated to five body regions: head, neck, thorax, knee-thigh-hip (KTH) and foot/ankle. Some researchers found the KTH equation underestimates the true real-world injury risk [20]-[21]-[22]. In an effort to develop an improved KTH criterion, one approach included an impulse variable in addition to the existing axial force variable. However, this new approach appeared to under-predict the real-world risk of belted drivers in crashes similar to NCAP-type frontal crashes [20]. Nevertheless, the authors of the present study used the KTH equation to assess the relative KTH risk in the three different crash types. In comparison to the other four body regions, assessing the risk of foot/ankle injury based on laboratory testing is a recent pursuit. Based on real-world crash data, one study found that the injury risk equation for the foot/ankle approximates the true AIS ≥ 2 traumas [23]. In the between-rail crash, the dummy’s leg nearer the vehicle centerline recorded a higher instrumentation reading than the leg farther away from the centerline.

Computational Modeling

The National Crash Analysis Center (NCAC) built (reverse engineered) a detailed, finite element model (FEM) of the model year 2001 Ford Taurus [24]. The FEM consists of 778 parts and 1,057,113 elements. The model was validated against actual laboratory crashes of the (1) NCAP full frontal rigid barrier test at 56 km/h, (2) IIHS 40% frontal offset deformable barrier test at 64.4 km/h and (3) the IIHS frontal center pole test at 64.4 km/h.

A simulation with the FEM was compared to a laboratory test of the 2002 Ford Taurus in the IIHS center pole test. The simulation showed a vehicle acceleration of over 40 G’s and occupant compartment intrusion that fell outside the *good* region. The FEM of the baseline Ford Taurus was redesigned to lower the vehicle acceleration and reduce the occupant compartment intrusion values to fall into the *good* region. The between-rail redesign was simulated in the NCAP frontal test and in the IIHS frontal 40% offset test to ensure that the redesign passed all the tests.

The acceleration pulse and force-versus-crush of the between-rail redesign vehicle were compared for all three test types.

III. RESULTS

Each bar in Figure 4 shows the average injury risk of the driver in four sedans, e.g., the sum of the four driver head risks in the cars divided by 4. For the head, the average injury risks for both the NCAP rigid barrier and the IIHS offset test are low, about 1%. The average head injury risk in the center pole test is almost 11%. The risks for the neck are very low, all less than 0.05%. The average chest risk in the center pole test is double the other two test types. The equation for the KTH underestimates the true risk, but the trend is that the KTH risk in the center pole test is roughly 4 ½ times the risk in the NCAP rigid wall and the IIHS 40% offset tests. Likewise the foot/ankle risk in the center pole test is roughly 4 ½ times the foot/ankle risk in the NCAP rigid wall and the IIHS 40% offset tests. The error bars in Figure 3 are at the 2 sigma (or 95%) level.

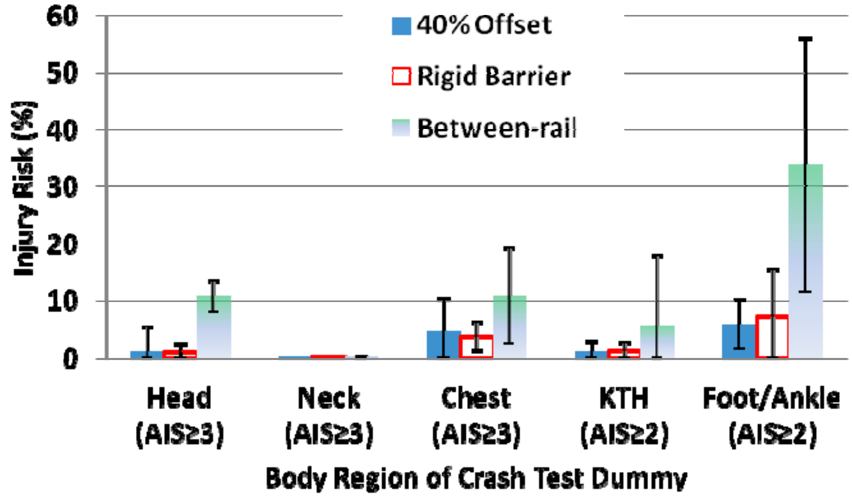


Figure 4. Average driver injury risk by body region for four sedans in three types of frontal tests

Each bar in Figure 5 shows the average injury risk of the right-front passenger in four sedans. The average head injury risk in the center pole test is almost nine times the average head risk of the passenger in the NCAP rigid wall test. The risks for the neck are very low, all less than 0.09%. The average chest risk in the center pole test is double the average chest risk in the NCAP rigid wall test. Again, the equation for the KTH underestimates the true risk, but the trend is that the KTH risk in the center pole test is roughly 1 ½ times the risk in the NCAP rigid wall test. The foot/ankle risk in the center pole test is roughly 3 times the foot/ankle risk in the NCAP rigid wall test. The error bars in Figure 4 are at the 2 sigma (or 95%) level.

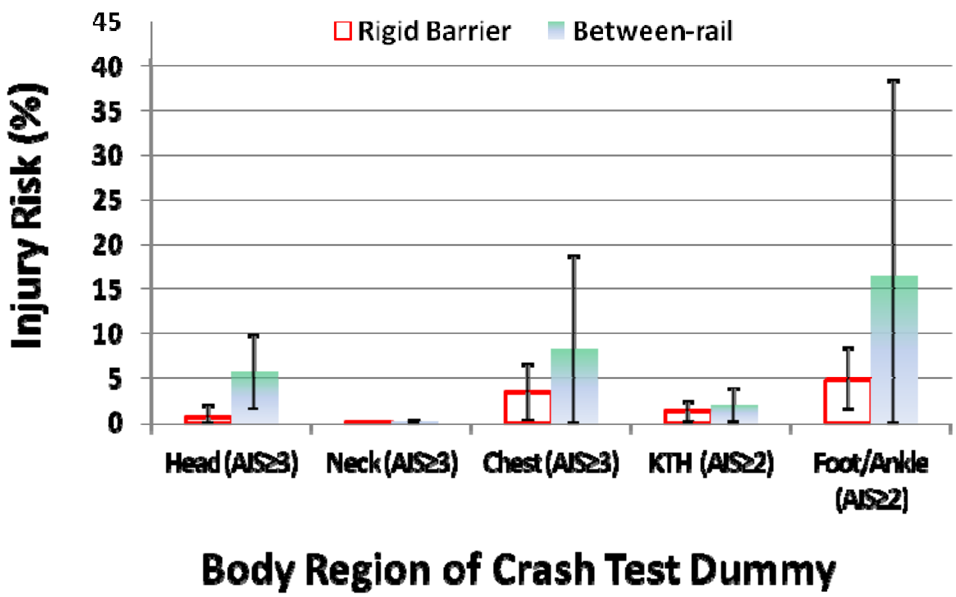


Figure 5. Average right front passenger injury risk by body region for four sedans in three types of frontal tests

To grasp the consequences of intrusion measurements into the occupant compartment, the reader needs to know where and how interior deformation was measured. For this study, the intrusion measurements followed the procedure of IIHS [9]. Intrusion represents the residual movement (pre-crash minus post-crash difference) of interior structures in front of the driver dummy. The movements of seven points on the vehicle interior contain the intrusion amounts. Two of the interior points are located on the lower instrument panel, in front of the dummy's knees; four points are in the footwell area, three across the toepan and one on the driver's outboard footrest; and the last point is on the brake pedal. The pre-crash and post-crash locations of these points are measured with respect to a coordinate system originating on a part of the vehicle that did not locally deform during the test. The measured travel of the interior seven points is adjusted to reflect movement toward the driver's seat.

Figure 6 is a plot of the maximum intrusion into the occupant compartment on the driver's side. The value of the maximum intrusion is overlaid on the rating scheme used by IIHS [9]. Each test type is represented by a unique symbol, e.g., a triangle for a between-rail test. All the NCAP rigid wall and IIHS 40% offset tests had maximum intrusions that fell in the *good* region. For the between-rail crashes, the intrusions farther from the vehicle center line fell in the *good* or *acceptable* region. The intrusion of the center toepan in the between-rail crash was in the *acceptable* region. The intrusion of the right toepan in the between-rail crash was in the *acceptable* and *marginal* regions. Considering all twelve laboratory tests, no intrusion was recorded in the *poor* region.

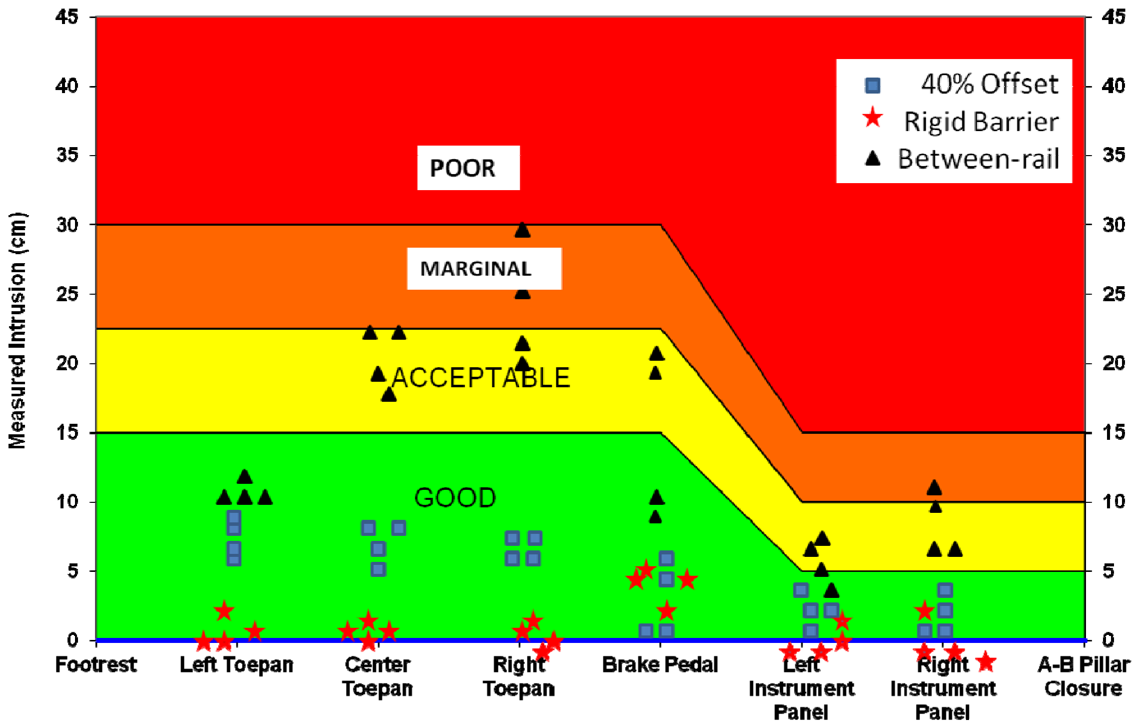


Figure 6. Driver side compartment intrusion in three types of frontal crashes overlaid on IIHS structural rating scheme [9]

Turning to FEM simulations, Figure 7 shows the intrusion in the laboratory test of the 2001 Ford Taurus and the FEM simulation of the baseline Ford Taurus. Both the actual test and the baseline simulation had center toepan intrusion and right toepan intrusion falling in the *acceptable* region. Also in Figure 7 are the results of a simulation of a *between-rail redesign* of the Ford Taurus. This redesign (of the 2001 Ford Taurus) reduced intrusion downward into the *good* region. The between-rail redesign was undertaken to assess the mass increase that would be required to improve safety in the between-rail crash.

As to the details of the between-rail redesign, the changes made to the baseline Ford Taurus are presented in Figure 8. The bumper, radiator support structure and forward beam of the sub-frame have been made stronger, and represent an increase in weight of 18.2 kg, a growth in overall Ford Taurus mass by about 1.2%. The between-rail redesign is a concept to estimate the weight increase associated with addressing the between-rail crash, and the authors did not study cost, manufacturability, alternate designs or other practical considerations.

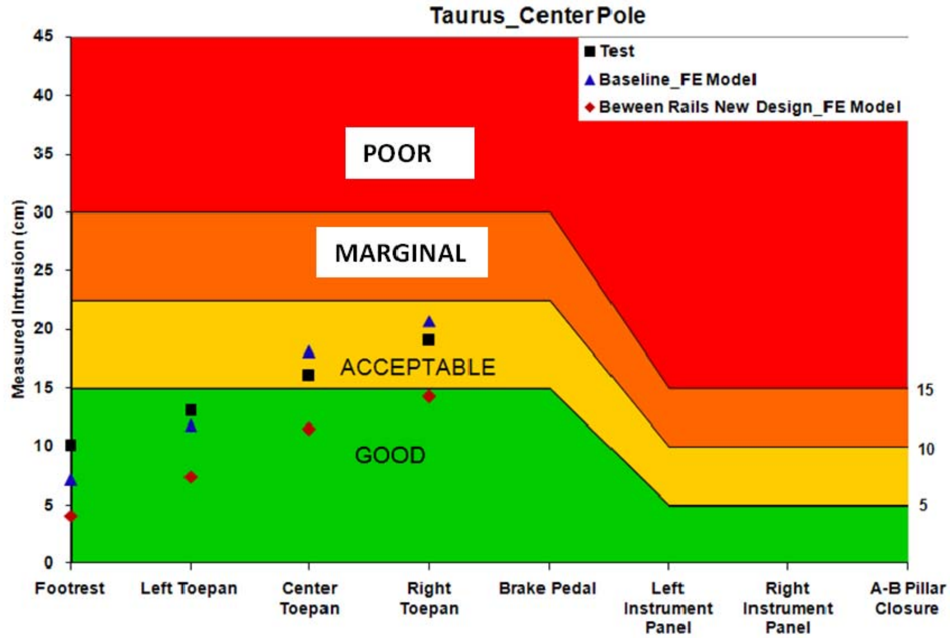


Figure 7. Driver side compartment intrusion of 2001 Ford Taurus in laboratory test and two FEM simulations

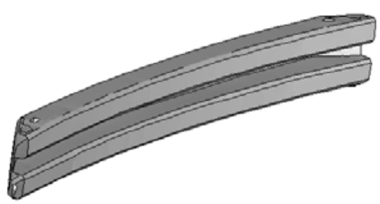
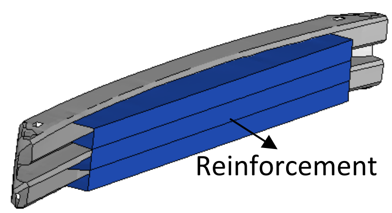
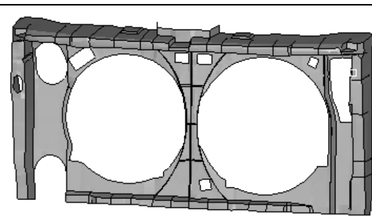
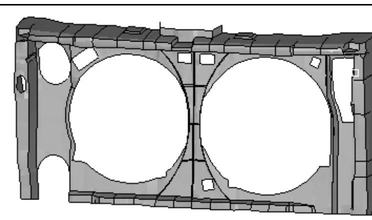
	Baseline Ford Taurus	Redesign of Ford Taurus for Between-Rails Crash	Weight Increase
Bumper (The redesigned piece was connected to the frontal rails by spot-weld)	 Steel: Yield Strength=800 MPa	 Steel: Yield Strength=800 MPa	3.6 kg
Radiator structure	 Plastic	 Steel: Yield Strength=300 MPa	14.6 kg
Lateral beam of Sub-frame	 Steel: Yield Strength=180 MPa	 Steel: Yield Strength=300 MPa	0 kg

Figure 8. Redesign of 2001 Ford Taurus to improve safety performance in IIHS center pole test

Figure 9 shows the acceleration pulse (average of the accelerometer at the left and right rear seats in the x-direction) for the baseline Ford Taurus and the between-rail redesign. The between-rail redesign reduced the acceleration by about 4 G's. The force-versus-crush (force was approximated by the vehicle mass times the vehicle acceleration) for the baseline Ford Taurus and the between-rail redesign is shown in Figure 10. The crush force of the redesign increased (over the baseline) during the initial crush and the total crush of the redesign was less than the baseline. Simulations of the between-rail redesign in the NCAP frontal test and the IIHS frontal offset test showed that the redesign performed the same as the Ford Taurus in the frontal laboratory tests, i.e., the between-rail redesign did not deteriorate safety performance in the two standard frontal tests.

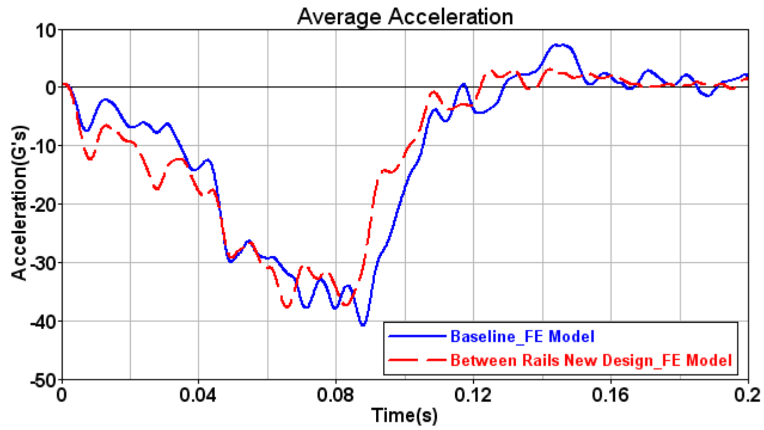


Figure 9. Comparison of between-rail-redesigned Ford Taurus acceleration to baseline Ford Taurus acceleration in center pole test

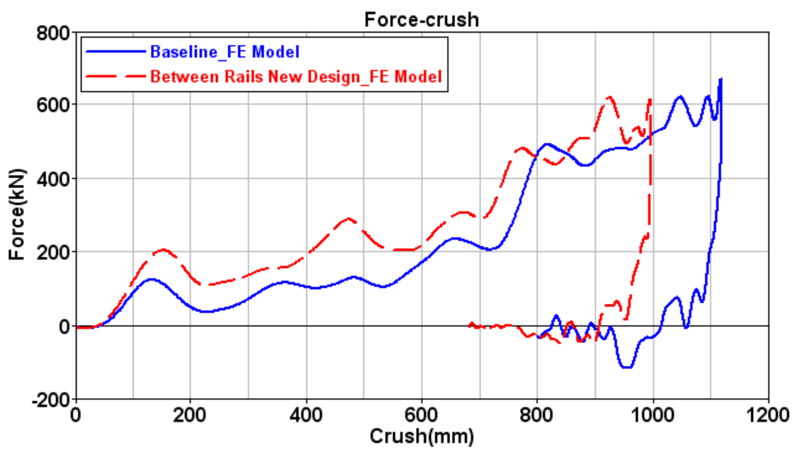


Figure 10. Comparison of between-rail-redesigned Ford Taurus force-versus-crush to baseline Ford Taurus Force-versus-crush in center pole test

The next two figures illustrate the dynamic behavior of the redesigned Ford Taurus in the three types of frontal tests. Figure 11 presents the acceleration pulse of the Ford Taurus with the between-rail redesign in the (1) NCAP frontal, (2) IIHS frontal and (3) between-rail frontal tests. The center pole test and the NCAP test have roughly the same pulse width. The IIHS offset test has a longer pulse width. The maximum acceleration of the center pole test is about 6 G's higher than the NCAP test. The IIHS offset test has a lower maximum acceleration. Figure 12 presents an estimation of the force-versus-crush of the three test types. In the IIHS offset test, the crush is the aggregate of the deformation of the deformable aluminum barrier and the deformation of the vehicle structure. Consequently, the IIHS offset test shows more crush in the diagram. During the initial onset of crush, the NCAP force level is greater than the center pole force level, which is greater than the force level of the IIHS offset test.

IV. DISCUSSION

Two research papers have studied US field data and found that the between-rail frontal collision has a higher risk of injury than other studied frontal crashes [2]-[6]. If these real-world crash analyses are valid, then laboratory crash tests should corroborate that the between-rail laboratory crash forecasts a higher level of injury than the injury predicted in the NCAP frontal and IIHS frontal tests. The authors assumed that the center pole frontal test approximates the attributes of the between-rail frontal crash. In comparing the injury risk prediction of the center pole test to the injury risk prediction of the NCAP frontal and IIHS frontal offset tests, the center pole test consistently forecasted a higher injury level, just as the field data suggested.

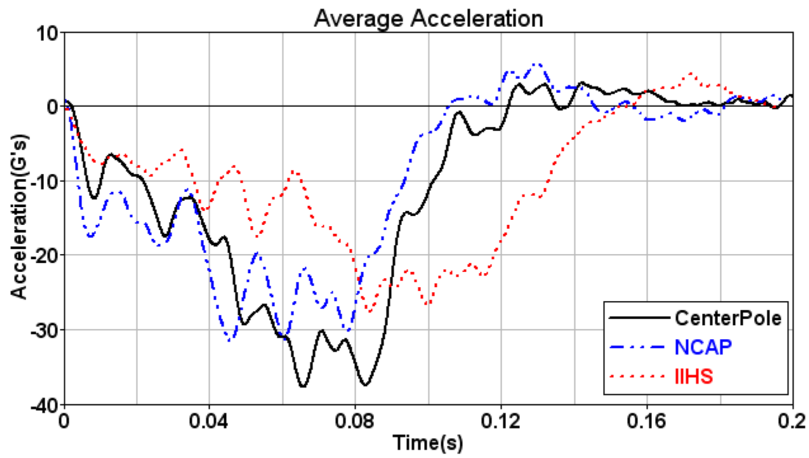


Figure 11. Vehicle acceleration for the between-rail-redesigned Ford Taurus in three frontal test types

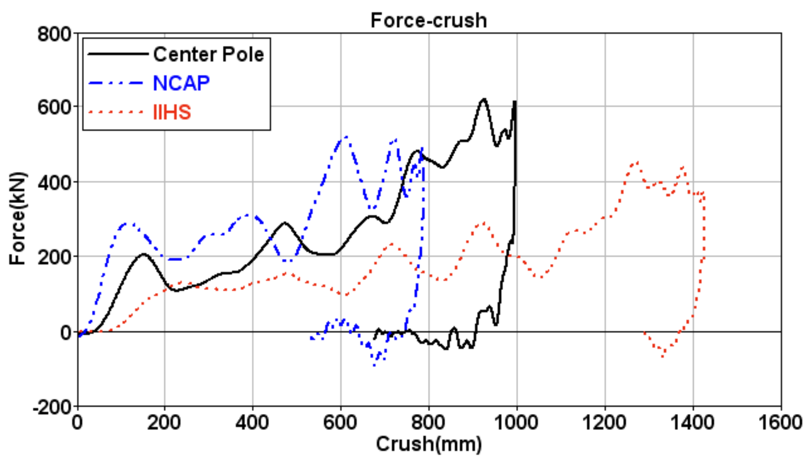


Figure 12. Vehicle force-versus-crush for the between-rail-redesigned Ford Taurus in three frontal test types

Likewise, the intrusion into the driver's compartment for the center pole test was generally greater than the intrusion into the driver's compartment for the NCAP frontal and IIHS frontal offset tests. The intrusion difference was especially true at the center toepan, right toepan, and right instrument panel where intrusion for the between-rail test was in or near the *marginal* region of the IIHS rating scheme. These findings—that laboratory injury risk and laboratory intrusion are higher in the IIHS center pole test—suggest that the previous results based on field data are significant.

The speed of the IIHS center pole laboratory impact is 64 km/h. This may be a limitation of the analysis herein because the NASS-CDS derived ΔV is prone to inaccuracy when applying WinSmash to a vehicle subjected to a small area of loading at the front. The determination of the best laboratory speed might be subject to further research. To the authors, the sedans undergoing the IIHS center pole test had an extent of damage [25] at the end of zone 5 and beginning to cross the threshold into zone 6, a pattern which is found in rear-world, between-rail crashes.

As explained in the Experimental Testing section, the KTH injury equation predicts a lower risk than found in field data. For example and based on field data, Kirk and Kuppa [20] found about 20 percent KTH risk for drivers in high-severity full-frontal crashes. They found the predicted risk using the KTH equation in NCAP laboratory tests to be about 5.2 percent. Similarly, Dalmotas et al. [21] found the knee-thigh-hip injury based on field data to be 14 percent for high-severity full-frontal crashes, but 4.9 percent based on the KTH equation in NCAP frontal tests. For NCAP-type crashes, Laituri et al. [22] found 20 percent risk based on NAS-CDS and 5 percent using the KTH injury equation. While the injury equation for KTH underestimates injury, the dummy's foot instrumentation (biaxial accelerometer array at the dummy's heel) identifies the high risk of foot/ankle trauma [23]. If using just the underestimating KTH injury curve to assess occupant trauma in a laboratory test, the design engineer might fail to detect the high propensity for lower extremity injury (AIS ≥ 2).

V. CONCLUSIONS

US field data suggests the between-rail frontal crash has a higher trauma risk than either the full-engagement or 40% offset crash. This study compared these three test types using four sedans that had been rated *good* by IIHS: (1) 2006 Volkswagen Passat, (2) 2007 Toyota Camry, (3) 2007 Chevrolet Malibu and (4) 2007 Subaru Legacy.

Based on the 50th percentile male Hybrid III dummy in the driver and right front passenger seats, injury risks were calculated for five body regions: head, neck, thorax, knee-thigh-hip (KTH), and foot/ankle. For the five body regions, the average injury risk in the center pole test was always larger than the average injury risk for the NCAP frontal test and the IIHS frontal test. Similarly, the driver compartment intrusion in the center pole test was larger than the intrusion in the NCAP frontal test and the IIHS frontal test.

The center pole laboratory tests indicate a high incidence of chest and lower extremity injuries. To a lesser extent, head injury is identified as a body region of concern. Dummy ankle/foot injury risk rates were approximated using a risk curve developed by Smith [17].

The societal benefit associated with designing countermeasures against the between-rail frontal crash is likely great. Assuming that the center pole test is a practical laboratory test representing the between-rail crash, a concept for a between-rail countermeasure for a 2001 Ford Taurus was designed (simulation). The between-rail redesign increased the mass of the Ford Taurus by 18.2 kg, an increase of the Ford Taurus mass by 1.2%, which could be a sizable societal cost.

VI. ACKNOWLEDGEMENT

The authors thank Chris Sherwood and David Aylor (IIHS) for their technical input and dialogue on the physics of the center pole frontal crash. While at George Washington University, Paul Scullion (Global Automakers) carried on constructive scientific discussions with the authors about the center pole impact.

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VIII. APPENDIX

The purpose of this appendix is to list the equations (biomechanical risk curves) used for the approximation of injury risk for each body region. The risks to the five body regions were calculated by:

Head Injury For the head, the authors used the injury curve proposed by NCAP [16]:

$$P_{head}\,(AIS \geq 3) = \Phi[(\ln(HIC_{15}) - 7.45231)/0.73998)],$$

where Φ = cumulative normal distribution (e.g., use NORMDIST(LN(cell),7.45231,0.73998,1) in Excel).

Neck Tension Assessing the neck, the authors used the tension risk curve proposed by NCAP [16]:

$$P_{neck}\,(AIS \geq 3) = 1/[1 + e^{(10.9745 - 2.375\,F)}],$$

where F = either axial tension or axial compression in kN.

Thorax Assessing the chest, the authors used the chest deformation risk curves proposed by NCAP [16]:

$$P_{chest}\,(AIS \geq 3) = [1 + \exp(12.597 - 0.05861{*}35 - 1.568\,\delta^{0.4612})]^{-1},$$

where δ is Hybrid III 50^{th}% male chest deflection (mm).

Knee-Thigh-Hip (KTH) Assessing the knee-thigh-hip region, the authors used curve proposed by NCAP [16]:

$$P_{KTH}\,(AIS \geq 2) = [1 + \exp(5.7949 - 0.5196\,F_{femur})]^{-1},$$

where F = femur force in kN.

Foot & Ankle Injuries Assessing the foot-ankle region, the authors used the forefoot injury criteria develop by Smith [17]-[18]-[19]:

$$P_{foot}\,(AIS \geq 2) = [1 + \exp(4.25 - 0.01169875\,A_{foot})]^{-1},$$

where A_{foot} = acceleration in G's.