FRONTAL CRASHES BETWEEN THE LONGITUDINAL RAILS

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ABSTRACT

The *objective* of this study is to further investigate the injuries and injury mechanisms associated with belted front-row occupants in *Between Rail* frontal crashes. This study examines *real-world crash data from the NASS-CDS* between the years 1998-2009 with a focus on frontal crashes involving 1997 and later model year vehicles. This study expands upon a *methodology* developed by Ford Motor Co. for classifying frontal impacts based upon the Collision Deformation Classification (CDC) [SAE J224] and the location of direct damage relative to the estimated location of the underlying vehicle frame-rail structure. This Frontal Impact Taxonomy will be used to identify those crashes with damage localized between the vehicle frame-rails. In a recent study, it was identified that *Between Rail* impacts had a higher risk of front row occupants sustaining either an MAIS 2+, or MAIS 3+ injury, compared to all other frontal impact damage classifications (Full engagement, Offset, Moderate offset, Small Overlap, and so on). The extent of damage will be used as a measure of impact severity. This study will investigate a laboratory test by the Insurance Institute for Highway Safety. This laboratory test involves crashing the front of a passenger vehicle into a rigid pole along the longitudinal line of the vehicle. The laboratory test will be compared with real-world crash data.

INTRODUCTION

Arbelaez et al. (2006) analyzed real-world crash data to suggest that frontal collisions with narrow objects contribute significantly to occupant fatalities and injuries. He found that the fatality rate for this type of crash was declining less quickly than other types of frontal crashes. Arbelaez proposed that safety professionals for government regulation and consumer information should study with more concern the frontal collision with narrow objects.

Sullivan et al. [2008] 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 Sullivan 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). The Ford study defined a *D, Y, Z No-Rail* crash. This classification involved direct damage to one of the larger frontal crash zones (SHL = D, Y, or Z; see SAE J224) and having none of the rails engaged. Sullivan reported that the *D, Y, Z No-Rail* crash had the highest risk of AIS ≥ 3 injury of any frontal crash type. The Ford paper did not specify that the stuck object had to be a narrow tree or pole, but did caution that some of the *D, Y, Z No-Rail* crashes involve a complex collision event.

Padmanaban and Okabe (2008) examined belted drivers of passenger vehicles in frontal crashes with narrow objects using US field data. As part of their study, they did a detailed examination of 400 NASS-CDS cases where the passenger vehicle impacts a narrow object in a frontal collision. Padmanaban and Okabe suggested that (1) frontal crashes with poles, posts, or trees are relatively infrequent and (2) the fatality risk is lower in narrow-object collisions than in other frontal crashes.

Hong et al. (2008) 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. The behavior of the frame rail was of key importance in understanding the structural behavior. It was found that the passenger vehicle well managed the full-frontal crash and 40% offset frontal crash 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. This study suggested the occupants in the *Between Rail* type of crash would

benefit by a transverse connection (or coupling) to the longitudinal frame rails.

At the IRCOBI Conference later in 2008, Hong et al. presented a step-by-step (and side by side) comparison of the (1) full-frontal impact, (2) 40% frontal offset impact, and (3) a center rigid pole impact. The graphical comparison (in 20-msec increments) illustrated the side rails crushed greatly in the full-frontal and the 40% offset crash. In the center pole impact, the pole misses the frame rails. While not shown in detail in the paper because of space limitation, compartment intrusion and dummy readings were high in the *Between Rail* type of crash.

The researchers of the Insurance Institute for Highway Safety (IIHS, 2009) 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. They had done center pole impacts with a 25.4-mm diameter pole in the laboratory. IIHS had concerns in matching the predicted injury risk from the laboratory tests with chest and abdominal trauma found in field data.

In 2010, Scullion et al. applied the Ford taxonomy (see Sullivan 2008) to classify real-world frontal-impact crashes based on the National Automotive Sampling System (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. The Scullion findings suggested that the *Between Rail* crash—where the direct damage is between the two longitudinal rails—accounts for (1) 5.7% of all frontal crashes and (2) has a higher injury risk than any other crash type studied.

METHODOLOGY

This study incorporated the use of real-world crash data from the NASS-CDS to further investigate occupant injuries in *Between Rail* frontal crashes. The following case selection criteria were applied to the NASS-CDS data:

- NASS-CDS data 1997-2009
- Passenger cars or Light Trucks and Vans
- Vehicle model years 1997+
- Vehicles with a General Area of Damage to the Front of the vehicle
- Vehicles with a Direction of Force of 11, 12, or 1 o'clock
- Vehicles with a secondary impact where the extent of damage was greater than 2 were excluded.

Sullivan Frontal Impact Taxonomy

As previously mentioned Sullivan et al. (2008) developed a Frontal Impact Taxonomy (FIT) as a method for classifying vehicle damage based upon the post-crash damage profile and estimated location of the underlying vehicle frame rail structure.

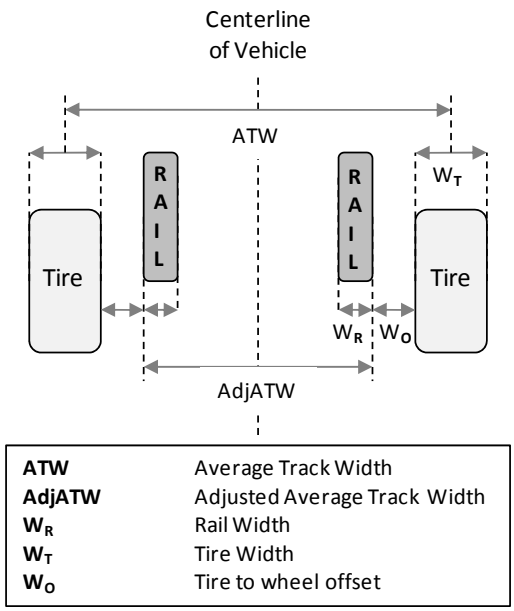

Figure 1. Estimated location of underlying vehicle structure (Sullivan, 2008).

In NASS-CDS there are no measurements that indicate the location of the vehicle frame rails relative to the centerline of the front-end of the vehicle. Sullivan used a sample of vehicles with known measurements to determine a ratio between the vehicle Average Track Width (ATW), which provided in NASS-CDS, and the width of the vehicle frame rails. The Adjusted Average Track Width (AdjATW) was calculated for both passenger cars and light trucks and vans (LTVs) using the formula shown in Equation 1.

$$\mathbf{AdjATW = ATW - WT - 2\ WO} \qquad \text{(Eq. 1).}$$

The AdjATW to ATW ratio was 0.7 for passenger cars and 0.6 for LTVs. The estimated location of the underlying frame rails for passenger cars in NASS-CDS was calculated using the formula shown in Equation 2.

Passenger Cars: **AdjATW = ATW * 0.7** (Eq. 2).
LTVs: **AdjATW = ATW * 0.6**

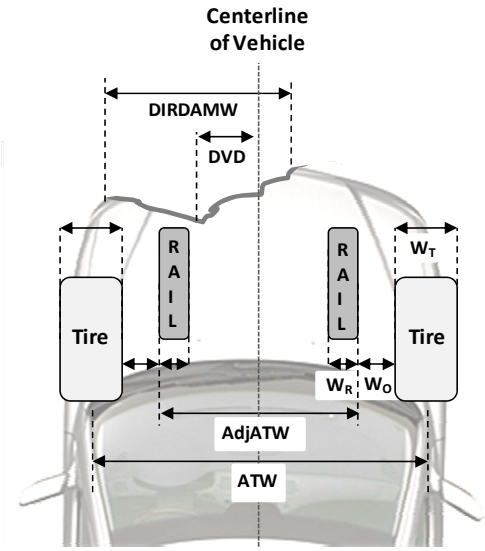

Figure 2. Direct damage location relative to estimated location of the underlying vehicle frame rails (Sullivan, 2008)

The Sullivan methodology is based upon the concept of classifying damage based on the engagement of the underlying frame-rail structure. In NASS-CDS the crash investigation report typically includes the direct damage width (DIRDAMW) as well as the location of the center of direct damage relative to the centerline of the vehicle (DVD). Assuming symmetry of the vehicle frame rails, if the location of direct damage was identified as having overlapped the location of a given frame rail, it was classified as having been engaged during the collision (Figure 2). Conversely, if the direct damage did not overlap the estimated location of a given frame rail it was classified as non-engaged.

In this study, the primary focus of analysis is on *Between Rail* crashes whereby it was determined that there was no rail engagement, with the direct damage located entirely between the vehicle frame rails.

The following additional selection criteria were applied to the data to ensure that vehicles could be classified based on post crash damage for the purpose of identifying *Between Rail* impacts in NASS-CDS:

- Known direct damage width
- Known direct and indirect damage width
- Known or non-missing average track width

The methods used in the Sullivan study were expanded to define a modified classification for frontal crashes designed to specifically address the *Between Rail* frontal crash. The taxonomy that was used in this study was comprised of seven distinct classification groups:

- Full Engagement
- Offset
- Moderate Offset
- Small Offset
- Between Rail
- Underride
- Other

RESULTS

Based on these NASS-CDS vehicle selection criteria, there were a total of 12,854 FIT classifiable vehicles (5,030,413 weighted) available for analysis. The graph in Figure 3 shows the distribution of frontal crashes by FIT classification. Further details of these classification groups are provided in Appendix A.

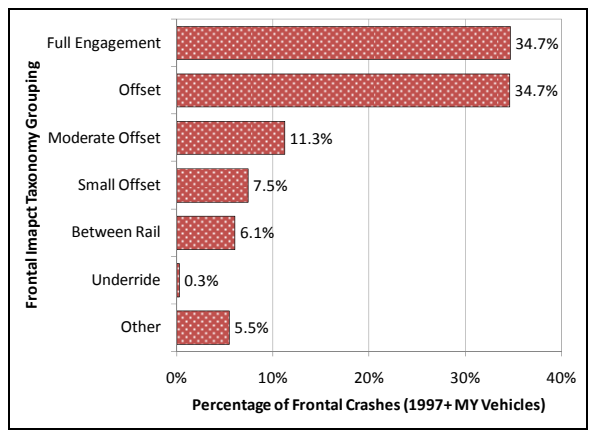

Figure 3. NASS-CDS 1997-2009 – Distribution of 1997+ MY Frontal Impact Taxonomy Classified Vehicles (weighted).

The highest distribution of frontal crashes involving 1997+ model year vehicles were attributable to *Full Engagement* and *Offset* crashes, in which each accounted for approximately 35% of the overall total. *Small Offset* crashes, where the direct damage occurred outside (with no engagement) of the vehicle frame rails were observed in 7.5% of frontal impact crashes (375,026).

Approximately one-in-twenty (6.1%) frontal crashes were classifiable as a being a *Between Rail* crash indicating that this type of impact damage is not an entirely uncommon occurrence with respect to frontal crashes occurring in the real-world.

Additional criteria were applied to the data for the analysis of occupant injury in 1997+ model year vehicles.

- Belted occupants aged 16 years old or older
- Occupants seated in the left-front (driver) or right-front (passenger) seat
- Vehicles were not involved in a rollover

Occupant injuries in NASS-CDS are recorded using the Abbreviated Injury Scale (AIS) developed by the Association for the Advancement of Automotive Medicine. This provides a measurement scale for assessing the severity of injuries to individual occupant body regions. This scale ranges from 1 (minor injury) to 6 (maximum injury). This analysis will provide crash injury data for both moderate or greater injuries (AIS 2+), and serious or greater injuries (AIS 3+). The highest severity injury sustained by an occupant is referred to as the Maximum AIS, or MAIS.

In Figure 4 the risk of MAIS 2+F and MAIS 3+F injuries to the nearside front-row occupant is displayed for each of the FIT groups.

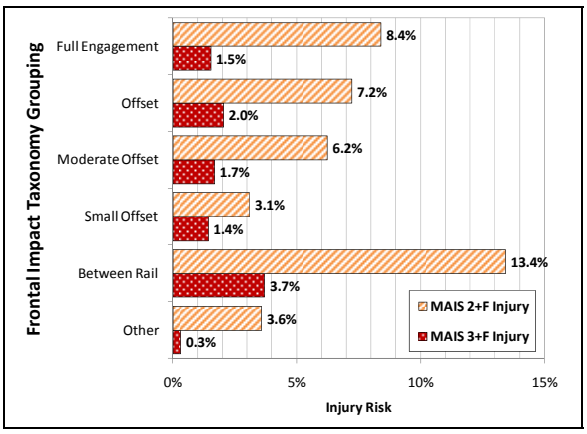

Figure 4. NASS-CDS 1997-2009 – Front row occupant injury risk in frontal impacts to 1997+ Model year vehicles (weighted).

The risk of an MAIS 2+ or MAIS 3+ injury was calculated by dividing the total number of injured occupants by the total number of front-seat occupants for each of the FIT groups. The risk of MAIS2+F and MAIS 3+F injury was greatest for those exposed to a Between Rails frontal crash compared to any other type of frontal crash, with risk values of 13.4% and 3.7% respectively. The risk of MAIS 3+F injury was similar among the Full Engagement, Offset, Moderate Offset, and Small Offset groups, with risks ranging between 1.4% and 2.0%. The weighted risk for underride crashes was not calculated due to small sample size.

The focus of this study is to assess the injuries associated with *Between Rail* frontal crashes. Based on the aforementioned case selection criteria there were a total of 903 occupants (274,458 weighted) in Between Rail frontal crashes that were available for analysis.

The Body Region AIS (BAIS) is the highest AIS severity injury sustained to each individual body region. Figure 5 show the weighted distribution of BAIS 2+ and BAIS 3+ injuries for each of the occupant involved in a *Between Rail* frontal crash.

The graph in Figure 5 provides an overview of the distribution of BAIS 2+ injuries in *Between Rail* frontal crashes. For the purposes of this study the following body regions were used in the classification of BAIS injuries: Head (including face), Neck (including C-Spine), Thorax, Abdomen, Spine (excluding C-Spine), Upper Extremity, Foot & Ankle, and Knee-Thigh-Hip (and other non-foot & ankle injuries).

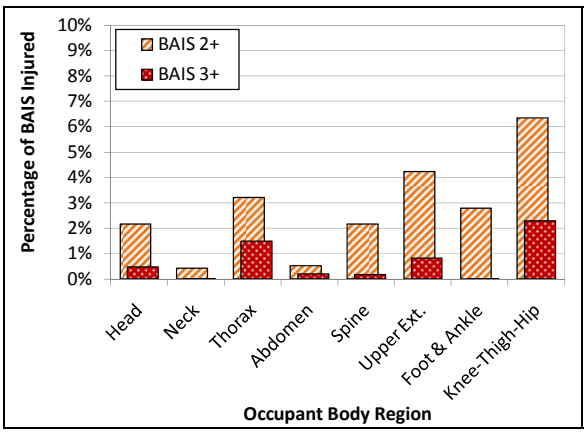

Figure 5. NASS-CDS 1997-2009 – Distribution of BAIS 2+ and BAIS 3+ Injured Occupants (weighted).

As well know in the safety community, the disability consequences of foot and ankle trauma can be severe. For example, Dischinger et al. (2005) found that 28% of patients with ankle/foot fractures in automotive collisions were unable to work one year post injury.

Parenteau et al. (1995) studied Swedish field data gathered by Folksam Insurance. She found that 76% of all the AIS = 2 or 3 foot-ankle injuries were produced in frontal car crashes. The graph in Figure 5 indicates that both BAIS 2+ and BAIS 3+ injuries for belted adult occupants in *Between Rail* crashes are strongly driven by trauma to the lower extremities.

IIHS Center Pole Frontal Impact Test Procedure

The authors considered the question of what sort of laboratory test might serve to represent the between rail frontal crash. One possible candidate is the center pole investigated by IIHS (IIHS Tech Data, 2011).

The Insurance Institute of Highway Safety crashed four recent passenger vehicles inducing direct damage between the longitudinal rails (Figure 6). Two Hybrid III 50th% dummies were positioned in the front-seat area. The test speed was 64-kph. The vehicles struck a rigid pole with a diameter of 25.4-centimeters.

Figure 6: IIHS Pole Impact Test Procedure – Test Number CF07003 (IIHS, 2011)

Assessing Injury Using Biomechanical Risk Curves

During the IIHS center pole tests, dynamic measurements were made in the Hybrid III dummies to approximate injury risk. The approximation of risk is done by using biomechanical risk curves for each body region. The risk to five body regions was calculated for:

<u>Head Injury</u> For the head, the authors used the injury curve proposed by NCAP (NHTSA 2008):

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

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

<u>Neck Tension</u> Assessing the neck, the authors used the tension risk curve proposed by NCAP (NHTSA 2008):

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

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

<u>Thorax</u> Assessing the chest, the authors used the chest deformation risk curves proposed by NCAP (NHTSA 2008):

$$P_{chest}\,(AIS \geq 3) = [1 + \exp(12.597 - 0.5861*35 - 1.568\,\delta^{0.4612})]^{-1},$$

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

<u>Knee-Thigh-Hip (KTH)</u> Assessing the knee-thigh-hip region, the authors used curve proposed by NCAP (NHTSA 2008):

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

where F = femur force in kN.

<u>Foot & Ankle Injuries</u> Assessing the foot-ankle region, the authors used the forefoot injury criteria develop by Smith (Smith 2003 and Murat 2007):

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

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

Comparison of IIHS Pole Impact Test Risks with Real-World Crash Data Risk

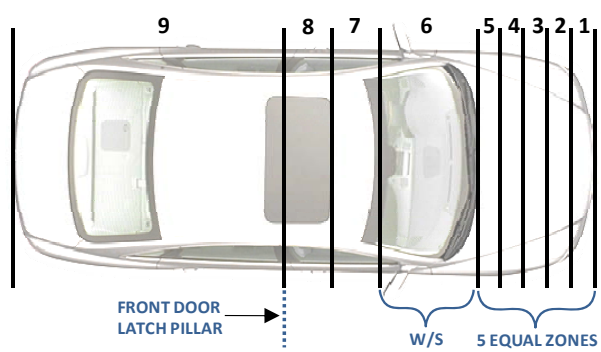

Figure 7. SAE Standard J224 – Extent of Damage

The diagram in Figure 7 provides an overview of the SAE Standard of classifying the extent of post-impact vehicle damage for crashes whereby the general area of damage was to the front of the vehicle. The vehicle is divided into nine cross-sections. The extent of damage classification is assigned based upon the vehicle cross-section where the highest residual deformation was observed to have extended.

Figure 8. IIHS Pole Impact Test CF07002 – Side and Oblique View of Post-Crash Damage (SAE J224 Extent of Damage – Zone 5) (IIHS).

The post-crash vehicle images in Figure 8 were provided by IIHS (2011). The graph in Figure 9 shows the results of logistic regression analysis of the weighted NASS-CDS data for *Between Rail* impacts by increasing extent of damage (as defined in SAE Standard J224). At an equivalent extent of damage observed to that of the IIHS frontal impact test (at the transition plane going from Zone 5 to Zone 6), the risk of sustaining an MAIS 2+F injury was 55.3% compared to 18.5% for an MAIS 3+F injury. As previously indicated, the injuries in the *Between Rail* frontal crash are primarily driven by the lower extremities. The risk of sustaining a BAIS 2+ injury is approximately 30% for the Knee-Thigh-Hip and 15% for the foot & ankle. The BAIS 3+ injury risk for chest injuries is over 7%, however the BAIS 3+ injury risks for the head, abdomen, and neck are all below 5%.

Table 1 provides a comparison of the occupant injury risks from the NASS-CDS *Between Rail* frontal impacts with those obtained from the series of IIHS pole tests. The injury risks for the head, neck, and chest are based on the risk of an AIS 3+ injury, and the KTH and foot & ankle injury are based on the risk of sustaining an AIS 2+ injury. The extent of damage for the vehicles tested in the IIHS test series approximately extended to the start of zone 6. The injury risks presented from the real-world data analysis include extent of damage zones between 4 and 6+.

The risk of sustaining a neck injury in the real world was found to be low (less than 1%) which agreed with the risks being predicted in the IIHS tests. The risk of average head injury risk was slightly over-predicted in the IIHS pole test compared to the risk observed in the real world. The risk of chest injury was similar for both the IIHS pole test and the real world when considering the risk of chest injury between Zone 5 and 6+. Using the Smith injury risk curves, a similar phenomenon was observed for injury risk for injuries sustained to the foot-ankle. The KTH risk derived from the IIHS pole test dummy readings indicated that the average risk was 3.7%. This was much lower than the injury risks observed in the real world that were found to range between 17.76% (extent 4) and 46.37% (extent 6+).

LIMITATIONS

Limitations of this study are that only vehicles with either (1) no secondary damage or (2) vehicles with the Extent of Damage for the secondary impact ≤ 2 were used for the analysis. This reduced the overall number of cases that were availble for analysis.

CONCLUSIONS

This study examined real-world crash data from the NASS-CDS between the years 1997-2009 with a focus on frontal crashes involving 1997 and later model year vehicles. It was found that *Between Rail* impacts had (1) a frequency of about 6.1% of all frontal crashes and (2) a higher risk of front row occupants sustaining either an MAIS ≥ 2, or MAIS ≥ 3 injury, compared to any other frontal impact studied.

In the NASS-CDS investigation of the *Between Rail* crash, a sample of 903 raw (un-weighted) crashes that corresponded to approximately 274,458 weighted crashes were investigated. While the *Between Rail* collision has the highest injury risk of any crash studied, the in-depth investigation suggests that this high risk may be due to exceeding numerous, lower-extremity trauma.

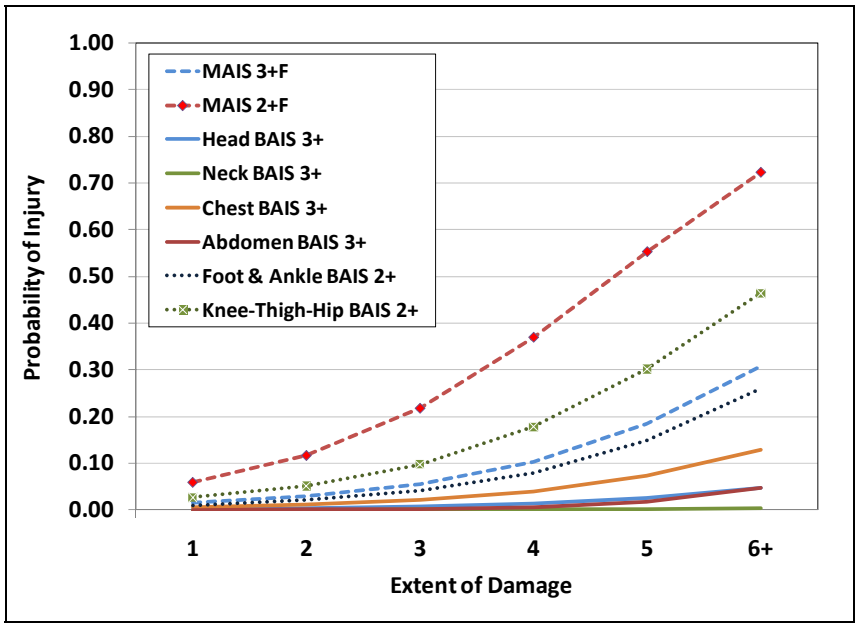

Figure 9. NASS-CDS 1997-2009 – Front Seat Occupant Injury Risk by Vehicle Extent of Damage (weighted).

Table 1.
Comparison of Injury Risks from NASS-CDS (weighted) and IIHS Center Pole Impacts

Body Region	Injury Rates (NASS-CDS)			Injury Rates IIHS Tests
	Extent of Damage 4	Extent of Damage 5	Extent of Damage 6	
Neck	0.09%	**0.18%**	0.38%	**0.14%**
Head	1.28%	**2.49%**	4.78%	**8.25%**
Chest	3.97%	**7.24%**	12.83%	**9.60%**
Foot-Ankle	7.92%	**14.82%**	26.03%	**25.50%**
KTH	17.76%	**30.17%**	46.37%	**3.70%**

The Insurance Institute of Highway Safety crashed four recent passenger vehicles inducing direct damage between the longitudinal rails. Two Hybrid III 50th% dummies were positioned in the front-seat area. The test speed was 64-kph. The vehicles struck a rigid pole with a diameter of 25.4-centimeters.

Using biomechanical risk curves to transform the dummy measure into injury risk, the IIHS center-pole laboratory test reasonably matched the field data, with one noteworthy exception. The exception is that the Knee-Thigh-Hip risk curves gave injury rates approximately one order of magnitude lower than the field data risk. Logically, the non-fidelity of the KTH risk curve and laboratory test combination would lead the safety community to bad design changes. The laboratory test would indicate a low risk for the lower extremities of the occupants. Consequently, the design engineer would fail to detect the high propensity for lower extremity trauma observed in the *Between Rail* field data.

While more research is needed to reconcile the wide difference between the KHT risk curve and the field data, this analysis suggests that other instrumentation in the laboratory test identifies the high risk of foot-ankle trauma. Using the risk curve developed by Smith (2003) and the bi-axial accelerometer on the foot of the Hybrid III dummy, ankle-foot injury risk rates approximate the field data although slightly higher. This finding suggests using both the existing KHT risk curve (until a better risk curve with fidelity is available) in combination with the foot-ankle risk curve. With the addition of the accelerometer instrumentation in the foot of the Hybrid III dummy, the authors suggest that a test along the design of the IIHS center-pole test might lead to design improvements for vehicle safety in the high-risk, *Between Rail* crash.

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APPENDICES

Appendix A

The following section provides an overview description of the selection criteria used to classify frontal impacted vehicles. All classified vehicles had a general area of damage to the front of the vehicle, known damage and average track width, and were not subsequently involved in a rollover. With the exception of the 'other' group, all vehicles had a direction of force of 11, 12, or 1 o'clock.

Full Engagement Both vehicle frame rails were engaged as the result of collision.

Offset One vehicle frame rail was engaged as the result of collision, with the center of direct damage located inside the outer edge of the vehicle frame rail.

Moderate Offset One vehicle frame rail was engaged, with the center of direct damage located outside the outer edge of the vehicle frame rail.

Small Offset No vehicle frame rail engagement as the result of collision, with direct damage located entirely outside of the vehicle frame rails.

Between Rail No vehicle frame rail engagement as the result of collision, with direct damage located entirely between the vehicle frame rails.

Underride Type of damage distribution classified as an overhanging structure, or a specific vertical location of damage at the belt line or above.

Other Vehicles that with a direction of force of 9, 10, 2, or 3 o'clock, or not otherwise classifiable based on the aforementioned criteria.

Appendix B

The purpose of this appendix is to summarize the basic Hybrid III 50th% dummy readings for the crash of four make/models into a pole centered at the front of the vehicle. The tests were conducted by IIHS and the data were provided by IIHS (IIHS TechData). The test speed was 64-kph, and the rigid pole had a diameter of 25.4 cm.

TABLE 2.
Summary of Hybrid III Dummy Readings in IIHS Center Pole Tests

Measure	2006 Volkswagen Passat		2007 Chevrolet Malibu		2007 Subaru Legacy		2007 Toyota Camry	
	Driver	Passenger	Driver	Passenger	Driver	Passenger	Driver	Passenger
HIC_{15}	696	473	729	566	700	466	638	614
Axial tension neck (N)	1800	1000	1900	2000	2000	1400	2200	1500
Axial compress neck (N)	800	1000	1000	300	1500	200	600	1500
Chest deformation (mm)	38	30	43	43	39	34	32	31
Femur left (kN)	1.3	4.3	3.4	4.1	5.7	1.4	2.6	3.8
Femur right (kN)	2.1	1.9	7.7	2.8	4.4	0.8	2.6	0.1
Foot left (G's)	92	241	125	139	128	166	88	294
Foot right (G's)	309	127	297	174	250	90	357	288

The laboratory-derived probabilities of trauma (AIS ≥ 2 for the KTH and ankle/foot and AIS ≥ 3 for other body regions) based on these Hybrid III 50th% dummy readings are listed in TABLE 3. All probabilities are in percent.

TABLE 3.
Summary of Injury Risk Based on Hybrid III Dummy Readings and Biomechanical Curves

Body Region	2006 Volkswagen Passat		2007 Chevrolet Malibu		2007 Subaru Legacy		2007 Toyota Camry	
	Driver	Passenger	Driver	Passenger	Driver	Passenger	Driver	Passenger
Head	11	4	6.6	12.2	11.2	3.9	9	8.1
Neck	0.12	0.02	0.2	0.16	0.2	0.05	0.32	0.06
Chest	10.4	4.7	16	16	11.4	7.1	5.8	5.2
KTH left	0.6	2.8	2.5	1.7	5.6	0.6	1.2	2.1
KTH right	0.9	0.8	1.3	14.3	2.9	0.5	1.2	0.3
Foot left	4	19.3	6.8	5.8	6	9	3.8	30.8
Foot right	34.6	5.93	9.8	31.5	21	3.9	48.2	29.3