CORRELATION OF VEHICLE AND ROADSIDE CRASH TEST INJURY CRITERIA

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ABSTRACT

The vehicle safety and roadside safety communities utilize full-scale crash tests to assess the potential for occupant injury during collision loadings. While the vehicle community uses instrumented full-scale crash test dummies (ATDs), the roadside community relies on the flail space model and the Acceleration Severity Index (ASI) models, which are based primarily on the deceleration of the test vehicle. Unfortunately, there has been little research relating the roadside injury criteria to those used in the vehicle community. This paper investigates the correlation of these differing metrics to gain insight to potential differences in threshold occupant risk levels in the roadside and vehicle safety communities.

Full-scale vehicle crash tests are analyzed to compare the flail space model and ASI to ATD-based injury criteria for different impact configurations, including frontal and frontal offset crash tests. The Head Injury Criterion (HIC), peak chest acceleration, peak chest deflection, and maximum femur force are each compared to the ASI, and flail space parameters. With respect to the vehicle crash test injury criteria, the occupant impact velocity and ASI are found to be conservative in the frontal collision mode. The occupant ridedown acceleration appears to have the strongest correlation to HIC while the ASI appears to have the strongest correlation to peak chest acceleration.

INTRODUCTION

Full-scale crash testing is the traditional method of evaluating both vehicles and roadside safety hardware. A critical part of these evaluations is the assessment of occupant risk potential. Although the basic goal is the same, the vehicle and roadside communities approach the assessment differently. The vehicle safety community has developed impact configuration-specific crash test dummies to serve as a surrogate for the human response. Due to the propensity for oblique collisions but a lack of mechanical test devices, the roadside safety community has developed occupant risk models, such as the flail space model and the Acceleration Severity Index (ASI), that utilize only the measured vehicle kinematics. Note that the roadside hardware occupant risk guidelines are set forth in NCHRP Report 350 [1] while the occupant risk procedures for vehicle crashworthiness are set forth in FMVSS 201 [2], FMVSS 208 [3], and FMVSS 214 [4].

Both the roadside and vehicle safety communities have attempted to link the respective criteria to the probability of actual occupant injury. Little is known, however, with respect to how these criteria relate to one other. As the update to NCHRP 350 is eminent, this issue is especially crucial to the roadside safety community.

OBJECTIVE

The purpose of this study is to compare roadside crash test injury criteria to vehicle crashworthiness test injury criteria utilizing full-scale crash test data.

BACKGROUND INFORMATION

Roadside Crash Test Injury Criteria

Flail Space Model Prior to the flail space model, a majority of the roadside occupant risk criteria were based simply on limiting the lateral and longitudinal vehicle accelerations during impact [5], [6]. In an attempt to better define the occupant risk criteria, Michie introduced the flail space concept in 1981 [7]. The model assumes that the occupant is an unrestrained point mass, which acts as a "free-missile" inside the occupant compartment. Prior to impacting the vehicle interior, the point-mass occupant is allowed to "flail" 0.6 meters in the longitudinal direction (parallel to the typical direction of vehicle travel) and 0.3 meters in the lateral direction. Measured vehicle kinematics are used to compute the difference in velocity between the occupant and occupant compartment at the instant the occupant has reached either 0.3 meter laterally or 0.6

meter longitudinally. For ease of computations, the vehicle yaw, pitch, and roll motions are ignored, all motion is assumed to be in the horizontal plane, and the lateral and longitudinal motions are assumed to be independent. At the instant of occupant impact, the largest difference in velocity (lateral and longitudinal directions are handled independently) is termed the occupant impact velocity (V_I). The occupant ridedown acceleration is the maximum 10 ms moving average of the accelerations subsequent to the occupant impact with the interior. Again, the lateral and longitudinal directions are handled separately producing two maximum occupant ridedown accelerations.

To ensure that the device does not create undo risk to the occupants of an impacting vehicle, the V_I and subsequent occupant ridedown acceleration are compared against established thresholds. Table 1 summarizes the current threshold values, as prescribed in NCHRP 350. Although values below the "preferred" are desirable, values below the "maximum" category are considered acceptable. Note that the "maximum" thresholds correspond to serious but not life-threatening occupant injury [7].

Table 1.

Current US Occupant Risk Threshold Values. [1]]

Occupant Impact Velocity Limits

Component Direction	Preferred Value	Maximum Value
Lateral and Longitudinal	9 m/s	12 m/s

Occupant Ridedown Acceleration Limits

Component Direction	Preferred Value	Maximum Value
Lateral and Longitudinal	15 g	20 g

European test procedures (CEN) utilize the flail space concept to compute the Theoretical Head Impact Velocity (THIV) and Post-Impact Head Deceleration (PHD), which are analogous to V_I and the occupant ridedown acceleration, respectively [8]. Unlike the NCHRP 350 version, the CEN version of the model utilizes the coupled equations of motion, includes vehicle yaw motion, and computes the resultant velocities and accelerations rather than resolving them into components. To ensure adequate occupant protection, the THIV and PHD are compared to established threshold values. The THIV threshold is 33 km/hr (~9 m/s), which corresponds to the "preferred" NCHRP 350 V_I value, while the PHD threshold is 20 g, equal to the "maximum" NCHRP 350 ridedown acceleration threshold.

The Acceleration Severity Index

Using measured vehicle acceleration information, CEN test procedures [8] indicate the ASI is computed using the following relationship:

$$ASI(t) = \left[\left(\frac{\bar{a}_x}{\hat{a}_x} \right)^2 + \left(\frac{\bar{a}_y}{\hat{a}_y} \right)^2 + \left(\frac{\bar{a}_z}{\hat{a}_z} \right)^2 \right]^{\frac{1}{2}}$$

where $\bar{a}_x$, $\bar{a}_y$, and $\bar{a}_z$ are the 50-ms average component vehicle accelerations and $\hat{a}_x$, $\hat{a}_y$, and $\hat{a}_z$ are corresponding threshold accelerations for each component direction. The threshold accelerations are 12 g, 9 g, and 10 g for the longitudinal (x), lateral (y), and vertical (z) directions, respectively. Since it utilizes only vehicle accelerations, the ASI inherently assumes that the occupant is continuously contacting the vehicle, which typically is achieved through the use of a seat belt. The maximum ASI value over the duration of the vehicle acceleration pulse provides a single measure of collision severity that is assumed to be proportional to occupant risk. To provide an assessment of occupant risk potential, the ASI value for a given collision acceleration pulse is compared to established threshold values. Although a maximum ASI value of 1.0 is recommended, a maximum ASI value of 1.4 is acceptable [8]. Note that if two of the three vehicular accelerations components are zero, the ASI will reach the recommended threshold of unity only when the third component reaches the corresponding limit acceleration. If more than one component is non-zero, however, the unity threshold can be attained when the components are less than their corresponding limits. According to the EN-1317 [8], the ASI preferred threshold corresponds to "light injury, if any". No corresponding injury level, however, is provided for the ASI maximum threshold.

Although the CEN procedures do not provide detail regarding the basis for ASI threshold values, the computation of the ASI is identical to the "severity index" proposed by researchers at Texas Transportation Institute investigating injury in slope-traversing events in the early 1970's [9]. The maximum threshold values proposed in the TTI study for the longitudinal, lateral, and vertical directions are shown in Table 2, based on the level of occupant restraint. Note that the "lap belt only" limits correspond to those utilized in the current version of the ASI. According to Chi [10], these limits are based principally on a military specification for upward ejection seats [11] and a study done by Hyde in the late 1960's [12]. Chi also notes that neither study provides any "supporting documentation or references" for the presented information.

Table 2.

Tolerable Acceleration Limits [9]

Restraint	Maximum Acceleration (G)		
	Longitudinal	Lateral	Vertical
Unrestrained	7	5	6
Lap Belt Only	12	9	10
Lap and Shoulder Belt	20	15	17

Vehicle Crashworthiness Injury Criteria

The Head Injury Criterion A refinement of the Gadd Severity Index [13], the Head Injury Criterion (HIC) was first defined in 1971 by Versace [14] as follows:

$$HIC = \max\left[\left[\frac{\int_{t_1}^{t_2} a(t)dt}{t_2 - t_1}\right]^{2.5}(t_2 - t_1)\right]$$

Where a(t) is the resultant linear acceleration time history (G's) of the center of gravity of the head, and t_1 and t_2 are two particular time values that maximize the above expression. Traditionally, the National Highway Traffic Safety Administration (NHTSA) has limited the separation between to t_1 and t_2 to no more than 36 milliseconds. Based on this separation, the maximum value for the HIC for an adult mid-size male anthropomorphic test dummy is 1000 [3]. Recent research completed by NHTSA in 2000, however, has led to the addition of a 15 millisecond HIC with a corresponding limit of 700 [15].

Chest Injury Criterion Several injury criteria have been developed to predict chest injuries in humans. Most notable perhaps is the viscous criterion developed by Viano and Lau [16] which is based on the assumption that a certain level of injury will occur if the product of the compression and rate of compression of the chest exceeds a particular limiting value. Currently, NHTSA mandates a variation of this idea that accounts for the chest compression as well as chest acceleration independently. For chest acceleration, NHTSA prescribes a maximum of 60 G's, except in cases where the duration of the peak is less than 3 ms (often referred to as simply the "3 ms Clip"). For chest deflection, a maximum value of 76 mm (3 inches) was previously prescribed. This criterion is based on a study by Neathery [17] that analyzed previous cadaver data to estimate that a 33% chest compression (or 76 mm in a 50th percentile male) would result in severe but not life threatening injury (AIS value of 3). In conjunction with the update to the HIC requirements, NHTSA reduced the maximum chest compression value to 63 mm (2.5 inches) [15].

Lower Extremity Injury Traditionally, lower extremity injury has focused on limiting the axial force in the femur. NHTSA requires that the peak force in each femur should not exceed 10 kN and 6.8 kN for the 50th percentile male and 5th percentile female crash test dummies, respectively [4]. A comprehensive study of femur impact test data, done by Morgan et al [18] found that the femur force is a good predictor of knee and upper leg injury and that the 10 kN threshold value corresponds to a 35 percent probability of fracture.

CORRELATION BETWEEN INJURY CRITERION

Despite a long history of injury criteria usage in both the roadside safety and vehicle safety communities, there has been only a relatively small amount of research aimed at establishing a correlation between the criteria. As a critical goal for both groups is to provide enhanced protection for the vehicle occupant, regardless of the collision type, an understanding of this link is advantageous to both parties.

As part of the development of the current roadside safety crash testing guidelines, Ray et al. [19],[20] investigated the correlation of the flail space model to the HIC. A total of 7 sled tests were performed using a 1979 Honda Civic body buck: 3 frontal impacts (25, 35, and 45 fps) using a 5th percentile female dummy and 4 side impacts (20, 30, 35, and 45 fps) using a 50th percentile side impact dummy (SID). Note that in both test types, the surrogate occupant was not restrained. For each sled test, the crash dummy response was compared to the respective flail space occupant risk value. A 40 fps (12 m/s) occupant impact velocity was estimated to coincide with HIC_{36} value of 1000 while an occupant impact velocity of 35 fps (10 m/s) appeared to coincide with a peak chest acceleration of 60 G's. With respect to the lateral flail space limits, the sled tests indicated that the roadside criteria may be overly conservative as a 25 fps (8 m/s) occupant impact velocity corresponded to a mild 316 HIC and a relatively low Thoracic Trauma Index (TTI) of 113 (16% probability of AIS 3 injury or greater). Note that the results from this study led to the subsequent increase in the lateral occupant impact velocity from 30 fps (9 m/s) to 40 m/s (12 m/s) in NCHRP Report 350.

More recently, Shojaati [21] correlated the ASI to risk of occupant injury via HIC. For nine lateral sled tests, the HIC determined from a Hybrid III dummy was plotted against the ASI as determined from the measured vehicle acceleration. The available data suggested an exponential relation between HIC and the ASI. Up to an ASI value of 1.0, Shojaati approximates that the value of the HIC is below 100. Likewise, ASI values of 1.5 to 2.0 are estimated to correlate to HIC values ranging between 350 and 1000.

APPROACH

The general approach of this portion of the analysis is to use full-scale vehicle crash tests, with reported vehicle injury criteria, and compute the roadside injury criteria based on the available vehicle kinematics information. For each selected full-scale crash test, the occupant impact velocity, occupant ridedown acceleration, and ASI values are computed for comparison purposes.

Case Selection Using the crash tests available from NHTSA, an attempt was made to select tests with varying impact speeds. A particular emphasis was placed on the frontal and frontal offset configurations due to the availability of these test types. Table 3 summarizes the data selected for analysis.

A total of 24 crash tests are evaluated which results in a total of 44 occupant responses (a number of tests have crash test dummies in the right and left front seats). Approximately fifty percent of the vehicles chosen are passenger cars while the remaining fifty percent are LTV type vehicles including pickup trucks, sport utility vehicles as well as full size vans and minivans. Although vehicle type would not be expected to have a large impact on any correlation between the criteria, an effort was made to choose tests with varied vehicle types. Also note that all tests utilized the Hybrid III 50th percentile male crash test dummy.

Table 3.

Summary of Selected NHTSA Crash Test Data

Test Speed/Type	Number of Tests	Occupant Responses	Restraint Status
25 MPH/ Frontal	4	8	Airbag Only
30 MPH/Frontal	4	8	Airbag Only
35 MPH/Frontal	12	24	Airbag and Belt
40 MPH/Frontal Offset (40%)	3	3	Airbag and Belt
40 MPH/Frontal	1	1	Airbag and Belt
Totals	24	44	

Flail Space Computations As the NHTSA full-scale crash tests provide measured vehicle kinematics analogous to those recorded in a roadside hardware crash test, the computation of the occupant impact velocity and occupant ridedown acceleration is identical to the procedures outlined in NCHRP Report 350 [1]. Accelerometer data was chosen as close to the vehicle center of gravity as possible to best describe the movement of the occupant compartment. Typically, utilized sensors included those attached to the vehicle rear floor pan, rear sill, or rear seat. The raw acceleration data from the selected channel is filtered using CFC 180 filter prior to integrating for velocity of position. Note that for the frontal offset tests that both the lateral and longitudinal vehicle accelerations are considered whereas the purely frontal collisions only consider longitudinal information.

ASI Computations For the frontal offset tests, the procedure for the ASI computations is identical to that outlined in both NCHRP Report 350 and the EN-1317 [8]. The same accelerometer channel used for the flail space computations is also used for the ASI computations. A slightly modified procedure is adopted for the computation of the ASI in the purely frontal tests since only information in the longitudinal direction is provided. For these cases, it is assumed that the lateral and vertical motions of the vehicle are negligible. The ASI relation then simplifies to the maximum 50 ms average acceleration over the duration of the pulse divided by the respective acceleration limit in the longitudinal direction (12 G).

RESULTS

Correlation of Roadside Criteria to HIC

Based on the analysis of the full-scale vehicle crash tests, the roadside criteria are plotted as a function of HIC. Figure 1, Figure 2 and Figure 3 show the occupant impact velocity, ASI, and occupant ridedown acceleration as a function of HIC, respectively. Each figure is divided by crash type: the "open" points represent full frontal collisions while the "closed" points represent the frontal offset crashes. Note that differing impact speeds for the full frontal collisions are signified through the use of differently shaped data points. For instance, the square points correspond to the 25 mph tests in the data set while the diamond-shaped points indicate the 30 mph tests.

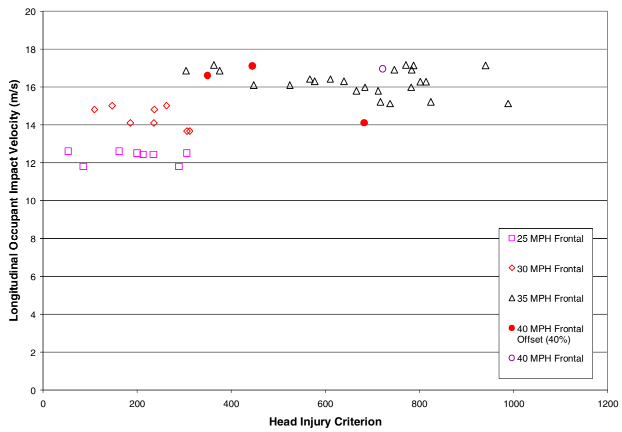

Figure 1. Occupant Impact Velocity and HIC

Especially evident in Figure 1 and Figure 2 is the relatively small variation in the roadside criteria occupant impact velocity and ASI) while there is a large variation of HIC. The range of occupant impact velocity is approximately 12 m/s to 17 m/s while the range of ASI values is approximately 1.4 to 2.35. Unlike the variation observed in these roadside criteria, the HIC ranges from 50 to approximately 1000; essentially a zero value to the current maximum threshold specified by NHTSA for a 36 millisecond time separation. As expected, this reinforces that the vehicle occupant risk criteria is much more dependent on the occupant restraints than the roadside criteria. It is also noteworthy to view these plots with respect to the threshold values. Essentially, all of the ASI values in Figure 2 are greater than the current prescribed maximum limit of 1.4. A similar observation can be gleaned from Figure 1 as all but 2 of the data points are in excess of the occupant impact velocity maximum threshold of 12 m/s. Although both of the roadside criteria indicate unacceptable levels of occupant risk, all HIC values in the plot fall below the maximum limit of 1000 suggesting that the ASI and occupant impact velocity may be conservative in comparison to HIC in the frontal collision mode.

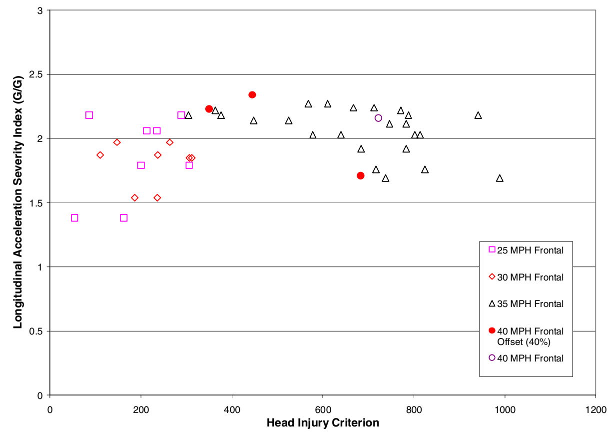

Figure 2. ASI and HIC

Unlike the occupant impact velocity and the ASI, however, the occupant ridedown acceleration appears to show evidence of a correlation to HIC. Although there is evidence of scatter in Figure 3, a trend of increasing occupant ridedown acceleration values is apparent as the value of HIC increases. More data points and statistical analysis would be necessary to quantify the level of correlation. Another interesting difference is the distribution of the points with respect to the corresponding threshold limits. Unlike the occupant impact velocity and ASI, all but one case is at or below the maximum occupant ridedown acceleration of 20 G.

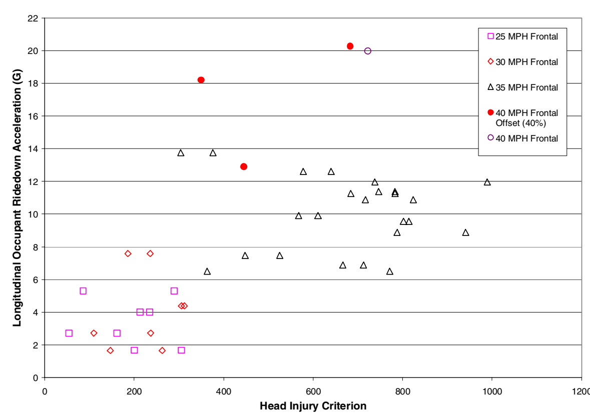

Figure 3. Occupant Ridedown Acceleration and HIC

Correlation of Roadside Criteria to Chest 3-ms Clip

Based on the analysis of the full-scale vehicle crash tests, the roadside criteria are plotted as a function of chest 3 millisecond clip. Figure 4, Figure 5, and Figure 6 show the occupant impact velocity, ASI and occupant ridedown acceleration as a function of chest 3 millisecond clip, respectively. Each figure is divided by crash type: the "open" points represent full frontal collisions while the "closed" points represent the frontal offset crashes. Again, note that the full frontal collisions use differing shapes to differentiate between the vehicle impact speeds.

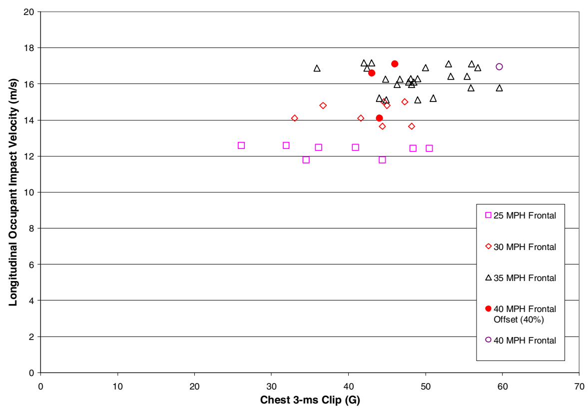

Figure 4. Occupant Impact Velocity and 3 ms Chest Clip

The obvious observation from this series of plots is the much smaller range of chest 3 ms clip values, especially in comparison to the analysis involving HIC. In Figure 4, the range of the occupant impact velocity remains between 12 and 18 m/s while the corresponding range for 3 ms clip is between 26 and 60. Although still a large range, in terms of percentage of the limiting value, it is about half of that observed in the HIC analysis. The same holds for Figure 5 involving the ASI. There does, however, appear a stronger relation between the ASI and chest 3 ms clip than evident in the occupant impact velocity data. Perhaps the ASI is more indicative of an occupant subjected to the damped accelerations of the vehicle caused by the interaction with the seat belt. With respect to the differences in occupant restraint systems, the smaller range of 3 ms clip values may suggest that this vehicle injury criterion is less sensitive to changes in the restraints. Again, however, it is interesting to note that both the occupant impact velocity and ASI are in excess of the current recommended maximum limits while all 3 ms clip values are below the recommended limit of 60 G.

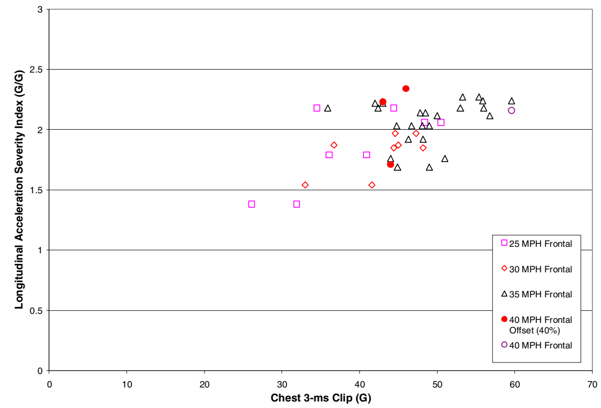

Figure 5. ASI and 3 ms Chest Clip

Although evidence of a correlation between the HIC and occupant ridedown acceleration is evident, Figure 6 appears to imply a weaker correlation to chest 3 ms clip. This may be a result of the timing of the ridedown acceleration. If the peak acceleration value occurs later in the collision when the dummy is interacting with the belt and bag system, vehicle accelerations will be transferred mechanically to the occupant. However, if the peak accelerations occur earlier in the collision before the occupant has taken up all the seatbelt slack, then the chest acceleration will not be directly influenced by the accelerations. The latter situation is more dependent on the relative speed of the occupant and vehicle when the occupant begins to load the restraint system. Based on the available data, the occupant ridedown acceleration appears to increase at a faster rate than the peak chest acceleration when the impact speed is increased. As with the HIC investigation, more data coupled with a statistical analysis would be necessary to determine the level of correlation.

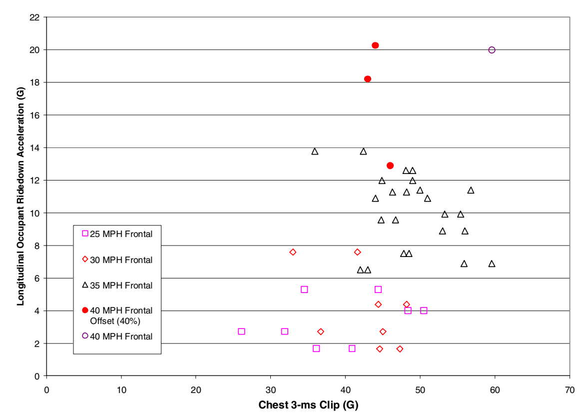

Figure 6. Occupant Ridedown Acceleration and 3 ms Chest Clip

Correlation of Roadside Criteria to Chest Deflection

Based on the analysis of the full-scale vehicle crash tests, the roadside criteria are plotted as a function of chest deflection. Figure 7, Figure 8, and Figure 9 show the occupant impact velocity, ASI, and occupant ridedown acceleration plotted as a function of chest deflection, respectively. Each figure is divided by crash type: the "open" points represent full frontal collisions while the "closed" points represent the frontal offset crashes. Again, note that the full frontal collisions use differing shapes to differentiate between the vehicle impact speeds.

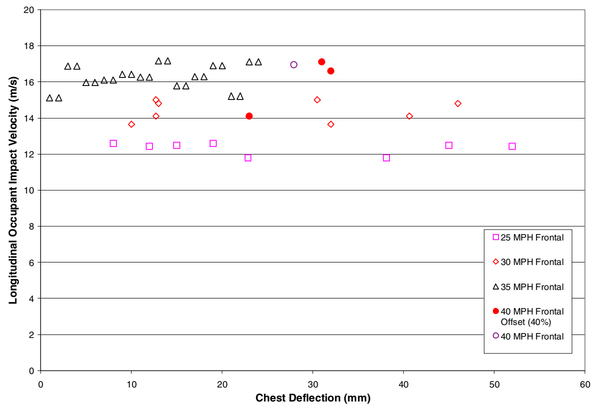

Figure 7. Occupant Impact Velocity and Chest Deflection

For the occupant impact velocity and ASI, the plots as a function of chest deflection exhibit the characteristics observed in the HIC plots. Both Figure 7 and Figure 8 indicate a large amount of variation in the chest deflection compared to a relatively small change occupant impact velocity and ASI, respectively. Likewise, all the chest deflection values are within acceptable FMVSS limits while a majority of the ASI and occupant impact velocity values exceed the currently prescribed thresholds.

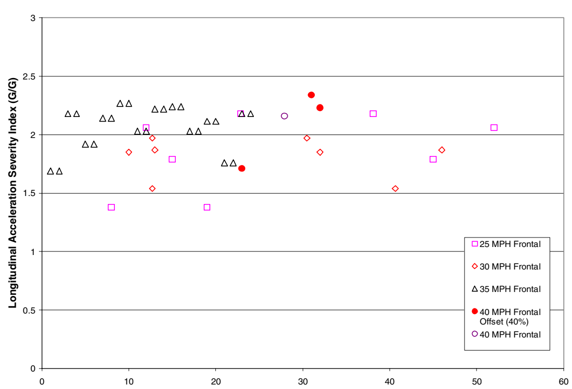

Figure 8. ASI and Chest Deflection

Based on Figure 9, there is no evidence of a strong correlation between the occupant ridedown acceleration and chest deflection. Again, the distribution of both criteria is analogous: approximately all the data points fall at or below the current threshold limits. The available data does appear to suggest a weak inverse relation between the ridedown acceleration and chest deflection. As expected, this suggests that the chest deflection criterion is a more crucial injury mechanism in lower speed collisions. Conversely, the weakly positive relation evident in Figure 6 suggests that the peak chest acceleration is the more significant criteria in higher speed collisions.

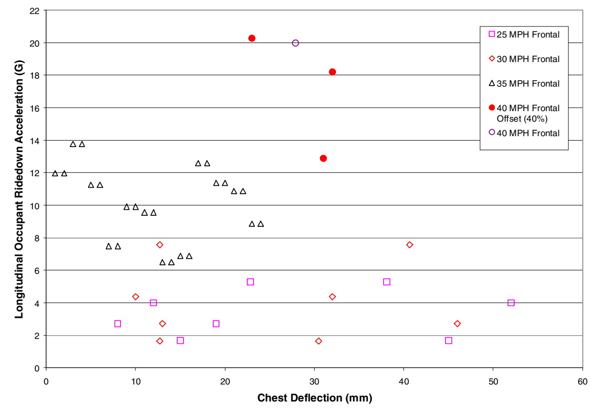

Figure 9. Occupant Ridedown Acceleration and Chest Deflection

Correlation of Roadside Criteria to Maximum Femur Force

Based on the analysis of the full-scale vehicle crash tests, the roadside criteria are plotted as a function of maximum femur force. Figure 10, Figure 11, and Figure 12 show the occupant impact velocity, ASI and occupant ridedown acceleration as a function of maximum femur force, respectively. Each figure is divided by crash type with the "open" points representing full frontal collisions and the "closed" points representing the frontal offset crashes. Again, the various data point shapes distinguish the differing impact speeds of the analyzed full frontal crash tests.

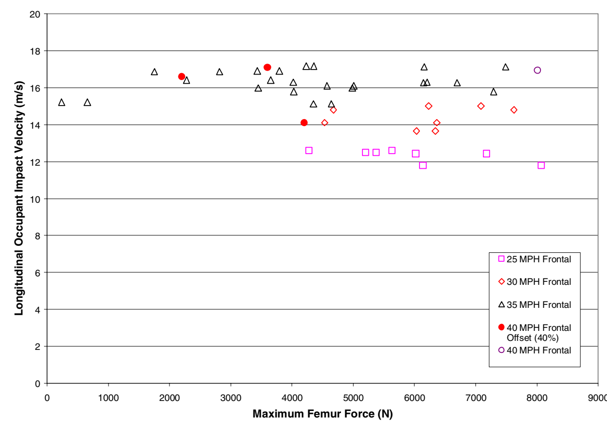

Figure 10. Occupant Impact Velocity and Maximum Femur Force

Figure 10 and Figure 11 demonstrate a scatter of the maximum femur force analogous to that observed in the HIC analysis. This variation may be due to the differences in vehicle structures (especially with respect to the toe pan area) for the chosen crash tests. Note the higher levels of femur force in the 25 and 30 mph crashes which is due to the unbelted crash test dummy. Again, the levels of the occupant impact velocity and ASI are in excess of the prescribed maximum values while the femur loads are within current NHTSA limits. The lack of correlation in Figure 11 is surprising due to the findings of Morgan et al [18] indicating a strong correlation of femur force to injury as well as the findings of Gabauer and Gabler [22] indicating a statistically significant correlation between ASI and low severity injury to the lower extremities.

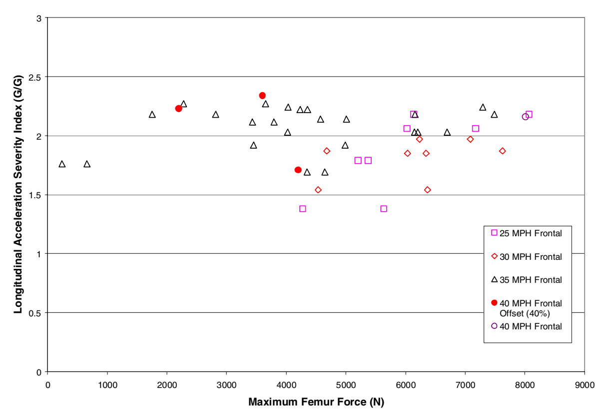

Figure 11. ASI and Maximum Femur Force

Consistent with the chest deflection plots, the occupant ridedown acceleration appears to have a negative correlation to the maximum femur force. This is more evident in Figure 12 than in Figure 9. Additional data coupled with a statistical analysis, however, would be needed to confirm this correlation. As with the chest deflection, note the higher femur forces in the lower speed frontal impact tests, presumably due to the unrestrained surrogate occupant.

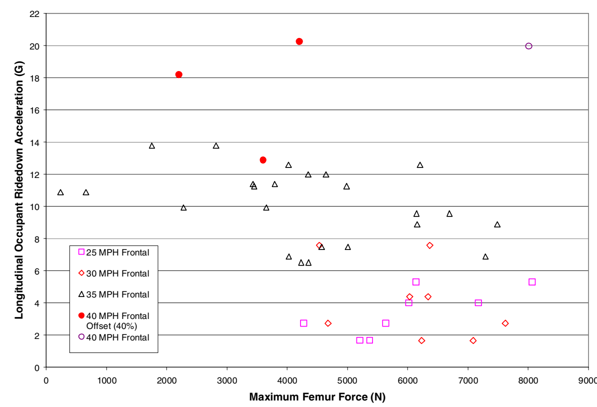

Figure 12. Occupant Ridedown Acceleration and Maximum Femur Force

CONCLUSIONS

The following conclusions can be drawn from the available data:

1. HIC and chest deflection appear severely dependent on the vehicle's restraint system. This is especially evident when comparing these criteria to the occupant impact velocity and the ASI.
2. The occupant ridedown acceleration appears to have the strongest correlation to HIC of the three examined roadside injury criteria.
3. The ASI appears to have the strongest correlation to the maximum chest acceleration of the three examined roadside injury criteria.
4. With respect to vehicle crash test injury criteria, the occupant impact velocity and ASI appear conservative in the frontal collision mode.

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