A COMPARISON OF ROADSIDE CRASH TEST OCCUPANT RISK CRITERIA USING EVENT DATA RECORDER TECHNOLOGY

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ABSTRACT

Full-scale crash tests involving roadside safety hardware utilize the flail space model and Acceleration Severity Index (ASI) injury criteria to assess the potential for occupant injury. Little is known, however, regarding the correlation of these criteria to actual occupant injury. Event Data Recorders (EDRs) are a new technology capable of recording vehicle kinematics during a collision. Using EDR data, the effectiveness of the flail space model and ASI are compared in terms of maximum injury, head injury and thoracic/abdominal injury.

KEYWORDS: Injury Criteria, Event Data Recorders, Roadside Safety, Flail Space Model, Acceleration Severity Index

FULL-SCALE CRASH TESTING has been the traditional method used to evaluate roadside safety hardware. Roadside safety hardware refers to devices installed near or on a roadway intended to provide a forgiving roadside environment should a vehicle depart from the roadway. The goal of crash testing procedures is to evaluate hardware performance in representative worst-case impact scenarios. Although there are minor differences between US and European procedures, both test protocols evaluate devices based on vehicle behavior, the response of the device, and the potential for injury to vehicle occupants. The US procedures are prescribed in NCHRP Report 350 (Ross et al., 1993), while the European procedures are presented in EN-1317 (CEN, 1998).

Because the goal of roadside hardware is to perform its intended task while minimizing injury to vehicle occupants, the assessment of occupant risk is crucial to the full-scale crash test evaluation of these devices. Unlike vehicle crashworthiness testing, crash tests of roadside safety devices do not use a crash test dummy. Roadside hardware collisions typically involve an oblique impact of a vehicle into a structure such as a guardrail. To date, no crash test dummies have been developed to simulate the human response to oblique crash loadings. Instead, the occupant risk is based on metrics derived from vehicle kinematics measured during the crash test. Since 1981, the US procedures have calculated occupant risk with the flail space model. The European procedures use a variation of this model in conjunction with the Acceleration Severity Index (ASI) to assess occupant injury risk.

OBJECTIVE

The purpose of this study is to evaluate the injury predicting capabilities of flail space model and the ASI using Event Data Recorder (EDR) technology.

OCCUPANT RISK CRITERIA

FLAIL SPACE MODEL: Prior to the flail space model, a majority of the roadside occupant risk criteria were based on limiting the lateral and longitudinal vehicle accelerations during impact (Bronstad & Michie, 1974; TRC 191, 1978). In an attempt to better define the occupant risk criteria, Michie introduced the flail space concept (1981). 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 (Michie, 1981).

Table 1 Current US Occupant Risk Threshold Values (Ross et al., 1993)

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 (CEN, 1998). 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.

ACCELERATION SEVERITY INDEX: The CEN procedures use the Acceleration Severity Index (ASI) in conjunction with a variation of the flail space model to evaluate occupant risk in full-scale crash tests. Using measured vehicle acceleration information, the ASI is computed using the following relation:

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

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 values are 12 g, 9 g, and 10 g for the longitudinal (x), lateral (y), and vertical (z) directions, respectively. Since it utilizes only the vehicle accelerations, the ASI inherently assumes that 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. Like the flail space model, threshold values are used to evaluate excessive injury risk. Although a maximum ASI value of 1.0 is recommended, a maximum ASI value of 1.4 is acceptable. 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. In contrast to the flail space model, the ASI preferred threshold corresponds to "light occupant injury, if any" (CEN, 1998).

LINK TO OCCUPANT INJURY

Although the flail space model and ASI are used to indicate occupant injury potential, there has been little research to date characterizing either model's relationship to occupant injury. Previous research has utilized real-world accident data since the occupant injury information is available. Because real-world accident data lacks detailed vehicle kinematics data, however, the correlation to occupant injury remains tenuous at best. Since decisions to accept or reject roadside safety hardware are partially based on these criteria, there is a strong motivation to ensure the accuracy of these models.

With respect to the US flail space model, two studies attempted to define a correlation to occupant injury. Ray et al. (1986) investigated the occupant injury mechanisms in longitudinal barrier collisions. The effort focused particularly on the lateral occupant impact velocity since a series of side impact sled tests, performed as part of the study, indicated that the current threshold might be overly conservative. By reconstructing seventeen longitudinal barrier accidents that produced severe occupant injury, the authors found that the lateral component of the first impact was not the cause of the serious injury in any case. A significant conclusion of this study is that the flail space model, although a useful tool for the estimation of occupant risk, does not appear to be a discerning factor in redirectional crash tests. A more recent study by Stewart and Council (1993) utilized accident data in an attempt to link occupant risk (as calculated in crash tests) to actual injury attained in collisions. The procedure matched instrumented full-scale crash tests with similar vehicle characteristics (make, model and year), crash characteristics (object struck, impact location on vehicle, etc.), and crash severity (as measured by vehicle deformation) in actual crashes. With regard to the flail space model, the limited data sample prevented any conclusions.

Regarding the CEN procedures, no studies have been found relating the modified version of the flail space model to occupant injury. Shojaati (2003) attempted to correlate the ASI to risk of occupant injury via the Head Injury Criterion (HIC), a metric used by NHTSA to assess head injury potential. 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 but did not provide a direct correlation to occupant injury.

NEED FOR ROADSIDE INJURY CRITERIA REASSESSMENT

The flail space model was intended to model an unrestrained occupant. At the inception of the model in 1981, belt usage rates in the US were approximately 15% and use of airbags was not widespread. Today, however, US belt usage rates exceed 60% and driver and passenger airbags are required equipment on all new passenger cars. In addition, belt usage rates have been historically much higher in Europe than in the US. The longitudinal V_I threshold values are based principally on two studies involving head impact experiments into windshields (Kay et al., 1973 and Begeman et al., 1978). In the current vehicle fleet, however, head impact with the airbag is more likely than head impact with the windshield in frontal collisions. Are the longitudinal V_I thresholds now overly conservative? More importantly, is the unrestrained occupant assumption still valid despite the presence of airbags and changes in seat belt use? The investigations of both Ray et al. (1986) and Stewart and Council (1993) were performed on a predominantly non-airbag-equipped vehicle fleet

and were unable address this issue. Also, these studies lacked vehicle kinematics information for the real-world collisions, which is crucial to the computation of the flail space criteria.

Considering these changes in the vehicle fleet, the ASI may be a more suitable predictor of occupant injury risk since it simulates a restrained occupant subjected to accelerations similar to that of the vehicle. This simplified metric is very similar to the pre-flail space model occupant risk criteria, however, and may not be the optimal method of evaluating occupant risk. An evaluation of the injury predicting capabilities of the ASI and flail space model is needed for airbag-restrained occupants to determine the applicability of these metrics to the current vehicle fleet. A better understanding of how these metrics relate to each other as well as to occupant injury is required to develop improved procedures to evaluate occupant risk.

EDR TECHNOLOGY

Previous investigations attempting to relate occupant risk criteria to injury have lacked the detailed vehicle kinematics information recorded in full-scale crash tests. Recent advances in vehicle technology, however, have allowed for an unprecedented opportunity to obtain information during a highway traffic collision. One such technology is Event Data Recorders (EDRs), which are being installed in numerous late model vehicles in conjunction with the advanced occupant safety systems. EDRs are similar to "black boxes" in airplanes as they record information in the event of a highway collision. Information typically stored by these manufacturer-specific devices includes seat belt status, airbag deployment status, and vehicle speed prior to impact (NHTSA, 2001). Of particular interest to this study is the EDRs ability to record the vehicle velocity profile during a collision event.

Under sponsorship of the National Highway Traffic Safety Administration (NHTSA), Rowan University is developing a first-of-a-kind database of EDR data collected from traffic collisions in the United States (Gabler et al., 2004). Currently, the database consists of EDR data for over five hundred (500) cases, all of which are GM vehicles. These EDRs have the ability to store a description of both the crash and pre-crash phase of a collision. The crash parameters in the database include longitudinal velocity vs. time during the impact at 10 ms intervals, airbag trigger times, and seat belt status for the driver. Pre-crash data includes vehicle speed prior to impact, engine throttle position as well as brake status for five seconds preceding the impact. As these cases were collected in conjunction with National Automotive Sampling System (NASS) studies, the corresponding NASS information is matched to the EDR data. NASS case investigators collect in-depth information about each crash including details regarding injury to the occupants.

METHODOLOGY

OVERALL APPROACH AND CASE SELECTION: The overall methodology of this study is to use the EDR velocity information to compute the occupant risk criteria metric values for suitable real-world collisions and compare the prediction to the injury attained by the vehicle occupants. Only cases adhering to the following criteria were included in the analysis:

1. Airbag deployment
2. Known occupant injury for either left or right front seat occupant
3. Comprised of a single event
4. Frontal collision with no vehicle rollover

Limiting suitable cases to those involving airbag deployment ensures higher severity collisions and addresses the implications of airbag-restrained occupants to the validity of the current criteria. EDR velocity information is required to compute the occupant risk criteria. An additional stipulation is that the velocity information is "complete", or converges to a constant velocity, so that the ASI computation is not erroneous. Reduction of the data set to include only single impact collisions ensures that the EDR velocity data corresponds to the injury-producing event. As the GM EDR only measures velocity information in the longitudinal direction, the data set has been constrained to frontal collisions only. A frontal collision, for the purpose of this study, is defined as

damage to the front of the vehicle and a principal direction of force (PDOF) of 0 degrees plus or minus 10 degrees in either direction. An intrinsic requirement of flail space model is that the vehicle remains upright; thus, vehicle rollover is not permitted. Although the flail space model and the ASI are utilized for roadside hardware collisions, the data set includes both vehicle-to-fixed object collisions (26%) as well as vehicle-to-vehicle collisions (74%). Any correlations of these metrics to occupant injury should be evident regardless of the object struck.

A total of 69 cases have been identified as suitable for analysis; 55 left front seat occupant cases and 14 right front seat occupant cases. Note that there is potential overlap in the available cases. For instance, one vehicle may have injury information for both left and right front seat occupants, resulting in two suitable cases for analysis.

FLAIL SPACE MODEL COMPUTATIONS: The following procedure was used to calculate the longitudinal occupant impact velocity for the suitable cases in the database:

1. Convert longitudinal EDR relative velocity data to metric units (m/s) and numerically integrate to obtain occupant relative position as a function of time.
2. Interpolate to determine the time at which the occupant impacts the interior (relative distance = 0.6 meters).
3. Use the occupant impact time and the EDR relative velocity data to obtain the longitudinal V_I.
4. For cases where the theoretical occupant does not exceed the longitudinal flail space limit, first check that the EDR velocity information is "complete" or converges to a constant velocity. If "complete", set V_I to the maximum velocity change of the vehicle.

For cases where the occupant does not reach the flail space limit, NCHRP 350 specifies that V_I should be set equal to the vehicle's change in velocity that occurs during contact with the test article. The maximum overall change in vehicle velocity (recorded by the EDR) is used to provide an estimate of this quantity in these cases. A "complete" pulse ensures that EDR vehicle velocity change includes spans the event. A total of 11 of the 69 cases fall into this category, all with "complete" pulses. As expected, all are lower severity collisions; no V_I exceeds 8 m/s and the highest injury level is AIS 1.

The occupant ridedown acceleration was computed for suitable cases. Because the continuous longitudinal velocity profile is recorded at discrete points by the EDR, the question of validity arises (as it requires a derivative). Although the GM EDR records velocity information at coarse 10 millisecond intervals, these values are based on more frequent acceleration information sampled every 0.312 milliseconds (Correia et al., 2001), which should provide a better acceleration estimate than if the velocity was directly sampled every 10 milliseconds. To further investigate the accuracy of the occupant ridedown acceleration computations, six New Car Assessment Program (NCAP) frontal barrier tests were examined. Each car tested had GM EDR data available in conjunction with the more detailed vehicle acceleration data typically recorded for the test. The EDR consistently overestimated the occupant ridedown acceleration on average by 40 percent with an overall range between 2 and 68 percent. For comparison purposes, the average error for the EDR-determined V_I was 4 percent with a 6 percent maximum. Thus, this estimate of the occupant ridedown acceleration is an upper bound on this index, and should over predict injury potential. Performing the calculations on the suitable cases in the database, however, no cases were in excess of the NCHRP 350 maximum threshold. The problem of estimating acceleration information is confounded by the relatively short GM EDR recording duration. In light of these limitations and the lack of values in excess of the current thresholds, the occupant ridedown acceleration has not been included in this analysis.

ASI COMPUTATIONS: The frontal collisions considered in this analysis are assumed to have negligible accelerations in the lateral and vertical directions such that the ASI computation involves only the longitudinal component and associated 12 G threshold. The following procedure was used to compute the longitudinal ASI for the suitable cases with "complete" pulses:

1. Using the metric EDR velocity data, calculate the 50-ms average acceleration values by computing the difference in velocity at points 50-ms apart and dividing by 0.05 seconds.

$$\bar{a}(t_i) = 50 \text{ ms moving average} = \frac{\sum_{i-5}^{i} a(t_i)}{\Delta t} = \frac{\sum_{0}^{i} a_i - \sum_{0}^{i-5} a_i}{\Delta t} = \frac{v_i - v_{i-5}}{0.05s}$$

2. Choose the largest absolute 50-ms acceleration value and convert to G units.
3. Divide the largest 50-ms acceleration by the longitudinal threshold value of 12 G.

The 50-ms averages are only computed for known velocity points. For instance, if a pulse is 50 ms in duration, only a single 50-ms average acceleration is computed from the EDR data (0-50 ms). Similarly, because the GM EDR provides the velocity information in 10 ms increments, the 50-ms averages step in 10 ms increments until the end of the velocity pulse. Figure 1 illustrates the longitudinal ASI computation based on the shown EDR vehicle change in velocity versus time. Note that the first 50-ms average point is the average acceleration from 10 to 60 milliseconds. The remaining points proceed in a similar manner.

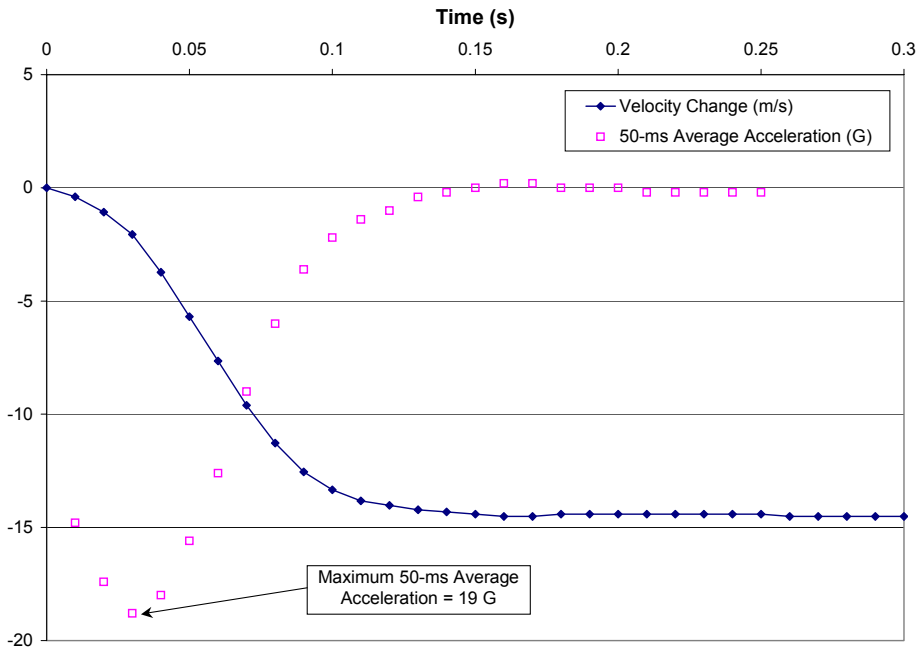

Figure 1 Longitudinal ASI Computation

To investigate the error associated with moving the 50-ms window by coarse 10 millisecond increments, the six NCAP frontal barrier collisions are reexamined. The results of the comparison are summarized in Table 2. In contrast to the occupant ridedown acceleration, there is reasonable agreement between the EDR and NCAP-determined ASI values. Although the EDR-determined value typically underestimates this quantity, the value is within 10 percent of the value calculated with the NCAP accelerometer data.

Table 2 NCAP and EDR ASI Comparison

Test Designation	EDR ASI Value (G)	NCAP ASI Value (G)	% Error
4487	24.81	26.18	-5.2
4472	19.50	20.30	-3.9
4244	24.87	26.89	-7.5
4198	24.21	26.61	-9.0
3952	25.81	26.19	-1.4
3851	22.01	21.15	+4.0

QUANTIFYING INJURY: The NASS/CDS database used in this study rates the severity of each injury using the Abbreviated Injury Scale (AIS) (AAAM, 1990). The AIS scale is an injury severity metric that measures threat to life. Michie indicates that the flail space model thresholds are intended to correspond to the transition between an AIS 3 and AIS 4 injury severity (1981). On the other hand, the ASI preferred threshold appears to be set between AIS 1 and AIS 2 injury severity levels.

RESULTS

OCCUPANT IMPACT VELOCITY AND INJURY: To determine the relation between the occupant impact velocity and injury in real-world frontal collisions, occupant injury, as quantified with the AIS scale, is plotted as a function of the longitudinal occupant impact velocity. Both the maximum and preferred V_I threshold values prescribed by NCHRP 350 are plotted as dashed lines. The NASS occupant belt status is indicated for each case on the plot. Open diamond points are used to signify occupants restrained by an airbag and seat belts, closed square points signify unbelted occupants restrained only by an airbag, and open triangular points signify occupants with unknown belt usage.

Maximum Injury: Figure 2 is a plot of occupant maximum injury as a function of longitudinal V_I. Note that the following plots contain a total of 69 cases. In the 11 additional cases, the vehicle velocity information was not complete, however, occupant impact occurred prior to the termination of the velocity data (i.e. the occupant impact velocity is valid but the maximum ASI value may not have been captured). The data set for Figure 2 contains 51 belted occupants, 14 unbelted occupants, and 4 cases with unknown belt usage.

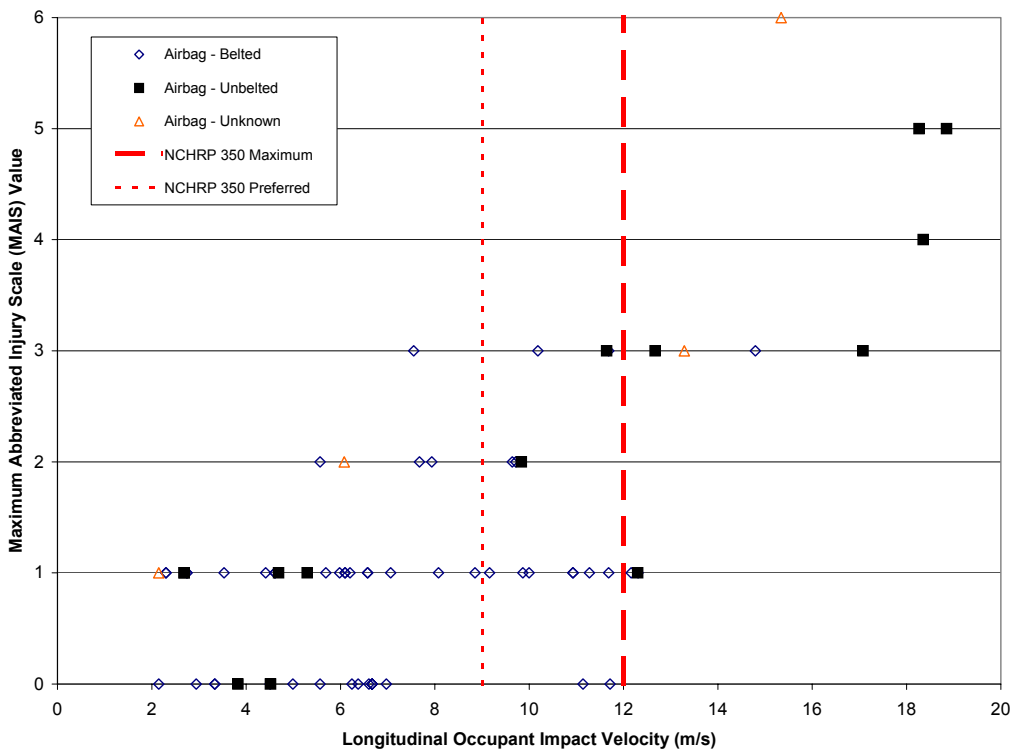

Figure 2 Maximum Occupant Injury In Single Event Frontal Deployment Collisions

According to the flail space model, injury severity should increase as the occupant impact velocity increases. As such, most points would be expected to fall within a diagonal band from the origin to the upper right corner of the plot. Also, if the current NCHRP 350 maximum longitudinal VI threshold of 12 m/s is valid, a majority of the more serious injuries (MAIS ≥ 3) should occur at occupant impact velocities that exceed this limit. As evident in Figure 2, occupant injury increases

with increasing longitudinal VI. Also, with the exception of two AIS 1 values just above the 12 m/s threshold, all the occupants subjected to a longitudinal VI in excess of the threshold suffered severe injury (MAIS ≥ 3). Conversely, all cases below the current maximum VI threshold have a less severe injury rating (MAIS ≤ 3). Despite the small number of cases, the observed trend appears applicable even considering only unbelted occupants. In the original formulation of the model, Michie (1981) suggests that the implementation of airbags will result in overly conservative threshold values. The available data, however, suggests that the current longitudinal VI thresholds are appropriate. Perhaps the use of the flail space model on non-airbag-restrained occupants was not as conservative as previously thought.

Head Injury: Figure 3 is a plot of occupant head injury as a function of longitudinal V_I. Note that this plot only includes 66 cases. Although the MAIS value is known, three of the unknown belt usage cases have missing body region injury information. A significant relation between head injury was expected since the current NCHRP 350 longitudinal V_I thresholds are based on head impact experiments into windshields. Examining Figure 3, however, V_I appears to be a weak predictor of occupant head injury. There is a large horizontal scatter at the lower injury levels; AIS 1 values span from about 2 m/s up to 17 m/s while the AIS 0 values span from 2 m/s to 19 m/s. With respect to the current maximum threshold, a V_I in excess of this value does not result in severe injury in most cases. Also, there is substantial overlap and encapsulation of injury levels. For example, AIS 2 values are observed between 7 and 10 m/s while both AIS 0 and AIS 1 values are also observed in this range. This behavior could be a result of the limited sample size or the lack of higher V_I cases. On the other hand, these results could be attributed to the fact that the head is free to rotate with respect to the "point mass" portion of the body via the neck.

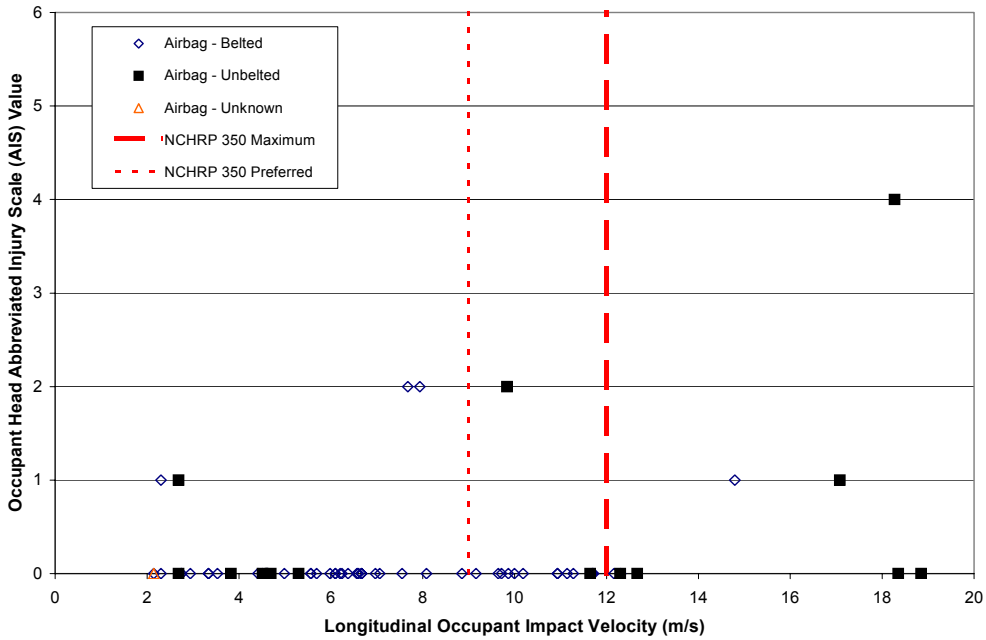

Figure 3 Occupant Head Injury and the Occupant Impact Velocity

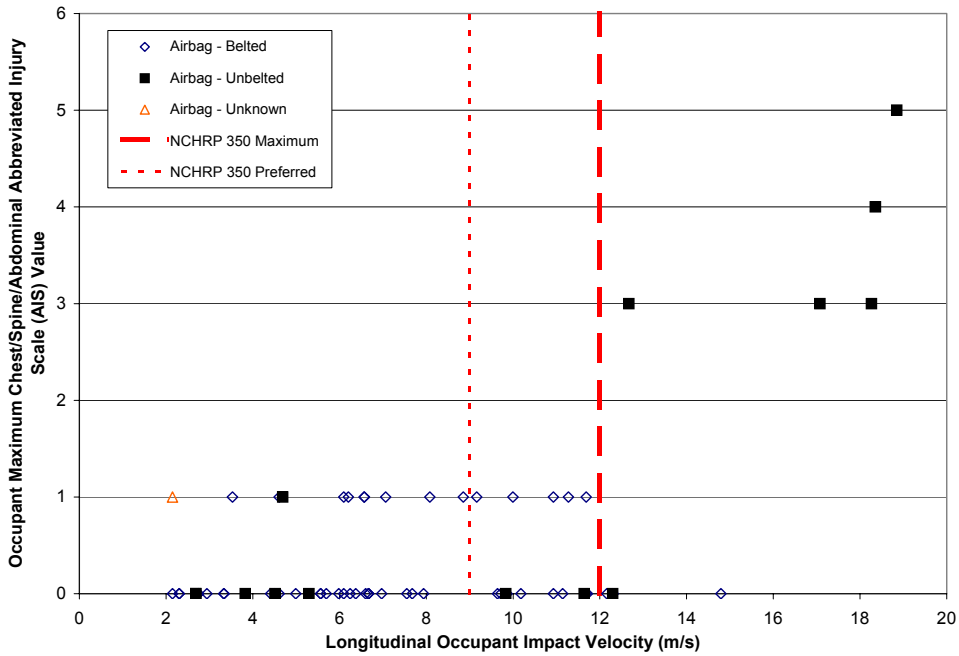

Figure 4 Occupant Thoracic/Abdominal Injury and the Occupant Impact Velocity

Thoracic/Abdominal Injury: Figure 4 presents the maximum AIS value for the chest, spine and abdomen of the occupant as a function of longitudinal V_I. Again, since this plot utilizes body region information, only 66 cases are included. As this portion of the human anatomy is closest to a point mass representation, a strong correlation is expected between injury and V_I. Unlike occupant head injury, V_I appears to be a substantial predictor of occupant thoracic/abdominal injury. The data follows the anticipated "diagonal band" trend with injury severity increasing as occupant impact velocity increases. From the available data, the current longitudinal threshold of 12 m/s appears slightly conservative but definitely within a reasonable range. It is interesting to note the significant portion of thoracic/abdominal injuries in unbelted occupants subjected to a V_I in excess of the current threshold.

ASI AND INJURY: To determine the relation between the ASI and injury in real-world frontal collisions, occupant injury, as quantified with the AIS scale, is plotted as a function of the longitudinal ASI in Figure 5 through Figure 7. Both the maximum and preferred ASI thresholds are plotted as dashed lines. Also, each plot indicates NASS occupant belt status. Open diamond points are used to signify occupants restrained by an airbag and seat belts, closed square points signify unbelted occupants restrained only by an airbag, and open triangular points signify occupants with unknown belt usage.

ASI was first computed for the 58 cases for which complete velocity versus time profile was available. Examination of the 50 ms moving average acceleration versus time for these cases revealed that most cases were characterized by a sine-like acceleration pulse with only a single maximum. As the maximum average acceleration was typically observed early in the crash event, the 11 cases with incomplete velocity were reexamined to determine if the maximum average acceleration occurred early enough in these cases to be included in the analysis. For the cases with incomplete velocity information, the 50 ms moving average acceleration versus time was plotted and examined for this characteristic sine-like acceleration shape. If the slope of the acceleration pulse changed sign, the assumption was made that the maximum acceleration was indeed the correct ASI that would have been computed if the full velocity information had been available. Indeed, in all 11 cases, the characteristic sine-like acceleration shape could be identified, and a maximum ASI could be computed.

Maximum Injury: Figure 5 is a plot of occupant maximum injury as a function of longitudinal ASI. Similar to the V_I plot involving maximum injury, this plot contains a total of 69 cases: 51 belted occupants, 14 unbelted occupants, and 4 cases with unknown belt usage.

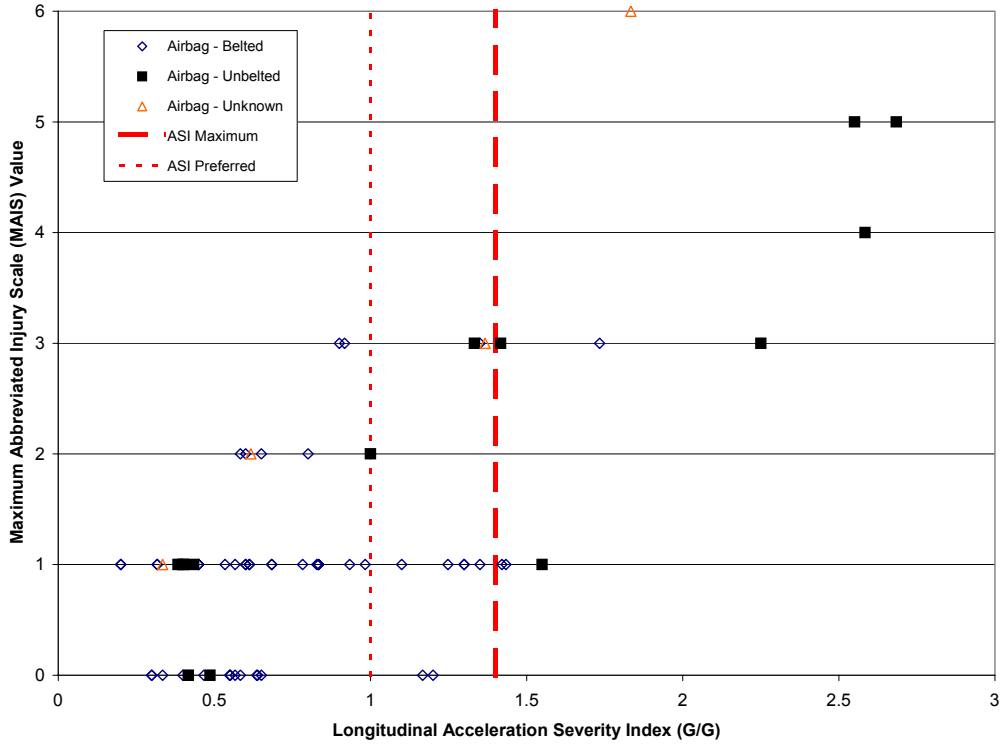

Figure 5 Maximum Occupant Injury and the ASI

Similar to V_I, the ASI is assumed to be proportional to the risk of occupant injury and the points are expected to fall in a diagonal band from the origin to the upper right hand corner of the plot. Also, if the longitudinal preferred threshold of 1.0 is valid, only MAIS ≤ 1 injuries should occur below the threshold. Examining Figure 5, there is significant evidence of the anticipated diagonal band trend, however, all of the MAIS 2 and two of the MAIS 3 values fall below the preferred threshold. Also, there are a number of MAIS 0 and MAIS 1 values in excess of the preferred ASI threshold. From the available data and with respect to the intent of each model's threshold value, the ASI appears to be a weaker indicator of maximum occupant injury than the occupant impact velocity. One particularly interesting note is the striking similarity between the arrangement of points in Figure 2 and Figure 5. Also, the maximum ASI threshold value appears equivalent to the maximum occupant impact velocity threshold in terms of injury prediction for this data set.

Head Injury: Figure 6 is a plot of occupant head injury as a function of longitudinal ASI. Similar to the body region plots for V_I, this plot includes 3 fewer cases than the maximum injury plot since 3 of the unknown belt usage cases have missing body region injury information. Similar to the plot of head injury and V_I, there is appears to be no correlation between the ASI criterion and occupant head injury in the available single event frontal collisions. There is no evidence of the expected diagonal band trend. A majority of the occupants subjected to ASI values in excess of the preferred threshold suffered no head injury (AIS = 0). Also, all AIS 2 injury occurs at or below the ASI preferred threshold. Again, note the similarity of this plot to the corresponding plot involving V_I.

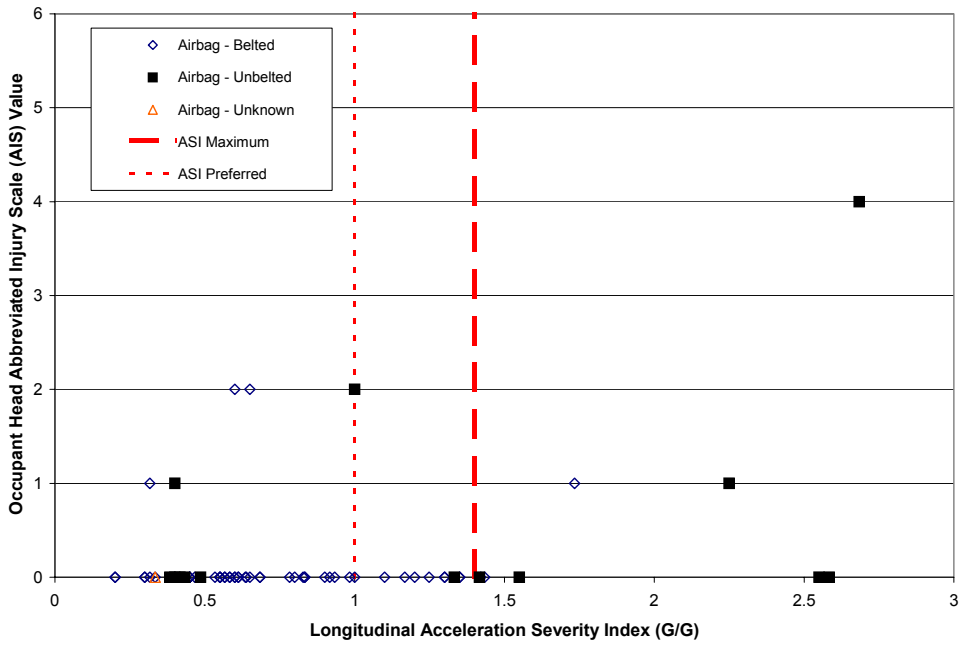

Figure 6 Occupant Head Injury and the ASI

Thoracic/Abdominal Injury: Figure 7 is a plot of occupant thoracic/abdominal injury as a function of longitudinal ASI. Again, only 66 cases are plotted due to missing body region injury information for 3 unknown belt usage cases. As in the plot with the occupant impact velocity, there is evidence of the expected diagonal band trend and all the more severe injuries (AIS ≥ 3) occur above the preferred threshold. For the lower severity injuries, however, there are AIS 0 and AIS 1 values in excess of the preferred ASI threshold indicating that this metric is a weaker predictor of injury than V_I. Similar to the previous plots, there is a striking resemblance between Figure 4 and Figure 7 and the maximum ASI threshold of 1.4 appears equivalent to the maximum V_I threshold.

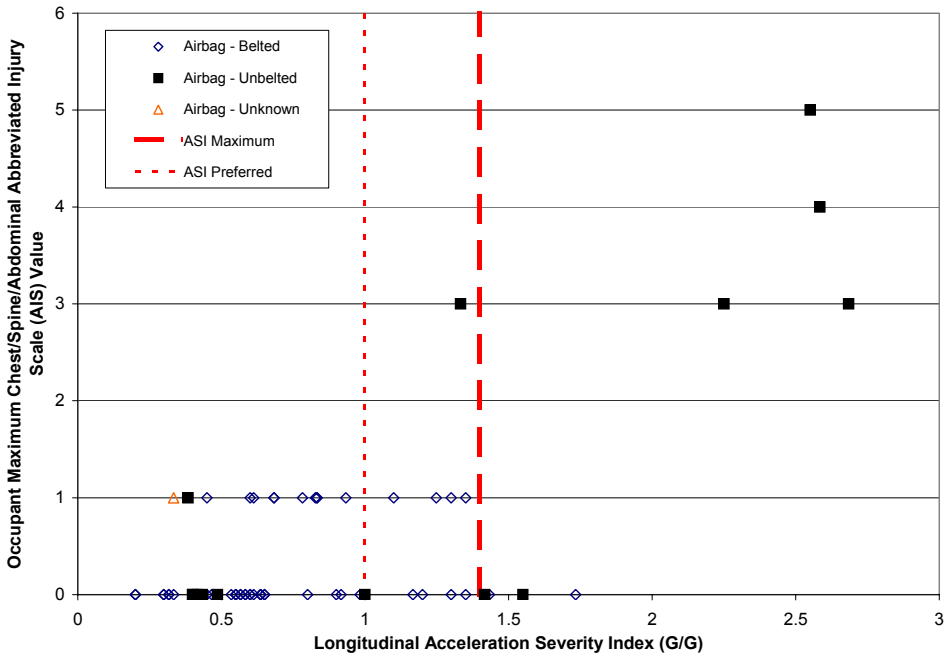

Figure 7 Occupant Thoracic/Abdominal Injury and the ASI

LIMITATIONS

As with any study of this nature, the results should be considered in parallel with the limitations inherent to the available data and methodology utilized. These include, but may not be limited to, the following:

1. Size of the available data set: The data sets used in the analyses range from 66 to 69 cases.
2. Longitudinal Information Only: A complete analysis of the flail space model requires information regarding the lateral motion of the vehicle. For the ASI, vertical and lateral information is required for a complete analysis.
3. Occupant Ridedown Acceleration: The ridedown acceleration needs to be investigated in order to provide a true representation of the effectiveness of the flail space model at predicting occupant injury.
4. EDR Data Recording Interval: Although vehicle acceleration is sampled every 0.312 milliseconds (Correia et al., 2001), the GM EDR only records velocity changes every 10 milliseconds. This coarse recording interval prevents an adequate estimate of the occupant ridedown acceleration. This also introduces error into the computation of the ASI, although it appears significantly less than that of the occupant ridedown acceleration.
5. Duration of EDR Recording Capability: The EDR information available in the database has a total duration of either 150 milliseconds or 300 milliseconds (depending on the EDR model). Although longer multiple event collisions are not included in the analysis, the 150 milliseconds may not be a sufficient window to capture the entire dynamic behavior of the vehicle in some longer duration crashes.
6. GM Vehicles Only: Although a large deviation between vehicle manufacturers is not expected, further analysis should include information from other vehicle manufacturers as feasible.
7. Occupant Compartment Intrusion: This analysis did not control for occupant compartment integrity required by the flail space model. Of the 66 cases used in the V_I investigation, 43 cases had no intrusion, 15 cases had intrusion, and intrusion was unknown in the remaining 8 cases. For the 15 intrusion cases, minor occupant injury (MAIS $\leq$ 2) was noted in 8 instances while the remaining cases resulted in severe injury (four MAIS 3 values, two MAIS 4 values, and one MAIS 5).

CONCLUSIONS

This study provides a first glimpse of the relative performance of different injury criteria at predicting injury to airbag-restrained occupants and has established a methodology for future studies. A better understanding of the link between occupant injury and these metrics may lead to improved criteria. Specific conclusions include:

1. The longitudinal ASI is a weaker predictor of occupant injury than the longitudinal occupant impact velocity.
2. The maximum ASI threshold and the maximum occupant impact velocity threshold appear to correspond to the same potential for occupant injury.
3. Although the longitudinal occupant impact velocity threshold values have been based on frontal head impacts with windshields, the occupant impact velocity is a weak predictor of occupant head injury in this data set.
4. Occupant impact velocity appears to be a good predictor of maximum injury and thoracic/abdominal injury for single event, frontal collisions.

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