A Methodology to Evaluate the Flail Space Model Utilizing Event Data Recorder Technology

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Abstract

Developed in the early 1980's, the flail space model has become the standard method for estimating occupant risk in full-scale crash tests involving roadside safety features. The widespread availability of airbags and increased seat belt usage rates in today's vehicle fleet, however, raise serious questions regarding the validity of the model. Recent implementation of Event Data Recorder (EDR) technology in a number of late model vehicles presents a different perspective on the assessment of the validity of occupant risk based on the flail space model. EDRs are capable of electronically recording data such as vehicle speed, brake status and throttle position just prior to and during an accident. Of particular interest is the EDRs ability to document the deceleration of a vehicle during a collision event. This paper presents a methodology utilizing EDR data to investigate the capability of the flail space model to predict injury to airbag-restrained occupants. Results of a preliminary analysis are presented based on implementation of the developed methodology on a limited data set. A majority of the analysis is limited to the occupant impact velocity due to complications in estimating the occupant ridedown acceleration. The longitudinal occupant impact velocity is found to be a good predictor of overall injury, chest injury and, to a lesser extent, lower extremity injury. For the head, and upper extremity body region, the longitudinal occupant impact velocity is a weak predictor of injury.

INTRODUCTION

Full-scale crash testing has been the traditional method of evaluating the effectiveness of roadside safety improvements. The intent is to provide a measure of how a particular device compares to similar devices in representative worst-case impact scenarios. Currently, the evaluation criterion is based on structural adequacy of the appurtenance, post-impact vehicle trajectory, and occupant risk.

As the purpose of roadside safety hardware is to be functional while minimizing the risk of occupant injury, the occupant risk criteria is vital to the assessment of these devices. For occupant risk determination in full-scale vehicle crashworthiness testing, crash test dummies have been developed specifically to mimic the human response in frontal and side impact collisions. Roadside hardware collisions, however, have a greater propensity for oblique impact angles. To date, no crash test dummies have been developed which can accurately reproduce the human response in this crash mode. Instead, the flail space model has been developed and implemented to evaluate occupant risk in roadside safety hardware crash tests.

Evolution of the Occupant Risk Criteria

Flail Space Model

Prior to the introduction of the flail space model, a majority of the occupant risk criteria were based on limiting the peak 50 ms acceleration of the vehicle (*1,2*). Procedures for evaluating crash test data involved computing these values (both lateral and longitudinal directions) and comparing them with threshold limits. Although the determination of the occupant risk criteria was specified in excruciating detail, the authors of the guidelines cautioned that these evaluation procedures "…are not directly applicable to the complex highway collision" (*2*). In an attempt to better define the occupant risk criteria, Michie introduced the flail space concept formally in 1981 (*3*). This model was quickly incorporated into NCHRP Report 230, "Recommended Procedures for the Safety Evaluation of Highway Appurtenances" (*4*) and the subsequent update to these procedures, NCHRP Report 350 (*5*).

Hypothesizing that occupant injury severity is a function of the velocity at which the occupant impacts the interior and the subsequent acceleration forces, Michie assumed the occupant to be an unrestrained point mass, which acts as a "free-missile" inside the occupant compartment in the event of a collision. The 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 prior to impacting the vehicle interior. 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 and pitch 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). Once the impact with the interior occurs, the occupant is assumed to remain in contact with the interior and be subjected to any subsequent accelerations of the vehicle. The maximum 10 ms moving average of the accelerations subsequent to the occupant impact with the interior is termed the occupant ridedown acceleration. Again, the lateral and longitudinal directions are handled separately producing two maximum occupant ridedown accelerations.

Both the V_I and subsequent occupant ridedown acceleration are compared with established thresholds to ensure that the device does not create undo risk to the occupants of an impacting vehicle. Current threshold values as prescribed in NCHRP 350 (*5*), are summarized in TABLE 1. Note that this table excludes the limiting values for work zone devices and support structures.

TABLE 1 Current Occupant Risk Threshold Values

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

According to NCHRP 230 (*4*), the V_I limit in the longitudinal direction was based principally on head impact experiments into windshields (*6,7*). The lateral threshold was based mainly on French accident statistics (*8*) and research aimed at developing FMVSS 214 (*9*), a U.S. vehicle standard for side impact protection. Occupant ridedown acceleration threshold values have been established mainly from exhaustive human impact tolerance review documents from the 1970's (*10,11*). Although converted to SI units, the NCHRP 230 values were essentially retained in NCHRP 350 based on consultation with biomechanics experts, a General Motors (GM) research study (*12*), an evaluation report of current (NCHRP 230) guidelines (*13*), and an investigation of impact attenuator systems (*14*).

Model Validity

Unlike real-world crashes, roadside hardware crash tests are performed in a controlled environment with precise instrumentation. The result is exact values for the prescribed flail space model criteria. What is not well known is how this criterion relates to occupant injury in actual collision events. As discussed below, this relationship has traditionally been tenuous at best. Since decisions regarding the acceptance or rejection of roadside hardware are partially based on the flail space model criteria, there is a strong motivation to ensure the accuracy of this relationship.

Stewart and Council (*15*) 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. Results of this study indicated the lack of a strong relationship between injury severity and vehicle momentum change and 50-ms peak acceleration values. With regard to the flail space model, the limited data sample prevented any conclusions. In another study, Ray et al. (*16*) 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.

Flail Space Model Revisited

The original intent of the flail space model was to provide a gross indication of the likelihood of severe occupant injury to facilitate proper evaluation of roadside hardware devices. Despite the lack of evidence linking the flail space criteria to occupant injury, researchers have long questioned the validity of the assumptions of the model. As a result, several versions of the flail space model have emerged. In conjunction with the report evaluating NCHRP 230 procedures, Ray et al. (*17*) presented a method that considers the yaw rate of the vehicle using the coupled equations of motion. Similarly, Ross et al. (*18*) developed a program that considers vehicle yaw motion and a more exact "flail space", depending on occupant seating location. Ray and Carney (*19*) developed a program that utilizes the coupled equations of motion, considers vehicle yaw motion, and calculates occupant position beyond the initial impact. Also, the European Committee for Normalization (CEN) has adopted a modified version of the flail space model to evaluate occupant risk (*20*). Differences include the use of resultant velocity and acceleration values to determine the impact velocity and ridedown acceleration, inclusion of vehicle yaw motion, and the addition of an acceleration-based model to account for belted occupants. Although the improved versions better characterize occupant motion, the linkage to occupant injury remains tenuous at best. Thus, it is questionable whether utilization of these improved models will impart a more efficient means of injury prediction.

Advancing vehicle technologies and changing operating trends have further complicated the model assumptions and the correlation to occupant injury. At the inception of the flail space model in 1981, belt usage rates were approximately 15% and use of airbags was not widespread. Today, however, belt usage rates exceed 60% and driver and passenger airbags are required equipment on all new passenger cars. Is the unrestrained occupant assumption still valid despite these changes? Both previous investigations (*15,16*) of the flail space model were performed on a predominately 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. The previously tenuous correlation to occupant injury coupled with fleet changes since the inception of the flail space model raise serious questions regarding its current applicability and demonstrates the necessity for a reassessment of the model.

EDR Technology and the Rowan University EDR Database

Recent advancements in vehicle technology 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, deployment of the airbag, and vehicle speed prior to impact (*21*). Of particular interest to this study is the EDRs ability to record the vehicle velocity profile during a collision event.

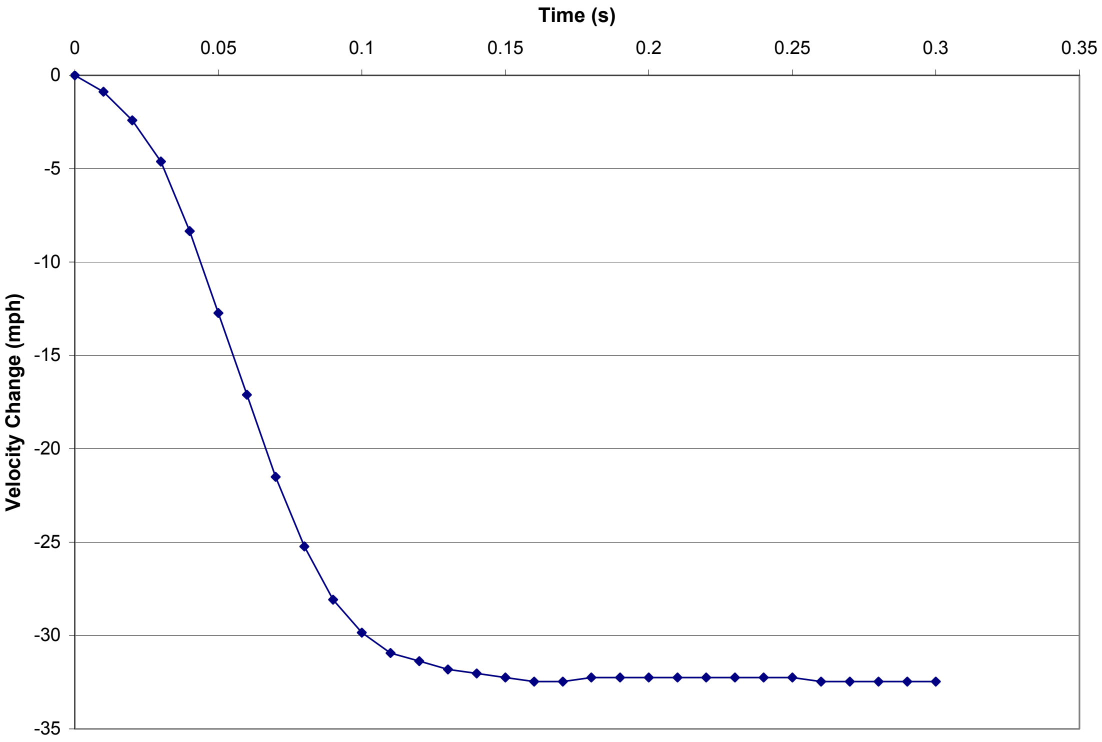

FIGURE 1 Longitudinal Velocity Profile: 1999 Chevrolet Cavalier

Under sponsorship of the National Highway Traffic Safety Administration (NHTSA), Rowan University is in the process of developing a first-of-a-kind database of EDR data collected from traffic collisions in the United States (*22*). 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 (shown in FIGURE 1), 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.

OBJECTIVE

The purpose of this study is to present a framework for the use of EDR data to investigate the correlation between the flail space model and injury to airbag-restrained occupants. Results of a preliminary analysis are presented using the developed methodology on a limited data set.

METHODOLOGY

The Rowan EDR database was first searched to identify those cases suitable for analysis. Suitable cases have the following characteristics:

1. Airbag deployment with associated velocity versus time data
2. Known NASS injury data for either the left or right front seat occupant
3. Comprised of a single impact only
4. Frontal collision

In an attempt to utilize cases that have a higher potential for occupant injury, the data was narrowed to include only deployment events. Note that the typical velocity change threshold for airbag deployment in frontal collisions is approximately 5 m/s (11 mph) (*23*). Limited to information for a maximum of two impacts, the GM EDR will not capture all the events if a crash has more than two impacts. 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. A total of 88 cases have been identified as suitable for analysis; 68 left front seat occupant cases and 20 right front seat occupant cases. Seven (7) cases have been omitted from the analysis due to suspect velocity information. Note that there is potential overlap in the available cases. For instance, one vehicle may have injury indications for both left and right front seat occupants, resulting in two suitable cases for analysis.

The final data set includes both frontal vehicle-to-fixed object (24%) and frontal vehicle-to-vehicle collisions (76%). If there is indeed a relationship between the flail space model and injury severity, it should be as equally relevant to vehicle-to-vehicle crashes as to vehicle-to-fixed object crashes.

The following procedure was used to determine the longitudinal occupant risk criteria for the suitable cases in the EDR database:

1. Numerically integrate the longitudinal EDR relative velocity data 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. For cases where the theoretical occupant does not exceed the longitudinal flail space limit, V_I is set to the maximum velocity change of the vehicle (as recorded by the EDR).
4. Obtain vehicle accelerations by numerically computing the derivative of the longitudinal EDR relative velocity and convert to G's.
5. After the time of occupant impact, choose the largest absolute acceleration value as the occupant ridedown acceleration.
6. If the occupant does not reach the longitudinal flail space limit, the ridedown acceleration is set to zero.

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. As this would be extremely difficult to estimate with absolute certainty from EDR data, the maximum overall change in vehicle velocity is used to provide a conservative estimate of this quantity. A total of 32 of the 88 cases fall into this category; all have a V_I less than 10 m/s and the highest injury level is AIS 3 (one case only). The occupant ridedown acceleration for these cases is set to zero since occupant impact does not occur. Note that NCHRP 350 provides no specific guidance on the occupant ridedown in this instance.

Because the continuous longitudinal velocity profile is recorded at discrete points by the EDR, the question of validity arises for the computation of occupant ridedown acceleration (as it requires a derivative). To investigate the accuracy of the flail space model computations outlined above, 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. Performing the flail space computations with each data source revealed an average error for the EDR-determined V_I of 4 percent (6% maximum). The EDR consistently overestimated the occupant ridedown acceleration on average by 40 percent with an overall range between 2 and 68 percent. Thus, this estimate of the occupant ridedown acceleration is an upper bound on this index, and should over predict injury potential.

As long as the occupant impact occurs within the recorded velocity profile, V_I will be accurate regardless of the completeness of the EDR velocity information. The ridedown acceleration, however, could be erroneous if the entire collision is not captured. The pulses of the 88 eligible cases have been examined for completeness (i.e. convergence to a constant velocity as shown in FIGURE 1). A total of 54 cases have been deemed complete; ridedown computations are limited to these cases only.

For the quantification of occupant injury, the Abbreviated Injury Scale (AIS) is used as illustrated in TABLE 2 (*24*). The AIS scale is an injury severity metric that measures threat to life. The NASS/CDS data, collected in parallel with the EDR data, rates the severity of each occupant injury using this scale. Note that the intent of the flail space model threshold values is to prevent occupants from sustaining injury severity values of AIS 4 or greater (*4*).

TABLE 2 The Abbreviated Injury Scale

AIS Value	Injury Characterization
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum/Fatal

RESULTS

Flail Space Model as a Predictor of Maximum Occupant Injury

To investigate the overall predictive capabilities of the flail space model, NASS/CDS maximum abbreviated injury scale (MAIS) values are plotted as a function of both the longitudinal V_I and subsequent longitudinal occupant ridedown acceleration. FIGURE 2 is a plot for the suitable cases in the database with each series representing a different level of actual occupant injury based on the AIS scale. Note that this includes only 54 cases since both V_I and the ridedown acceleration must be known. Lower severity injuries (MAIS < 3) are delineated with open points while higher severity injuries (MAIS ≥ 3) are delineated with closed points. For comparison purposes, the NCHRP Report 350 maximum allowable thresholds for V_I and occupant ridedown acceleration are plotted as dashed lines. The shaded region delineates the occupant risk value combinations considered acceptable by NCHRP Report 350.

Intuition dictates that the more severe injuries should occur at both higher V_I values and higher occupant ridedown accelerations. 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 longitudinal NCHRP 350 limits are valid, a majority of the seriously injured occupants (closed points) should occur outside of the shaded region. FIGURE 2 demonstrates the expected "diagonal" trend although it appears more a function of V_I. As expected, a majority of the lower severity injuries (open points) occur within the shaded region. For the more serious MAIS 3 values, about 60% of the values are within the shaded region, while the remaining 40% fall outside of this region. All the other serious injuries (closed points) fall outside of the "acceptable" shaded region. Note that the AIS 3 case with V_I approximately 8 m/s was an airbag-induced injury.

Even though the occupant ridedown acceleration is overestimated, no cases exceed the current threshold. Within this data set, this metric appears to be a poor discriminator of occupant injury. There are significant caveats to the ridedown acceleration, however, that must be considered. The validation using the NCAP tests is only valid for crashes involving peak decelerations within 150 ms after impact and for collisions with broad, rigid objects. Additional validation should be performed for impacts with less rigid as well as narrow objects. Also, the potential error implications of deriving vehicle accelerations from discrete velocity information should be examined for collisions with non-rigid and narrow objects. In light of these limitations and the lack of values in excess of the current thresholds, the remainder of the discussion will focus on the occupant impact velocity.

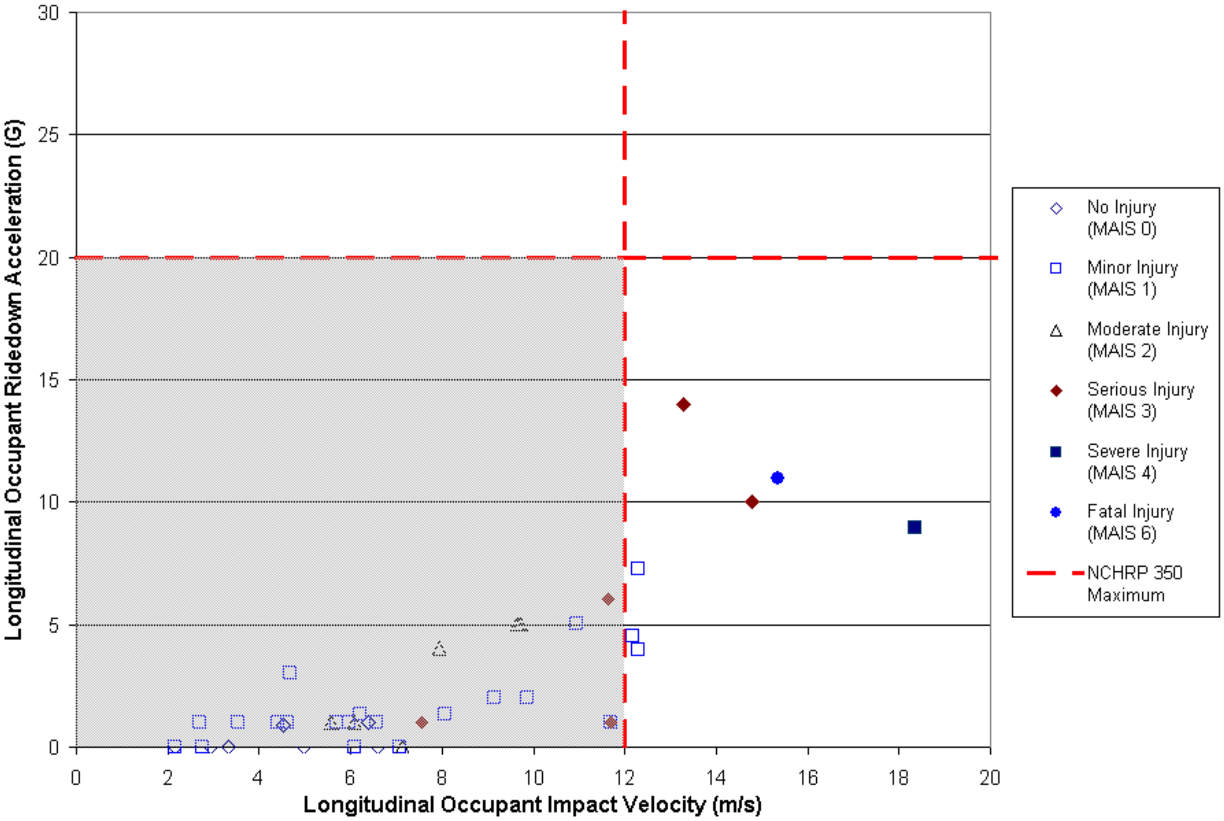

FIGURE 2 Maximum Occupant Injury In Single Event Frontal Collisions

Occupant Impact Velocity as a Predictor of Occupant Injury by Body Region

The flail space model assumes that the occupant can be grossly represented by a point mass. Of all body regions, the chest and abdomen are best represented by a point mass. The arms, legs, and to a lesser extent, the head, are free to rotate about the occupant's center of gravity and are expected to be less well represented by the point mass assumption. To investigate this hypothesis, occupant injury was plotted as a function of V_I for each body region.

Due to missing body region AIS values in six cases, the following plots include only 82 cases. Also, each plot indicates NASS occupant belt status. The current data set contains 67 belted occupants, 14 unbelted occupants, and a single case with unknown belt usage.

Head Injury

FIGURE 3 is a plot of occupant head injury as a function of longitudinal V_I. 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 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 6 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 contrary, 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.

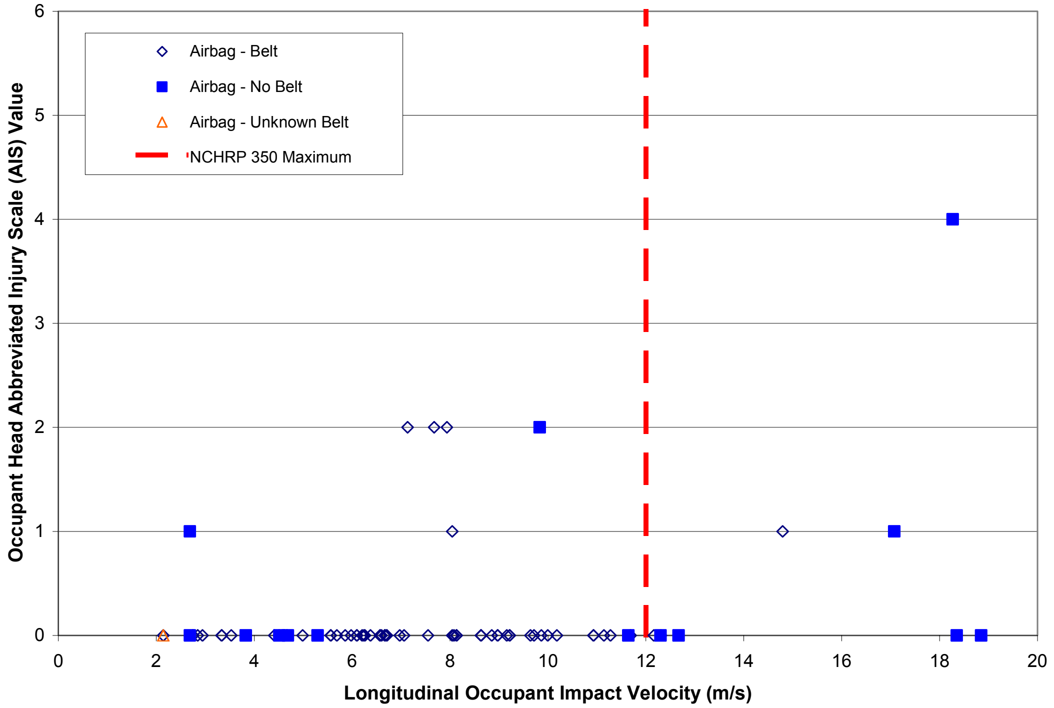

FIGURE 3 Occupant Head Injury in Single Event Frontal Collisions

Chest Injury

FIGURE 4 presents the maximum AIS value for the chest, spine and abdomen of the occupant as a function of longitudinal V_I. As this portion of the human anatomy is closest to a point mass representation, a strong correlation is expected between injury and V_I.

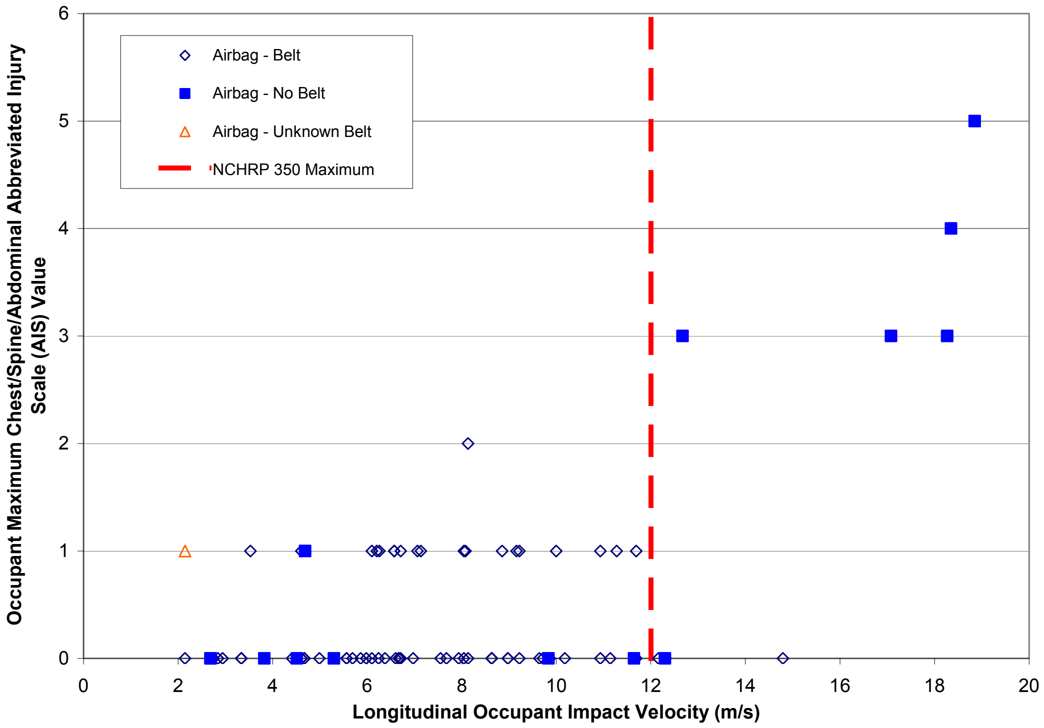

FIGURE 4 Occupant Upper Trunk Injury In Single Event Frontal Collisions

Unlike occupant head injury, V_I appears to be a substantial predictor of occupant chest/upper trunk 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 upper trunk injuries in unbelted occupants subjected to a V_I in excess of the current threshold.

Extremity Injury

FIGURE 5 and FIGURE 6 show occupant upper and lower extremity injury, respectively, as a function of V_I. As the extremities are less indicative of the point mass assumption of the flail space model, the correlations are expected to be less apparent.

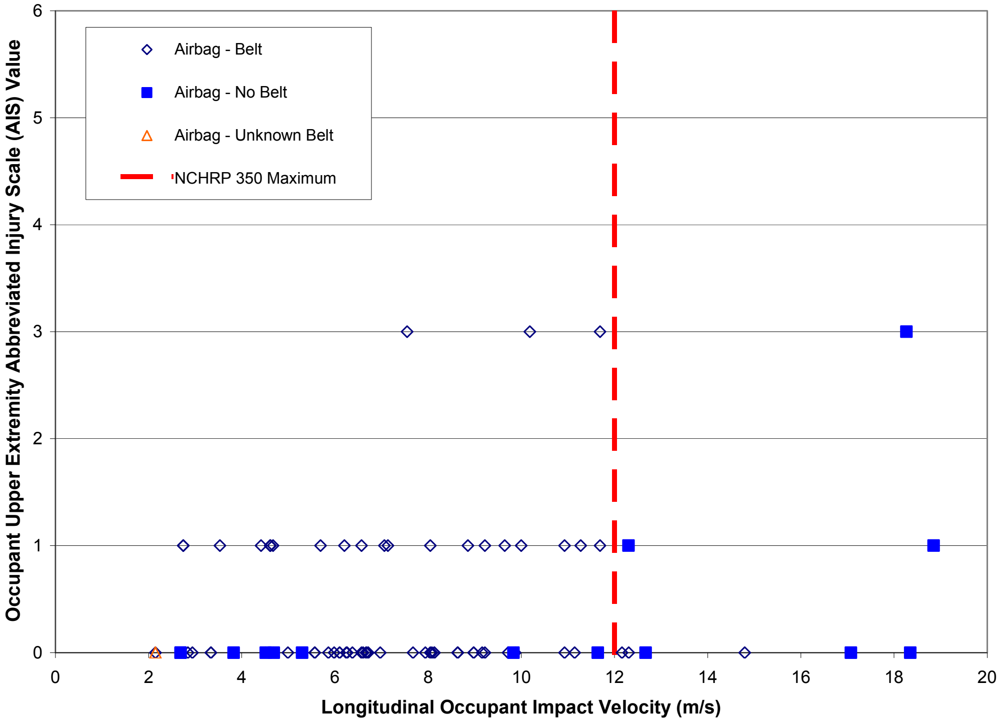

FIGURE 5 Occupant Upper Extremity Injury In Single Event Frontal Collisions

Examining FIGURE 5, V_I appears to be a weak indicator of occupant upper extremity injury in this data set. The data points exhibit substantial scatter in the horizontal direction and overlap in the vertical direction (i.e. differing injury severity for the same occupant impact velocity values). With respect to the current NCHRP threshold, there is no indication that higher severity injury occurs at higher V_I values as many points that exceed the threshold have little or no injury. Obviously this data is subject to the same injury tolerance differences as the other body regions and may impart the same influence on the scatter of the data. Of particular note, though, is the possible variation in occupant upper extremity position in the event of a collision. The actual position of the upper limbs may play a much more significant role in occupant injury than differences in injury tolerances. This fact is more evident when considered in light of FIGURE 6, occupant lower extremity injury.

As evident in FIGURE 6, V_I appears to be a better predictor of occupant lower extremity injury than upper extremity injury. Although the correlation is not as obvious as in upper trunk injury, the correlation for lower extremity injury is substantially better than the correlation for upper severity injury. Other than the two AIS 1 cases at V_I values of approximately 19 m/s, the injury severity increases with increasing V_I. One possible explanation for this is that lower extremities have fewer tendencies to vary position in comparison to the upper extremities.

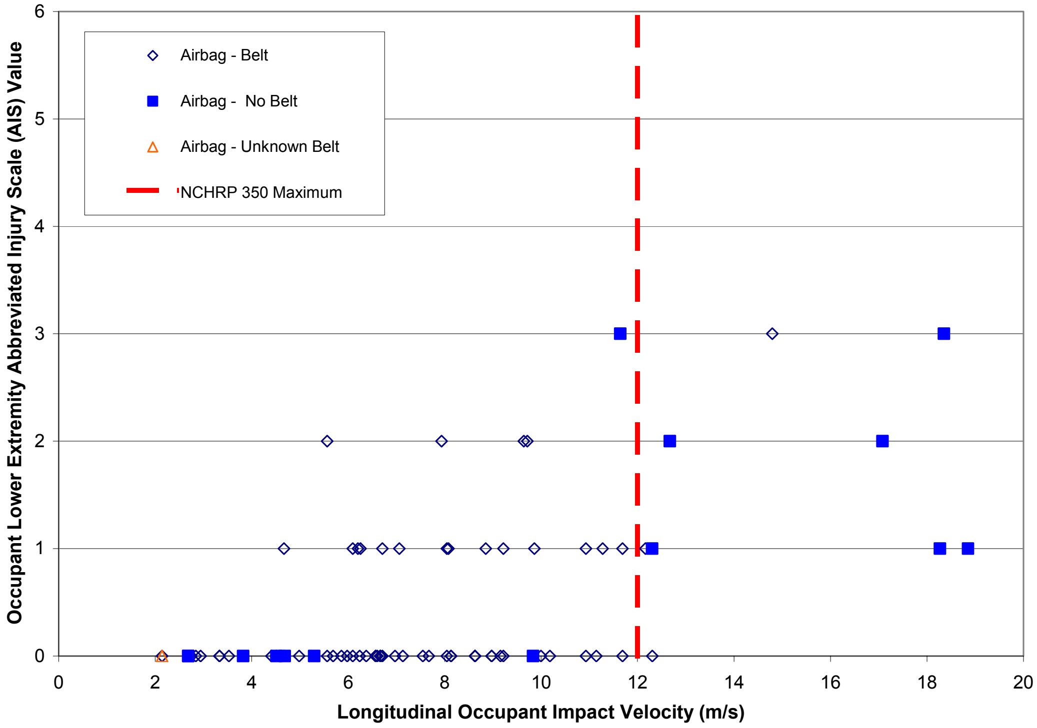

FIGURE 6 Occupant Lower Extremity Injury In Single Event Frontal Collisions

Neck Injury

An attempt has been made to correlate occupant neck injury to the longitudinal V_I with the generation of a plot consistent with those shown above, however, there were insufficient neck injuries to perform an analysis.

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: A majority of the analysis is limited to 82 suitable cases.
2. Distribution of Flail Space Criteria: Only 11 percent of the available cases have V_I values in excess of the current NCHRP 350 threshold while none of the eligible cases have occupant ridedown accelerations in excess of the current threshold. Additional cases with higher V_I and ridedown acceleration values are necessary to more fully describe the correlation of the model to occupant injury.
3. Absence of Lateral Information: A complete analysis of the linkage between the flail space model and occupant injury requires information regarding the lateral motion of the vehicle.
4. Occupant Ridedown Acceleration Computations: The ridedown calculation methodology is only validated as an upper bound for short duration collisions into broad, rigid objects. Longer collisions and those involving narrow and non-rigid objects must also be investigated.
5. EDR Data Recording Interval: Although vehicle acceleration is sampled every 0.312 milliseconds (*25*), the GM EDR only records vehicle velocity changes every 10 milliseconds. For comparison, NCHRP 350 recommends vehicle acceleration to be recorded at least once every millisecond.
6. 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 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.

7. GM Vehicles Only: The Rowan University EDR database only contains information regarding GM vehicles. Although a large deviation between vehicle manufacturers is not expected, further analysis should include information from other vehicle manufacturers.

CONCLUSIONS

This study provides a first glimpse at the relation between the flail space model and injury to airbag-restrained occupants and has established a methodology for future studies. A better understanding of this relation may lead to an improved injury criteria, or, in the least, enable the roadside safety community to make better informed decisions regarding the implementation of roadside safety hardware on our nation's highway system. Specific conclusions include:

1. 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.
2. Occupant impact velocity appears to be a good predictor of chest injury and, to a lesser extent, lower extremity injury for single event, frontal collisions.
3. For the upper extremity body region, the occupant impact velocity is a weak predictor of injury in this data set.
4. In single event frontal collisions, the longitudinal occupant impact velocity is a substantial predictor of overall occupant injury.
5. The injury predictive capability of the longitudinal occupant ridedown acceleration is unknown.

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REFERENCES

1. Bronstad, M.E. and J. D. Michie. *Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances*, NCHRP Report No. 153, Washington, DC, 1974.
2. *Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances.* Transportation Research Board, Transportation Research Circular No. 191, Washington, DC, February, 1978.
3. Michie, J. D. Collision Risk Assessment Based on Occupant Flail-Space Model. In *Transportation Research Record 796*, TRB, National Research Council, Washington, D.C., 1981, pp 1-9.
4. Michie, J. D. *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, NCHRP Report 230, TRB, National Research Council, Washington, D.C., 1981.
5. Ross, Hayes E., Sicking, D.L., Zimmer, R.A., and J.D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. NCHRP Report 350, TRB, National Research Council, Washington, D.C., 1993.
6. Kay, S.E., Pickard, J., and L.M. Patrick. Improved Laminated Windshield with Reduced Laceration Properties. *Proceedings of the 17th Stapp Car Crash Conference*, Paper 730969, 1973.
7. Begeman, P., King, A., Weigt, P. and L.M. Patrick. *Safety Performance of Asymmetric Windshields*. SAE Paper 791009. Society of Automotive Engineers, New York, 1978.
8. Hartman, F., Thomas, C., Foret-Bruno, J., Henry, C., Fayon, A., and C. Tarriere. Occupant Protection in Lateral Impacts. *Proceedings of the 20th Stapp Car Crash Conference*, 1976.
9. NHTSA. Federal Motor Vehicle Safety Standards: Side Impact Protection. 49 C.F.R., Part 571.214.
10. Chi, M. *Assessment of Injury Criteria in Roadside Barrier Tests*. Report FHWA-RD-75-74. FHWA, U.S. Department of Transportation, Washington, D.C., 1976.
11. Snyder, R.G., *State-of-the-Art – Human Impact Tolerances*. SAE 700398, International Automobile Safety Conference Compendium, May 1970.
12. Viano, D.C., and I.V. Lau. *Biomechanics of Impact Injury*. Research Publication GMR-6894, General Motors Research Laboratories, December 1989.
13. Ray, M. H., Michie, J. D., Hunter, W., and J Stutts. *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware, Volume IV: The Importance of the Occupant Risk Criteria*. FHWA RD-87/099, U.S. Department of Transportation, Washington, D.C., 1987.

14. Hinch, J. et al. Impact Attenuators: A Current Engineering Evaluation. In *Transportation Research Record 1198*, TRB, National Research Council, Washington, D.C., 1988, pp. 76-89.
15. Council, Forrest M., and J. Richard Stewart. Attempt to Define Relationship between Forces to Crash-Test Vehicles and Occupant Injury in Similar Real-World Crashes. In *Transportation Research Record 1419*, TRB, National Research Council, Washington, D.C., 1993, pp 78-85.
16. Ray, Malcolm H., Michie, Jarvis D., and Martin Hargrave. Events That Produce Occupant Injury in Longitudinal Barrier Accidents. In *Transportation Research Record 1065*, TRB, National Research Council, Washington, D.C., 1986, pp. 19-30.
17. Ray, M.H., Michie, J.D., and L.R. Calcote. *Evaluation of Design Analysis Procedures and Acceptance Criteria for Roadside Hardware, Volume III: Evaluating Pre-Report 230 Crash Tests*. FHWA RD-87/098, U.S. Department of Transportation, Washington, D.C., 1987.
18. Ross, H.E., Jr., Perera, H.S., Sicking, D.L., and R. P. Bligh. *Roadside Safety Design for Small Vehicles*. NCHRP Report 318, TRB, National Research Council, Washington, D.C., 1988.
19. Ray, M.H. and J. F. Carney. Improved Method for Determining Vehicle and Occupant Kinematics in Full-Scale Crash Tests. In *Transportation Research Record 1233*, TRB, National Research Council, Washington, D.C., 1989.
20. *International Crash Test Standards for Roadside Safety Features*. Transportation Research Circular 451, TRB, National Research Council, Washington, DC, 1995.
21. National Highway Traffic Safety Administration (NHTSA). *Event Data Recorders - Summary of Finding by the NHTSA EDR Working Group*. Final Report. August 2001.
22. Gabler, H.C., Hampton, C., and T. Roston. Estimating Crash Severity: Can Event Data Recorders Replace Crash Reconstruction? *Proceedings of the Eighteenth International Conference on Enhanced Safety of Vehicles*, Paper 490. Nagoya, Japan. May 2003.
23. Chidester, A., Hinch, J., Mercer, T., and K. Schultz. Recording Automotive Crash Event Data. Proceedings of the International Symposium on Transportation Recorders, Arlington, Virginia, May 1999.
24. Association for the Advancement of Automotive Medicine. *The Abbreviated Injury Scale*, 1990 Revision, Update 98.
25. Correia, J.T.; Iliadis, K.A.; McCarron, E.S.; Smole, M.A. June 2001. Utilizing Data From Automotive Event Data Recorders. Hastings, Bouldong, Correia Consulting Engineers. . *Proceedings of the Canadian Multidisciplinary Road Safety Conference XII*; June 10-13, 2001; London, Ontario.

List of Figures

List of Tables

TABLE 1 Current Occupant Risk Threshold Values

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

TABLE 2 The Abbreviated Injury Scale

AIS Value	Injury Characterization
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum/Fatal

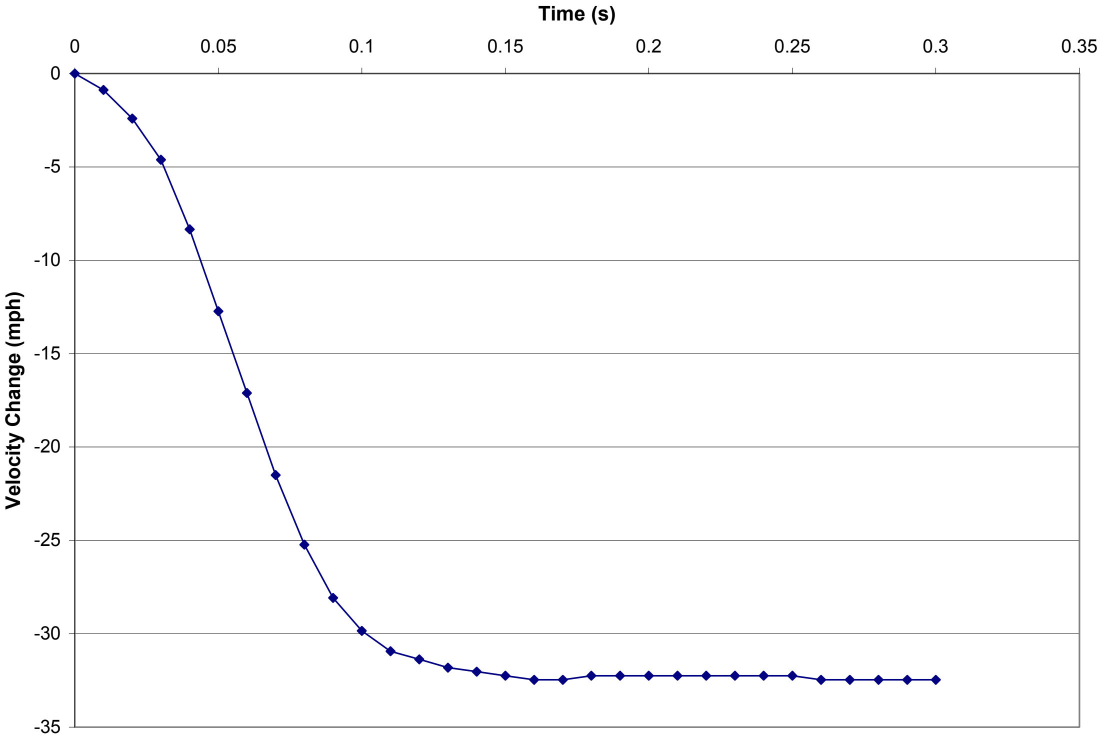

FIGURE 1 Longitudinal Velocity Profile: 1999 Chevrolet Cavalier

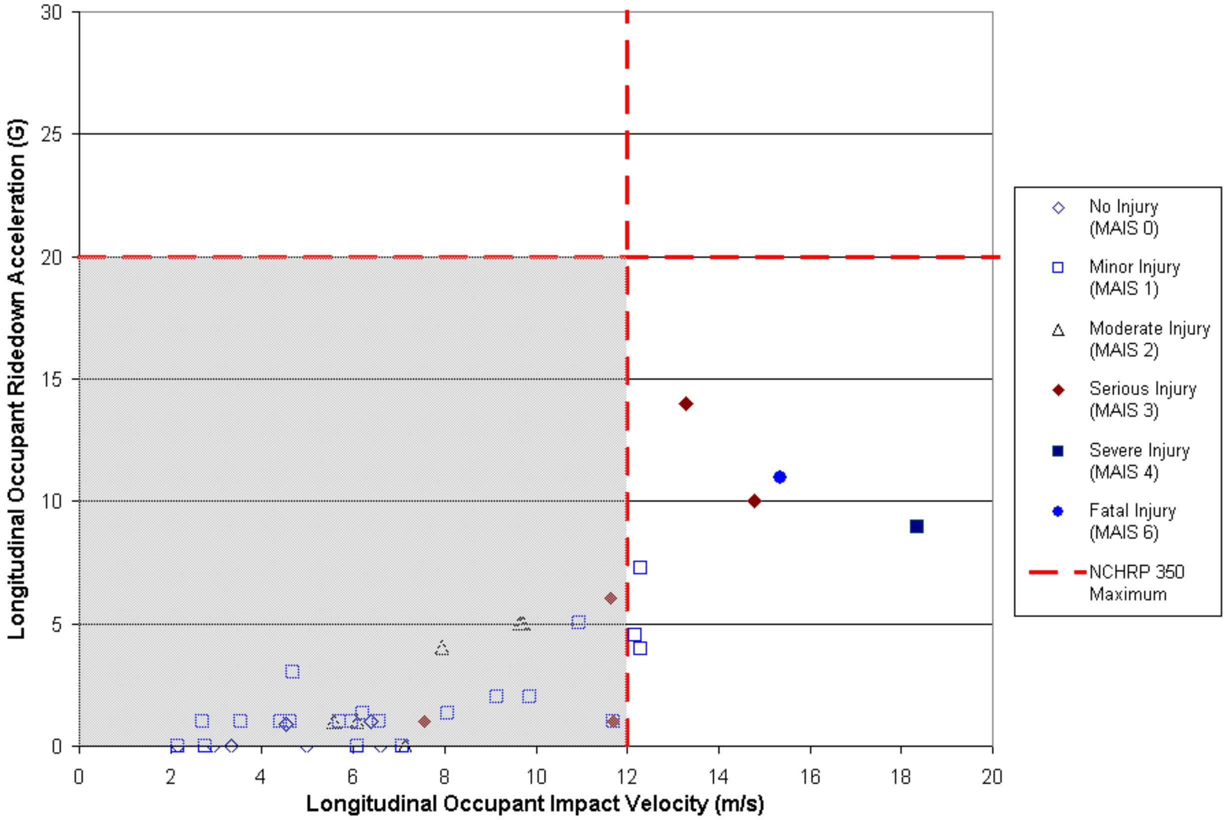

FIGURE 2 Maximum Occupant Injury In Single Event Frontal Collisions

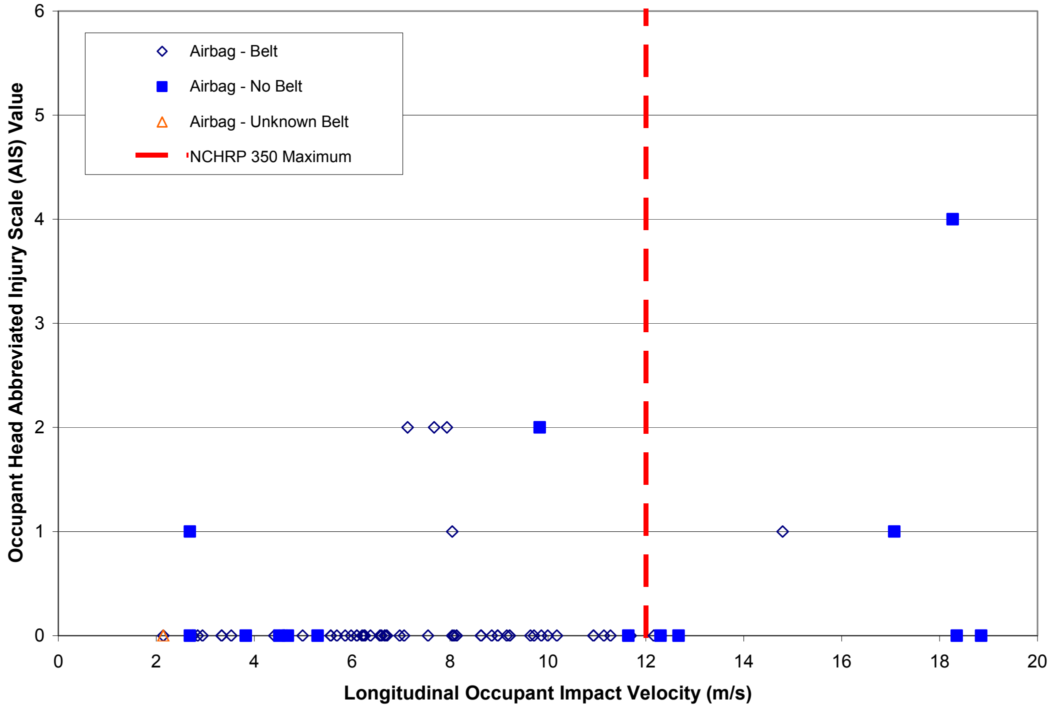

FIGURE 3 Occupant Head Injury in Single Event Frontal Collisions

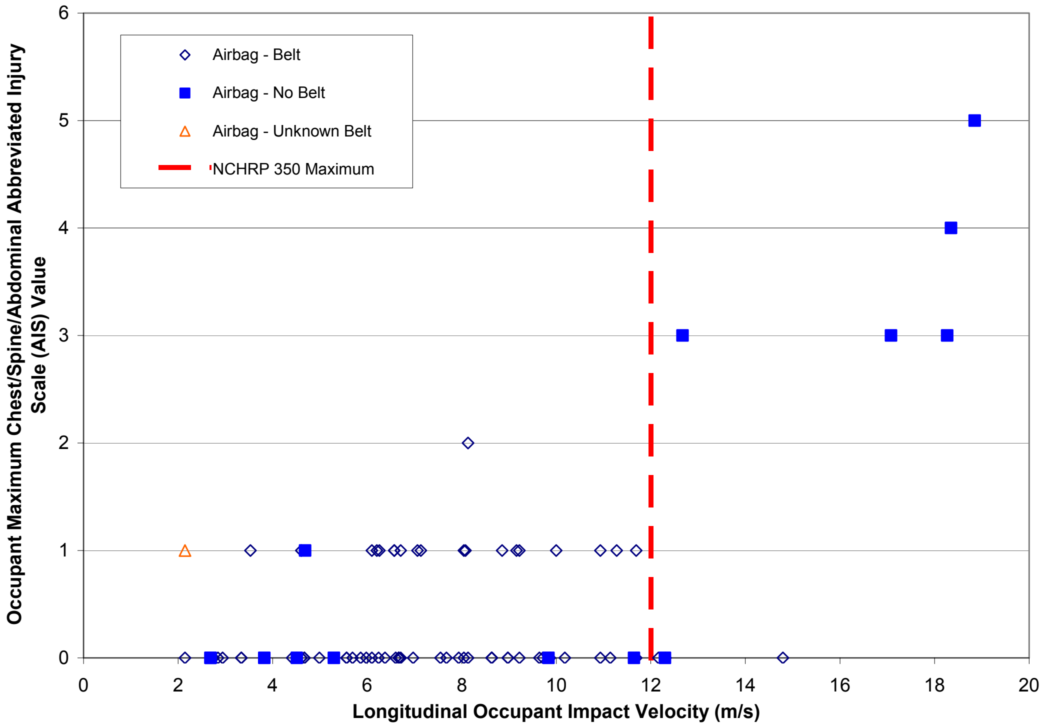

FIGURE 4 Occupant Upper Trunk Injury In Single Event Frontal Collisions

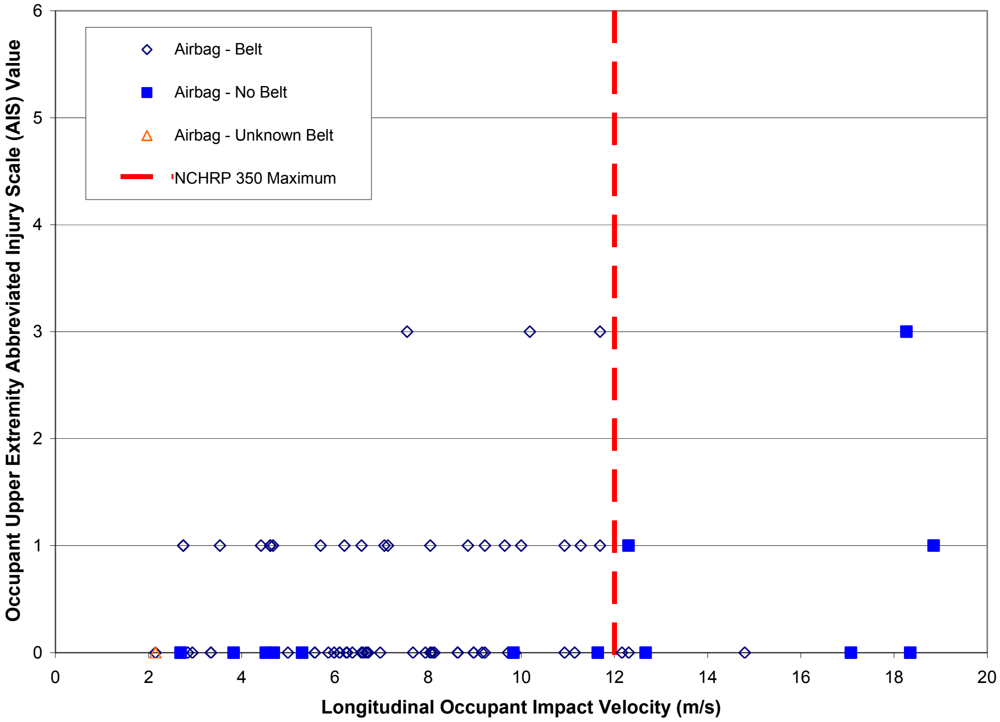

FIGURE 5 Occupant Upper Extremity Injury In Single Event Frontal Collisions

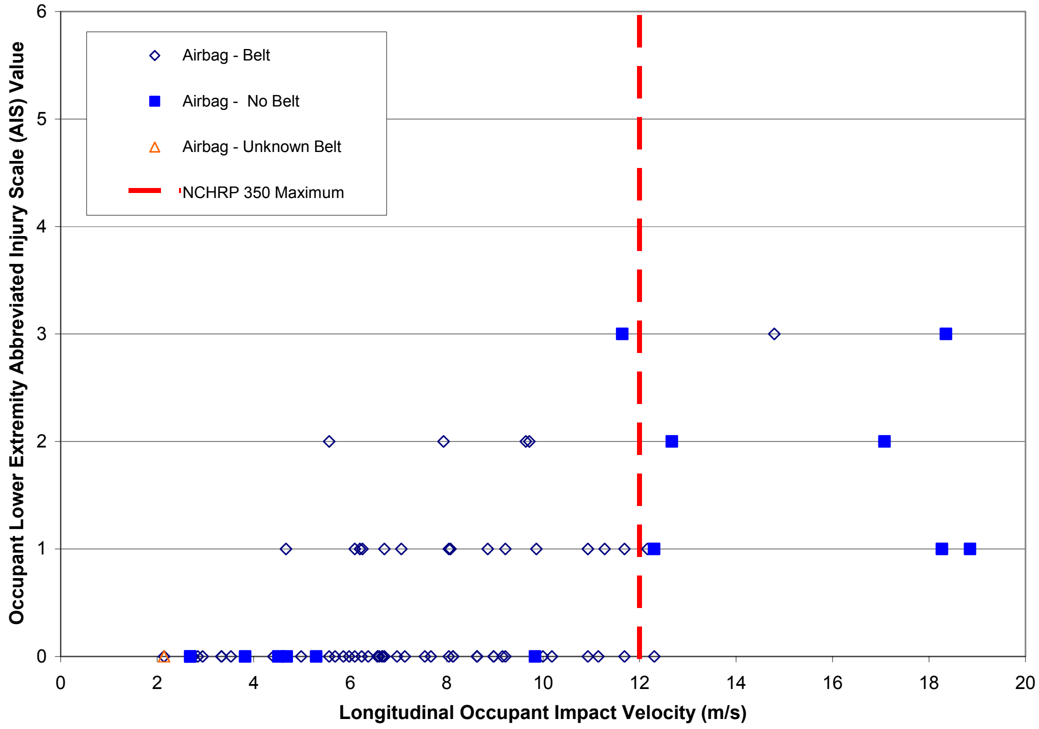

FIGURE 6 Occupant Lower Extremity Injury In Single Event Frontal Collisions