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Comparison of Roadside Crash Injury Metrics using Event Data Recorders

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Title

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Abstract

The occupant impact velocity (OIV) and acceleration severity index (ASI) are competing measures of crash severity used to assess occupant injury risk in full-scale crash tests involving roadside safety hardware, e.g. guardrail. Delta-V, or the maximum change in vehicle velocity, is the traditional metric of crash severity for real world crashes. This study compares the ability of the OIV, ASI, and delta-V to discriminate between serious and non-serious occupant injury in real world frontal collisions. Vehicle kinematics data from Event Data Recorders (EDRs) were matched with detailed occupant injury information for 180 real world crashes. Cumulative probability of injury risk curves were generated using binary logistic regression for belted and unbelted data subsets. By comparing the available fit statistics and performing a separate ROC curve analysis, the more computationally intensive OIV and ASI were found to offer no significant predictive advantage over the simpler delta-V.

Keywords

Roadside, Injury Criteria, Crash, Flail Space Model, Occupant Impact Velocity, Acceleration Severity Index, Delta-V, Event Data Recorders

1. Introduction

Roadside safety hardware, including guardrail and crash cushions, is installed near a roadway to provide a forgiving roadside environment in the event a vehicle departs from the roadway. Full-scale crash testing is the traditional method used to assess the crash performance of these devices (Ross et al., 1993). In each test, a particular device is evaluated in representative worst-case impact scenarios based on the behavior of the vehicle, the behavior of the device, and the potential for injury to vehicle occupants. In the US, roadside crash tests are conducted according to NCHRP Report 350 (Ross et al., 1993). In Europe, roadside crash tests are conducted according to EN-1317 (CEN, 1998).

As the ultimate goal of these devices is to minimize occupant injury, the assessment of occupant risk is crucial. Unlike vehicle crashworthiness testing, however, these crash tests do not use a crash test dummy to assess occupant risk. Instead, occupant injury potential is based on metrics derived from vehicle kinematics measured during the crash test. Since 1981, the US procedures (Ross et al., 1993) have calculated occupant risk using the Flail Space Model (FSM). The European procedures (CEN, 1998) use a variation of the FSM in conjunction with the Acceleration Severity Index (ASI) to gauge occupant injury risk.

Despite extensive use of these vehicle-based metrics, there has been little research into how well these injury metrics predict actual occupant injury. The purpose of this study is to compare and contrast the injury predicting capability of the FSM and ASI roadside safety injury criteria. This study will also compare the FSM and ASI metrics to the traditional vehicle-based metric of crash severity, the maximum vehicle velocity change, or delta-V.

2. Injury Metrics and Correlation to Occupant Injury

2.1 Flail Space Model

Introduced by Michie (1981), the flail space model assumes that occupant injury severity is related to the velocity at which the occupant impacts the interior and the subsequent acceleration experienced by the occupant. The occupant is assumed to be an unrestrained point mass that behaves as a "free-missile" inside the occupant compartment in the event of a collision (see Figure 1). 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 displaced either 0.3 meters laterally or 0.6 meters longitudinally. For ease of computation, 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 (OIV). Once the impact with the interior occurs, the occupant is assumed to remain in contact with the interior and be subjected to any subsequent vehicular acceleration. 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.

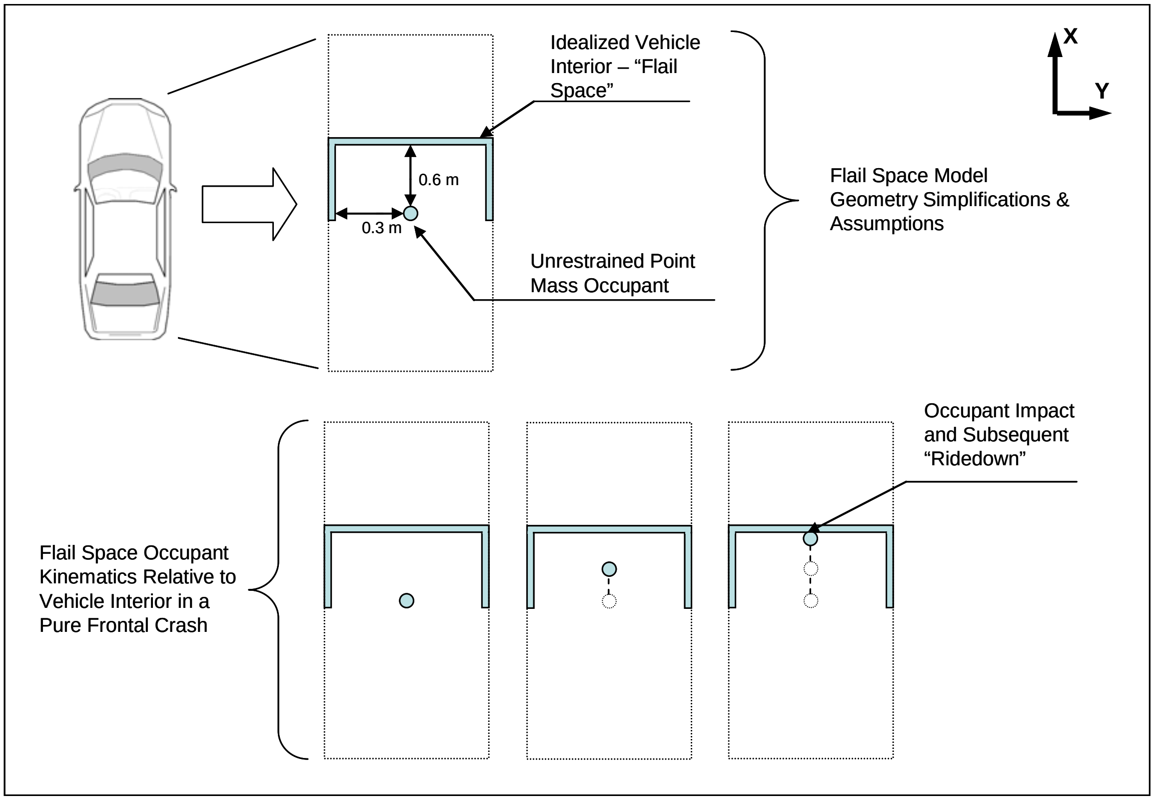

Figure 1. Flail Space Model Assumptions and Simplifications (as described by Michie, 1981)

Both the OIV and subsequent occupant ridedown acceleration are compared with established thresholds to ensure that the device does not create undo risk for the occupants of an impacting vehicle. Current threshold values are prescribed by NCHRP Report 350 (Ross et al., 1993) and are summarized in Table 1. These values are applicable to both the lateral and longitudinal direction. Although values below the "preferred" level are desirable, values below the "maximum" category are considered acceptable. Note that the "maximum" thresholds are intended to correspond to serious but not life-threatening occupant injury (Michie, 1981).

Table 1
Current Flail Space Model Threshold Values

Metric	Preferred Value	Maximum Value
OIV (m/s)	9	12
Ridedown Acceleration (G)	15	20

2.2 The Acceleration Severity Index

Using measured vehicle acceleration information, the ASI is computed using the following relationship (CEN, 1998):

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

where $\overline{a}_x$, $\overline{a}_y$, and $\overline{a}_z$ 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 (CEN, 1998). 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 (CEN, 1998), the ASI preferred threshold corresponds to "light injury, if any". No corresponding injury level, however, is provided for the ASI maximum threshold.

2.3 Correlation to Occupant Injury

Despite long-term usage to evaluate occupant risk in full-scale crash tests of roadside safety hardware, there is little information correlating the FSM to occupant injury. Ray et al. (1986) investigated the occupant injury mechanisms in longitudinal barrier collisions, focusing mainly on the lateral OIV. By reconstructing 17 longitudinal barrier crashes 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. Council and Stewart (1993) attempted to link occupant risk (calculated from crash tests) to actual injury attained in similar real-world collisions but limited data prevented any conclusions. More recently, OIV was found to be a good predictor of maximum occupant injury in 58 frontal crashes (Gabauer and Gabler, 2004a).

Similary, there has been little research relating the ASI to actual occupant injury. Shojaati (2003) attempted to correlate the ASI to risk of occupant injury via the Head Injury Criterion (HIC), a metric used by the National Highway Traffic Safety Administration (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. More recently, the authors examined the ASI threshold values in 120 real-world frontal collisions (Gabauer and Gabler, 2005). The current thresholds were found to be a reasonable marker of "light injury, if any" for belted and airbag-restrained occupants.

In terms of comparing these metrics, preliminary work (Gabauer and Gabler, 2004b) compared the OIV and the ASI in frontal collisions and found the OIV to be a stronger predictor of occupant injury. Although this study was a useful exploratory step, the data set was limited to 66 crashes and lacked strong statistical comparison techniques. More recently, the OIV was found to offer no statistically significant advantage over the traditional and simpler metric of crash severity, delta-V (Gabauer and Gabler, 2006). This study combines and expands these preliminary studies to provide the first comprehensive evaluation and comparison of these three competing crash severity metrics using real world crash data.

3. EDR Technology

Recent advances in vehicle technology have allowed for an unprecedented opportunity to obtain information during a highway traffic collision. Event Data Recorders (EDRs), which are being installed in numerous late model vehicles in conjunction with the advanced occupant safety systems, are similar to "black boxes" in airplanes as they record information in the event of a highway collision (Gabler et al., 2004). Of particular interest to this study is the EDRs ability to record the vehicle velocity profile during a collision event.

Virginia Tech has developed a database of EDR data collected from traffic collisions in the United States from year 2000 through 2005. Currently, the database consists of EDR data for over 2200 cases, all of which are General Motors (GM) vehicles. These EDRs have the ability to store a description of both the crash and pre-crash phase of a collision. Crash parameters in the database include longitudinal delta-V vs. time during the impact at 10 ms intervals (see Figure 2), airbag trigger times, and seat belt status for the driver (Gabler et al., 2003). Pre-crash data includes vehicle speed prior to impact, engine speed, engine throttle position as well as brake status for five seconds preceding the impact. The EDR data was collected in conjunction with the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS), which provides detailed information on a random sampling of approximately 5,000 US crashes annually (USDOT, 1999). This includes detailed occupant injury information that is matched to the available EDR data.

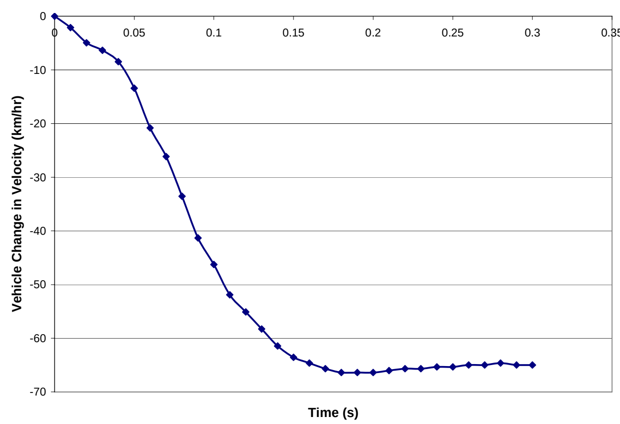

Figure 2. Example EDR Change in Velocity versus Time: 1998 Chevrolet Lumina into Utility Pole, NASS Case 2004-008-112

4. Objective

The purpose of this study is to (1) compare the effectiveness of two roadside crash test injury criteria, the OIV and ASI, based on their injury predicting capabilities in real-world frontal crashes and (2) compare these metrics to the standard crash severity metric, delta-V.

5. Data and Methods

The general methodology for this study included (1) selecting appropriate cases from the Virginia Tech EDR database, (2) computing OIV, ASI and delta-V for each case, (3) fitting binary logistic regression models between the crash injury criteria and occupant injury, and (4) comparing the injury predictive capability of these three crash injury criteria.

5.1 Case Selection

Only cases adhering to the following criteria were included in the analysis: (1) crashes comprised of a single event, (2) airbag deployment, (3) complete EDR vehicle crash pulse data, (4) known driver injury information (including no injury cases), and (5) a frontal collision with no vehicle rollover.

Limiting suitable cases to those involving a single event with airbag deployment ensures that the EDR data corresponds to the injury-producing event. In multiple impact cases, it can be difficult to know which impact caused occupant injury. In addition, if the airbag is not deployed, the GM EDR stores only information pertaining to the event with the highest delta-V and has the ability to overwrite data pertaining to less severe non-deployment events. This makes it difficult to ensure that the EDR data recorded corresponds to the most harmful event noted in NASS/CDS. Once the airbag is deployed, however, the EDR information becomes overwrite protected providing a much higher confidence that the recorded EDR data corresponds to the injury-producing event. EDR delta-V information is required to compute the OIV, ASI and delta-V. An additional stipulation is that the delta-V information is “complete”, or converges to a constant velocity, so that the delta-V or ASI computations are not erroneous. Only occupants seated in the driver position with known injury (or known non-injury) have been included; occupants with unknown injury levels have been excluded. As the GM EDRs in our dataset only measured velocity information in the longitudinal direction, the data set has been constrained to frontal collisions only. For the purpose of this study, a frontal collision was defined as damage to the front of the vehicle and a principal direction of force (PDOF) of 0 degrees plus or minus 10 degrees. A requirement of the flail space model (as well as a meaningful delta-V) is that the vehicle remains upright; thus, vehicle rollover cases were excluded.

A total of 180 cases were identified as suitable for analysis. Of the suitable cases, 145 occupants were restrained by both a belt and airbag while the remaining 35 were restrained only by an airbag. The average occupant age was 38.9 years with range between 16 and 95 years. The final data set included both vehicle-to-fixed object (12%) and vehicle-to-vehicle (88%) collisions. If there is a relationship between roadside injury criterion and occupant injury, this relationship should be equally relevant to vehicle-to-vehicle crashes as vehicle-to-fixed object crashes.

5.2 Computations

5.2.1 Delta-V

For longitudinal delta-V, the largest relative change in vehicle velocity was used from the available EDR information. A comparison of EDR data to accelerometers in 37 full-scale crash tests conducted by Niehoff et al. (2005) suggests that, on average, EDR estimates of frontal crash longitudinal delta-V are within 6 percent of the true delta-V. Figure 3 is a typical comparison of EDR-recorded delta-V to the lab grade instrumentation from the Niehoff study. Note how closely the EDR velocity trace follows the velocity derived from the vehicle-mounted accelerometers. For reference, the coefficient of variation in delta-V of the 35 mph crash tests analyzed by Niehoff et al., as measured by the lab grade instrumentation, was 8.6 percent, which is comparable to the EDR error. In this case, the coefficient of variation was computed by dividing the standard deviation of the delta-V measurements by the mean delta-V.

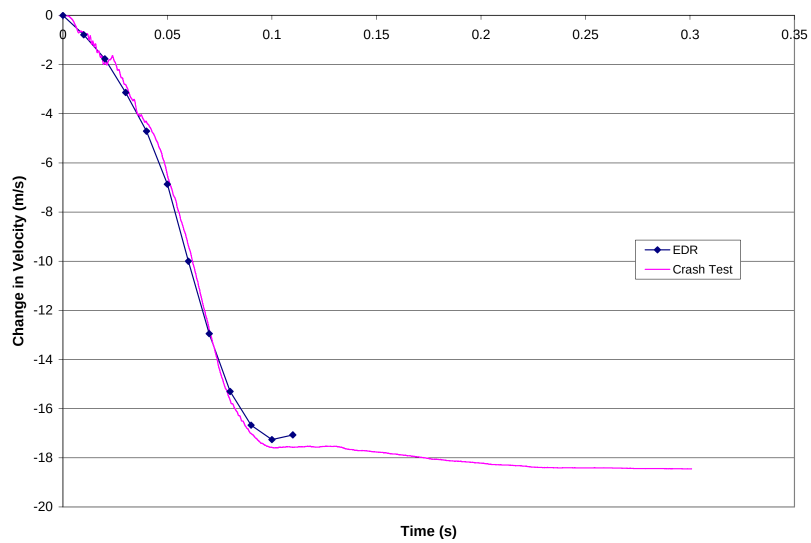

Figure 3. Evaluation of EDR in NHTSA Crash Test 4487 (from Niehoff et al., 2005)

5.2.2 Flail Space Model

For each case, OIV was computed using the following procedure based on NCHRP Report 350 (Ross et al., 1993):

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 OIV. For cases where the theoretical occupant does not exceed the

longitudinal flail space limit, OIV is set to the maximum velocity change of the vehicle (as recorded by the EDR).

For cases where the occupant does not reach the flail space limit, NCHRP 350 specifies OIV to 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. Of the 180 total cases, 45 fall into this category. As expected, the majority of cases were lower severity collisions; no OIV exceeds 9 m/s and 96 percent of the occupants sustained no injury or AIS 1 injuries. The remaining 4 percent (2 occupants) sustained either AIS 2 or AIS 3 level injury. Due to relatively short EDR recording times (typically 100-150 ms), the occupant ridedown acceleration was not examined.

5.2.3 Acceleration Severity Index

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 procedure to compute the longitudinal ASI for the suitable cases has been tailored to the GM EDRs which record longitudinal delta-V in 10ms intervals. The procedure is as follows:

1. Using the measured 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.

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

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 4 illustrates the longitudinal ASI computation for a sample case 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.

To investigate the accuracy of the ASI computations outlined above, six (6) New Car Assessment Program (NCAP) frontal barrier tests conducted by the National Highway Traffic Safety Administration (NHTSA) were examined. Each car tested had GM EDR data available in conjunction with the more detailed vehicle acceleration data typically recorded for the test. As shown in Table 2, 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. The coefficient of variation for the ASI computed from the lab grade instrumentation was 10 percent, which was comparable to the error in ASI computed from the EDR.

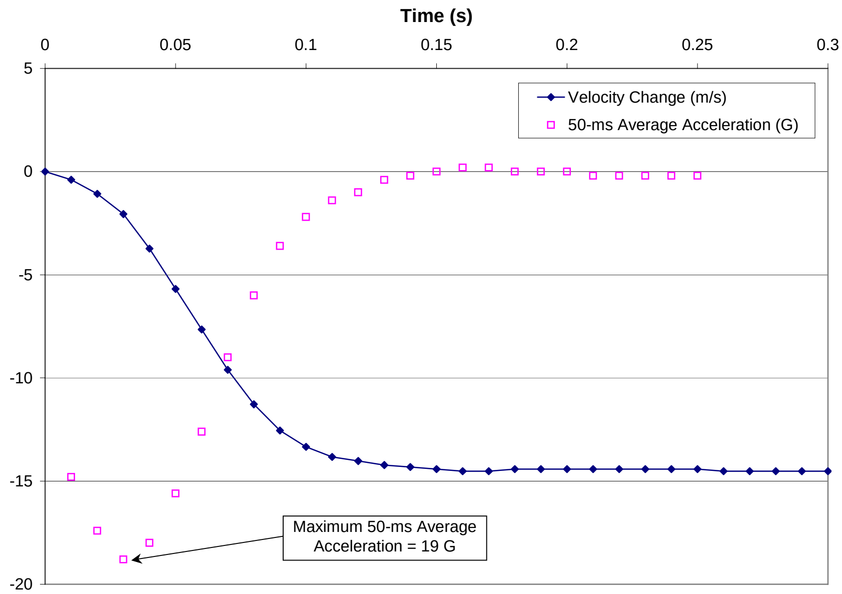

Figure 4. Longitudinal ASI Computation

Table 2
NCAP and EDR ASI Comparison

NHTSA Test Designation	EDR ASI Value (G/G)	NCAP ASI Value (G/G)	% Error
4487	2.07	2.18	-5.0
4472	1.63	1.69	-3.5
4244	2.07	2.24	-7.5
4198	2.02	2.22	-9.0
3952	2.15	2.18	-1.4
3851	1.83	1.76	+4.0

5.3 Model Fitting and Comparison

Binary logistic regression models were fit to the available data using OIV, ASI and then delta-V as a predictor. Occupant injury response was classified into "serious" injury and "non-serious" injury based on the Abbreviated Injury Severity (AIS) scale (AAAM, 2001). Two injury threshold levels were used to define "serious" injury: (1) maximum AIS value of 3 or greater (MAIS 3+), and (2) MAIS 2+. Drivers who were fatally injured as a result of the crash were coded as seriously injured regardless of their MAIS level. For each of these threshold definitions, injury risk curves were generated for all three predictors for two data subsets: (1) belted and airbag restrained occupants (referred to hereafter as 'belted') and (2) airbag-only restrained occupants (referred to hereafter as 'unbelted').

Note that since all three of these metrics are correlated, their relative effect could not be examined by incorporating all three into a single model. The three models were compared using various fit statistics and a Receiver Operating Characteristic (ROC) curve analysis. All statistical analyses were completed with the SAS® v9.1 software.

6. Results

6.1 Logistic Regression Models

Logistic regression results are presented graphically in Figure 5 through Figure 16. Figure 5 and Figure 6 show the MAIS 2+ injury risk curves for the belted and unbelted data subsets, respectively, with OIV as the predictor. Figure 7 and Figure 8 are the OIV injury risk curves for the MAIS 3+ injury level. Similar plots are provided for ASI (Figure 9 through Figure 12) and delta-V (Figure 13 through Figure 16) predictors. The corresponding shaded areas represent the 95 percent confidence bounds. The data points are plotted as a function of each predictor; note that a value of "1" corresponds to the "serious" injury group. As expected, the belted occupants have lower predicted risk of injury for the same predictor value as compared to the unbelted occupants in all cases.

Table 3 summarizes the logistic regression model results. For the belted subset, all tests for the global null hypothesis and Wald Chi Square values were significant to the 0.0003 level or better. For the unbelted subset, all tests for the global null hypothesis and Wald Chi Square values were significant to the 0.025 level or better. As all three of these predictors are continuous, the Hosmer and Lemeshow test is used to determine goodness-of-fit. All models generated statistically adequate (>0.05) fits with Hosmer and Lemeshow values of 0.0961 or greater.

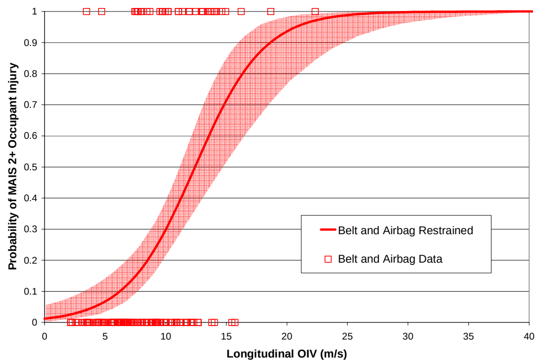

Figure 5. OIV MAIS 2+ Injury Risk Curve, Belted

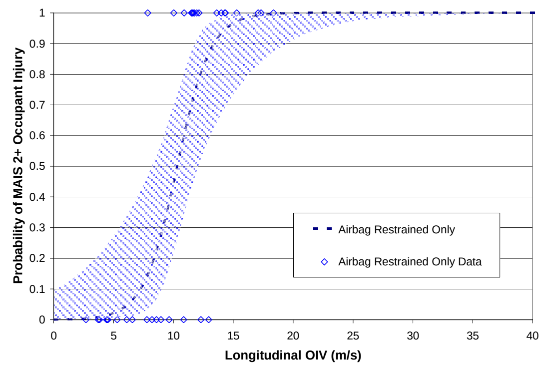

Figure 6. OIV MAIS 2+ Injury Risk Curve, Unbelted

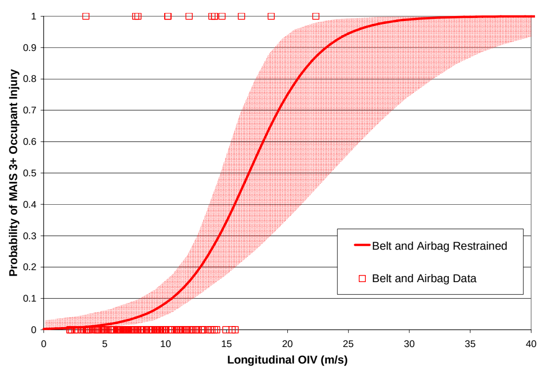

Figure 7. OIV MAIS 3+ Injury Risk Curve, Belted

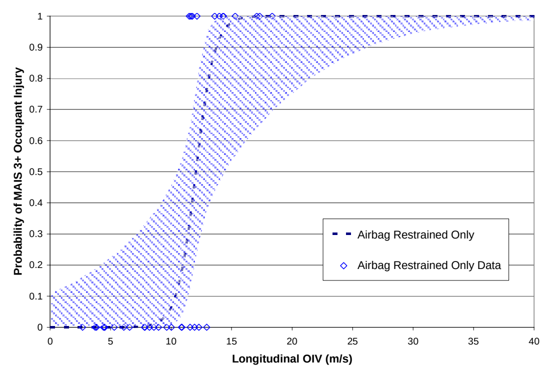

Figure 8. OIV MAIS 3+ Injury Risk Curve, Unbelted

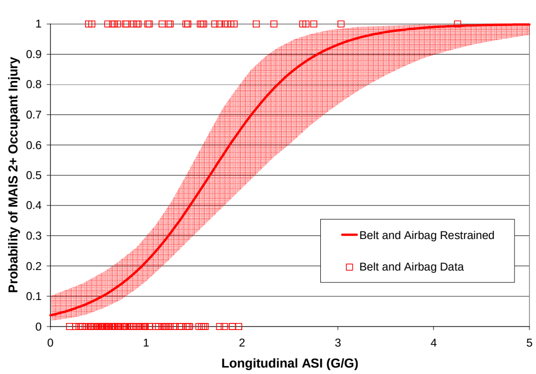

Figure 9. ASI MAIS 2+ Injury Risk Curve, Belted

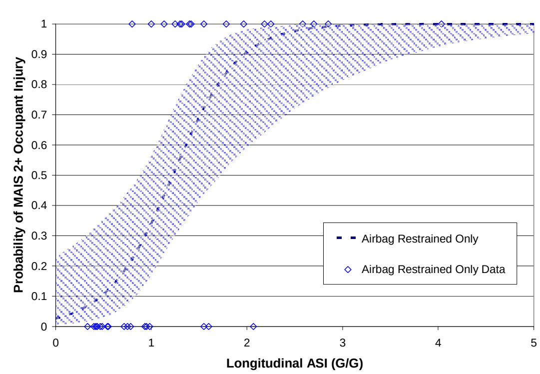

Figure 10. ASI MAIS 2+ Injury Risk Curve, Unbelted

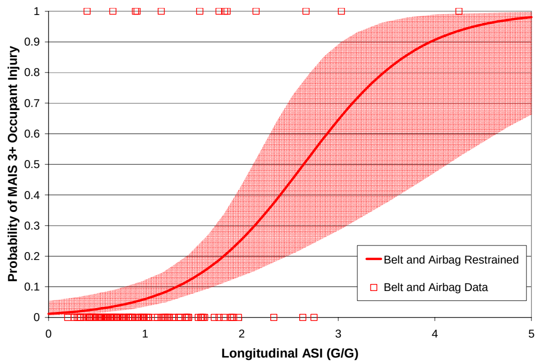

Figure 11. ASI MAIS 3+ Injury Risk Curve, Belted

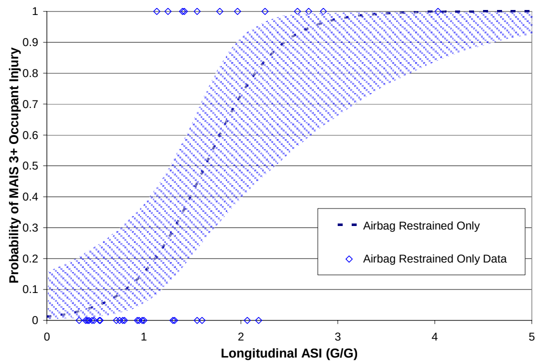

Figure 12. ASI MAIS 3+ Injury Risk Curve, Unbelted

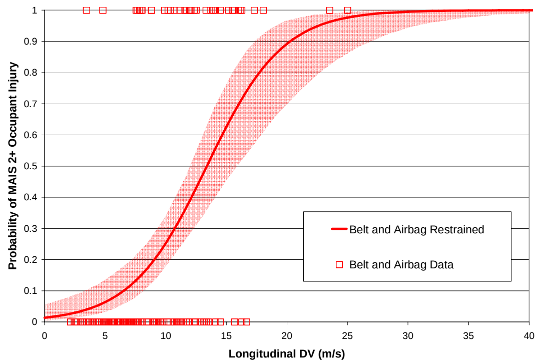

Figure 13. Delta-V MAIS 2+ Injury Risk Curve, Belted

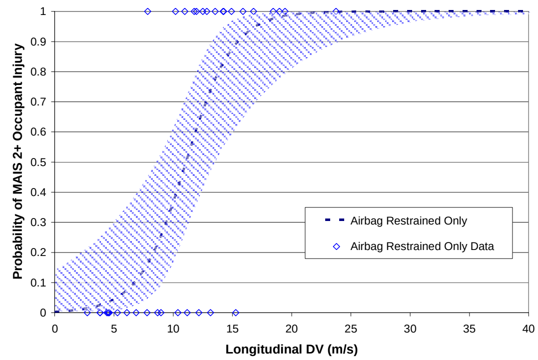

Figure 14. Delta-V MAIS 2+ Injury Risk Curve, Unbelted

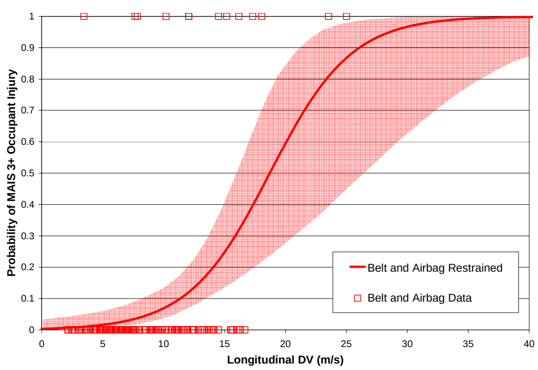

Figure 15. Delta-V MAIS 3+ Injury Risk Curve, Belted

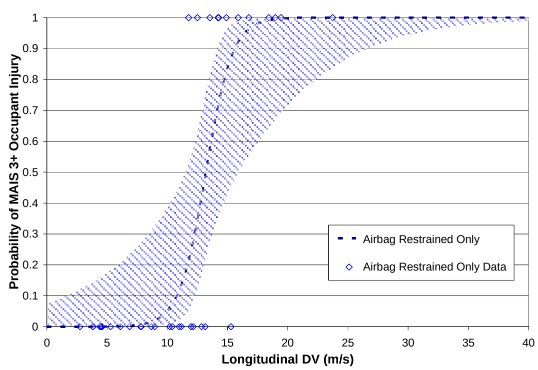

Figure 16. Delta-V MAIS 3+ Injury Risk Curve, Unbelted

Table 3
Summary of Logistic Regression Model Parameters

Injury Level	Predictor	Data Set	Model Parameter Estimate	Std. Error	Wald χ^2	(p)	Hosmer & Lemeshow
3+	Delta-V	Belted	0.2991	0.0808	13.71	(0.0002)	0.1663
		Unbelted	0.9174	0.3741	6.014	(0.0142)	0.7043
	OIV	Belted	0.3477	0.0950	13.39	(0.0003)	0.0961
		Unbelted	1.3210	0.5880	5.047	(0.0247)	0.9896
	ASI	Belted	1.6725	0.4576	13.36	(0.0003)	0.4312
		Unbelted	2.6850	0.9087	8.731	(0.0031)	0.5801
2+	Delta-V	Belted	0.3199	0.0642	24.82	(<0.0001)	0.2892
		Unbelted	0.5043	0.1663	9.195	(0.0024)	0.6277
	OIV	Belted	0.3542	0.0722	24.06	(<0.0001)	0.1191
		Unbelted	0.7195	0.2427	8.787	(0.0030)	0.3051
	ASI	Belted	1.9571	0.4205	21.67	(<0.0001)	0.5922
		Unbelted	2.9351	0.9885	8.817	(0.0030)	0.2539

6.4 Model Comparison

OIV is intended to indicate occupant risk for an unrestrained occupant while the ASI is intended to predict risk for a belted occupant. Based on the assumptions of each model, we would expect the OIV to predict injury better for unbelted occupants and ASI to predict injury better for belted occupants. Likewise, we would expect ASI to better predict lower severity (MAIS 2+) injury and OIV to better predict higher severity (MAIS 3+) injury. Both of these metrics will be compared to the baseline measure of crash severity, delta-V.

6.4.1 Fit Statistics

Table 4 presents a summary of the fit statistics for the models generated using all three predictors. Measures of fit reported are the Akaike Information Criterion (AIC), where lower ‘intercept and covariate’ values indicate a better fit, and the maximum rescaled R^2 value where larger values indicate better fits.

Table 4
Summary of Model Fit Parameters

			Goodness-of-Fit Statistic		
			AIC		
Level	Data Set	Predictor	Intercept Only	Intercept and Covariate	Max Rescaled R^2
3+	Belted	OIV	89.50	73.32	0.2601
		ASI	89.50	74.59	0.2431
		Delta-V	89.50	72.50	0.2711
	Unbelted	OIV	47.00	19.75	0.7829
		ASI	47.00	30.83	0.5597
		Delta-V	47.00	20.94	0.7621
2+	Belted	OIV	164.53	132.84	0.3076
		ASI	164.53	135.74	0.2838
		Delta-V	164.53	130.61	0.3255
	Unbelted	OIV	50.49	27.18	0.6866
		ASI	50.49	33.62	0.5558
		Delta-V	50.49	30.43	0.6237

In general, the model fits are very similar. All three metrics predict injury better for unbelted occupants as the maximum rescaled R^2 values are largest and the AIC values have a larger reduction with the addition of the covariate. This could be partially attributed to the larger proportion of "serious" injuries present in the unbelted data sets. As expected, OIV appears to predict injury slightly better for unbelted occupants than either ASI or delta-V. ASI appears to have no advantage for belted occupants, even for the MAIS 2+ injury case where the R^2 value is the lowest and the AIC is the largest. All the values, however, are close to one another indicating similar fits between the more complex roadside criteria and delta-V, the traditional metric of crash severity.

Table 5 shows how well each model predicts the original data set assuming that a probability of serious injury greater than 50 percent results in "serious" occupant injury. "Correct" refers to the percentage of correct predictions. Sensitivity is a numerical measure of how well the model can predict serious injury when serious injury is observed while specificity is a measure of how well the model can avoid predicting injury when no injury is present. A value of 100 percent in each of the three categories would denote a model that matches the observed data perfectly.

Again, the OIV appears to be a slightly better predictor of injury for MAIS 2+ unbelted occupants with an increased sensitivity compared to ASI and delta-V. For the MAIS 3+ injury level, delta-V appears to be the best predictor for unbelted occupants. For belted occupants, all three metrics are less sensitive predictors of injury. ASI appears to have a slight advantage for MAIS 2+ injury to belted occupants. Again, however, note the similarity between all three criteria.

Table 5
Correlation of Models to Available Data (50% Probability of Injury)

Level	Data Set	Predictor	Correct (%)	Sensitivity (%)	Specificity (%)
3+	Belted	OIV	92.4	15.4	100.0
		ASI	91.0	15.4	98.5
		Delta-V	92.4	15.4	100.0
	Unbelted	OIV	80.0	66.7	87.0
		ASI	77.1	58.3	87.0
		Delta-V	88.6	83.3	91.3
2+	Belted	OIV	80.0	38.9	93.6
		ASI	80.7	36.1	95.4
		Delta-V	80.0	38.9	93.6
	Unbelted	OIV	85.7	88.2	83.3
		ASI	80.0	76.5	83.3
		Delta-V	80.5	82.4	77.8

6.4.2 ROC Comparison

To further compare OIV, ASI and delta-V, an ROC curve analysis was performed for the belted and unbelted data subsets. Figure 17 through Figure 20 provide a graphical comparison of the ROC curves. Referring to the figures, note that an ROC curve that follows the diagonal offers no advantage over random guessing while a curve that follows the left and upper bounds of the plot is a perfect predictor. From inspection, both OIV and delta-V are better predictors of serious injury for unbelted occupants, which is also evident previously from the higher R^2 values.

The area under the ROC curve provides a means of statistically comparing different predictors. Pairwise comparisons of the area under the ROC curve for all three predictors are summarized in Table 6. In all cases, the p-values exceed 0.05 suggesting no statistically significant difference between the area under the respective ROC curves. This implies that there is no statistically significant difference in injury predicting capability between OIV, ASI or delta-V.

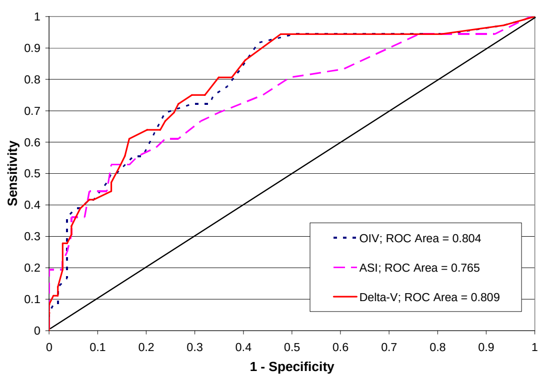

Figure 17. ROC Curve Comparison: Belted Occupants, MAIS 2+

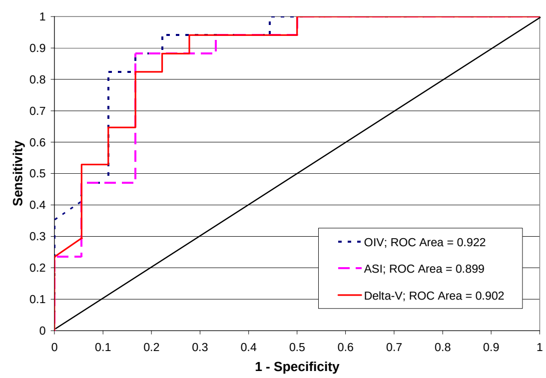

Figure 18. ROC Curve Comparison: Unbelted Occupants, MAIS 2+

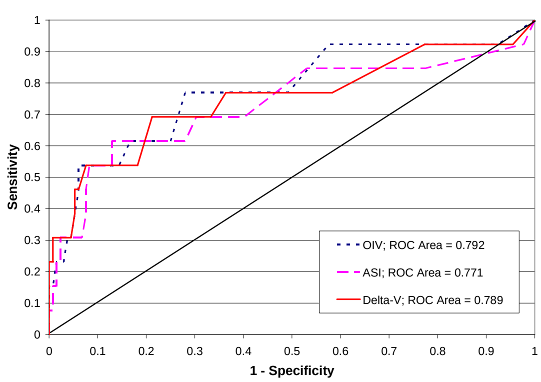

Figure 19. ROC Curve Comparison: Belted Occupants, MAIS 3+

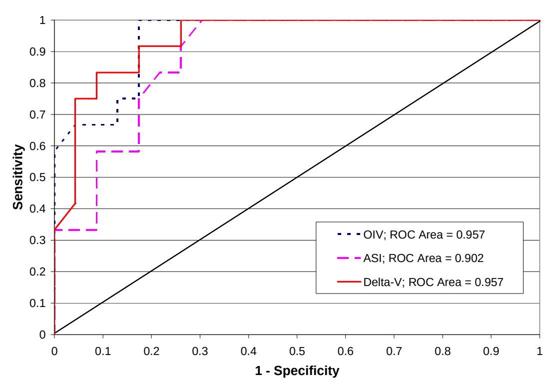

Figure 20. ROC Curve Comparison: Unbelted Occupants, MAIS 3+

Table 6
Summary of ROC Pairwise Comparisons

Level	Comparison	Data Subset	p
3+	OIV vs. ASI	Belted	0.532
		Unbelted	0.105
	OIV vs. Delta-V	Belted	0.862
		Unbelted	1.000
	ASI vs. Delta-V	Belted	0.629
		Unbelted	0.146
2+	OIV vs. ASI	Belted	0.108
		Unbelted	0.374
	OIV vs. Delta-V	Belted	0.679
		Unbelted	0.256
	ASI vs. Delta-V	Belted	0.082
		Unbelted	0.916

7. Discussion

The primary finding of this study is that neither OIV nor ASI offer a significant advantage over the simpler delta-V metric in terms of predicting serious occupant injury in real world frontal crashes. Based on the available data, all three metrics appear to be reasonable predictors of overall occupant injury. All three metrics were found to be better predictors of injury for unbelted occupants. For the OIV, this is intuitive as the occupant is modeled as an unrestrained occupant. Likewise, vehicle delta-V is more representative of the force experienced by an unbelted occupant. Belted occupants have very different kinematics than unbelted occupants. None of the three competing metrics appear to predict injury to belted occupants as well as to unbelted occupants. As current belt usage rates in the US exceed 80 percent (NHTSA, 2007), this has important policy repercussions for the continued use of OIV to design roadside barriers.

Despite being originally designed for belted occupants, the ASI did not exhibit a greater ability than OIV to predict serious occupant injury for belted occupants. Note that the models using any of the three predictors had a reduced ability to predict injury when injury was observed in the belted population (sensitivity ≤ 39 percent). Again, this underscores the importance of developing metrics that are able to predict injury to restrained occupants.

Limitations are that this study investigated purely frontal collisions and cannot necessarily be extrapolated to all collision modes. Newer versions of the GM EDR, however, will provide velocity information in the lateral direction (Niehoff et al., 2005). Additional cases with lateral and longitudinal velocity information could provide information on how these metrics predict occupant injury severity in a broader set of collision modes. It should be noted, however, that although the OIV and ASI are used primarily for oblique collisions, both have been developed by combining biomechanical data obtained from purely frontal and side impact data. Another study limitation is that data is limited to a single vehicle manufacturer. Although large variations across manufacturers is not expected, only GM vehicles have been included in the analysis.

With respect to the EDRs, there is the potential for EDRs to underestimate vehicle delta-V but based on previous research, the EDR estimate is within 6 percent of true delta-V, on average (Niehoff et al. 2005). This error, or the resulting error in OIV or ASI, was not accounted for in the logistic regression models which may cause overestimation of the models' performance. One concern that has been raised is the relatively short EDR recording duration; in this study, this issue has been addressed by using only cases with complete EDR vehicle velocity information. Also, the EDR data did not allow for analysis of the occupant ridedown acceleration component of the flail space model. Previous work (Gabauer and Gabler, 2004) revealed that there was no apparent correlation between occupant injury and the ridedown acceleration in frontal collisions. Although useful for crash events with longer durations, such as vehicle to guardrail, the occupant ridedown acceleration is not believed to be as significant as OIV in predicting injury for shorter duration frontal collisions. Regardless, it would be interesting to revisit this issue, should longer duration EDR data be available in future studies.

8. Conclusions

This study has conducted an analysis of the OIV, ASI, and delta-V injury criteria based on EDR data coupled with detailed injury data for 180 real-world crashes. The study has generated injury risk curves to predict the probability of serious occupant injury in frontal collisions using OIV, ASI and delta-V as predictors. The study found that the more computationally intensive OIV and ASI offer no statistically significant advantage over the simpler delta-V crash severity metric in discriminating between serious and non-serious occupant injury. Despite being designed specifically for restrained occupants, the ASI appears to offer no advantage over OIV or delta-V for belted occupants.

9. Acknowledgements

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