

COMPARISON OF DELTA-V AND OCCUPANT IMPACT VELOCITY CRASH SEVERITY METRICS USING EVENT DATA RECORDERS

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ABSTRACT

This research compares the ability of delta-V and the occupant impact velocity (OIV), a competing measure of crash severity, to predict occupant injury in real world collisions. A majority of the analysis is performed using 191 cases with vehicle kinematics data from Event Data Recorders (EDRs) matched with detailed occupant injury information. Cumulative probability of injury risk curves are generated using binary logistic regression for all data, a belted subset, and an unbelted subset. By comparing the available fit statistics and performing a separate ROC curve analysis, the more computationally intensive OIV is found to offer no significant predictive advantage over delta-V.

Delta-V has traditionally been used as a measure of crash severity and predictor for occupant injury for vehicular crashes. The occupant impact velocity (OIV), as defined by the flail space model (Michie, 1981), is a competing severity metric used by the roadside safety community to evaluate occupant risk. Unlike delta-V, the OIV requires a full crash pulse to calculate a theoretical impact velocity of the occupant with the vehicle interior. Although this provides a more physically representative model of occupant kinematics, there has been no study to date evaluating whether the flail space model provides additional benefit in terms of injury prediction in real world collisions.

INJURY METRICS AND INJURY CORRELATION

DELTA-V – The longstanding metric of crash severity is simply defined as the total change in vehicle velocity over the duration of the crash event. This severity metric is the most widely used in crash databases and is typically estimated using measured vehicle post-crash damage in tandem with computer codes such as WinSmash or CRASH3 (Gabler et al., 2003). Intuitively, the

assumption is that larger changes in velocity correlate with a higher propensity for occupant injury.

Since vehicle kinematics information has traditionally been unavailable for real-world collisions, researchers have long used delta-V as a surrogate metric to relate gross vehicle kinematics to resultant occupant injury. Most recently, Dischinger et al. (1998) investigated the association between delta-V and subsequent medical complications. Winnicki and Eppinger (1998) developed chest injury risk curves for varying injury and delta-V levels in conjunction with a methodology to evaluate benefits associated with depowering airbags. To generate the frontal collision risk curves, the researchers applied logistic regression to weighted data from the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) for years 1991 through 1996 (402 unweighted cases total). There is no discussion, however, on how well the models fit the available data. Bahouth et al. (2004) generated a statistical predictive model based on delta-V for application in the URGENCY algorithm, a model used to assess the likelihood of injury in the event of a vehicular collision. The model was based on NASS/CDS data between 1997 through 2002 and included all crash modes and did not distinguish by occupant restraint. Models have even been generated to relate delta-V to specific population subsets, such as children involved in frontal impacts (Nance et al., 2006).

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 forces. 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. 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 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 (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.

Both the OIV 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 are prescribed by NCHRP Report 350 (Ross et al., 1993) and are summarized in Table 1. Note that these values are applicable to both the lateral and longitudinal direction. The OIV limit is based mainly on frontal head-form impacts into windshields (Kay et al., 1973; Begeman et al., 1978) and a statistical study of side collisions in France (Hartman et al., 1976). Occupant ridedown acceleration threshold values have been established from exhaustive human impact tolerance review documents from the 1970's (Snyder, 1970; Chi, 1976).

Table 1 – Current Flail Space Model Threshold Values

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

Despite long-term usage to evaluate occupant risk in full-scale crash tests of roadside safety hardware, there is little information correlating the flail space model 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 frontal crashes (Gabauer and Gabler, 2004)

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.

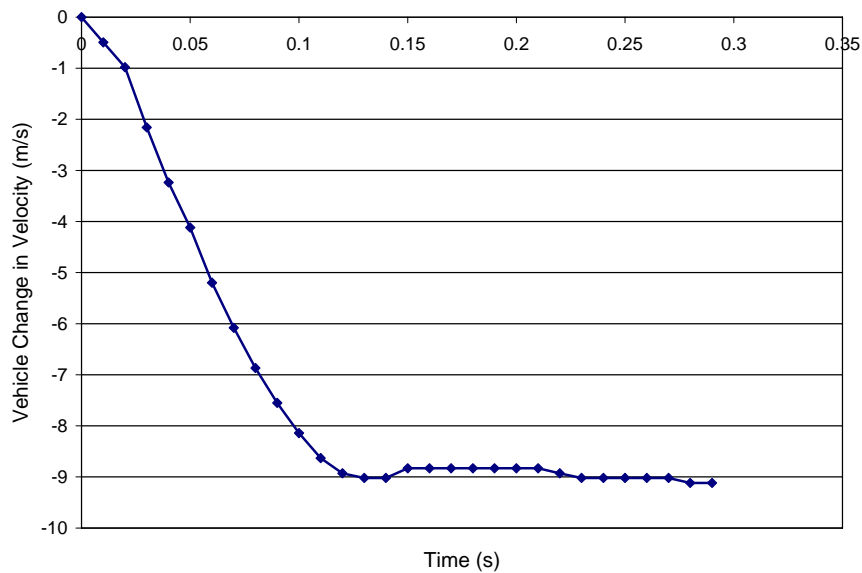


Figure 1 – EDR Change in Velocity vs. Time

The National Highway Traffic Safety Administration (NHTSA) collects EDR data in conjunction with NASS/CDS. Currently, the database consists of EDR data for over 1700 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 (see Figure 1), 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. As these cases were collected in conjunction with NASS/CDS, the corresponding occupant injury information is matched to the available EDR data.

OBJECTIVE

This research aims to determine if the OIV offers a significant advantage over delta-V in terms of predicting injury for real world crashes.

METHODS

The general methodology for this study included (1) selecting appropriate cases from the NHTSA EDR database, (2) computing delta-V and OIV for each case, (3) fitting binary logistic regression models to the available data, and (4) comparing the results of the OIV and delta-V models.

CASE SELECTION – Only cases adhering to the following criteria were included in the analysis:

- Crashes comprised of a single event
- Airbag deployment
- Complete EDR vehicle velocity versus time information
- Known occupant injury for either left or right front seat occupant
- Frontal collision with no vehicle rollover

Limiting suitable cases to those involving a single event as well as airbag deployment ensures that the EDR data corresponds to the injury-producing event. EDR velocity information is required to compute the OIV and delta-V. An additional stipulation is that the velocity information is “complete”, or converges to a constant velocity, so that the delta-V computation is not erroneous. As the GM EDRs in our dataset only measure 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 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. A requirement of the flail space model (as well as a meaningful delta-V) is that the vehicle remains upright; thus, vehicle rollover is not permitted.

A total of 191 cases were identified as suitable for analysis; 146 left front seat occupant cases and 45 right front seat occupant cases. Of the suitable cases, 158 occupants were restrained by both a belt and airbag while the remaining 33 were restrained only by an airbag. The average occupant age was 38.3 years with range between 8 and 95 years. 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.

COMPUTATIONS – 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 EDRs estimate frontal crash longitudinal delta-V to within 6 percent of the actual value. Figure 2 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. One concern that has been raised is the relatively short EDR recording duration; in this study this has been addressed by using only cases with complete EDR vehicle velocity information.

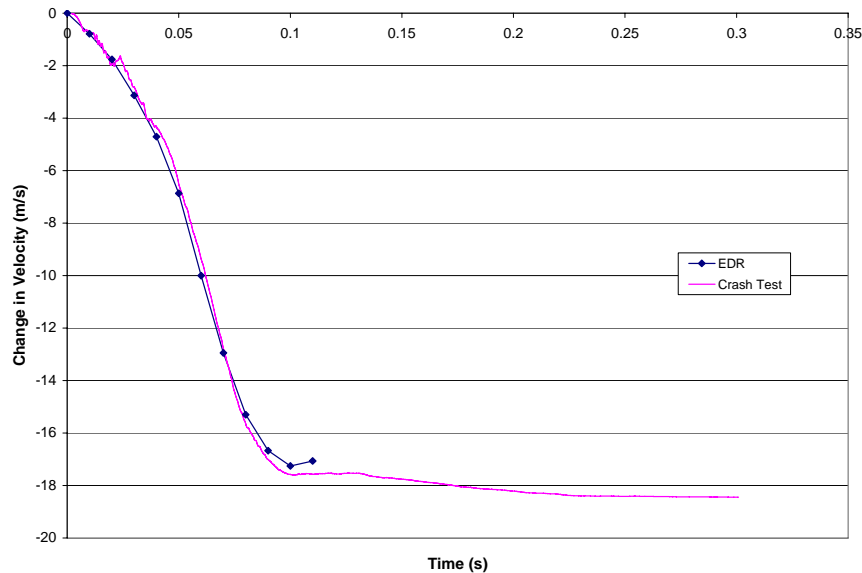


Figure 2 – Evaluation of EDR in NHTSA Crash Test 4487 (from Niehoff et al., 2005)

To compute the OIV for each case, EDR relative velocity data was first numerically integrated to obtain relative occupant position as a function of time. Following the flail space methodology, the occupant was assumed to strike the vehicle interior after traveling 60 cm (Ross et al., 1993). The impact time and EDR relative velocity were then used to obtain the longitudinal OIV. A more detailed description of the computational procedure is provided in a previous article by the authors (Gabauer and Gabler, 2004). Due to relatively short EDR recording times (typically 100-150 ms), the occupant ridedown acceleration was not examined. A total of 209 cases were available for the OIV analysis; the additional 18 cases were instances where the EDR velocity information was incomplete but the theoretical occupant impact occurred prior to the termination of the velocity data. For these cases, the OIV is valid but the delta-V is potentially erroneous.

MODEL FITTING AND COMPARISON – Binary logistic regression models were fit to the available data using delta-V as a predictor and then using OIV as a predictor. Occupant injury response was classified as “serious” or “non-serious” based on the Abbreviated Injury Severity (AIS) scale (AAAM, 2001). For this study, “serious” injury was defined as a maximum AIS value (MAIS) of 3 or greater while “non-serious” injury was defined as $MAIS \leq 2$. Injury risk curves were then generated for both predictors for all data and two 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 OIV and delta-V are correlated, their relative effect could not be examined by incorporating both into a single model. The two 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.

RESULTS

DELTA-V – Figure 3 presents the injury risk curve and corresponding 95 percent confidence bounds (dashed lines) generated based on all 191 suitable delta-V cases. Also, the data points are plotted as a function of longitudinal delta-V; note that a value of “1” corresponds to the “serious” injury group. For the entire dataset and the belted/unbelted subsets, all tests for the global null hypothesis were significant to the 0.0001 level or better and the Wald Chi Squares for the delta-V predictor were significant to the 0.0032 level or better. Table 2 summarizes the delta-V regression coefficients and evaluation of significance.

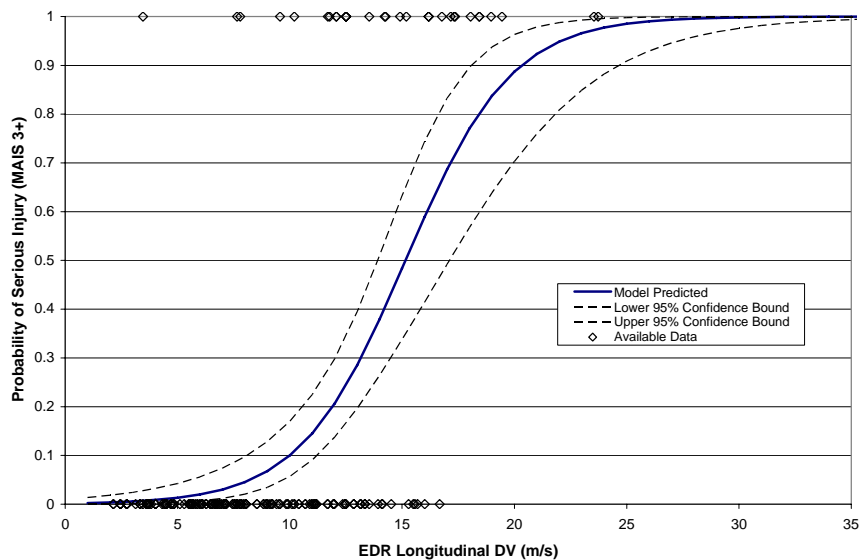


Figure 3 –Injury Risk as a Function of Delta-V: All Occupants

Table 2 – Summary of Delta-V Model Parameters

Data Set	Delta-V Parameter			
	Estimate	Standard Error	Wald χ^2	P
All	0.4262	0.0751	32.24	<0.0001
Belted	0.3566	0.0867	16.91	<0.0001
Unbelted	0.5472	0.1854	8.714	0.0032

Figure 4 provides an overlay of the delta-V injury risk curves for all data, the belted subset, and the unbelted subset. As expected,

the belted occupants have lower predicted risk of injury for the same delta-V compared to unbelted occupants.

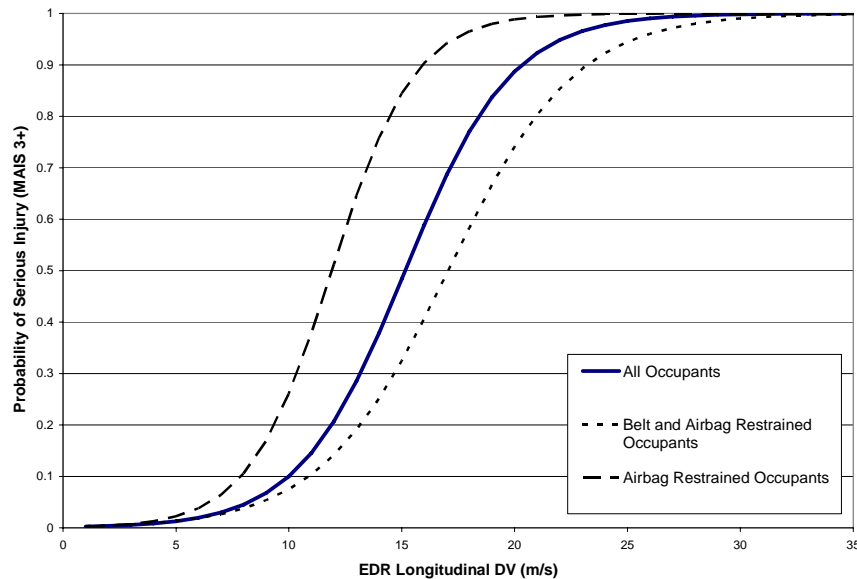


Figure 4 – Delta-V Injury Risk Comparison by Restraint

Table 3 presents a summary of the fit statistics for the generated models. As the delta-V predictor is continuous, the Hosmer and Lemeshow test is used to determine goodness-of-fit. All models generated statistically adequate (>0.05) fits with values of 0.0846 or greater. The unbelted model appears to provide a better fit to the available data with lower Akaike Information Criterion (AIC) values and the largest Hosmer and Lemeshow value. This could be partially attributed to the larger proportion of “serious” injuries present in the unbelted data set.

Table 3 – Summary of Delta-V Fit Statistics

Data Set	Hosmer & Lemeshow Goodness-of-Fit	AIC Model Fit Statistics	
		Intercept Only	Intercept and Covariate
All	0.1185	168.08	111.76
Belted	0.0846	101.17	78.80
Unbelted	0.7898	47.48	25.52

OCCUPANT IMPACT VELOCITY – Figure 5 is the injury risk curve and corresponding 95 percent confidence bounds (dashed lines) generated based on all 209 suitable OIV cases (168 belted and 41 unbelted). Also, the data points are plotted as a function of longitudinal OIV; note that a value of “1” corresponds to the “serious” injury group. For the entire dataset and the belted/unbelted subsets, all tests for the global null hypothesis were significant to the 0.0001 level or better and the Wald Chi Square values were

significant to the 0.001 level or better. Table 4 summarizes the OIV regression coefficients and evaluation of significance.

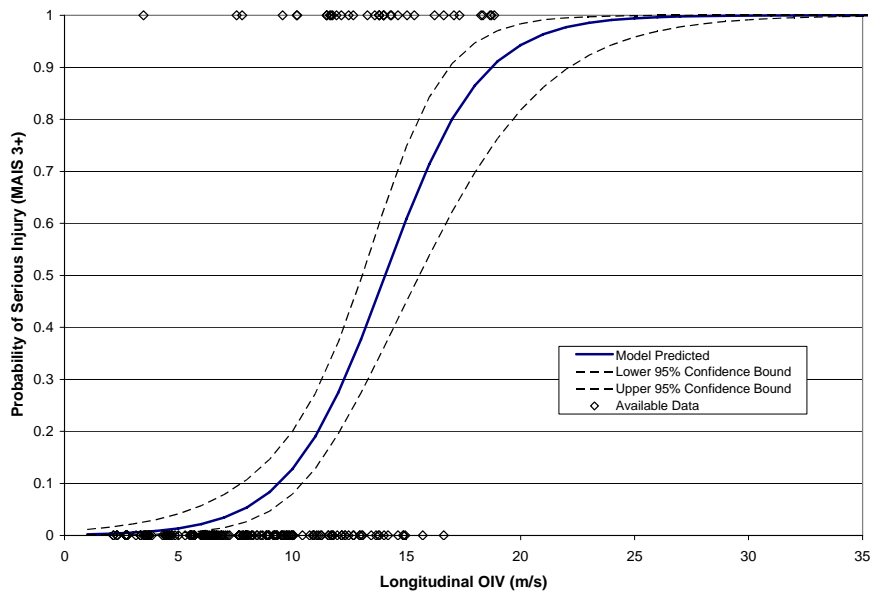


Figure 5 - Injury Risk as a Function of OIV: All Occupants

Table 4 – Summary of OIV Model Parameters

Data Set	OIV Parameter			
	Estimate	Standard Error	Wald χ^2	P
All	0.4725	0.0775	37.21	<0.0001
Belted	0.3746	0.0959	15.24	<0.0001
Unbelted	0.5636	0.1709	10.88	0.001

Figure 6 provides an overlay of the OIV injury risk curves for all data, the belted subset, and the unbelted subset. Similar to the delta-V results, the belted occupants have lower predicted risk of injury for the same delta-V compared to the unbelted occupants. Table 5 presents a summary of the fit statistics for the models generated using OIV as a predictor. According to the Hosmer and Lemeshow test, all models generated relatively good fits with values of 0.1816 or greater. Again, the unbelted model appears to provide a better fit to the available data with lower Akaike Information Criterion (AIC) values and the largest Hosmer and Lemeshow value.

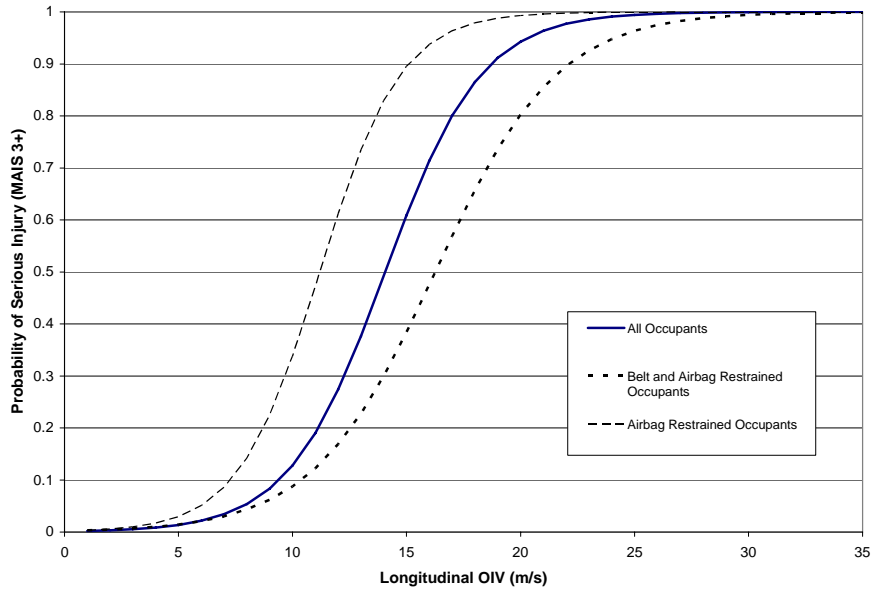


Figure 6 - OIV Injury Risk Curve Comparison by Restraint

Table 5 – Summary of OIV Fit Statistics

Data Subset	Hosmer & Lemeshow Goodness-of-Fit	AIC Model Fit Statistics	
		Intercept Only	Intercept and Covariate
All	0.1816	194.04	130.28
Belted	0.3610	103.10	85.00
Unbelted	0.6269	58.81	33.57

COMPARISON – To provide a comparison between the two predictive models, the OIV binomial logistic regression was refit to the smaller 191 case data set used for the delta-V analysis (191 cases as opposed to 209). Table 6 presents a summary of the AIC values; note the closeness of the AIC values indicating similar fits.

Table 6 – Summary of AIC Comparison Fit Statistics

Data Subset	Predictor	AIC Model Fit Statistics	
		Intercept Only	Intercept and Covariate
Belted	Delta-V	101.17	78.80
	OIV	101.17	79.66
Unbelted	Delta-V	47.48	25.52
	OIV	47.48	24.82

Table 7 presents the Hosmer and Lemeshow test results and the maximum rescaled R^2 values for the belted and unbelted subset models. The goodness-of-fit tests indicate statistically adequate fits for the belted models and good fits for the unbelted models. Based

on the model R^2 values, OIV and delta-V appear to be better predictors of injury for unbelted occupants. Note, however, that there is little variation in the model fit statistics when either delta-V or OIV is used as the predictor.

Table 7 – Summary of Comparison Fit Statistics

Data Subset	Predictor	Hosmer & Lemeshow Goodness-of-Fit	Max Rescaled R^2
Belted	Delta-V	0.0846	0.3065
	OIV	0.1241	0.2966
Unbelted	Delta-V	0.7898	0.6900
	OIV	0.7086	0.7037

Table 8 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, there is indication of a better applicability of these predictors to unbelted occupants. Also note the relatively small changes in sensitivity and specificity when switching from delta-V to OIV predictors.

Table 8 – Correlation of Models to Available Data

Data Subset	Predictor	Correct (%)	Sensitivity (%)	Specificity (%)
Belted	Delta-V	92.4	20.0	100.0
	OIV	91.1	13.3	99.3
Unbelted	Delta-V	84.8	86.7	83.3
	OIV	87.9	93.3	83.3

To further compare OIV and delta-V, an ROC curve analysis was performed for the belted and unbelted data subsets. Results are summarized in Table 9 as well as graphically in Figure 7 and Figure 8. In both belted and unbelted cases, the p-value exceeds 0.05 suggesting no statistically significant difference between the area under the respective ROC curves indicating no significant difference in predictors. 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 Hosmer and Lemeshow and R^2 values.

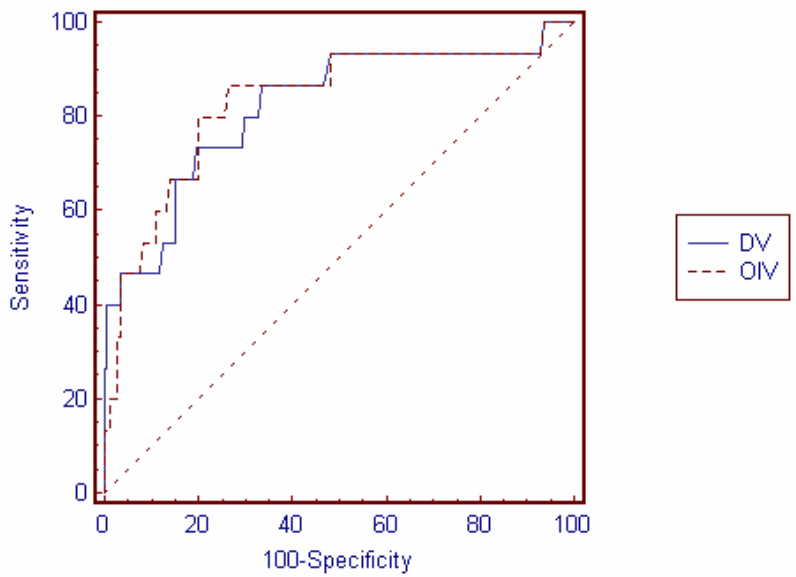


Figure 7 – ROC Curve Comparison: Belted Occupant Subset

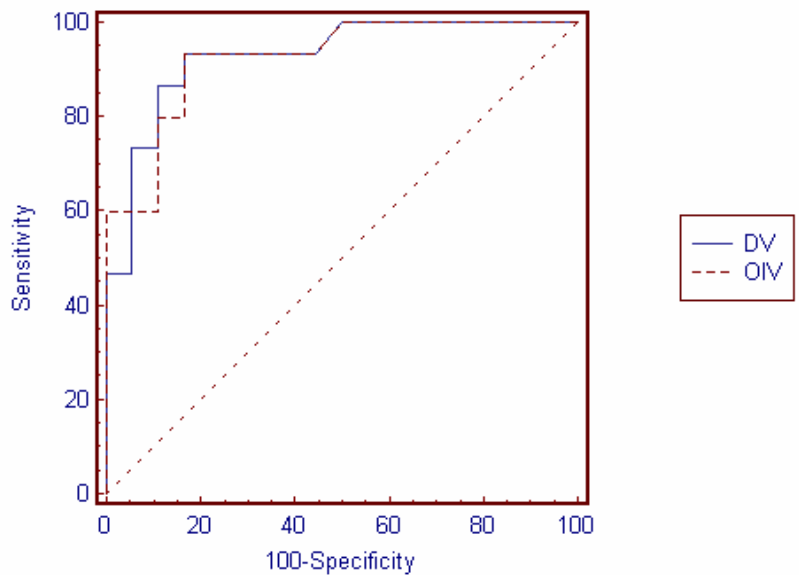


Figure 8 – ROC Curve Comparison: Unbelted Occupant Subset

Table 9 – ROC Analysis Summary for OIV and Delta-V

Data Subset	Predictor	Area Under Curve	Standard Error
Belted <i>P</i> = 0.603	Delta-V	0.819	0.068
	OIV	0.830	0.067
Unbelted <i>P</i> = 0.844	Delta-V	0.928	0.050
	OIV	0.924	0.051

DISCUSSION

The primary finding of this study is that OIV does not offer a significant advantage in terms of predicting serious occupant injury in real world crashes. Based on the available data, however, both OIV and delta-V appear to be reasonable predictors of overall occupant injury. In terms of occupant restraints, the models including only unbelted occupants had better fits than those including only belted 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. The usage of the safety belt obviously alters the occupant kinematics and demonstrates the potential limitation of continuing to use the OIV to predict occupant injury in a predominately seat belt restrained population.

Limitations are that this study investigates purely frontal collisions and cannot necessarily be extrapolated to all collision modalities. It should be noted, however, that newer versions of the GM EDR provide velocity information in the lateral direction (Gabler et al., 2004). Additional cases with lateral and longitudinal velocity information could provide information on how OIV and resultant delta-V predict occupant injury severity in a broader set of collision modes. 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 (Niehoff et al. 2005). 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, provided there was more sophisticated EDR data available.

Another limitation is that bias may be introduced with the inclusion of more than one occupant per vehicle. Since each case does not have both a driver and passenger, the presence of this bias is difficult to detect. As a surrogate detection method, the model including belted and unbelted occupants (using the smaller 191 case data set) has been generated using data only pertaining to drivers. The results were very similar to those shown in the paper with the regression coefficients significant (<0.0001 level) and with Hosmer and Lemeshow values indicating at least a statistically adequate fit. Although it does not appear to be a large issue in this data set, the bias issue should be investigated in future studies.

CONCLUSIONS

Based on an analysis of EDR data coupled with detailed injury data for approximately 200 real-world crashes, this study demonstrates that the more computationally intensive OIV offers no statistically significant advantage over the simpler delta-V crash severity metric. The study also generated injury risk curves to predict the probability of serious occupant injury in frontal collisions using OIV and delta-V as predictors.

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