Predicting Occupant Injury with Vehicle-Based Injury Criteria in Roadside Crashes

Douglas J. Gabauer

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Biomedical Engineering

H. Clay Gabler, Ph.D., Chair
Stefan M. Duma, Ph.D.
Joel D. Stitzel, Ph.D.
Michael L. Madigan, Ph.D.
Eric P. Smith, Ph.D.

June 6, 2008
Blacksburg, Virginia

Keywords: Delta-V, Flail Space Model, Restraint Performance

Predicting Occupant Injury with Vehicle-Based
Injury Criteria in Roadside Crashes

Douglas J. Gabauer

Abstract

This dissertation presents the results of a research effort aimed at improving the current occupant injury criteria typically used to assess occupant injury risk in crashes involving roadside hardware such as guardrail. These metrics attempt to derive the risk of injury based solely on the response of the vehicle during a collision event. The primary purpose of this research effort was to determine if real-world crash injury prediction could be improved by augmenting the current vehicle-based metrics with vehicle-specific structure and occupant restraint performance measures.

Based on an analysis of the responses of 60 crash test dummies in full-scale crash tests, vehicle-based occupant risk criteria were not found to be an accurate measure of occupant risk and were unable to predict the variation in occupant risk for unbelted, belted, airbag only, or belt and airbag restrained occupants. Through the use of Event Data Recorder (EDR) data coupled with occupant injury data for 214 real-world crashes, age-adjusted injury risk curves were developed relating vehicle-based metrics to occupant injury in real-world frontal collisions. A comparison of these risk curves based on model fit statistics and an ROC curve analysis indicated that the more computationally intensive metrics that require knowledge of the entire crash pulse offer no statistically significant advantage over the simpler delta-V crash severity metric in discriminating between serious and non-serious occupant injury. This finding underscores the importance of developing an improved vehicle-based injury metric.

Based on an analysis of 619 full-scale frontal crash tests, adjustments to delta-V that reflect the vehicle structure performance and occupant restraint performance are found to predict 4 times the variation of resultant occupant chest acceleration than delta-V alone. The combination of delta-V, ridedown efficiency, and the kinetic energy factor was found to provide the best prediction of the occupant chest kinematics. Real-world crash data was used to evaluate the developed modified delta-V metrics based on their ability to predict injury in real-world collisions. Although no statistically significant improvement in injury prediction was found, the modified models did show evidence of improvement over the traditional delta-V metric.

Acknowledgments

First and foremost, I would like to thank my parents, family and friends for their continual support. In particular, I thank Sarah for keeping me out of trouble and sharing many great times with me. Greg and Craig need to be recognized for managing to keep the office environment lively and even recreational at times. In addition to these individuals, I would like to thank all the other members of the Center for Injury Biomechanics for making my tenure at Virginia Tech so memorable.

I would also like to acknowledge my advisor, Dr. H. Clay Gabler, for providing guidance, sage advice, and the opportunity to present my research in both national and international venues. This research would not have been possible without him. I would also like to acknowledge all of my committee members for their time and insightful comments.

Grant Information

This research has been funded in part by two Federal Highway Administration (FHWA) Dwight D. Eisenhower Transportation Fellowships as well as a Student Endowment Grant through the Association for the Advancement of Automotive Medicine (AAAM). The views expressed herein do not necessarily reflect the views of the FHWA or AAAM.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. BACKGROUND AND RESEARCH OBJECTIVE

1.1 Injury Criteria

Injury criteria are a means of estimating the potential for injury to a human, and in the context of this research, an occupant of a motor vehicle involved in a crash. In general, there are two types of injury criteria used to assess occupant injury risk for a motor vehicle crash event:

(1) Anthropometric Test Device (ATD)-Based Injury Criteria

(2) Vehicle-Based Injury Criteria

An Anthropometric Test Device (ATD), or crash test dummy, refers to an instrumented human surrogate designed to assess injury potential in a repeatable manner (Mertz, 2002a). Typically, injury potential is evaluated by body region based on measured accelerations and displacements of the ATD during the crash event (Mertz, 2002b). These devices are used primarily in staged full-scale vehicle crash tests, as shown in Figure 1.

Figure 1. Full-Scale Vehicle Crash Test (NHTSA Test # 4484)

Vehicle-based injury criteria, on the other hand, refer to metrics that predict occupant injury potential using only the response of the vehicle during a crash event. Although generally less complex than ATD-based injury criteria, vehicle-based metrics are typically better suited for use in real-world crashes. These criteria are used primarily by roadside safety community to assess risk in crash tests with roadside hardware such as guardrail (see Figure 2). This type of injury criteria was the focus of this research.

Figure 2. Roadside Hardware: Weak-Post W-Beam Barrier along I-87 in New York State [Douglas Gabauer, 7/7/2003]

1.2 Vehicle-Based Injury Criteria

Below is a brief discussion of the more widely used vehicle-based injury criteria.

1.2.1 Delta-V

Delta-V is the longstanding metric of crash severity and is simply defined as the total change in vehicle velocity over the duration of the crash event (see Figure 3). 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; Sharma et al, 2007). The assumption is that larger changes in velocity correlate with a higher propensity for occupant injury.

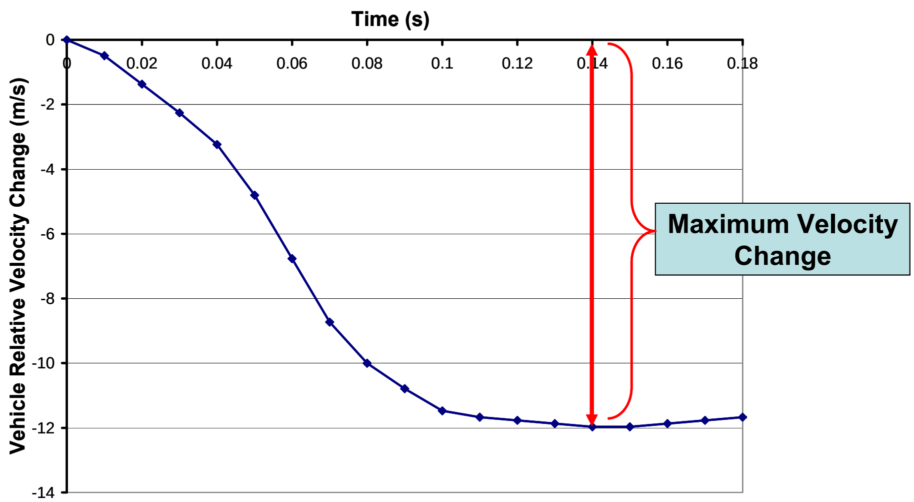


Figure 3. Vehicle Delta-V Illustration

1.2.2 Average Acceleration Criteria

Average acceleration injury criteria are based on the computation of a moving average across the entire vehicle acceleration pulse. Similar to delta-V, the underlying assumption is that higher vehicle accelerations result in greater the potential for serious occupant injury. In early roadside crash test procedures, limits were placed on the longitudinal, lateral and total 50 ms average accelerations of the vehicle during the impact, as measured at the center of mass of the vehicle (TRC 191, 1978; Bronstad and Michie, 1974). These limits are shown in Table 1.

Table 1. NCHRP Report 153 Redirection Impact Severity Thresholds (adapted from Bronstad and Michie, 1974)

Peak 50 ms Vehicle Accelerations (G)			
Category	**Longitudinal**	**Lateral**	**Total**
Preferred	5	3	6
Acceptable	10	5	12

1.2.3 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. This criterion is currently the primary vehicle-based criteria used to evaluate occupant risk in full-scale crash tests involving roadside hardware devices in the U.S. (Ross et al., 1993).

In the flail space model, 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 4). The occupant is allowed to “flail” 0.6 m in the longitudinal direction (parallel to the typical direction of vehicle travel) and 0.3 m in the lateral direction prior to impacting the vehicle interior. Measured vehicle kinematics is used to compute the difference in velocity between the occupant and occupant compartment at the instant the occupant has displaced either 0.3 m laterally or 0.6 m 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 to 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.

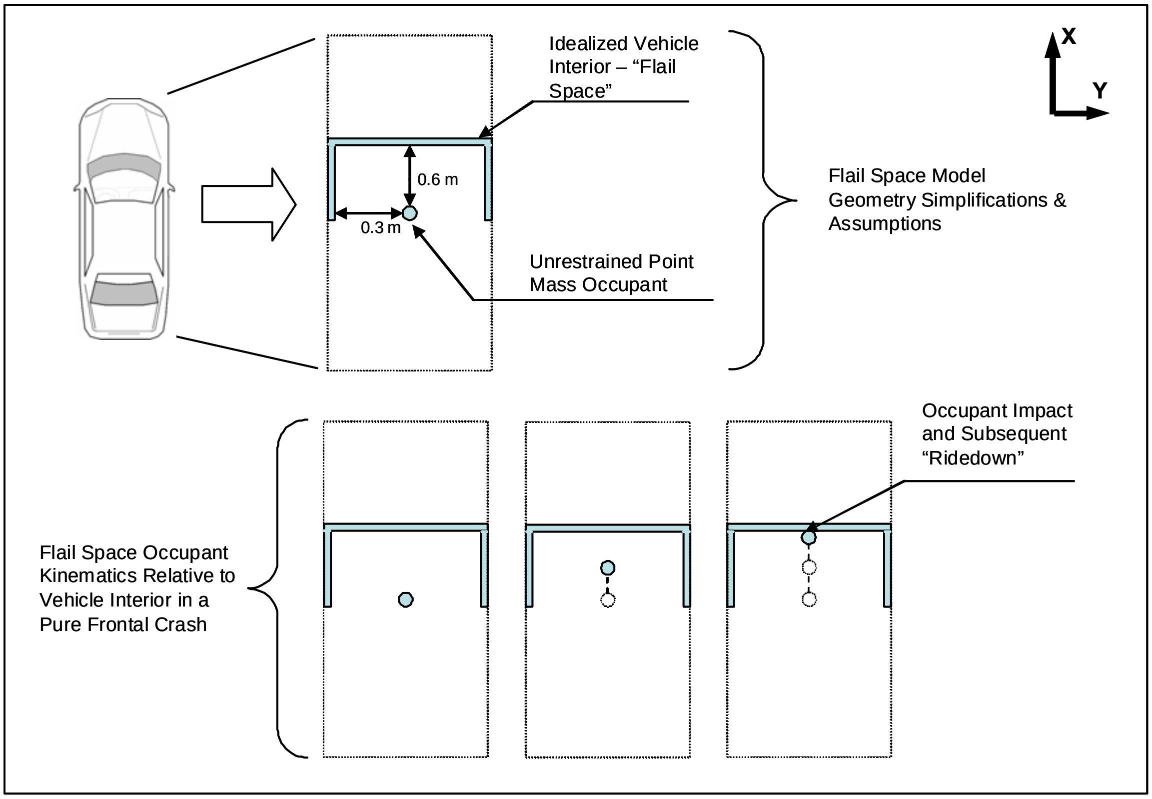


Figure 4. Flail Space Model Assumptions and Simplifications (Schematic drawn based on description by Michie, 1981)

Both the OIV and subsequent occupant ridedown acceleration are compared with established thresholds to ensure that the device does not create undue 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 2. 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. The "maximum" thresholds are intended to correspond to serious but not life-threatening occupant injury (Michie, 1981).

Table 2. Current Flail Space Model Threshold Values

Metric	Preferred Value	Maximum Value
OIV [m/s]	9	12
Ridedown Acceleration [G]	15	20

1.2.4 The Acceleration Severity Index

The Acceleration Severity Index (ASI) is a variation of the average acceleration criteria. This criterion is primarily used in Europe to assess occupant risk in crash tests involving roadside hardware (CEN, 1998). Using measured vehicle acceleration information, the ASI is computed using the following relationship (CEN, 1998):

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

where $\bar{a}_x$, $\bar{a}_y$, and $\bar{a}_z$ are the 50-ms average component vehicle accelerations and $\hat{a}_x$, $\hat{a}_y$, and $\hat{a}_z$ are corresponding threshold accelerations for each component direction. The threshold accelerations are 12 g, 9 g, and 10 g for the longitudinal (x), lateral (y), and vertical (z) directions, respectively. Since it utilizes only vehicle accelerations, the ASI inherently assumes that the occupant is continuously contacting the vehicle, which typically is achieved through the use of a seat belt.

The maximum ASI value over the duration of the vehicle acceleration pulse provides a single measure of collision severity that is assumed to be proportional to occupant risk. To provide an assessment of occupant risk potential, the ASI value for a given collision acceleration pulse is compared to established threshold values. Although a maximum ASI value of 1.0 is recommended, a maximum ASI value of 1.4 is acceptable (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.

1.3 Correlation to Occupant Injury

1.3.1 Delta-V

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. 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. Models have even been generated to relate delta-V to specific population subsets, such as children involved in frontal impacts (Nance et al, 2006).

1.3.2 Roadside Criteria

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.

Similarly, 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.

1.3.3 Limitations of Previous Studies and Vehicle-Based Metrics

A general lack of vehicle kinematics data for real-world crashes has been a limitation for all of these previous studies correlating vehicle-based metrics to occupant injury. Although delta-V can be estimated from post-crash vehicle crush, these traditional crash reconstruction methods are not able to estimate the vehicle change in velocity as a function of time (i.e. the crash pulse). Without this information, it is not possible to directly compute the more complex vehicle-based injury metrics, including the flail space model and the ASI, for real-world crashes. As an alternative, previous studies used post-crash vehicle damage to match real-world crashes to similar full-scale crash tests, where the crash-pulse based criteria could be computed directly. As a result, little is known with respect to how these more complex metrics relate to actual occupant injury and whether they offer an advantage over delta-V, the traditional crash severity metric.

In addition to this limited knowledge of how these metrics relate to occupant injury, these metrics do not account for the effects of occupant restraints, such as airbags, on resulting occupant injury potential. The potential of these devices to reduce occupant injury in real-world crashes has been well established (Evans, 1986; McGwin et al, 2003; Braver et al, 1997; Crandall et al, 2001). Current vehicle-based injury metrics alone, however, cannot capture the variation in safety performance of different occupant restraint systems. This is particularly evident in controlled full-scale crash tests. Figure 5 is a chart showing occupant chest injury potential, based on the deflection criteria, as measured by an instrumented ATD. All tests have a delta-V between 39 and 41 mph but the injury probability ranges from 28 to 61 percent due in part to differences in restraint performance among the vehicles.

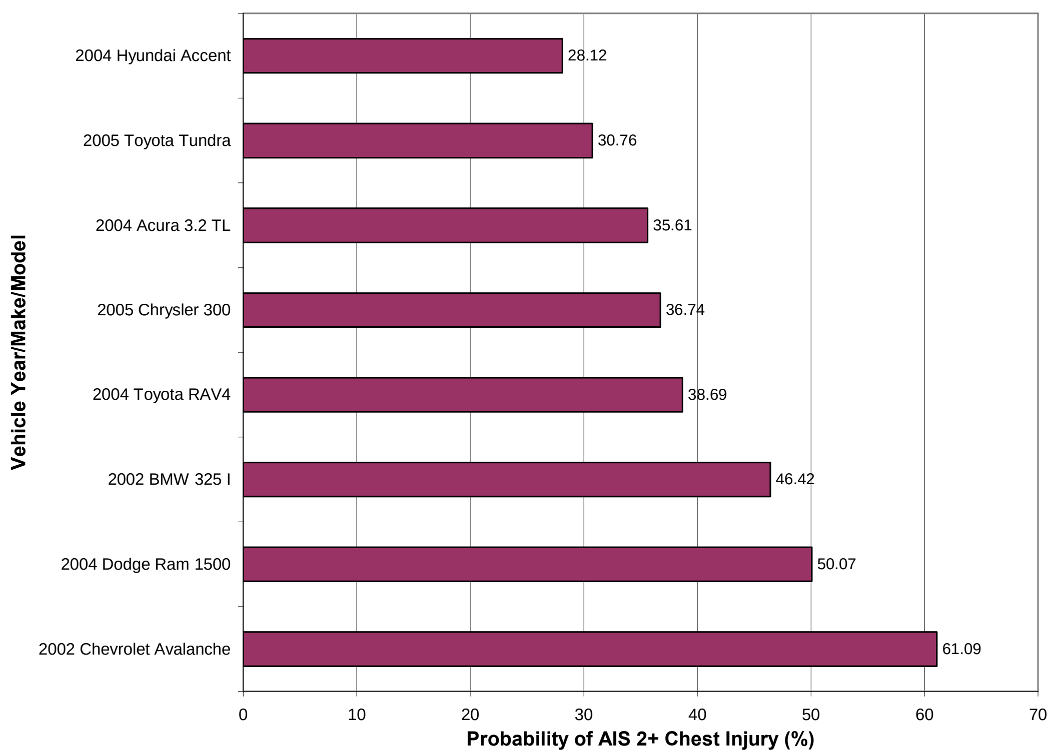


Figure 5. Variation in Chest Injury Potential across Vehicle Models: Current Vehicle-Based Metrics Alone Fail to Capture these Variations

1.4 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 research is the EDRs ability to record the vehicle velocity profile during a collision event. Traditionally unavailable for real-world crashes, the crash pulse data will allow for detailed study of vehicle-based metrics in a real-world crash setting.

NHTSA has collected EDR data from over 2700 General Motors (GM) cars and light trucks involved in traffic collisions in the United States from year 2000 through 2006. These EDRs have the ability to store a description of both the crash and pre-crash phase of a collision. Crash parameters in the EDR data include longitudinal delta-V vs. time during the impact at 10 ms intervals (see Figure 4), 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.

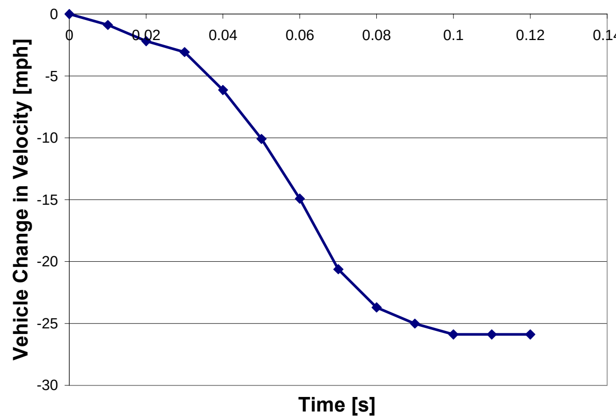


Figure 6. **2005 Chevrolet Malibu (left) after Impact with a Toyota 4Runner. EDR recorded Malibu change in velocity (right), NASS Case #2005-045-122**

1.5 Research Objectives

The objectives of this study were to develop an improved vehicle-based metric to predict injury in roadside crashes. This improved metric accounts for the differing performance of occupant restraints across vehicle types and has been validated against novel real-world collision data. In order to develop this improved vehicle-based injury metric, there were multiple research objectives that needed to be realized:

1. Compare vehicle-based and ATD-based injury criteria using full-scale crash tests.
2. Evaluate vehicle-based metrics for predicting injury in real-world crashes using Event Data Recorder (EDR) data.
3. Determine the effects of restraints on occupant injury in real-world crashes involving roadside hardware.
4. Evaluate potential restraint performance measures to be used to enhance current vehicle-based injury metrics.
5. Assess restraint performance-enhanced vehicle-based metrics in real-world crashes using EDR data.

The culmination of these research objectives will be the development of a restraint-enhanced vehicle-based metric for the prediction of occupant injury in full-scale crash tests involving roadside safety hardware and in real-world collisions.

2. Comparison of Vehicle-Based and ATD-Based Injury Criteria in Full-Scale Crash Tests

2.1 Introduction

Ideally, occupant risk in roadside barrier crash tests would be evaluated using an instrumented crash test dummy. Several practical considerations, however, have led the roadside safety community to avoid this option. Crash testing of roadside hardware is inherently more complex and must provide a structural evaluation of the device along with the occupant injury potential. Tests with longitudinal barriers, such as w-beam guardrail, are conducted at higher test speeds and oblique impact angles. In addition, the devices are typically tested in soil, which can make repeatability a challenge. A vehicle impacting one of these devices must travel over a surface sufficiently uneven to bounce a dummy out of position. As a result, the roadside safety community has developed occupant risk models, namely the flail space model, to indirectly predict occupant injury risk based on vehicle kinematics.

Human surrogates, or ATDs, used in vehicle crashworthiness testing are designed to evaluate the performance of in-vehicle occupant restraints, such as seatbelts and airbags, in terms of occupant injury risk. In the flail space model, the occupant is assumed to be completely unrestrained, i.e. without a seatbelt or airbag restraint. This represented a practical worst case scenario at the model's inception in the early 1980's as belt use rates were roughly 11 percent (Derrig et al, 2000) and airbags were rare. Since 1997, however, airbags have become required equipment on all new vehicles. There has also been a marked increase in belt usage rates to approximately 80 percent nationally (NHTSA, 2007). Despite the potentially large effect these shifts have on occupant risk, current roadside occupant risk criteria do not account for them.

The intent of this study was to illustrate the importance of developing roadside hardware crash test injury criteria that account for occupant restraints. Specifically, the study compared several vehicle-based injury criteria to corresponding ATD-based injury criteria. This provides a direct assessment of how well vehicle-based metrics estimate injury potential as measured by a crash test dummy for differing occupant restraint conditions. Vehicle-based injury metrics investigated included the Occupant Impact Velocity (OIV) and Occupant Ridedown Acceleration (ORA) of the Flail Space Model. ATD-based metrics included the Head Injury Criterion (HIC), maximum chest acceleration (3-ms Clip), maximum chest deflection, and a combined head and chest injury measure as an indicator of overall occupant injury risk.

2.2 Methodology

2.2.1 Case Selection

Vehicle-based injury criteria and ATD-based injury criteria were compared using data from full-scale crash tests. Comparisons were conducted for 4 distinct occupant restraint scenarios: (1) no restraint, (2) three-point belt restraint only, (3) airbag restraint only, and (4) three-point belt and airbag restraint.

Since roadside hardware crash tests rarely employ an instrumented anthropometric test device (ATD), finding roadside crash tests to satisfy all four restraint categories was not feasible. Where available, however, roadside tests employing fully instrumented ATDs were used in the analysis. Hinch et al (1988) used unrestrained ATDs in several high speed frontal tests involving sand-filled crash cushions. For all of these tests, the vehicle impacted at 97 km/hr (60 mph) and instrumented Hybrid II ATDs were used. Nine of these tests (11 occupant responses), as reported by Hinch et al (1988), were used to compare roadside injury criteria to human surrogate occupant risk for unrestrained occupants (i.e. restraint scenario #1).

For the remainder of the restraint scenarios, full scale vehicle crash tests were used as an alternate means of comparing roadside and ATD-based occupant risk. NHTSA maintains an electronic database of full-scale vehicle crashworthiness tests performed for Federal Motor Vehicle Safety Standards (FMVSS) compliance as well as various other research purposes (NHTSA, 2008a). All cases selected from the NHTSA database were frontal barrier collisions; particular emphasis was placed on frontal crashes due to the plethora of test data in the frontal crash mode. Tests selected for each restraint scenario use the same ATD and impact conditions to further reduce the variability of injury risk measured between tests.

A total of 30 vehicle crash tests were evaluated which resulted in a total of 60 occupant responses (ATDs in right and left front seats). For the unrestrained occupant restraint scenario, nine of the Hinch et al (1988) crash cushion tests were used. For each of the three restraint conditions remaining, 10 frontal barrier crash tests were used to provide a comparison of roadside and ATD-based occupant risk. The airbag only restraint condition used tests with 40 km/hr (25 mph) impact speed and Hybrid III 50th percentile male ATDs. The airbag and belt restraint condition used crash tests with 56 km/hr (35 mph) impact speed and Hybrid III 50th percentile male ATDs. Finally, the belt only scenario used tests with a 48 km/hr (30 mph) impact speed and Hybrid II 50th percentile male ATDs.

2.2.2 Computations

For each test, the vehicle-based injury criteria were computed using the measured vehicle kinematics information. The Flail Space Model criterion and ASI criterion were computed according to NCHRP Report 350 (Ross et al., 1993) and EN-1317 (CEN, 1998), respectively. Accelerometer data was chosen as close to the vehicle center of gravity as possible to best describe the occupant compartment movement. Sensors used in the calculations included those attached to the vehicle rear floor pan, rear sill, or rear seat; all of which were aligned in the longitudinal direction. Any errors incurred due to use of acceleration data not at the vehicle center of gravity are expected to be negligible as only minor roll and yaw motions are experienced by the vehicle during these perpendicular frontal-barrier tests. All data traces used were checked against redundant sensor traces, if available, to ensure data accuracy; corrections for sensor bias were made as necessary. The raw acceleration data from the selected channel was filtered with a Channel Filter Class (CFC) 180, as prescribed in NCHRP 350, prior to integrating for velocity or position. The CFC 180 filter used was a Butterworth 4-pole phaseless digital low pass filter with 3dB cutoff frequency of 300 Hz. Numerical integration was accomplished via the trapezoidal rule, as recommended in NCHRP 350.

Injury criteria reported in the NHTSA database include 36 ms Head Injury Criterion (HIC) and the peak chest acceleration (3 ms clip). The 15 ms HIC and maximum chest deflection were computed using the Signal Browser software, available from NHTSA (2008b). All head center of gravity acceleration traces were filtered at CFC 1000 prior to computation of the 15 ms HIC, as prescribed by SAE-J211 (SAE, 2007). Similarly, the chest deflection traces were filtered at CFC 600 prior to determining the maximum deflection. Also, any sensor bias problems were corrected prior to analysis.

Table 3 summarizes the relations used to compute human injury risk potential based on the ATD-based injury criteria values (NHTSA, 1999). Note that A_c indicates the maximum crash test dummy chest acceleration in gravity units and D_c indicates the maximum crash test dummy chest deflection in millimeters.

Table 3. **Computation of Injury Risk Based on Injury Criteria Values (adapted from NHTSA, 1999)**

Body Region	Injury Criteria	Probability of AIS 3+ Injury
Head	15 ms HIC	$p(AIS \geq 3) = \frac{1}{1+e^{((3.39+200/HIC)-0.00372HIC)}}$
Chest	3 ms Chest Clip (G)	$p(AIS \geq 3) = \frac{1}{1+e^{(3.1493-0.0630Ac)}}$
	Maximum Deflection	$p(AIS \geq 3) = \frac{1}{1+e^{(3.7124-0.0475Dc)}}$

As vehicle-based metrics are intended to predict overall occupant injury, the combined probability of AIS 3+ head and chest injury was used as an analogous ATD metric. The combined probability was computed by adding the AIS 3+ head and chest injury (based on 3 ms clip) probability and then subtracting the product; a procedure similar to how NHTSA determines vehicle star safety ratings. The assumption is that risk of head and chest injury are independent of one another.

P(Head/Chest Injury) = P(Head) + P(Chest) - P(Head)* P(Chest) **[Equation 1]**

Injury severity was graded by the Abbreviated Injury Severity (AIS) scale (AAAM, 1998), which methodically rates injury on a discrete 0 to 6 scale based on threat to life. Injury levels are summarized in Table 4 with corresponding examples for each injury level. The original intent of a majority of the vehicle-based criteria is to indicate the transition between AIS 3 and AIS 4 level injury (Michie, 1981). As such, injury risk computed for this analysis will be the probability of AIS 3 or greater occupant injury.

Table 4. Abbreviated Injury Severity (AIS) Scale Summary (adapted from AAAM, 1998)

AIS Value	Injury Description	Example
0	No Injury	-
1	Minor	Ankle Sprain
2	Moderate	Humerous Fracture (Closed, Undisplaced)
3	Serious	Femur Fracture
4	Severe	Subdural Hematoma (Cerebrum, < 50 cc)
5	Critical	> 3 Rib Fx (each side) & Hemo-/Pneumothorax
6	Maximum/Fatal	Brain Stem Transection

2.2.3 Comparison

Occupant injury risk for each occupant restraint scenario was first compared graphically for the combined risk of head and chest injury. Each value on the plot was normalized to the probability of injury of the best performer. Hence the lowest injury risk in each chart has a value of unity. Since each restraint scenario uses crash tests of nearly identical impact speeds, there is only small variation in vehicle-based injury criterion, e.g. the OIV. The mean OIV value and approximate range are noted on each plot. Appendix A contains additional graphical comparisons for head injury risk, acceleration-based chest injury risk, and deflection-based chest injury risk. Note that the chest deflection was only available in the airbag-only and airbag and belt restraint cases.

Linear regression analysis was used to provide further comparison. Ideally, if the vehicle-based injury criteria are indeed good predictors of occupant risk, a strong linear correlation should exist between these predictors and the ATD-based injury risk. This should be especially evident in the unrestrained scenario, as the flail space model was developed assuming this restraint condition. R^2 values are indicated for each available roadside-ATD criteria combination for each restraint condition.

2.3 Analysis of Results

Results are shown separately for each of the four occupant restraint scenarios investigated followed by the results of the linear regression analysis.

2.3.1 Unrestrained Occupant Risk Comparison

Figure 7 is a chart showing AIS 3+ head and chest normalized injury risk for the selected 97 km/hr (60 mph) frontal crash cushion tests. The vehicle make and model are shown with driver indicated by a solid bar and right front seat passenger indicated with a hatched bar. All vehicles were model year 1979. The corresponding test designation reported by Hinch et al (1988) is indicated in parentheses. All ATD occupants were Hybrid II 50th percentile males with no restraints. Probability of injury has been normalized to the Mercury Cougar driver in test B-09, which had a combined head and chest injury probability of 14 percent. The OIV varied within a small 1 m/s range suggesting a relatively constant risk whereas ATD occupant risk varied as much as four-fold in relation to the best performer. Although this variation is striking, there is the possibility that small changes in roadside risk criteria correlate to larger changes in ATD-based occupant risk. Note that the tests selected included two different crash cushion types (Energite III and Fitch System) under variable conditions (bagged sand or frozen sand in some instances), which may account for some of the variation in addition to vehicle interior differences.

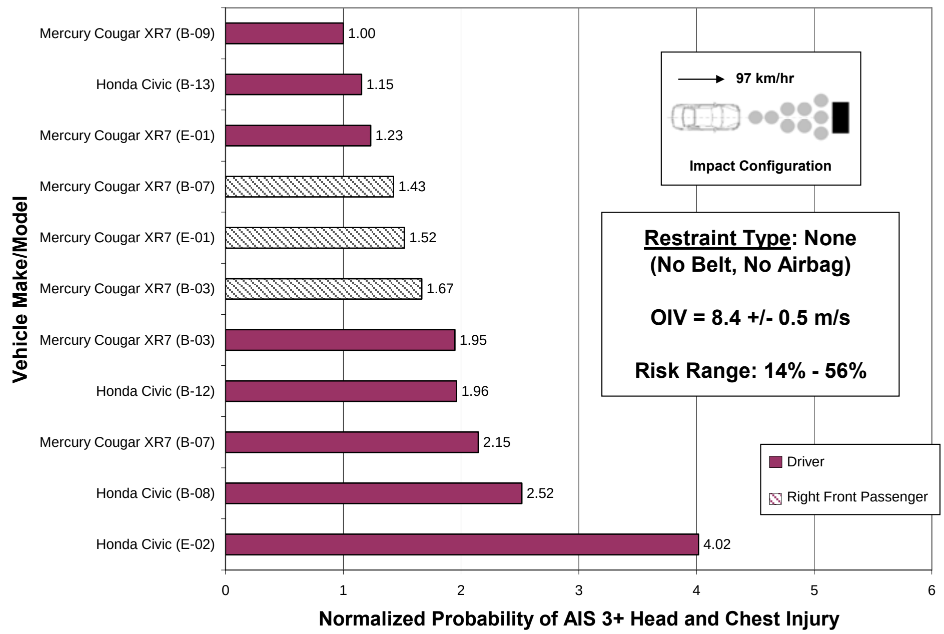


Figure 7. Probability of Serious Head and Chest Injury to Unrestrained Occupants Normalized to Best Performer

2.3.2 Airbag-Only Restrained Occupant Risk Comparison

Figure 8 is a chart showing AIS 3+ head and chest normalized injury risk for the selected 40 km/hr (25 mph) frontal barrier vehicle crash tests.

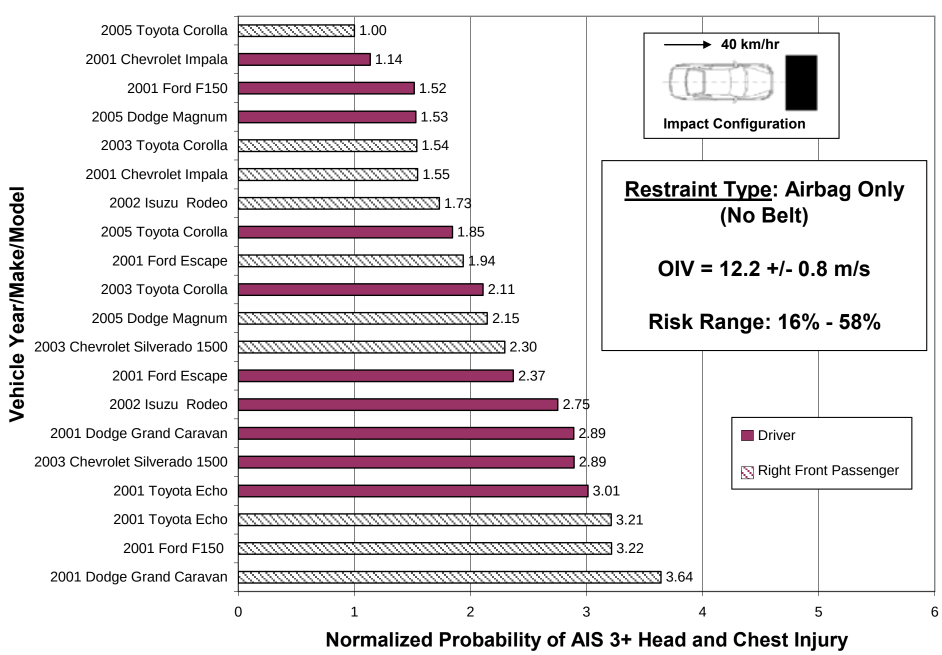


Figure 8. Probability of Serious Head and Chest Injury to Airbag-Restrained Occupants Normalized to Best Performer

Again, drivers are indicated by a solid bar and right front seat passengers are indicated with a hatched bar. Both front seat ATD occupants were Hybrid III 50th percentile males with only an airbag restraint. Probability of injury was normalized to the right front passenger of the 2005 Toyota Corolla, which had a combined head and chest injury probability of 16 percent. The OIV varied within a range of 1.5 m/s whereas ATD occupant risk varied as much as 3.6 times the injury probability of the best performer. Also note differences within the same vehicle where the roadside criteria are identical by design; for the same OIV, the Ford F150 driver had an injury probability 1.5 times that of baseline while the right front passenger risk exceeded 3 times the baseline.

2.3.3 Belt Only Restrained Occupant Risk Comparison

Figure 9 is a chart showing AIS 3+ head and chest normalized injury risk for the selected 48 km/hr (30 mph) frontal barrier vehicle crash tests. Both front seat ATD occupants were Hybrid II 50th percentile males with only a three-point belt restraint. Probability of injury was normalized to the right front passenger of the 1980 Ford Fairmont, which had a combined head and chest injury probability of 18 percent. The OIV varied within a range of 3 m/s whereas ATD occupant risk varied as much as five-fold. Again, note the differences within the same vehicle. In the Fairmont test, both dummies experienced the same OIV but the driver had more than a three-fold risk compared to the right front passenger.

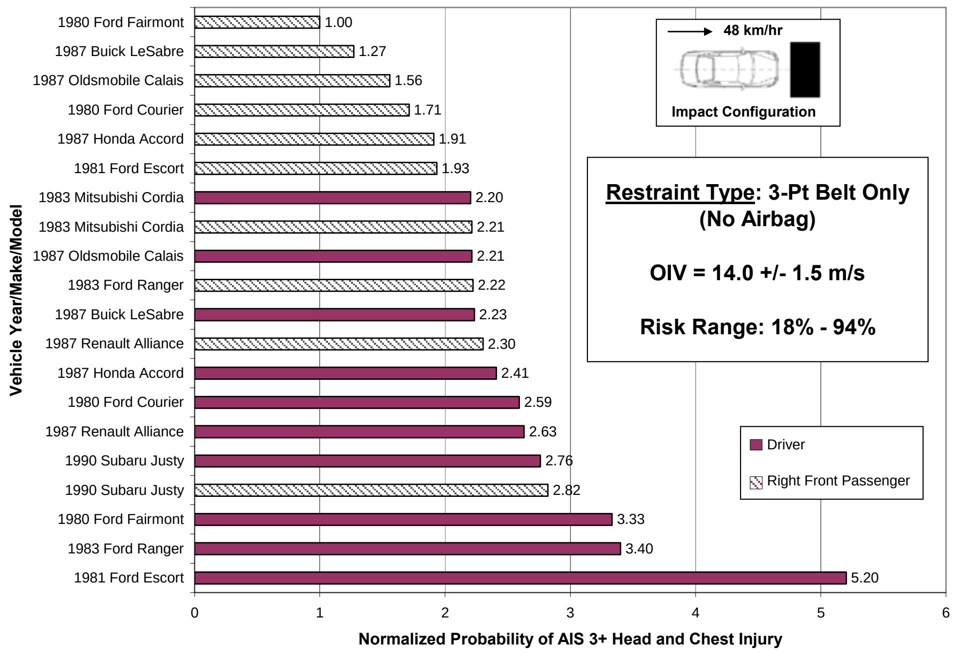


Figure 9. Probability of Serious Head and Chest Injury to Belt-Restrained Occupants Normalized to Best Performer

2.3.4 Airbag and Belt Restrained Occupant Risk Comparison

Figure 10 is a chart showing AIS 3+ head and chest normalized injury risk for the selected 56 km/hr (35 mph) frontal barrier vehicle crash tests. Drivers are indicated by a solid bar and right front seat passengers are indicated with a hatched bar. Both front seat ATD occupants were Hybrid III 50th percentile males with airbag and three-point belt restraints. Probability of injury was normalized to the right front passenger of the 2003 Saturn Ion, which had a combined head and chest injury probability of 30 percent. The OIV varied within a range of 2 m/s whereas ATD occupant risk varied as much as two-fold.

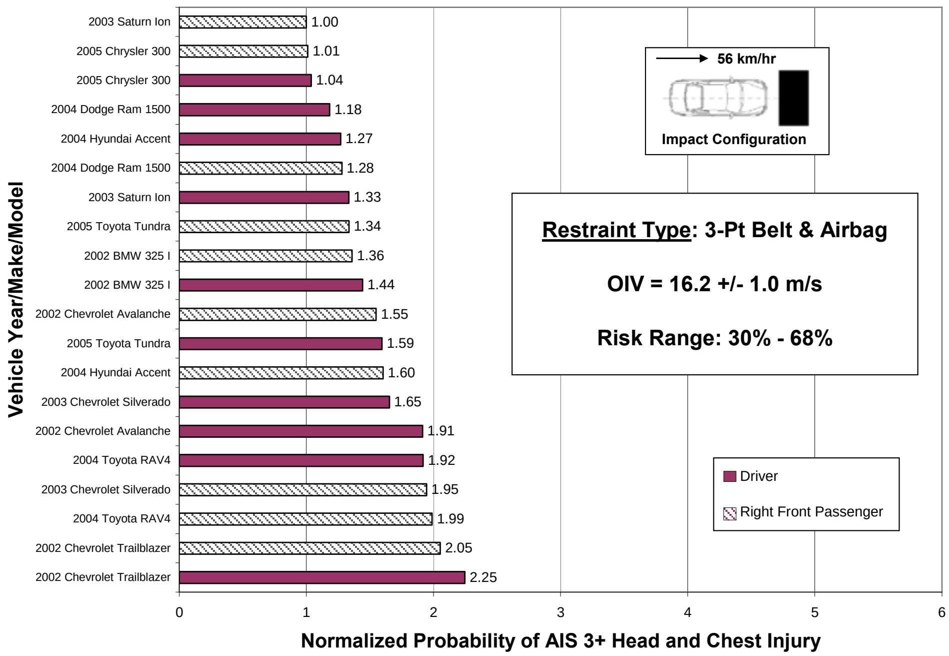


Figure 10. Probability of Serious Head and Chest Injury to Belt and Airbag Restrained Occupants Normalized to Best Performer

2.3.5 Linear Regression Comparison Results

The preceding plots showed wide variation in ATD-based risk for tests experiencing essentially the same OIV. There is still the possibility, however, that small changes in roadside criteria correlate to large changes in ATD-based risk. If this is the case, a strong linear regression correlation (e.g. R^2 value approaching unity) should be evident between the roadside and ATD-based criteria. Table 5 provides a summary of the linear regression analysis for each of the restraint scenarios analyzed. The slope of the regression line is indicated in parentheses for stronger fits (R^2 value above 0.20) and the corresponding p-values are indicated for each regression model (alpha significant to 0.05).

As expected, the strongest correlations are evident for the unrestrained occupant, especially with respect to the OIV parameter. All unrestrained occupant correlations were positive indicating direct proportionality (increasing ATD risk with increasing OIV). The lack of correlation in the ORA for the unrestrained condition was not expected and cannot be fully explained. Despite the comparatively larger R^2 values, the linear regression fits for the unrestrained occupants were not statistically significant ($p > 0.05$). For the belted only occupants and airbag restrained only occupants, all the R^2 values were 0.122 or smaller and the corresponding p-values were 0.13 or larger suggesting no correlation. A majority of the correlations were not statistically significant in the airbag and belt restrained occupant category. The correlations between OIV versus HIC and OIV versus chest deflection injury risk were found to be statistically significant and negative in nature. This was also not expected and may be an artifact of the relatively small data set or be a result of a tendency of vehicle manufacturers to design aggressive restraints for vehicles with stiffer front ends.

Table 5. Summary of Linear Regression Analysis

Configuration	Vehicle Injury Criteria	OIV		ORA		*n*
		R^2	*P*	R^2	*P*	
No Occupant Restraint (97 km/hr)	HIC	0.315 (+)	0.0711	0.079	0.4038	11
	3 ms Clip	0.280 (+)	0.0904	0.094	0.3598	
	Head/Chest	0.326 (+)	0.0642	0.088	0.3757	
Airbag Only (40 km/hr)	HIC	<0.001	0.9414	<0.001	0.9384	20
	3 ms Clip	<0.001	0.9318	0.106	0.1619	
	Chest Deflection	0.031	0.4692	0.004	0.7996	
	Head/Chest	<0.001	0.9276	0.092	0.1925	
Belt Only (48 km/hr)	HIC	0.011	0.6534	0.006	0.7404	20
	3 ms Clip	<0.001	0.9708	0.122	0.1319	
	Head/Chest	0.007	0.7272	0.010	0.6714	
Airbag and Belt (56 km/hr)	HIC	0.488 (-)	0.0006	0.025	0.5052	20
	3 ms Clip	0.061	0.2928	0.197	0.0503	
	Chest Deflection	0.225 (-)	0.0348	0.002	0.8719	
	Head/Chest	0.174	0.0676	0.120	0.1350	

2.4 Discussion

In general, there appears to be little correlation between roadside injury criteria and ATD-based criteria at a given test speed for any of the restraint scenarios considered. This is evident graphically in Figure 7 through Figure 10. For each occupant restraint scenario, the roadside injury criteria predicted a virtually identical injury risk, but the ATD-based measures indicated a large distribution of combined head and chest injury risk. This risk range varied from 38 percentage points for the 56 km/hr tests to 76 percentage points for the 48 km/hr tests. As measured by the instrumented ATD, the occupant of the worst performing vehicle had an injury risk up to five times the risk of the best performer. In addition, injury risk was also found to vary based on seating position within the same vehicle. The ATD-based graphical findings were confirmed using linear regression analysis where OIV and ORA were predictors of head, chest, and combined head and chest injury probability for each occupant restraint scenario. Although the OIV explained the largest amount of the variation for the unrestrained occupant scenario, none of the fits were statistically significant. For the other occupant restraint scenarios, the OIV and ORA explained less than 10 percent of the risk variation for a majority of the ATD-based injury measures.

In stark contrast to the wide variation in injury risk predicted by the ATD, the roadside metrics varied only slightly for a particular impact speed. In addition, the risk of injury, based on the flail space model methodology, was assumed to be the same irrespective of whether the occupant was seated in the right front or left front occupant position. The presence of the occupant restraints as well as differences in vehicle crush characteristics and vehicle interior contributed to the wide variation of injury risk between vehicles as well as within vehicles at a given impact speed. As the roadside metrics are based solely on the response of the vehicle, they are unable to capture this injury risk variation.

2.5 Conclusions

This study highlights the importance of considering occupant restraints, from advanced passive restraints such as airbags to simple active restraints such as seatbelts, in injury criteria based solely on the response of the vehicle during a crash. The correlation between vehicle-based and ATD-based injury criteria has been examined across four different occupant restraint scenarios from completely unrestrained to both a belt and airbag restraint. Characterization of this relationship is crucial to understanding the limitations of the current vehicle-based criteria for use in the current restraint-equipped vehicle fleet and will serve as a basis for the development of an improved vehicle-based criterion. Specific conclusions include the following:

1. Current injury criteria are out of step with current restraint usage in the U.S. In a fleet with 80% belt usage and 100% airbags installation in vehicles manufactured after 1998, an unbelted occupant without an airbag is no longer the practical worst case. Even the 20% of occupants who are hard core non-belt users are protected by an airbag. At a minimum, the roadside criteria should be updated to reflect the presence of airbags in all cars and light trucks manufactured since 1998.

2. In frontal crash tests, current roadside occupant risk criteria are not an accurate measure of occupant risk for individual vehicles. The flail space algorithm was unable to predict the variation in occupant risk for unbelted, belted, airbag only, or belt and airbag restrained occupants.

3. The objective of this paper was to evaluate roadside injury criteria not the use of crash test dummies in roadside hardware tests. Although it is difficult to measure occupant risk without measuring anything on the occupant, it may still be possible to conduct occupant risk assessment with an improved vehicle-acceleration based metric. Alternatives such as a modified OIV or other vehicle-acceleration based metric should be explored. It is clear however that current vehicle-acceleration based metrics, e.g. OIV, do not provide an accurate measure of occupant injury.

4. At a given impact speed, variation in ATD-based risk between occupants in the same vehicle can be vastly different in some instances; all roadside criteria, however, are the same for a particular vehicle and crash event.

3. EVALUATION OF VEHICLE-BASED METRICS FOR PREDICTING INJURY IN REAL-WORLD CRASHES

3.1 Introduction

Full-scale crash tests are ideal for studying crash kinematics in detail and, as shown in the previous chapter, can be used to compare vehicle-based injury criteria against the more complex ATD-based injury criteria. Crash tests, however, only provide an estimate of the occupant injury risk that would have been experienced by an actual occupant exposed to the same crash conditions. To truly evaluate the injury predictive capabilities of vehicle-based metrics, real-world collisions must be analyzed. Numerous researchers have developed correlations between vehicle delta-V and resultant occupant injury in real-world crashes (Roberts and Compton, 1993; Bahouth et al, 2004; Dischinger et al, 1998; Nance et al, 2006; Winnicki and Eppinger, 1998). There has been very little research, however, correlating the more complex injury metrics, such as the Flail Space Model or ASI, to occupant injury in real-world crashes. Only two previous studies (Council and Stewart, 1993; Ray et al, 1986) attempted to develop these correlations. Both studies were based on less than 60 crashes and produced only limited results.

A general lack of vehicle kinematics data for real-world crashes has been a limitation for all of these previous studies correlating vehicle-based metrics to occupant injury. Typical crash reconstruction techniques are capable of estimating delta-V from post-crash vehicle deformations, but recent research has shown that these methods can underestimate the delta-V by 23 percent on average (Niehoff and Gabler, 2006). In addition, traditional crash reconstruction methods are unable to estimate the vehicle change in velocity as a function of time (i.e. the crash pulse). Without the crash pulse, it is not possible to compute the more complex vehicle-based injury metrics, such as the Occupant Impact Velocity (OIV) and the Acceleration Severity Index (ASI). As an alternative, previous studies have used post-crash vehicle damage to match real-world crashes to similar full-scale crash tests, where the crash-pulse based criteria could be computed directly.

Event Data Recorders (EDRs), typically installed in tandem with a vehicle's airbag system, have the capability of capturing the crash pulse of a real-world collision. These devices allow for a better estimate of vehicle delta-V and allow for the computation of more complex vehicle-based injury measures for real-world crashes. This study uses EDR data matched with detailed occupant injury information for real-world crashes to develop correlations between vehicle-based metrics and actual occupant injury. The objective of this study is to use these correlations to compare the injury predictive capabilities of different vehicle-based metrics. One objective is to determine if the more complex vehicle-based metrics offer an advantage over the simpler delta-V metric in terms of predicting occupant injury. Metrics evaluated include the OIV, ASI, average peak accelerations (10 ms to 50 ms moving averages), as well as delta-V.

3.2 Methodology

The general methodology for this study included (1) selecting appropriate cases from the available NASS/CDS cases with matched EDR data, (2) computing the vehicle-based metrics for each case, (3) fitting binary logistic regression models between each vehicle-based metric and occupant injury, and (4) comparing the injury predictive capability of the metrics.

3.2.1 Case Selection

Suitable cases for analysis were selected from the available NASS/CDS cases with matched EDR data from year 2000 through 2006. Only cases adhering to the following criteria were included in the analysis:

(1) Crashes comprised of a single event

(2) General Motors (GM) vehicles only

(3) Airbag deployment

(4) Complete EDR vehicle crash pulse data

(5) Known driver injury information (including no injury cases)

(6) A frontal collision with no vehicle rollover or driver ejection

In multiple impact cases, it can be difficult to know which impact caused occupant injury. Limiting the analysis to those cases involving a single event ensures that the impact caused (or did not cause) occupant injury. Only GM vehicles have been included in this analysis as this vehicle make comprises the majority of the EDR data collected in conjunction with NASS/CDS. In addition, this study includes only cases where the airbag was deployed. GM EDRs only lock in their recorded data for the event which deploys the airbag. Data for lower severity impacts that do not deploy the airbag can be overwritten by subsequent post-crash events, e.g. recovery efforts. Hence, unless the airbag deployed, one cannot be certain that the recorded GM EDR data corresponds to the injury-causing event.

EDR delta-V information is required to compute any of the vehicle-based criteria. An additional stipulation will be that the delta-V information is "complete", or converges to a constant velocity, so that the delta-V, ASI, and peak acceleration 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 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 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 214 cases were identified as suitable for analysis. Of the suitable cases, 176 occupants were restrained by both a belt and airbag while the remaining 38 were restrained only by an airbag. The average occupant age was 39.3 years with range between 16 and 95 years. The final data set included both vehicle-to-fixed object (15%) and vehicle-to-vehicle (85%) collisions. If there is a relationship between vehicle-based injury criterion and occupant injury, this relationship should be equally relevant to vehicle-to-vehicle crashes as vehicle-to-fixed object crashes.

3.2.2 Computations

Longitudinal 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 11 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.

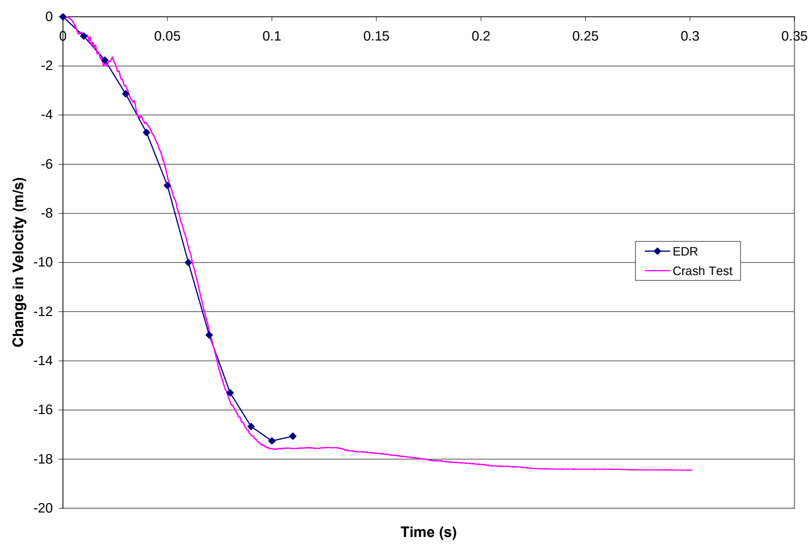


Figure 11. Evaluation of EDR in NHTSA Crash Test 4487 (adapted from Niehoff et al, 2005)

Flail Space Model

For each case, OIV will be 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 214 total cases, 54 fall into this category. As expected, the majority of cases were lower severity collisions; no OIV exceeds 10 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.

Twenty-seven (27) New Car Assessment Program (NCAP) frontal barrier tests conducted by the NHTSA were examined to estimate the accuracy of the OIV computations outlined above. The EDR error (compared with the lab grade instrumentation) was 4.3 percent on average with a range between 0.2 and 9 percent. For reference, the coefficient of variation in OIV, as computed by the lab grade instrumentation, was 11.8 percent, which is comparable to the maximum EDR delta-V error observed.

Acceleration Severity Index

The frontal collisions considered in this analysis were 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 10-ms intervals. The procedure was 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.

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

2. Select 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.

Note that *a* is acceleration, *v* is velocity, Δt is the time step, and Δt_{TOTAL} is the moving average time window, which is 50 ms in this case. The 50-ms averages were only computed for known velocity points. For instance, if a pulse is 50 ms in duration, only a single 50-ms average acceleration would be 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 12 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 proceeded in a similar manner.

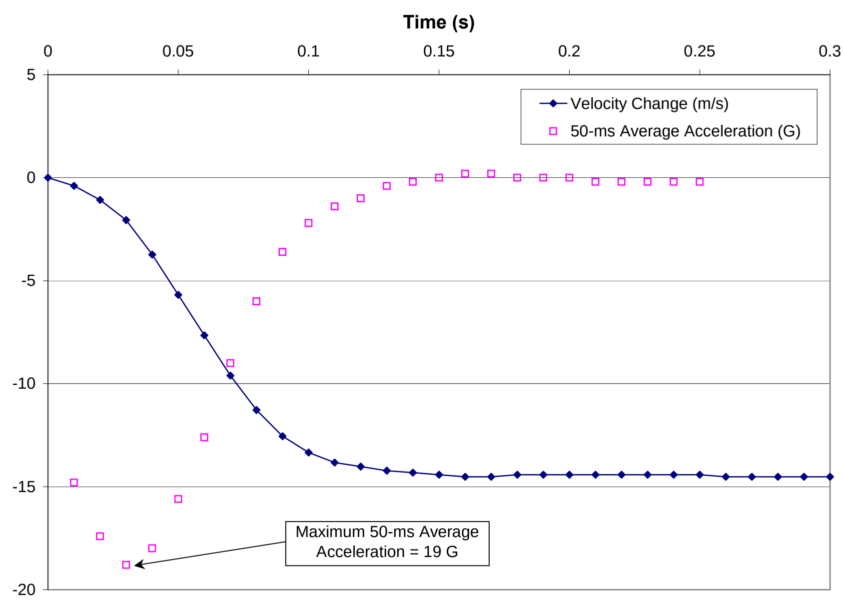


Figure 12. Longitudinal ASI Computation

To investigate the accuracy of the ASI computations outlined above, the same 27 NCAP frontal barrier tests were examined. The average EDR error (compared with the lab grade instrumentation) was 7.1 percent with a range between 0.3 and 18.3 percent. The coefficient of variation in ASI, as computed by the lab grade instrumentation, was 18.5 percent, which is comparable to the maximum EDR error.

Moving Average Accelerations

The average peak vehicle accelerations were computed using a procedure similar to the ASI computation without the normalization to a threshold acceleration value. Averaging time intervals ranged from 10-ms to 50-ms in 10-ms increments. To compute the 10-ms average accelerations, the following relation was used:

$$\overline{a}(t_i)_{10} = \text{10 ms moving average} = \frac{\sum_{i-1}^{i} a(t_i)\Delta t}{\Delta t_{TOTAL}} = \frac{\sum_{0}^{i} a_i \Delta t - \sum_{0}^{i-1} a_i \Delta t}{\Delta t_{TOTAL}} = \frac{v_i - v_{i-1}}{0.01s}$$

The maximum of these average acceleration values is then selected and converted to G-units. Using the 27 NCAP frontal barrier tests, the accuracy of the average acceleration computations outlined above was estimated. For the 10 ms average acceleration, the EDR error (compared with the lab grade instrumentation) was 6.9 percent on average with a range between 0.4 and 18 percent. For the 50 ms average acceleration, the EDR error was 7.1 percent on average with a range between 0.3 and 18.2 percent.

3.2.3 Model Development and Comparison

Binary logistic regression models were fit to the available data using each vehicle-based injury metric as a predictor. Occupant injury response was classified into “serious” injury and “non-serious” injury based on two rating schemes: the Abbreviated Injury Severity (AIS) scale

(AAAM, 2001) and the Injury Severity Score (ISS). The ISS scores injury on a 1 to 75 scale based on the maximum AIS injury scores in three of six different body regions (Baker et al, 1974). Note that an ISS value of 75 is also assigned if an AIS value of 6 is sustained. For the AIS scheme, two injury threshold levels were used to define “serious” injury: (1) AIS value of 3 or greater (AIS 3+), and (2) AIS 2+. For the ISS scheme, a single threshold level was used to define “serious” injury: an ISS value of 9 or greater. For each of these threshold definitions, injury risk curves were generated for all 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’).

Each binary logistic model accounted for the effects of occupant age. Several age classification schemes were investigated including a single threshold resulting in two age categories (e.g. age < 25 years or age ≥ 25) or a dual threshold resulting in three categories (e.g. age < 25 years, 25 ≤ age < 55, or age ≥ 55). Based on the available data, a single threshold of 35 years was selected for this analysis.

Note that since all of these vehicle-based metrics are correlated, their relative effect could not be examined by incorporating all metrics into a single model. The models were compared using various fit statistics and a Receiver Operating Characteristic (ROC) curve analysis. All statistical analyses were completed with the SAS® v9.1.3 software. ROC curve analysis was conducted using the SAS macro *%ROC* (SAS® Institute) based on DeLong et al (1988).

3.3 Results

3.3.1 MAIS Logistic Regression Models

Figure 13 presents sample graphical MAIS 3+ logistic regression results that have been age-adjusted. The plot shown is for belted occupants with OIV as a predictor. The corresponding shaded areas represent the 95 percent confidence bounds. The available data have been plotted as a function of OIV; note that a value of "1" corresponds to the "serious", or MAIS 3+, group in this case. As expected, the younger occupants (age ≤ 35) have lower predicted risk of injury for the same predictor value as compared to older occupants (age > 35). This is evident graphically as the injury risk curve for the older occupants is shifted left compared to the younger occupants.

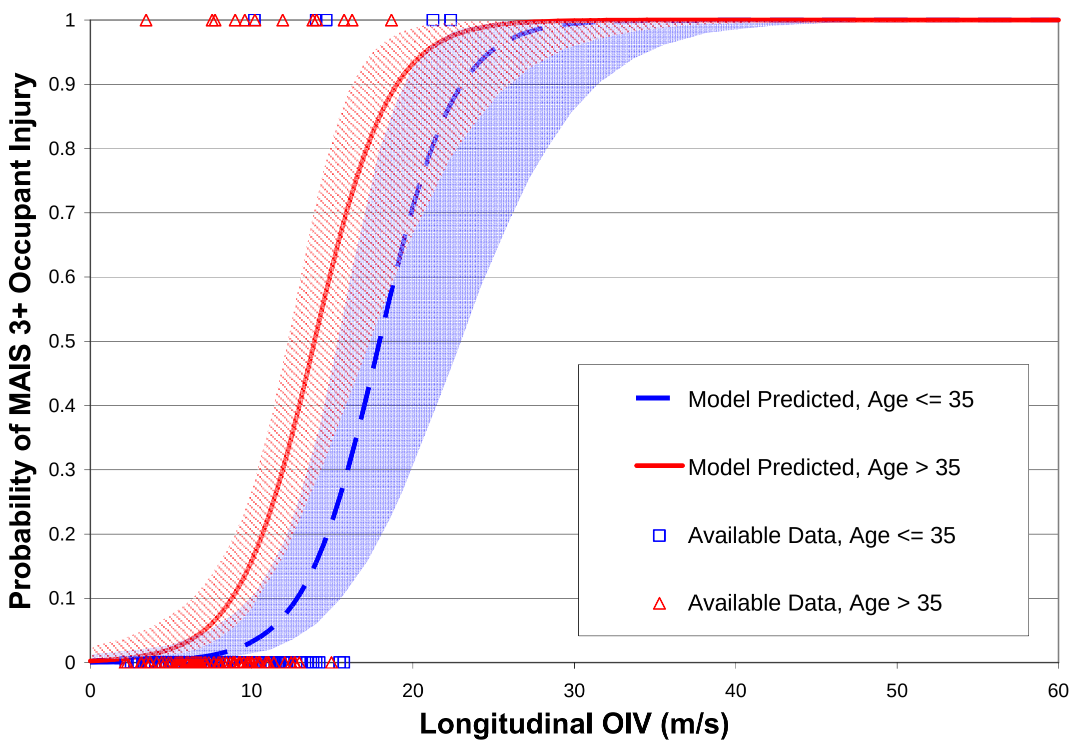


Figure 13. OIV MAIS 3+ Injury Risk Curves, Belted Occupants: Age Adjusted

For simplicity and clarity, the remainder of the graphical injury risk curves shown have not been adjusted for occupant age. The remainder of the analysis, however, does use the age-corrected values to compare the ability of the metrics to predict occupant injury. Figure 14 through Figure 18 show the non age-corrected MAIS 2+ injury risk curves based on the available data. Figure 14 presents the MAIS 2+ risk curves with OIV as the predictor; the left portion of the figure shows the belted occupant risk curve while the right portion shows the unbelted occupant risk curve. MAIS 2+ risk curves with ASI, delta-V, maximum 10 ms acceleration, and maximum 50 ms acceleration are shown in Figure 15, Figure 16, Figure 17, and Figure 18, respectively. The MAIS 2+ risk curves for the 20 ms, 30 ms and 40 ms maximum accelerations can be found in Appendix B along with the MAIS 3+ risk curves for all predictors. In all figures, 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.

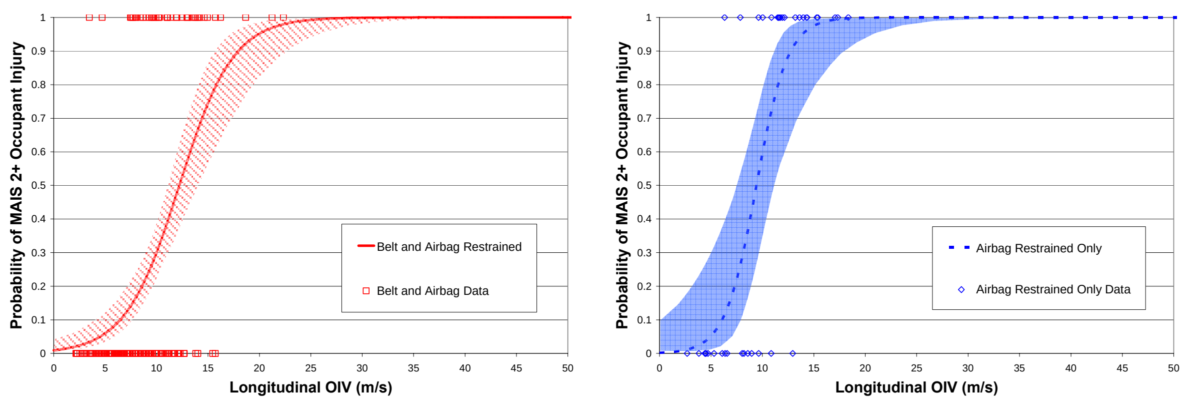


Figure 14. OIV MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

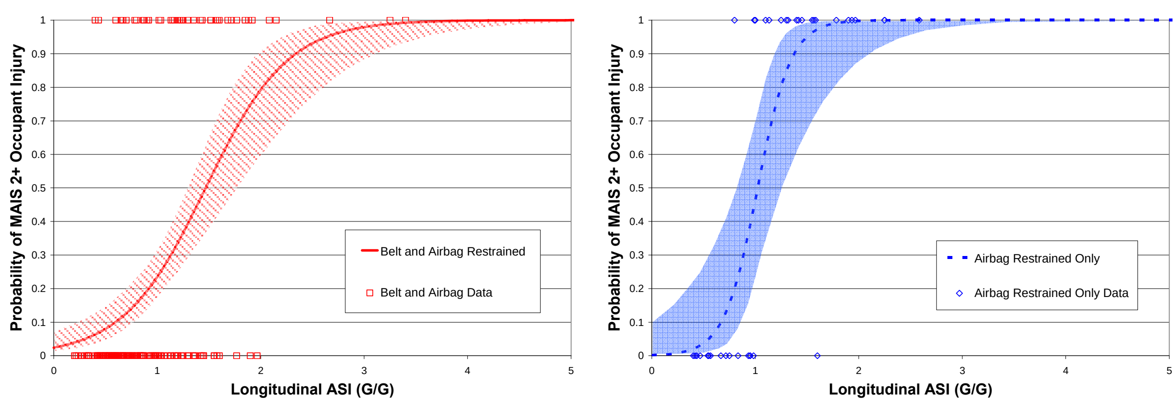


Figure 15. ASI MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

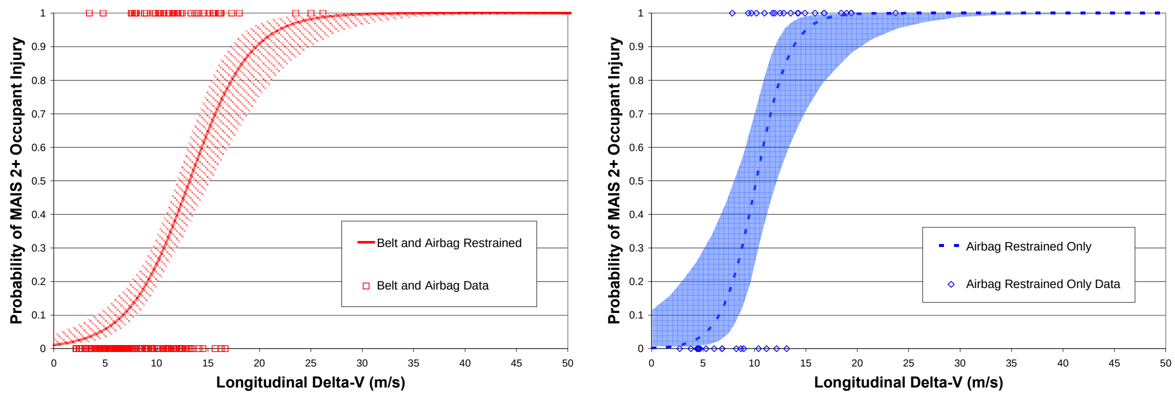


Figure 16. Delta-V MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

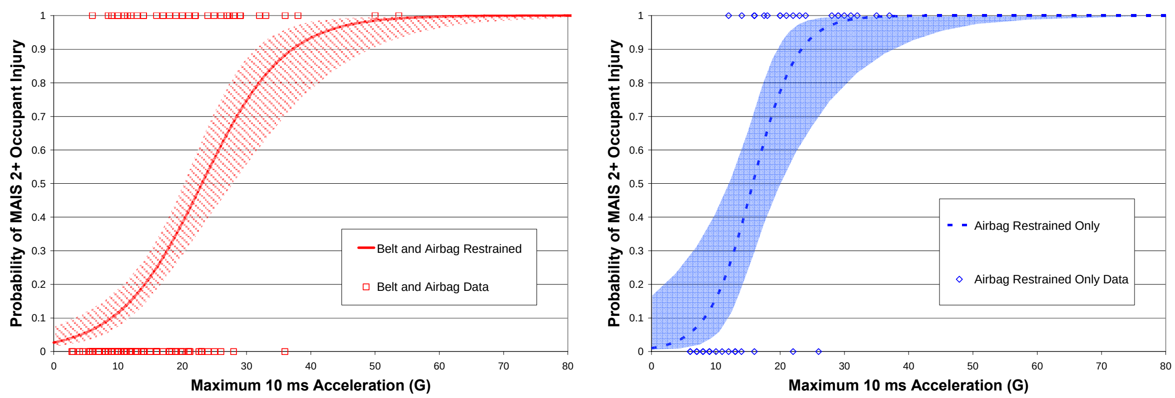


Figure 17. 10 ms Acceleration MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

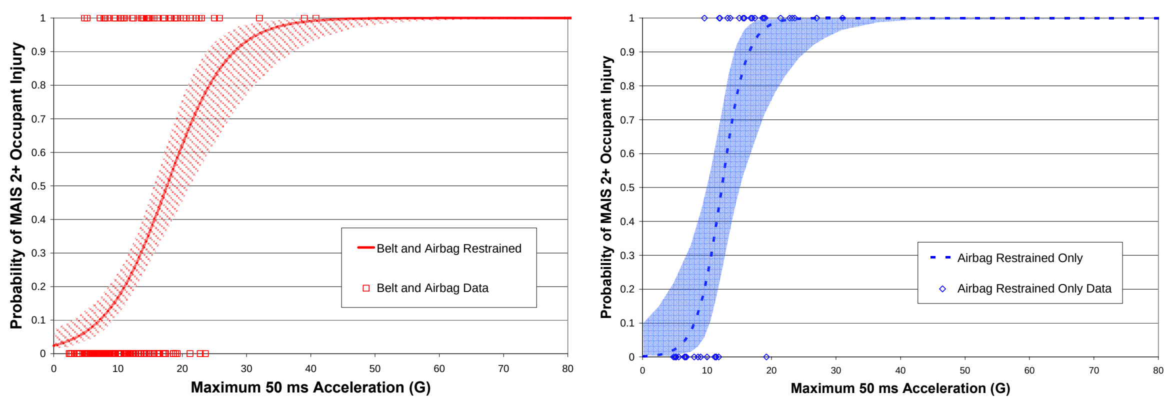


Figure 18. 50 ms Acceleration MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

Table 6 summarizes the age-corrected MAIS logistic regression model results. For the belted subset, all tests for the global null hypothesis and Wald Chi Square values were significant to the 0.0001 level or better. For the unbelted subset, all tests for the global null hypothesis and Wald Chi Square values were significant to the 0.0088 level or better. As all of the vehicle-based metric predictors are continuous, the Hosmer and Lemeshow test is used to determine goodness-of-fit. With the exception of the MAIS 2+ unbelted model with 40 ms maximum acceleration as the predictor (Hosmer and Lemeshow value of 0.0108), all models generated statistically adequate (>0.05) fits with Hosmer and Lemeshow values of 0.1016 or greater.

Table 6. Summary of Age-Corrected MAIS Logistic Regression Model Parameters

Injury Level	Predictor	Data Set	Model Parameter				Hosmer & Lemeshow
			Estimate	Std. Error	Wald χ^2	(p)	
MAIS 3+	Delta-V	Belted	0.3479	0.0787	19.55	(<0.0001)	0.3595
		Unbelted	0.9277	0.3542	6.862	(0.0088)	0.6318
	OIV	Belted	0.4302	0.0955	20.29	(<0.0001)	0.8468
		Unbelted	1.0392	0.3833	7.351	(0.0067)	0.9954
	ASI	Belted	3.0000	0.6837	19.26	(<0.0001)	0.7142
		Unbelted	5.6425	1.8407	9.396	(0.0022)	0.9926
	10 ms	Belted	0.1879	0.0402	21.87	(<0.0001)	0.7670
		Unbelted	0.2496	0.0777	10.31	(0.0013)	0.4213
	20 ms	Belted	0.2036	0.0438	21.59	(<0.0001)	0.7502
		Unbelted	0.3166	0.0977	10.49	(0.0012)	0.6432
	30 ms	Belted	0.2167	0.0478	20.56	(<0.0001)	0.5110
		Unbelted	0.3654	0.1155	10.01	(0.0016)	0.8099
	40 ms	Belted	0.2307	0.0513	20.25	(<0.0001)	0.7642
		Unbelted	0.4199	0.1353	9.634	(0.0019)	0.8946
	50 ms	Belted	0.2500	0.0570	19.26	(<0.0001)	0.7142
		Unbelted	0.4702	0.1534	9.396	(0.0022)	0.9926
MAIS 2+	Delta-V	Belted	0.3840	0.0690	31.01	(<0.0001)	0.6720
		Unbelted	0.6300	0.2035	9.582	(0.0020)	0.1016
	OIV	Belted	0.4471	0.0807	30.73	(<0.0001)	0.1989
		Unbelted	0.6609	0.2030	10.59	(0.0011)	0.7309
	ASI	Belted	3.0105	0.5602	28.88	(<0.0001)	0.4274
		Unbelted	6.2500	2.0545	9.255	(0.0023)	0.1838
	10 ms	Belted	0.1804	0.0327	30.35	(<0.0001)	0.1930
		Unbelted	0.2914	0.0931	9.789	(0.0018)	0.3910
	20 ms	Belted	0.1970	0.0358	30.26	(<0.0001)	0.5765
		Unbelted	0.4164	0.1339	9.674	(0.0019)	0.1037
	30 ms	Belted	0.2111	0.0391	29.22	(<0.0001)	0.3089
		Unbelted	0.4551	0.1476	9.510	(0.0020)	0.1942
	40 ms	Belted	0.2302	0.0425	29.31	(<0.0001)	0.2117
		Unbelted	0.5016	0.1652	9.215	(0.0024)	0.0108
	50 ms	Belted	0.2509	0.0467	28.88	(<0.0001)	0.4274
		Unbelted	0.5208	0.1712	9.255	(0.0023)	0.1838

For the MAIS 2+ and MAIS 3+ belted occupant data subsets, older occupants (age > 35) were found to have a higher likelihood of injury. This effect was statistically significant with *p* values ranging between 0.0016 and 0.0203 (data not shown). A similar effect was observed for the unbelted occupant data subsets, however, it was not found to be statistically significant with *p* values ranging between 0.4180 and 0.9338 (data not shown). This is likely due to the smaller number of unbelted occupant cases available.

3.3.2 ISS Logistic Regression Models

Figure 24 through Figure 23 show the non age-corrected ISS 9+ injury risk curves based on the available data. The plots have the same scheme used in the MAIS investigation with the left portion showing the belted occupant risk and the right portion showing the unbelted occupant risk. In all figures, 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. The ISS 9+ risk curves for the 20 ms, 30 ms and 40 ms maximum accelerations can be found in Appendix B.

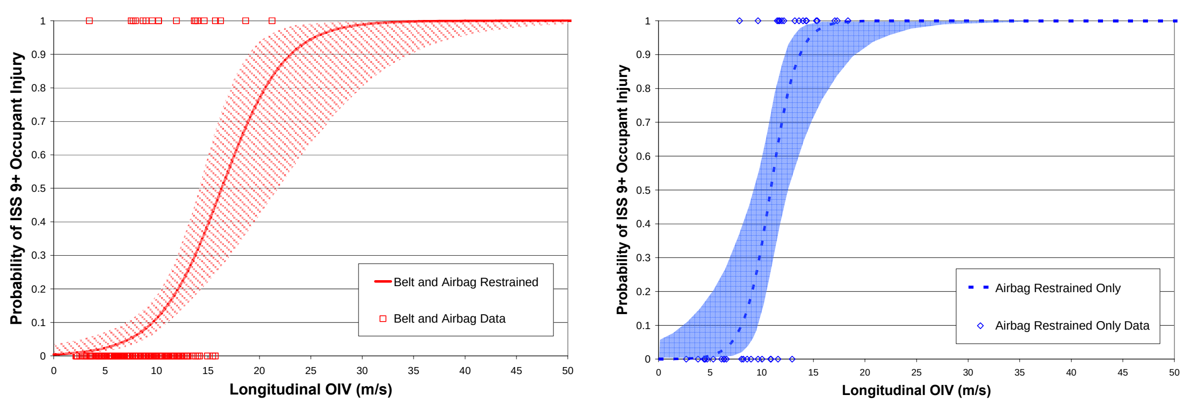


Figure 19. OIV ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)

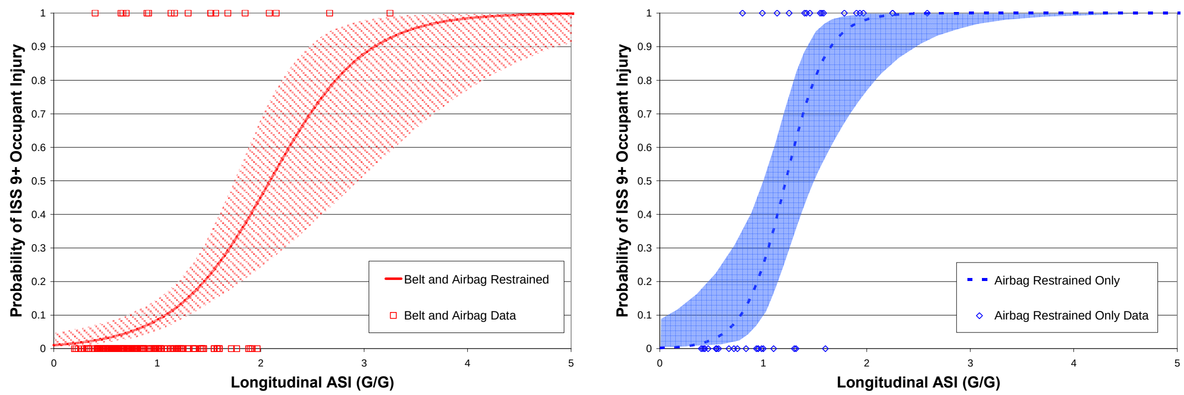


Figure 20. ASI ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)

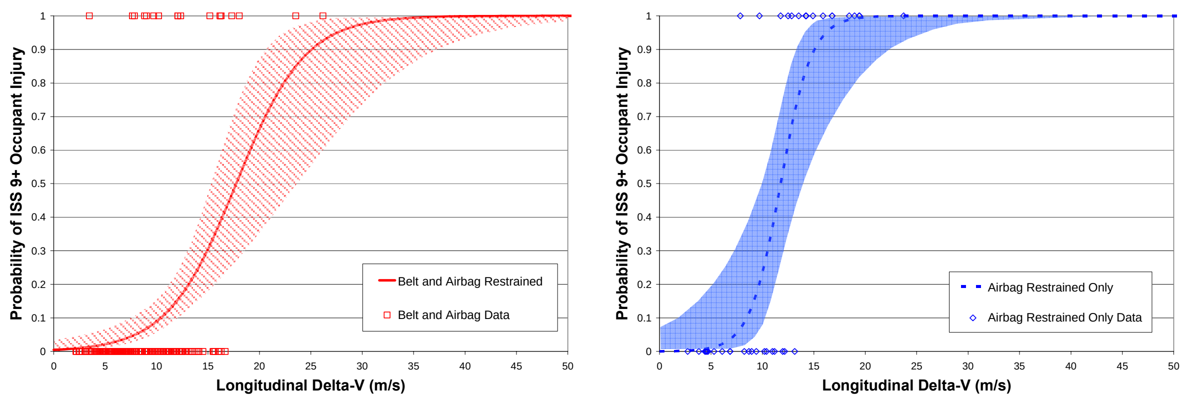


Figure 21. Delta-V ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)

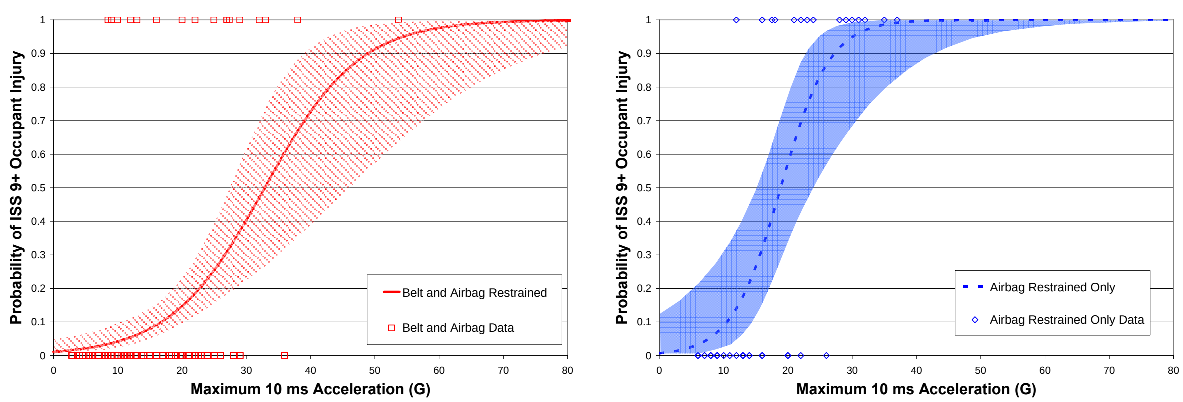


Figure 22. 10 ms Acceleration ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)

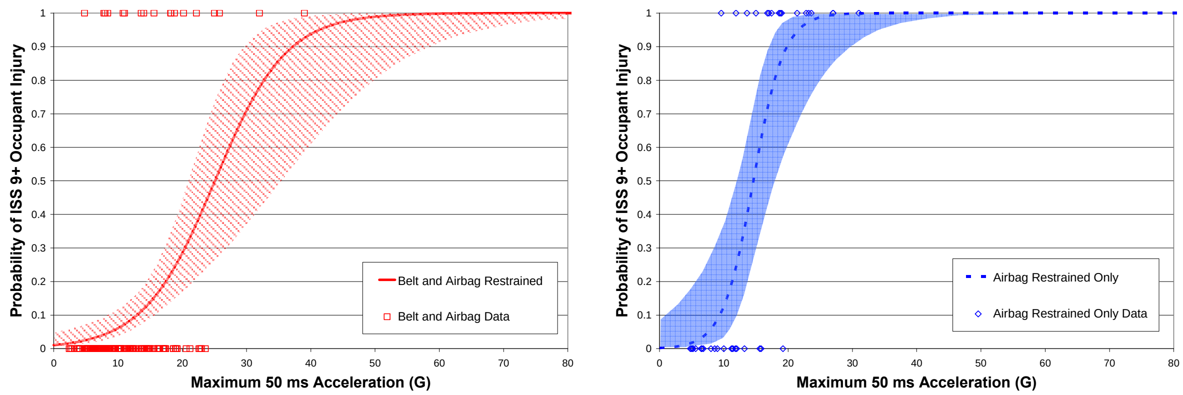


Figure 23. 50 ms Acceleration ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)

Table 7 summarizes the age-corrected ISS logistic regression model results. For the belted subset, all tests for the global null hypothesis and Wald Chi Square values were significant to the 0.0001 level or better. For the unbelted subset, all tests for the global null hypothesis and Wald Chi Square values were significant to the 0.0038 level or better. As all of the vehicle-based metric predictors are continuous, the Hosmer and Lemeshow test was used to determine goodness-of-fit. All models generated statistically adequate (>0.05) fits with Hosmer and Lemeshow values of 0.1519 or greater.

Table 7. Summary of Age-Corrected ISS Logistic Regression Model Parameters

Injury Level	**Predictor**	**Data Set**	**Model Parameter**			**Hosmer & Lemeshow**
			Estimate	**Std. Error**	**Wald χ^2 (p)**	
ISS 9+	Delta-V	Belted	0.3347	0.0791	17.91 (<0.0001)	0.5001
		Unbelted	0.7527	0.2599	8.388 (0.0038)	0.1519
	OIV	Belted	0.3775	0.0901	17.55 (<0.0001)	0.6453
		Unbelted	0.8206	0.2730	9.036 (0.0026)	0.3614
	ASI	Belted	2.5430	0.6168	17.00 (<0.0001)	0.3938
		Unbelted	5.0945	1.5910	10.25 (0.0014)	0.7817
	10 ms	Belted	0.1587	0.0370	18.44 (<0.0001)	0.4162
		Unbelted	0.2616	0.0820	10.19 (0.0014)	0.7587
	20 ms	Belted	0.1754	0.0403	18.94 (<0.0001)	0.8517
		Unbelted	0.3335	0.1027	10.53 (0.0012)	0.8900
	30 ms	Belted	0.1875	0.0440	18.13 (<0.0001)	0.7282
		Unbelted	0.3447	0.1067	10.44 (0.0012)	0.9365
	40 ms	Belted	0.1984	0.0472	17.69 (<0.0001)	0.4908
		Unbelted	0.3903	0.1220	10.23 (0.0014)	0.9459
	50 ms	Belted	0.2119	0.0514	17.00 (<0.0001)	0.3938
		Unbelted	0.4245	0.1326	10.25 (0.0014)	0.7817

Similar to the MAIS analysis, older occupants (age > 35) were found to have a higher likelihood of injury in the belted occupant data subset. This effect was statistically significant with p values ranging between 0.0109 and 0.0198 (data not shown). A similar, but not statistically significant, age effect was observed for the unbelted occupant data subsets. In this case, the p values ranged between 0.1299 and 0.4756 (data not shown). This is likely due to the smaller number of unbelted occupant cases available.

3.3.3 MAIS and ISS Model Comparisons

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. As the average acceleration metrics are most similar to the ASI, we expect these metrics to predict injury best for belted occupants. All of these vehicle-based metrics will be compared to the baseline measure of crash severity, delta-V.

Fit Statistics Comparison

Table 8 presents a summary of the MAIS model fit statistics for the models generated using all 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 8. Summary of MAIS Model Fit Parameters

Level	Data Set	Predictor	Goodness-of-Fit Statistic: AIC: Intercept Only	AIC: Intercept and Covariate	Max Rescaled R^2
MAIS 3+	Belted	OIV	113.77	83.54	0.3759
		ASI	113.77	80.29	0.4080
		Delta-V	113.77	84.52	0.3662
		10 ms	113.77	78.06	0.4297
		20 ms	113.77	77.18	0.4381
		30 ms	113.77	79.84	0.4124
		40 ms	113.77	80.20	0.4089
		50 ms	113.77	80.29	0.4080
	Unbelted	OIV	52.98	25.25	0.7665
		ASI	52.98	28.82	0.7087
		Delta-V	52.98	24.04	0.7850
		10 ms	52.98	36.09	0.5727
		20 ms	52.98	33.11	0.6316
		30 ms	52.98	31.52	0.6612
		40 ms	52.98	29.74	0.6927
		50 ms	52.98	28.82	0.7087
MAIS 2+	Belted	OIV	197.71	145.78	0.4057
		ASI	197.71	149.42	0.3830
		Delta-V	197.71	145.46	0.4076
		10 ms	197.71	148.56	0.3884
		20 ms	197.71	147.39	0.3957
		30 ms	197.71	149.70	0.3813
		40 ms	197.71	149.15	0.3848
		50 ms	197.71	149.42	0.3830
	Unbelted	OIV	54.26	32.34	0.6617
		ASI	54.26	28.97	0.7191
		Delta-V	54.26	30.91	0.6866
		10 ms	54.26	35.45	0.6039
		20 ms	54.26	30.39	0.6955
		30 ms	54.26	29.81	0.7053
		40 ms	54.26	28.95	0.7195
		50 ms	54.26	28.97	0.7191

In general, the model fits are very similar. All 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. At the MAIS 3+ level for unbelted occupants, both delta-V and OIV have a slight advantage over the other metrics. At the

MAIS 2+ level, however, ASI and the 20 ms through 50 ms metrics predict injury slightly better for unbelted occupants. ASI and the average acceleration metrics appear to have no advantage for belted occupants at the MAIS 2+ level. At the MAIS 3+ level, the acceleration based metrics appear to have a small advantage. All the values, however, are close to one another indicating similar fits between the more complex crash pulse-based metrics and delta-V, the traditional metric of crash severity.

Table 9 presents a summary of the ISS model fit statistics for all predictors. As with the MAIS models, all predictors appear to predict injury better for unbelted occupants. Delta-V and OIV have a slight advantage over the acceleration-based metrics for unbelted occupants. For belted occupants, delta-V and the 20 ms acceleration metric are the best predictors. Similar to the MAIS analysis, though, all the values are close to one another indicating comparable fits.

Table 9. Summary of ISS Model Fit Parameters

			Goodness-of-Fit Statistic		
			AIC		
Level	**Data Set**	**Predictor**	**Intercept Only**	**Intercept and Covariate**	**Max Rescaled R^2**
ISS 9+	Belted	OIV	117.74	94.37	0.2997
		ASI	118.18	93.77	0.3056
		Delta-V	118.18	91.67	0.3267
		10 ms	118.18	92.85	0.3150
		20 ms	118.18	91.87	0.3247
		30 ms	118.18	93.15	0.3119
		40 ms	118.18	93.44	0.3090
		50 ms	118.18	93.77	0.3056
	Unbelted	OIV	54.26	28.37	0.7289
		ASI	54.26	30.89	0.6871
		Delta-V	54.26	27.14	0.7483
		10 ms	54.26	35.46	0.6038
		20 ms	54.26	32.52	0.6585
		30 ms	54.26	33.02	0.6494
		40 ms	54.26	31.57	0.6753
		50 ms	54.26	30.89	0.6871

Table 10 shows how well each MAIS 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.

Table 10. Correlation of MAIS Models to Available Data (50% Probability of Injury)

Level	Data Set	Predictor	Correct (%)	Sensitivity (%)	Specificity (%)
MAIS 3+	Belted	OIV	92.6	29.4	99.4
		ASI	93.2	35.3	99.4
		Delta-V	92.0	35.3	98.1
		10 ms	93.2	41.2	98.7
		20 ms	92.6	35.3	98.7
		30 ms	92.6	35.3	98.7
		40 ms	93.2	35.3	99.4
		50 ms	93.2	35.3	99.4
	Unbelted	OIV	81.6	73.3	87.0
		ASI	81.6	80.0	82.6
		Delta-V	86.8	80.0	91.3
		10 ms	76.3	66.7	82.6
		20 ms	78.9	73.3	82.6
		30 ms	78.9	73.3	82.6
		40 ms	78.9	73.3	82.6
		50 ms	81.6	80.0	82.6
MAIS 2+	Belted	OIV	80.1	41.9	92.5
		ASI	81.3	41.9	94.0
		Delta-V	80.7	41.9	93.2
		10 ms	83.0	44.2	95.5
		20 ms	83.5	48.8	94.7
		30 ms	81.3	39.5	94.7
		40 ms	81.3	41.9	94.0
		50 ms	81.3	41.9	94.0
	Unbelted	OIV	78.9	81.0	76.5
		ASI	84.2	85.7	82.4
		Delta-V	76.3	81.0	70.6
		10 ms	78.9	76.2	82.4
		20 ms	86.8	85.7	88.2
		30 ms	81.6	81.0	82.4
		40 ms	86.8	85.7	88.2
		50 ms	84.2	85.7	82.4

Again, the acceleration-based metrics appear to be slightly better predictors of injury for unbelted occupants at the MAIS 2+ level with sensitivities as high as 85.7 percent. For the

MAIS 3+ injury level, delta-V appears to be the best predictor for unbelted occupants. All metrics are less sensitive predictors of injury to belted occupants while the metrics are less specific for unbelted occupants. The 20 ms acceleration metric appears to have a slight advantage for MAIS 2+ injury to belted occupants. Again, however, note the similarity between all the criteria.

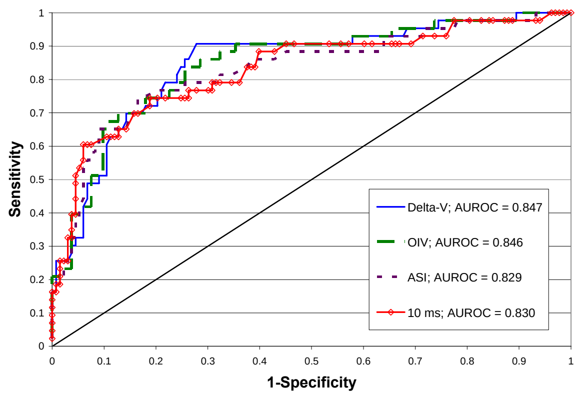
Table 11 shows how well each ISS model predicts the original data set assuming that a probability of serious injury greater than 50 percent results in "serious" occupant injury. Again, delta-V appears to have a slight advantage for unbelted occupants. All models are more sensitive to unbelted occupant injury. As with the MAIS data, all the fits are similar.

Table 11. Correlation of ISS Models to Available Data (50% Probability of Injury)

Level	Data Set	Predictor	Correct (%)	Sensitivity (%)	Specificity (%)
ISS 9+	Belted	OIV	91.4	22.2	99.4
		ASI	91.4	22.2	99.4
		Delta-V	90.8	27.8	98.1
		10 ms	90.8	22.2	98.7
		20 ms	90.8	22.2	98.7
		30 ms	90.8	22.2	98.7
		40 ms	91.4	22.2	99.4
		50 ms	91.4	22.2	99.4
	Unbelted	OIV	81.6	82.4	81.0
		ASI	84.2	82.4	85.7
		Delta-V	86.8	88.2	85.7
		10 ms	76.3	70.6	81.0
		20 ms	81.6	82.4	81.0
		30 ms	84.2	82.4	85.7
		40 ms	84.2	82.4	85.7
		50 ms	84.2	82.4	85.7

ROC Comparison

To further compare the vehicle-based injury metrics, an ROC curve analysis was performed for the belted and unbelted data subsets. Figure 24 through Figure 27 provide a graphical comparison of the ROC curves for the MAIS models. Figure 28 and Figure 29 provide a graphical comparison for the ISS models.



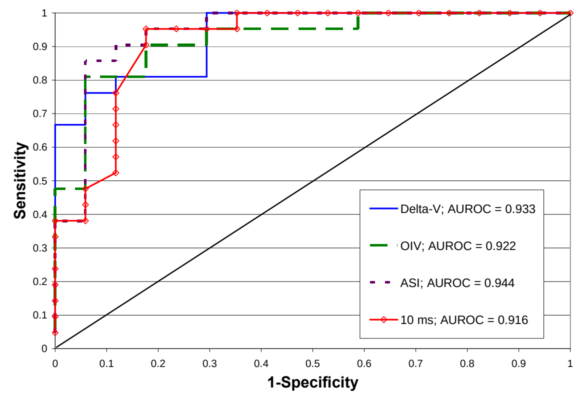
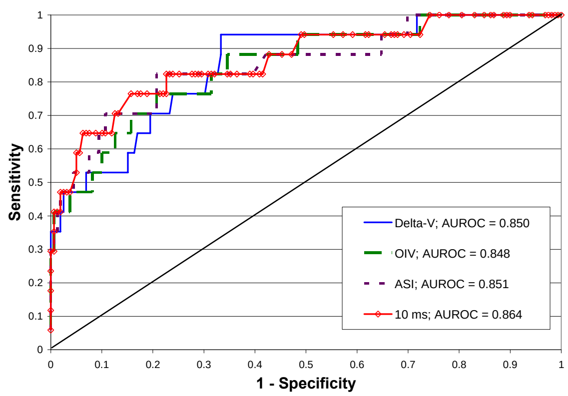


Figure 24. ROC Curve Comparison: Belted Occupants, MAIS 2+

Figure 25. ROC Curve Comparison: Unbelted Occupants, MAIS 2+



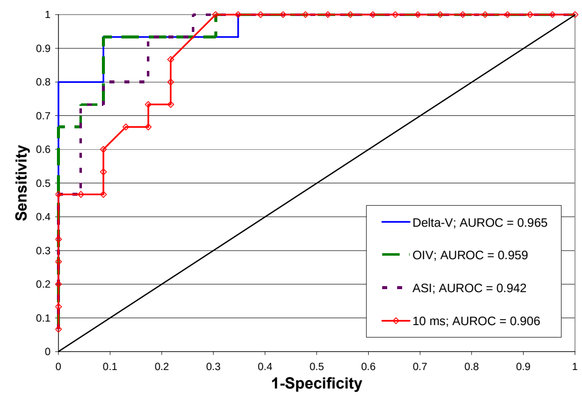
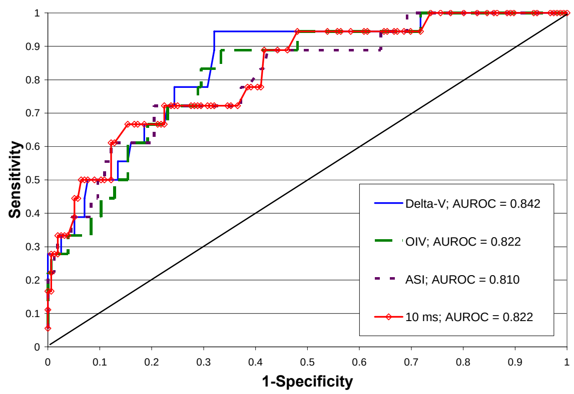


Figure 26. ROC Curve Comparison: Belted Occupants, MAIS 3+

Figure 27. ROC Curve Comparison: Unbelted Occupants, MAIS 3+



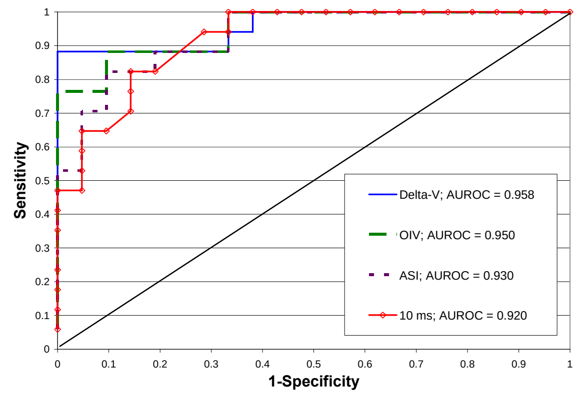


Figure 28. ROC Curve Comparison: Belted Occupants, ISS 9+

Figure 29. ROC Curve Comparison: Unbelted Occupants, ISS 9+

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, all metrics 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. Selected pairwise comparisons of the area under the ROC curve are summarized in Table 12. The overall comparison, between all metrics, is also shown. In all cases, the p-values exceeded 0.05 suggesting no statistically significant difference between the area under the respective ROC curves for any of the metrics. This implies that there is no statistically significant difference in injury predicting capability between OIV, ASI, the average acceleration metrics or delta-V.

Table 12. Summary of Selected MAIS ROC Pairwise Comparisons

Level	Data Subset	Data Subset	p	Overall p
MAIS 3+	Belted	OIV vs. ASI	0.865	0.915
		OIV vs. Delta-V	0.835	
		ASI vs. Delta-V	0.972	
		10 ms vs. Delta-V	0.689	
	Unbelted	OIV vs. ASI	0.317	0.812
		OIV vs. Delta-V	0.568	
		ASI vs. Delta-V	0.311	
		10 ms vs. Delta-V	0.106	
MAIS 2+	Belted	OIV vs. ASI	0.369	0.864
		OIV vs. Delta-V	0.975	
		ASI vs. Delta-V	0.468	
		10 ms vs. Delta-V	0.557	
	Unbelted	OIV vs. ASI	0.438	0.711
		OIV vs. Delta-V	0.652	
		ASI vs. Delta-V	0.709	
		10 ms vs. Delta-V	0.665	

3.4 Discussion

The primary finding of this study is that none of the more complex vehicle-based criterion offers 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 metrics appear to be reasonable predictors of overall occupant injury. All metrics were found to be better predictors of injury for unbelted occupants than 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 impact velocity experienced by an unbelted occupant. Belted occupants have very different kinematics than unbelted occupants. None of the 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 significantly greater ability than OIV to predict serious occupant injury for belted occupants. All developed models had a reduced ability to predict injury when injury was observed in the belted population (sensitivity ≤ 50 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 a large variation 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.

3.5 Conclusions

This study provides a comprehensive comparison of current vehicle-based injury metrics based on their ability to predict injury in real-world collisions. Although numerous studies have correlated delta-V to injury, this is one of the first studies to utilize the more robust EDR data to compute delta-V in lieu of the traditional crush-based method. More importantly, the availability of EDR data allowed for a first-of-a-kind evaluation of the more complex vehicle-based injury metrics that require the vehicle crash pulse. Development of injury risk curves for these metrics, typically used to assess occupant risk in roadside hardware crashes, will provide the roadside community a much needed link between crash test risk assessment and corresponding injury risk.

This study has conducted an analysis of the OIV, ASI, 10 ms through 50 ms average acceleration metrics, and delta-V injury criteria based on EDR data coupled with detailed injury data for 214 real-world crashes. The study has generated age-corrected injury risk curves to predict the probability of serious occupant injury in frontal collisions using these vehicle-based metrics as predictors. The study found that the more computationally intensive metrics that require knowledge of the entire crash pulse offer no statistically significant advantage over the simpler delta-V crash severity metric in discriminating between serious and non-serious occupant injury. This finding underscores the importance of developing an improved vehicle-based injury metric.

4. The Effects of Restraints on Occupant Injury in Roadside Hardware Crashes

4.1 Introduction

Current vehicle-based methods of assessing occupant risk in full-scale roadside hardware crash tests do not account for occupant restraints such as seatbelts or airbags. Chapter 2 described the effects of neglecting these occupant restraints through an analysis of full-scale crash tests. It is important, however, to verify that these restraints do in fact have an effect on occupant injury in real-world crashes involving roadside hardware. The study detailed in this chapter investigated the effect of these restraints on subsequent occupant injury.

The effects of occupant restraints in preventing injury in purely frontal crashes have been well documented (Evans, 1986; Braver et al., 1997; Crandall et al., 2001; Huere et al., 2001; McGwin et al., 2003). Little is known, however, with regard to their performance in longitudinal barrier collisions. A majority of the previous longitudinal barrier research has focused on real world crash injury prior to the widespread implementation of airbags.

Several studies were conducted in New York state examining injury and fatality in crashes with various types of roadside and median barriers (Carlson, Allison and Bryden, 1977; Zweden and Bryden, 1977; Hiss and Bryden, 1992). Viner (1995) used national data from 1985 to examine the costs of various roadside crash types, including guardrail impacts. Ray et al. (1986; 1987) investigated occupant injury mechanisms in longitudinal barrier collisions with a focus on secondary collisions. Perhaps the most in-depth longitudinal barrier crash data, the Longitudinal Barrier Special Study (LBSS), was collected in tandem with the National Automotive Sampling System (NASS) / Crashworthiness Data System (CDS) for approximately

600 barrier crashes occurring between 1982 and 1986. NASS/CDS provides detailed information, including restraint performance and occupant injury, for a random sample of approximately 5,000 U.S. crashes every year. Researchers (Erinle et al., 1994; Hunter, Stewart and Council, 1993) used this specialized database primarily to investigate injury differences between different barrier systems and investigate the performance of barrier end terminals. Elvik (1995) performed a meta-analysis of previous guardrail literature published between 1956 and 1993 to evaluate the safety effects of guardrails.

There have been a limited number of studies that provide an assessment of the performance of occupant restraints in these collisions. Council and Stewart (1996) and Council et al. (1997) examined state accident data to determine the effect of airbags on average injury severity in collisions with various roadside objects and safety devices. Airbags were found to decrease the average severity of roadside object collisions by 10 to 50 percent, but in most cases the decrease was not statistically significant due to small sample sizes. For these studies, the average severity was gauged primarily by the proportion of fatal and/or incapacitating driver injury. The study included data from only three states (North Carolina, Illinois and Utah), excluded pickup trucks and vans, and included only data through 1994, which was prior to the widespread implementation of airbags. Holdridge et al. (2005) used multivariable nested logit models to investigate the performance of roadside hardware on urban state highways in Washington State. Although airbags and seatbelts were found to reduce the severity of roadside fixed object crashes, the analysis was not specific to longitudinal barriers, was based on data from only a single state, and was limited to urban state highways.

Grzebieta et al. (2002) performed several full-scale crash tests with a small car impacting various roadside barriers to examine airbag performance and driver injury potential. The researchers demonstrated that advanced vehicle restraints, including airbags and seat belt pretensioners, can fire under certain barrier impact conditions. In terms of investigation of injury, however, the study was limited by the number of impact conditions and the use of a single vehicle type. Other researchers have suggested that impacts with the relatively flexible longitudinal barriers may actually cause the late deployment of an airbag, which may increase the propensity for occupant injury (Grzebieta et al, 2005). With the exception of the Grzebieta et al study, there is little full-scale roadside hardware crash test data to study airbag performance. In the US, the current NCHRP Report 350 crash testing procedures (Ross et al, 1993) does not specify that the airbags need to be on during the test. As a result, these devices are usually disabled prior to the crash test.

The purpose of this study was (1) to determine the extent to which occupant restraints are used or deployed in real-world longitudinal barrier collisions and (2) to examine the effects of vehicle restraints on occupant injury and injury patterns in these collision types. Examining airbag deployment and seat belt usage rates in real-world collisions was important to establish that these restraints are used and/or deployed in real world vehicle-to-roadside hardware crashes. Investigation of occupant injury as a function of restraint type was important for verifying that these devices reduce injury potential in these crash types.

4.2 Methods

Data from the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) was used to determine occupant restraint usage and deployment rates as well as compare injury based on occupant restraint condition. NASS/CDS provides a detailed record of approximately 5,000 tow-away level crashes investigated each year (NCSA, 2005). The NASS/CDS database includes a random sample of minor, serious and fatal crashes involving only cars, light trucks, vans and sport utility vehicles. Heavy vehicles and motorcycles are not included in the NASS/CDS database.

As NASS/CDS is a representative sample of all crashes that occur in a given year in the United States, the appropriate weighting factors were applied to the cases prior to analysis to obtain national estimates of injury. All statistical analyses were performed using the SAS V9.1.3 software package.

4.2.1 Case Selection

Cases were selected from a 14-year NASS/CDS data set spanning 1993 to 2006, inclusive. The study focused on tow-away level crashes, an inherent requirement of NASS/CDS, as the interest is on crashes with the potential to cause injury as opposed to minor crashes. Cases were selected from NASS/CDS based on the following additional criteria:

- Single event crash where a single passenger vehicle impacts a longitudinal barrier
- Damage to the front of the vehicle
- Occupant is seated in the front left or front right seating position (or both)
- No occupant ejection or vehicle rollover
- Known occupant belt and airbag status.

Inclusion of single event crashes ensures that the longitudinal barrier caused (or did not cause) the deployment of the airbag. Only passenger vehicles and light trucks and vans (LTVs) were included; all heavy vehicles were excluded from the analysis. For the purpose of this study, a longitudinal barrier included concrete barriers, metal beam guardrails, and cable barriers. Longitudinal barriers in NASS/CDS are grouped into one of two categories: (1) concrete barriers, and (2) other barriers. The latter category includes all types of steel guardrail systems such as w-beam guardrails, box beam barriers, and cable barriers. For these “other barriers”, an effort was made to ensure proper barrier classification by examining the available crash scene photographs for the NASS/CDS cases available online for cases occurring between 1997 and 2006 (NCSA, 2008). Photographs were not available for suitable crashes occurring between 1993 and 1996. Any concrete barriers classified in this category were reclassified accordingly. Likewise, any bridge rails were reclassified to the concrete barrier category. These barriers are often constructed of concrete or a very rigid steel structure.

As the focus of this study was on frontal airbag deployment, side impacts and rear impacts with longitudinal barriers have been excluded. Only non-ejected front seat occupants were selected for analysis as current longitudinal barrier occupant risk criteria focus only on the injury to these occupants. Another stipulation was that occupant belt and airbag status was known. For this study, only unbelted occupants or those restrained by a 3-point seatbelt were included. As with seat belt status, airbag status was determined separately for each occupant. Only occupants with no airbag available, airbag available but not deployed, or airbag deployed during the crash were included. Occupants with unknown belt use were excluded.

4.2.2 Restraint Usage and Airbag Deployment Rates

Restraint usage and airbag deployment proportions were determined directly from the suitable NASS/CDS cases after the application of the associated statistical weighting factors. Seat belt usage rates were determined for the entire data set and two subsets: (1) airbag restrained occupants and (2) non-airbag restrained occupants. Longitudinal barrier airbag deployment rates were determined for the entire data set as well as for the airbag restrained occupant data subset. Airbag deployment rates were also examined as a function of crash severity using the barrier equivalent speed metric. Although delta-V is the preferred measure of crash severity, delta-V is difficult to estimate for longitudinal barrier crashes (Smith and Noga, 1982). In addition, delta-V was not available for a majority of the suitable cases. Due to the uncertainty in the delta-V estimates for this crash mode, the multiple imputation approach was not pursued. For this portion of the analysis, cases were only included if the equivalent barrier speed (EBS) was known. EBS can be determined based on the crush of the subject vehicle. EBS avoids many of the difficulties associated with delta-V computations for vehicles impacting objects of unknown stiffness such as guardrails. Two airbag restrained occupant subgroups were also analyzed based on type of barrier impacted: (1) concrete barrier or (2) other barrier. Data from these subgroups were then used in a two-way contingency table analysis to determine if differences in airbag deployment rates exist by barrier type

4.2.3 Injury Risk Comparison by Restraint Type

To provide a comparison of injury risk by occupant restraint status, odds ratios were compared from developed binary logistic regression models. Each of the binary logistic regression models predicted occupant injury based on occupant restraint status, confounding factors, and the complex sampling design of NASS/CDS. This analysis considered four occupant restraint conditions: (1) airbag available, belted occupant, (2) airbag available, unbelted occupant, (3) no airbag, belted occupant, and (4) no airbag, unbelted occupant.

Confounding factors were vehicle, occupant and barrier related variables including vehicle type, occupant gender, occupant age, seating position, crash severity and type of barrier impacted. Vehicle type was grouped into one of two categories, passenger car or LTV, based on the "bodytype" variable in NASS/CDS. Gender and seating position were also considered dichotomous variables: male / female for gender and driver / right front passenger for seating position. Occupants were grouped into three categories based on age: up to and including 24, 25 to 54, or 55 and older. EBS was used to account for crash severity with three distinct categories: up to 16 km/hr (10 mph), 16 km/hr to 40 km/hr, and greater than 40 km/hr (25 mph).

The first level of stratification and clustering within NASS/CDS was accounted for by using the "surveylogistic" procedure available in SAS. Case stratification in NASS/CDS is based on vehicle tow status, occupant injury level, and hospitalization (NHTSA, 2005). The first level clusters are represented by the primary sampling units (PSU's) located across the United States. Each represents either a central city, a county surrounding a central city, an individual county or a continuous group of counties (NHTSA, 2005). A more detailed description of the NASS/CDS sampling design methodology can be found in the Analytical User's Manual (NHTSA, 2005).

Occupant injury severity was described using the Abbreviated Injury Severity (AIS) scale (AAAM, 1998), which methodically rates injury on a discrete 0 to 6 scale based on threat to life. In NASS/CDS, each injury an occupant acquires is rated based on this scale and the most severe of all the injuries is termed the maximum AIS (MAIS) score. Three injury thresholds were used to provide a binary (injury/no injury) response: (1) a maximum AIS value of 1 or greater (MAIS 1+), (2) MAIS 2+, and (3) MAIS 3+. The MAIS 2+ and MAIS 3+ thresholds were selected to determine the effects of restraints on more serious occupant injury. The MAIS 1+ threshold was selected to provide insight to whether airbags increase the likelihood of minor injuries in the event of a longitudinal barrier crash. For this portion of the analysis, cases with unknown or missing occupant injury data were excluded.

4.3 Analysis of Results

4.3.1 Restraint Usage and Deployment Rates

There were a total of 915 NASS/CDS cases suitable for analysis. After application of the NASS weights, these cases represent more than 475,000 occupants exposed to a longitudinal barrier collision. Table 13 shows the actual and weighted cases by restraint type. Note that these cases represent approximately 80 percent of unweighted (77 percent weighted) front seat occupants involved in a longitudinal barrier crash. A majority of the remaining cases (15 percent unweighted and 15 percent weighted) had an unknown belt use; these cases were excluded from the analysis. In the examination of the barriers classified as other barriers by the NASS/CDS investigator, a total of 24 barriers were reclassified to the concrete barrier category (19 concrete barriers and 5 bridge rails). Only 18 of these reclassified cases had occupant injury information. Based on this analysis, the predominant barrier was the strong post w-beam (65 %) followed by the strong post thrie beam barrier (12 %), weak post w-beam barrier (6 %), and box beam barrier (3 %).

Table 13 Summary of Suitable NASS/CDS Cases for Analysis

Belt Usage	Airbag Status	Raw Data		Weighted	
		Occupants	% of Total	Occupants	% of Total
Lap and Shoulder	Bag Deployed	247	27.0	165,048	34.6
	Non-Deployed	132	14.4	68,587	14.4
	Not Equipped	163	17.8	132,734	27.9
No Belt	Bag Deployed	109	11.9	23,975	5.0
	Non-Deployed	27	3.0	18,009	3.8
	Not Equipped	237	25.9	67,978	14.3

Figure 30 shows the distribution of occupants with an airbag available involved in longitudinal barrier impacts between 1993 and 2006 as well as the proportion of airbag deployments for occupants with an airbag available. Approximately 60 percent of occupants involved in a tow-away level longitudinal barrier impact between 1993 and 2006 had an airbag available. For those occupants where an airbag was present, the airbag deployed approximately 70 percent of the time. For all occupants, lap and shoulder belt usage rates were 77 percent. For the airbag restrained and non-airbag restrained data subsets, the lap and shoulder belt use rates were 85 percent, and 66 percent, respectively (data not shown).

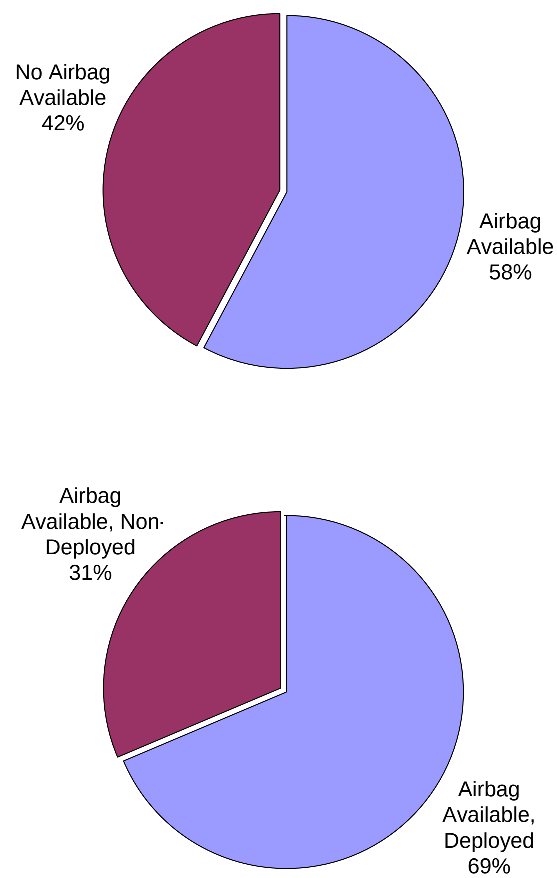
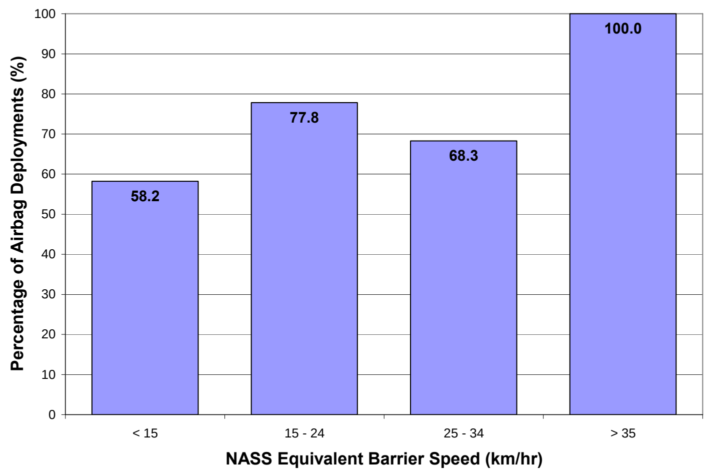


Figure 30. Distribution of Airbag Presence for Occupants Involved in a Longitudinal Barrier Impact (top) and Airbag Deployment Distribution for Occupants with an Airbag Available (bottom): 1993-2006

Figure 31 shows airbag deployment rates as a function of the NASS investigator determined barrier equivalent speed as well as the distribution of barrier equivalent speed for barrier crashes. The top portion of the figure was based on 498 raw cases (261,583 weighted cases) where the occupant had an airbag available and the barrier equivalent speed was estimated; the minimum number of raw observations for equivalent barrier speed in each category was 33. Of the 915 cases available, there were a total of 132 (14 %) with no estimate of barrier equivalent speed. The bottom portion of Figure 3 included both airbag-restrained occupants (498 cases) and non-airbag equipped occupants (285 cases). Note that all data presented in Figure 3 was based on weighted data.



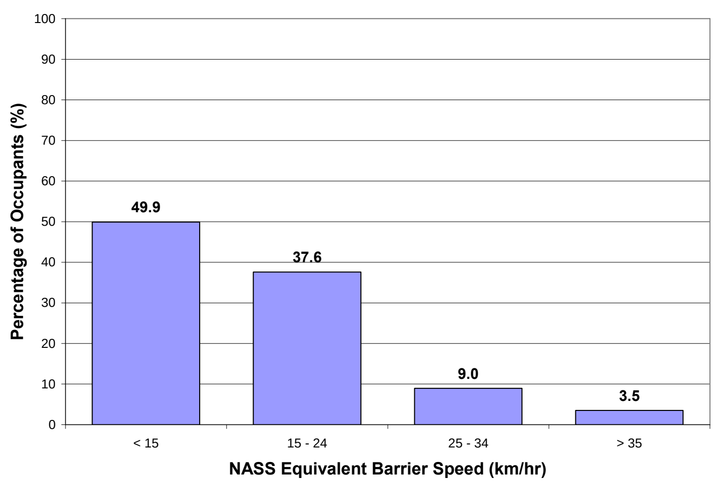


Figure 31. Airbag Deployment Distribution as a Function of Equivalent Barrier Speed (top) and Distribution of Equivalent Barrier Speeds for Longitudinal Barrier Crashes (bottom): Weighted Data

Table 14 shows the occupant airbag deployment rate by barrier type for airbag equipped occupants in the available data. The weighted values and associated percentages are shown along with the 95 percent confidence intervals for the weighted proportions. Based on the Rao-

Scott modified likelihood ratio chi-squared test, no statistically significant difference was found between airbag deployment rates for different barrier types ($p = 0.3693$).

Table 14 Airbag Deployment Rates by Object Contacted

Object Struck	Airbag Status	Raw Cases	Weighted		95% Confidence Bounds	
			Occupants	% of Total	Lower	Upper
Concrete Barrier	Bag Deployed	214	79,523	74.4	60.1	88.8
	Non-Deployed	58	27,334	25.6	11.2	39.9
Other Barrier	Bag Deployed	134	109,500	64.9	49.5	80.3
	Non-Deployed	101	59,262	35.1	19.7	50.5

4.3.2 Injury Risk Comparison by Restraint Type

A smaller data set of 847 unweighted cases (449,160 weighted) was available for the injury analysis as detailed injury data was unknown in 68 cases. There were two cases (145 weighted) where the injury severity was unknown but the NASS/CDS treatment variable indicated a fatality; these cases were assigned an MAIS value of 6. A total of 713 of the cases (398,350 weighted) had known EBS. Figure 32 shows the weighted distribution of occupant injury severity for all available cases (847 raw cases) and the EBS known cases (713 raw cases). The distributions of occupant injury are very similar. In both data sets, approximately 96 percent of the occupants had no injury or only minor (MAIS 1) injuries. The smaller 713 case data set was used for the remainder of the injury risk analysis.

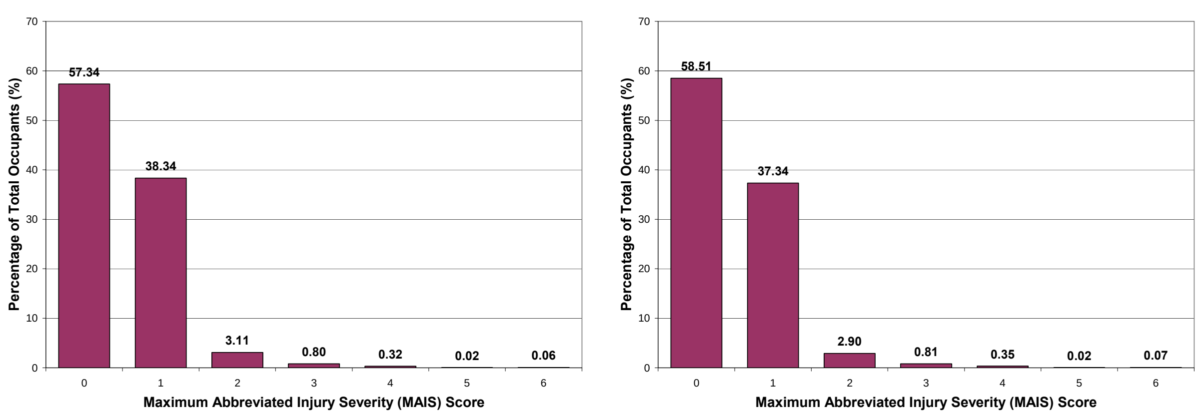


Figure 32. Weighted Distribution of Occupant Injury Severity: All Occupants (left) and Occupants with Known EBS (right)

A summary of the binary logistic regression model parameters is shown in Table 15. A total of three models were developed based on the three injury thresholds (MAIS 1+, 2+ and 3+) using EBS as a proxy for crash severity For each parameter, the Wald Chi-Square statistic and associated p-value has been included as well as the C-statistic for each model. The C-statistic represents the area under the Receiver Operator Characteristic (ROC) curve and provides a single numerical value of how well the model distinguishes between the response variable, in this case, occupant injury versus no injury.

Table 15. Summary of Logistic Regression Model Parameters, Equivalent Barrier Speed Adjusted

Injury Level	Parameter	Wald χ^2	*P*	C Statistic	*n* (No Injury/Injury)
MAIS 1+	Restraint Condition	10.410	0.0154	0.689	257,569 / 191,591
	Gender	5.321	0.0211		
	Vehicle Type	0.042	0.8386		
	Occupant Location	1.481	0.2237		
	Age Group	7.927	0.0190		
	Barrier Type	0.553	0.4572		
	Equivalent Barrier Speed	12.720	0.0017		
MAIS 2+	Restraint Condition	15.586	0.0014	0.787	429,782 / 19,378
	Gender	0.614	0.4332		
	Vehicle Type	2.516	0.1127		
	Occupant Location	6.817	0.0090		
	Age Group	2.665	0.2638		
	Barrier Type	7.857	0.0051		
	Equivalent Barrier Speed	10.868	0.0044		
MAIS 3+	Restraint Condition	15.522	0.0014	0.826	443,743 / 5,417
	Gender	0.292	0.5888		
	Vehicle Type	1.138	0.2861		
	Occupant Location	19.859	<0.0001		
	Age Group	6.694	0.0352		
	Barrier Type	2.523	0.1122		
	Equivalent Barrier Speed	5.163	0.0756		

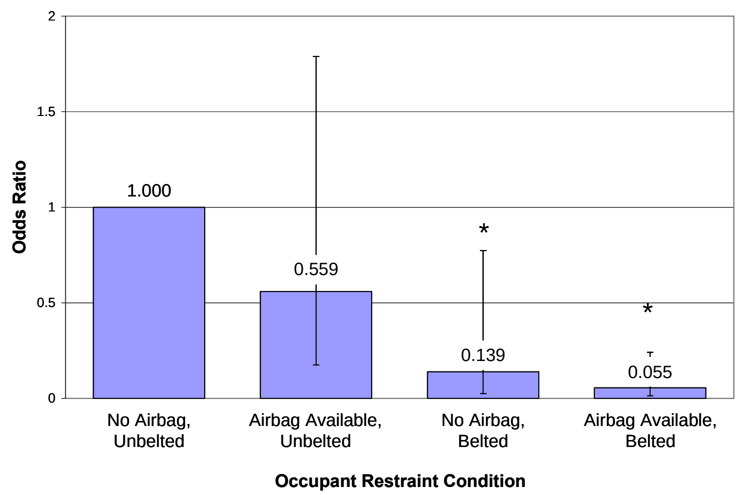
For all of the models, the effect of restraint condition was statistically significant. At the MAIS 2+ and MAIS 3+ levels, occupant location was statistically significant with higher injury risk associated with drivers. EBS was statistically significant at the MAIS 1+ and MAIS 2+ levels and nearly significant at the MAIS 3+ level (p = 0.0756). The effect of barrier type was statistically significant at the MAIS 2+ level; in all cases, concrete barrier impacts were associated with higher odds of occupant injury. Occupant age was found to be statistically significant at the MAIS 1+ and MAIS 3+ levels with higher odds of injury associated with older occupants. Occupant gender differences were only statistically significant at the MAIS 1+ level with females more likely to be injured. The reason for this observation is unclear. One potential explanation for this observation could be that females may be more likely to report or seek medical treatment for minor injuries typical of MAIS 1+ injuries. There were, however, no statistically significant interactions between gender and age, occupant location, or vehicle type (data not shown).

Table 16 shows the odds ratios for occupant restraint condition and barrier type for all three EBS-adjusted models. For the occupant restraint condition, the odds ratio represents a comparison to a completely unrestrained occupant, i.e. no belt used and no airbag available. For the barrier type, the odds ratio represents a comparison to rigid barriers, i.e. the concrete barriers and the small number of bridge rails that were reclassified. The 95 percent confidence bounds on each ratio are also shown.

Table 16. Summary of Odds Ratios and Associated Confidence Bounds, EBS Adjusted

Injury Level	Parameter	Value	Baseline Level	Odds Ratio	95% Confidence Bounds	
					Lower	Upper
MAIS 1+	Restraint Condition	Airbag, Belted	No Airbag, No Belt	0.289	0.090	0.929
		No Airbag, Belted		0.154	0.048	0.496
		Airbag, No Belt		0.573	0.149	2.203
	Barrier Type	Other Barrier	Concrete Barrier	0.732	0.321	1.667
MAIS 2+	Restraint Condition	Airbag, Belted	No Airbag, No Belt	0.055	0.013	0.241
		No Airbag, Belted		0.139	0.025	0.773
		Airbag, No Belt		0.559	0.175	1.789
	Barrier Type	Other Barrier	Concrete Barrier	0.236	0.086	0.648
MAIS 3+	Restraint Condition	Airbag, Belted	No Airbag, No Belt	0.052	0.012	0.226
		No Airbag, Belted		0.143	0.012	1.714
		Airbag, No Belt		0.348	0.110	1.102
	Barrier Type	Other Barrier	Concrete Barrier	0.287	0.061	1.340

All restraint conditions show a decrease in the odds of injury compared to the unrestrained condition. The decrease was statistically significant for the fully restrained occupant at all injury levels investigated. For the belt only restrained occupant, the decrease was statistically significant at the MAIS 1+ and MAIS 2+ injury levels. In terms of barrier type, the odds of occupant injury were decreased when impacting a non-rigid barrier. These decreases, however, were statistically significant only at the MAIS 2+ level.



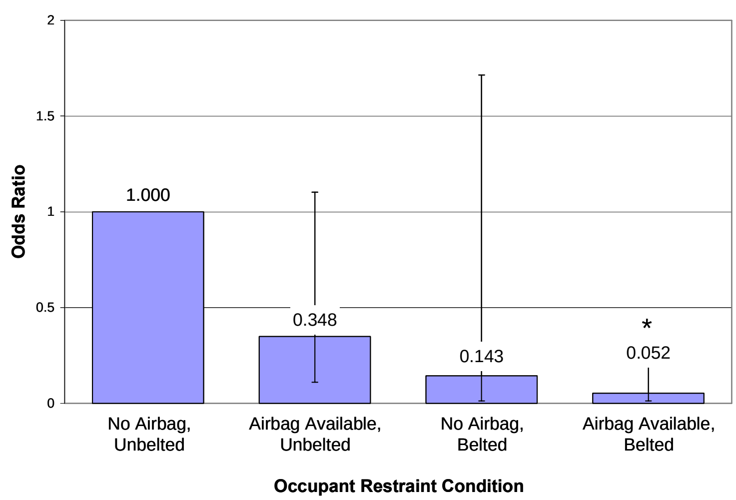


Figure 33. Equivalent Barrier Speed Adjusted Odds Ratio Summary: MAIS 2+ (top) and MAIS 3+ (bottom)

Figure 33 graphically shows the odds ratio results for the four occupant restraint conditions based on the EBS adjusted model. All odds ratios are with respect to the unrestrained condition and the error bars represent the 95 percent confidence bounds on the point estimates. Statistically significant differences from the completely unrestrained condition are noted by an asterisk (*).

4.4 Discussion

4.4.1 Restraint Usage and Deployment Rates

The available data suggest that a majority of occupants exposed to a longitudinal barrier collision are restrained by a lap and shoulder belt and, if the vehicle is equipped with an airbag, the airbag is deployed in almost three-fourths of tow-away severity crashes. Lap and shoulder belt usage rates were consistent with the US national average of approximately 80 percent (Glassbrenner, 2005), especially with respect to airbag restrained occupants. The belt use rate for non-airbag restrained occupants was found to be somewhat lower at 66 percent. One explanation for this observation could be that non-airbag equipped vehicles tend to be older model year vehicles; other researchers have linked nonuse of seatbelts to older vehicles (Reinfurt et al., 1996). These results confirm that airbag deployment is not a rare event in tow-away longitudinal barrier collisions and that a majority of occupants wear safety belts. Although the flail space model continues to be used to evaluate occupant risk in full-scale roadside hardware tests, it does not account for either of these occupant restraint types.

Although not found to be statistically significant, concrete barriers appear to have an increased propensity for airbag deployment compared to other metal beam or cable barriers. Based on the weighted data, the airbag deployment rates were 74 percent for concrete barriers compared to 64 percent for other longitudinal barriers. These barrier types are more rigid than the metal beam and cable barriers typically classified as "other barriers" in NASS/CDS. The lack of statistical significance may be a combination of the variation in the data due to the complex sampling design (there was a sampling design correction of 6.40). These deployment differences are also consistent with the limited amount of longitudinal barrier crash testing conducted with the airbag systems activated. Grzebieta et al (2002; 2005) found that concrete barriers caused airbag deployment for impacts of 80 km/hr (50 mph) at an angle of 45 degrees as well as 110 km/hr (68 mph) at an angle of 20 degrees. In two tests conducted with w-beam barrier, however, the airbag deployed only in a crash where the vehicle impacted at 80 km/hr (50 mph) at an angle of 45 degrees. The airbag did not in a crash into a guardrail at 110 km/hr (68 mph) at an angle of 20 degrees. Although the vehicle impact speed was higher in the 110 km/hr test, the vehicle kinetic energy perpendicular to the barrier was roughly half that of the 80 km/hr test with an impact angle of 45 degrees.

Figure 31 shows that airbag deployment probability in longitudinal barrier collisions increase roughly proportional to increasing barrier equivalent speed. Based on the available data, it appears that airbag deployment occurs in all barrier collisions with a barrier equivalent speed greater than 35 km/hr (21 mph). Approximately 90 percent of occupants exposed to a tow-away longitudinal barrier collision were in vehicles where the equivalent barrier speed was at or below 24 km/hr (15 mph). It should be noted that the procedure to determine equivalent barrier speed only accounts for the deformation of the vehicle and not any deformation of the longitudinal barrier. For this study, equivalent barrier speed is simply used as a surrogate for crash severity. Coon and Reid (2005; 2006) have developed a longitudinal barrier-specific methodology for determining vehicle delta-V in these collisions. These procedures are currently not incorporated into the NASS/CDS delta-V estimates.

4.4.2 Injury Risk Comparison by Restraint Type

In terms of occupant injury risk, the first observation is the low injury risk in the vehicle to barrier crashes. There were few high severity occupant injuries present in the available single event longitudinal barrier collisions. Approximately 96 percent of the weighted cases were occupants that sustained either no injury or an MAIS 1 level injury. Based on the weighted data available, approximately 1.2 percent of occupants exposed to a tow-away longitudinal barrier collision sustain potentially life threatening injuries (MAIS 3 or greater). These results are consistent with the findings of previous researchers combining results from several studies using police-reported injury data from guardrail crashes (Michie and Bronstad, 1994).

In terms of occupant injury risk by restraint condition, the results of the binary logistic regression models indicate a decrease in the odds of occupant injury for occupants that are restrained with an airbag, a seatbelt, or both. The greatest odds decrease was observed with the completely restrained occupant with odds of injury between 3.5 and 19 times less than that of a completely unrestrained occupant for the MAIS 1+ and MAIS 3+ thresholds, respectively. Unbelted occupants with an airbag had a 1.75 to 3 fold reduction in the odds of injury. Belted occupants not restrained by an airbag had a 6.5 to 7 fold reduction in the odds of injury suggesting that seatbelt use has a greater effect on occupant injury in single event longitudinal barrier collisions.

At the MAIS 1+ injury level, the absence of an airbag restraint resulted in a greater decrease in the odds of injury (OR = 0.154) compared to the fully restrained condition (OR = 0.289). A similar phenomenon has been observed by other researchers in frontal crashes (Segui-

Gomez, 2000). In general, the ability of the airbag to reduce occupant injury in tow-away longitudinal barrier crashes increased with increasing injury level. At the MAIS 3+ level, the injury reduction effect of the airbag alone was nearly statistically significant. Barrier type was found to have a statistically significant effect at the higher severity levels (MAIS 2+ and 3+). The odds of occupant injury were between 1.5 and 4 times lower when a barrier other than a concrete barrier or bridge rail was impacted.

4.5 Conclusions

The purpose of this study was to determine whether occupant restraints are used and/or deployed in roadside hardware crashes and investigate their effect on occupant injury in these collisions. Prior to the development of a vehicle-based injury metric for potential use in crash tests with roadside hardware, it is important to verify the hypothesis that these restraints do in fact affect occupant injury in real-world collisions involving these devices. Previous studies cannot be used to assess these affects as they have focused on a predominately non-airbag equipped vehicle fleet.

This study has investigated occupant restraint use and airbag deployment in longitudinal barrier collisions. In real world longitudinal barrier collisions, airbags were found to deploy in 70 percent of all tow-away collisions when the vehicle was equipped with an airbag. Seat belt usage rates in longitudinal barrier collisions were found to be 86 percent in airbag-equipped vehicles.

When adjusting for other confounding factors, seatbelts and airbags are found to reduce the odds of occupant injury in single event longitudinal barrier crashes. Compared with completely unrestrained occupants, the odds of occupant injury were found to be between 1.75 and 3 times lower if the occupant is airbag-equipped, between 6.5 and 7 times lower if the occupant is not airbag-equipped but belted, and between 3.5 and 19 times lower if the occupant is belted and airbag-restrained.

5. Enhancing Vehicle-Based Metrics with Vehicle Structure and Restraint Performance Metrics

5.1 Introduction

In previous chapters, an analysis of full-scale crash tests and real-world collisions has been used to examine existing vehicle-based metrics. These metrics, such as vehicle delta-V, do not typically account for the performance of occupant restraints or the performance of the vehicle structure. Occupant restraints include conventional three-point seat belts and airbags as well as more recent restraint innovations such as seat belt pretensioners and seat belt load limiters. Numerous researchers have substantiated that these restraints reduce occupant injury as measured either by a crash test dummy (Walz, 2004) or by analysis of detailed crash injury data (Foret-Bruno et al, 2001; Foret-Bruno et al, 1998; Huelke and Sherman, 1987; Evans, 1986). Vehicle structure performance refers to the ability of the structure to absorb crash energy, such as through a crumple zone.

Ideally, occupant injury prediction would be based on the kinematics or forces to which the occupant is exposed. For real-world crashes, however, the kinematics of the occupant is extremely difficult to estimate. Traditionally, occupant kinematics for real world crashes have been estimated either with a full-scale reconstruction of the crash (German et al, 1998; Bilston et al, 2007) or through computer modeling (Geigl et al, 2003; Jakobsson et al, 2004; Moran et al, 2004). Both of these methods are difficult or impractical to implement for a large number of real-world crashes.

The purpose of this study was to investigate potential measures of occupant restraint and vehicle structure performance that can be used to enhance existing vehicle-based metrics, specifically vehicle delta-V. Delta-V was selected instead of one of the more complex vehicle-based injury metrics for two primary reasons. First, delta-V is the traditional metric used worldwide to assess crash severity and has long been used as a predictor of occupant injury (Roberts and Compton, 1993; Bahouth et al, 2004; Nance et al, 2006). Second, the analysis presented in Chapter 3 suggests that there is no statistically significant difference between delta-V and the more complex vehicle-based metrics, such as the OIV and ASI, in terms of predicting occupant injury in real-world frontal collisions.

The hypothesis of this study is that coupling a vehicle-specific measure of restraint and a structure performance with delta-V will provide a better estimate of occupant injury kinematics and subsequent occupant injury potential. Candidate restraint and vehicle structure performance metrics were investigated through a detailed analysis of full-scale crash tests. Those measures that provide the highest correlation to injury potential, as measured by a crash test dummy, were selected for inclusion in the enhanced metric and further evaluation in real-world crashes.

5.2 Modifying Delta-V

For this study, the occupant response is assumed to be a function of three primary factors: (1) the vehicle crash severity, (2) the performance of the vehicle structure, and (3) the occupant restraint performance. Delta-V, in this case, is considered a measure of the vehicle crash severity. The idea is to supplement delta-V with one metric from each of the latter categories: vehicle structure performance and occupant restraint performance. These supplementary metrics would be vehicle specific and determined through analysis of full-scale crash tests.

Table 17 lists the candidate metrics to be considered in the analysis. These represent existing metrics available to characterize crash severity, the performance of the vehicle structure, and the occupant restraint performance. A brief discussion of each of these metrics is presented below.

Table 17. Candidate Metrics

Category	Metrics
1. Crash Severity	Delta-V (DV)
	Average Acceleration ($\Delta V/t_f$)
2. Vehicle Structure Performance	Ridedown Efficiency (μ)
	Maximum 50 ms Acceleration (50 ms)
	Maximum 10 ms Acceleration (10 ms)
	Crash Pulse Shape (t_c/t_m)
3. Restraint Performance	Restraint Quotient (RQ_c)
	Kinetic Energy Factor (E_c)

5.2.1 Vehicle Crash Severity

In addition to delta-V, another descriptor of the vehicle crash pulse is average acceleration. This metric is defined as the delta-V divided by the time over which the maximum change in vehicle velocity occurs.

5.2.2 Vehicle Structure Performance

For the purpose of this study, vehicle structure performance refers to the ability of the structure to absorb crash energy, such as through a crumple zone. Passenger compartment intrusion, another important aspect of structural performance, is not examined here. Intrusion is rarely observed in the full width barrier crash tests to be used in this study. Our study focuses on metrics that can be computed using the measured vehicle kinematics or vehicle kinematics in conjunction with the occupant kinematics measured during a full width frontal crash test. Candidate vehicle structure performance metrics are described below.

Ridedown Efficiency. The ridedown efficiency, μ, is defined as follows (Huang et al, 1995):

$$\mu = \frac{e_{rd}\,|_{\max}}{\frac{1}{2}V_o^2} \qquad (1)$$

where V_o is the initial velocity of the vehicle and e_{rd} is the vehicle ridedown energy density, defined as follows:

$$e_{rd} = \int_0^{x_f} \ddot{x}_o \, dx_v \qquad (2)$$

where $\ddot{x}_o$ represents the acceleration of the occupant (crash test dummy), x_v is the displacement of the occupant compartment, and x_f is the final displacement of the vehicle occupant compartment. This metric reflects the percentage of total kinetic energy absorbed by the vehicle structure and has been found to be closely related to vehicle dynamic crush (Huang et al, 1995). A slight variant on ridedown efficiency has been proposed by Katoh and Nakahama (1982) where e_{rd} is computed over the interval from zero to the maximum vehicle deflection.

Moving Average Accelerations. Both the maximum 10 ms and maximum 50 ms average accelerations are moving average metrics. The computation procedure is the same for both metrics, differing only by the time frame over which the acceleration is averaged. Higher moving average accelerations suggest that the vehicle structure deforms in a way which may increase injurious forces to an occupant. In contrast to the ridedown efficiency, the computation of these metrics only requires vehicle kinematics information.

TESW Relative Centroid Location. The Tipped Equivalent Square Wave (TESW) provides a 4 parameter approximation of a vehicle crash pulse that matches the vehicle velocity change and dynamic crush at the point of maximum velocity change (Huang et al, 1977). Figure 34 shows a TESW approximation of a rigid frontal barrier crash test.

One measure of the performance of the vehicle structure is the crash pulse shape. Here, the crash pulse shape is measured by the ratio of the centroid location to the time to maximum dynamic crush (t_c /t_m). The lower and upper bounds on this ratio can be shown to be 1/3 and 2/3, respectively. Values below 0.5 are said to be "front loaded" crash pulses while values above 0.5 are said to be "rear loaded" crash pulses. For the data shown in Figure 34, the relative centroid location was 0.58 indicating a "rear loaded" crash pulse. Similar to the moving average acceleration metrics, computation of this ratio only requires vehicle kinematics information.

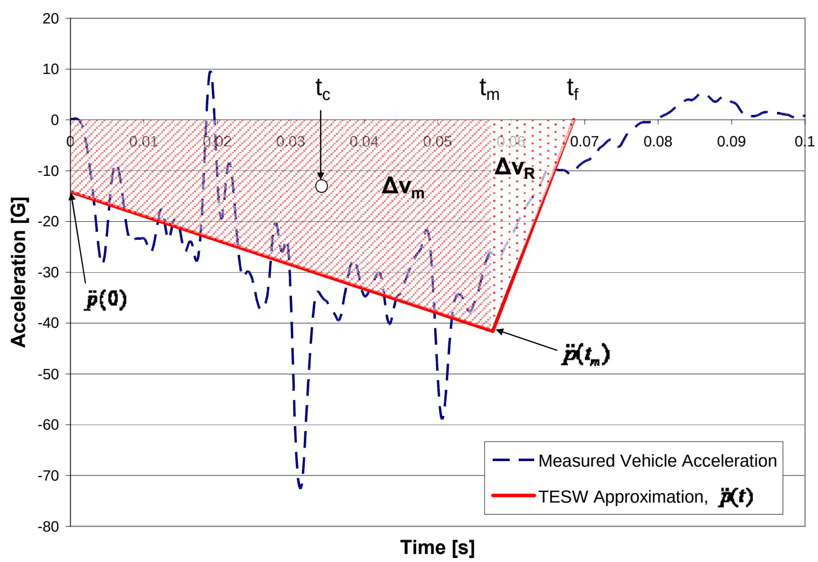


Figure 34. Tipped Equivalent Square Wave Approximation for a 2008 Scion XB (NHTSA Test #6076)

5.2.3 Occupant Restraint Performance

Restraint Quotient. This restraint performance metric proposed by Viano and Arepally (1990) is computed using the resultant acceleration (longitudinal and vertical directions only) of the occupant combined with the longitudinal deceleration of the vehicle occupant compartment. The Restraint Quotient is typically computed for the thorax (RQ_c) using the following relation:

$$RQ_c = \frac{V_c}{(\dot{x}_V)_{\max}} \qquad (3)$$

where V_c is the resultant velocity of the thorax with respect to the moving vehicle reference frame. This is computed by subtracting the respective velocity from that of the vehicle occupant compartment. $(\dot{x}_V)_{\max}$ is simply the maximum velocity change of the vehicle during the crash test. A restraint quotient value of 0 represents an occupant rigidly coupled to the vehicle interior and a value of 1 indicates an occupant attains the full velocity change of the vehicle prior to impacting the vehicle interior.

Relative Kinetic Energy Factor. Also suggested by Viano and Arepally (1990), the relative kinetic energy factor is simply a normalized measure of the occupant kinetic energy per unit mass (normalized by a velocity of 5 m/s). This metric (E_c) is computed based on the thorax accelerations using the following relation:

$$E_c = \frac{\max(V_c)^2}{25} \qquad (4)$$

As in the restraint quotient, V_c is the resultant velocity of the thorax with respect to the moving vehicle reference frame.

5.3 Methods

The general approach for this study was to (1) select appropriate full-scale crash tests, (2) compute metrics describing the three crash aspects for each test, and (3) use multiple linear regression analysis to compare the ability of the models to predict maximum chest acceleration.

5.3.1 Case Selection

The National Highway Traffic Safety Administration (NHTSA) maintains an electronic database of full-scale vehicle crashworthiness tests performed for the New Car Assessment Program (NCAP), Federal Motor Vehicle Safety Standards (FMVSS) compliance as well as various other research purposes (NHTSA, 2008a). Full-scale crash tests were first selected from this database based on the following criteria:

1. Vehicle impacting a flat rigid barrier with full frontal engagement
2. 50th percentile male Hybrid III crash test dummy seated in the driver position.
3. Occupant restrained by an airbag, seatbelt or both an airbag and seatbelt.

The Hybrid III crash test dummy was used as it is widely used in frontal crash tests and is more biofidelic than the earlier Hybrid II dummy. Restricting cases to crash tests using only the 50th percentile male crash test dummy was intended to limit variability in the occupant responses between cases. Based on these initial criteria, there were 894 suitable cases for analysis.

To ensure data accuracy, the electronic data for each of these cases was examined further. As a minimum, each case was required to have a single vehicle acceleration trace in the longitudinal (x) direction and two occupant chest acceleration traces: one in the longitudinal (x) direction and one in the vertical (z) direction. Cases not meeting this requirement were excluded from the analysis. For vehicle-mounted accelerometers, only sensors in the occupant compartment were used. Preference was given to those accelerometers located on either the right or left rear seats or door sills. In addition, the vehicle velocity traces from each case were examined visually and any questionable cases were excluded from the analysis. These included cases where the accelerometer failed or there was an apparent calibration error.

After this secondary screening process, there were a total of 619 total cases suitable for analysis. Table 2 presents the distribution of occupant restraint for the suitable cases. For this data set, the vehicle model years ranged from 1990 through 2008 and consisted of a slightly larger portion of cars (343, 55%) than light trucks and vans (276, 45%).

Table 18. Occupant Restraint for Suitable Cases

Occupant Restraint	Number of Cases	Percentage
Airbag Only	51	8.2
3 Pt Belt Only	21	3.4
Airbag and 3 Pt Belt	547	88.4

Due to the high proportion of occupants with both airbag and 3 point belt restraints, a second analysis was conducted with this subset separate from the overall data set. For this subset, the vehicle model year range was 1990 through 2008, inclusive, and the distribution of vehicle type was 55% (303) cars and 45% (244) light trucks and vans; very comparable to the entire data set.

5.3.2 Computations

For each case, the vehicle crash severity, vehicle structure performance, and occupant restraint performance metrics were computed using the available vehicle and crash test dummy acceleration data. Prior to computing the metrics, the vehicle accelerations and crash test dummy chest accelerations were filtered with a low pass filter (CFC 180), according to SAE-J211 (SAE, 2007). All integrations were computed numerically using the trapezoidal rule.

Vehicle Crash Severity. Delta-V was simply computed as the difference between the maximum and minimum vehicle velocity values. The average vehicle acceleration was computed by dividing the delta-V by the length of the crash event. For this study, the length of the crash event was the time to the maximum change in vehicle velocity.

Vehicle Structure Performance. To compute the ridedown efficiency, the acceleration of the crash test dummy thorax was integrated with respect to the vehicle displacement as shown in Equation 2. The maximum absolute value of this integral was used as the numerator in Equation 1 to determine the ridedown efficiency.

The maximum 10 ms and maximum 50 ms average accelerations were computed based on the vehicle acceleration trace in the longitudinal direction. For the 10 ms metric, the average acceleration is first computed from 0 to 0.01 seconds and then incremented by the time step until the end of the data; the largest of these average accelerations is then selected as the maximum 10 ms average acceleration. A similar procedure was used for the maximum 50 ms average acceleration with the averages computed over 50 ms time windows.

To compute the relative centroid location based on the TESW approximation, the following relation was used (Huang et al, 1977):

$$t_c = -\frac{x(t_m)}{\Delta v_m} = \frac{C_{\max}}{V_o} \qquad (5)$$

Where C_{max} is the maximum dynamic crush computed by doubly integrating the vehicle acceleration and selecting the maximum value. V_o is simply the vehicle impact speed. Relative centroid location was then computed by dividing t_c, centroid location, by the time corresponding to the maximum dynamic crush, t_m.

Occupant Restraint Performance. The restraint quotient was computed based on the crash test dummy thorax longitudinal and vertical accelerations using Equation 3. The term is fixed for a particular crash while the resultant relative velocity of the thorax with respect to the moving vehicle reference frame, V_c, varies throughout the crash. RQ_c is computed at each time step and the largest value is selected as a single measure of restraint performance.

The relative kinetic energy factor was computed by squaring the maximum value of V_c for the crash event and then dividing by 25 m^2/s^2, as shown in Equation 4.

5.3.3 Statistical Model Development and Comparison

The underlying assumption of this analysis is that occupant kinematics in a frontal crash is a linear function of the crash severity, vehicle structure performance and occupant restraint performance. Multiple linear regression analysis was used to correlate combinations of these metrics to the impact response of the crash test dummy, specifically the 3 ms maximum chest acceleration ("3 ms chest clip"). The 3 ms chest clip was selected as it reflects the acceleration response of the occupant and is one of two metrics widely used to determine chest injury risk in frontal full-scale crash tests. Maximum chest deflection, the other chest injury criteria, has not been included in this analysis.

Only combinations that included one metric from each category (crash severity, vehicle structure performance, and occupant restraint performance) were included in the analysis. Models were then ranked and selected based on the adjusted R^2 selection method, which accounts for the increase in R^2 resulting from an increase in the number of explanatory variables. These models were then compared to the simple linear regression model where delta-V was used as the sole predictor of 3 ms chest clip. Comparison includes the relative improvement in adjusted R^2 with the addition of vehicle structure and restraint performance modifiers as well as a graphical comparison of the model predicted versus actual data. All statistical analyses were completed with the SAS® v9.1.3 software.

5.4 Results

5.4.1 Parameter Distributions

Table 19 and Table 20 summarize the distribution of the crash severity, vehicle structure performance and occupant restraint performance metrics for all data and the airbag and belted data subset, respectively. Units are noted next to each metric; no units identified designate a dimensionless quantity.

Table 19. Metric Distribution Summary: All Cases

Metric	Mean	Std. Dev.	Min	Max
Delta-V [mph]	39.11	3.054	16.52	47.96
$\Delta V/t_f$ [G]	15.68	2.656	5.745	24.00
t_f [s]	0.116	0.018	0.074	0.160
μ	0.506	0.123	0.168	0.862
10 ms [G]	33.54	6.380	14.24	54.08
50 ms [G]	25.15	3.354	9.638	33.14
t_c/t_m	0.580	0.036	0.395	0.711
RQ_c	0.318	0.077	0.138	0.597
E_c	1.272	0.544	0.104	3.423
3 ms Clip [G]	46.17	7.632	15.00	74.20

Table 20. Metric Distribution Summary: Airbag and Belted Occupant Subset

Metric	Mean	Std. Dev.	Min	Max
Delta-V [mph]	39.74	2.369	16.52	46.05
$\Delta V/t_f$ [G]	16.05	2.443	5.745	24.00
t_f [s]	0.115	0.017	0.074	0.160
μ	0.524	0.109	0.230	0.862
10 ms [G]	34.25	6.064	14.24	54.08
50 ms [G]	25.69	2.943	9.638	33.14
t_c/t_m	0.582	0.035	0.395	0.711
RQ_c	0.305	0.068	0.138	0.554
E_c	1.221	0.516	0.104	3.423
3 ms Clip [G]	46.23	7.632	15.00	71.20

Figure 35 shows the variation in 3 ms chest clip grouped by vehicle delta-V in 5 mph increments. Note that groups with less than 10 observations have been omitted; the graph includes 611 of 619 cases. The top and bottom of the enclosed box for each group represents the 75^{th} and 25^{th} percentiles for the data. The middle line represents the median, the '+' denotes the mean value of each group, and the lines extending from each box indicate the range of the group. The corresponding mean 3 ms chest clip value is indicated to the right of each subgroup plot. There is a general increasing trend of average chest acceleration as delta-V increases. This increase was found to be statistically significant ($p < 0.0001$) with an R-square of 0.041.

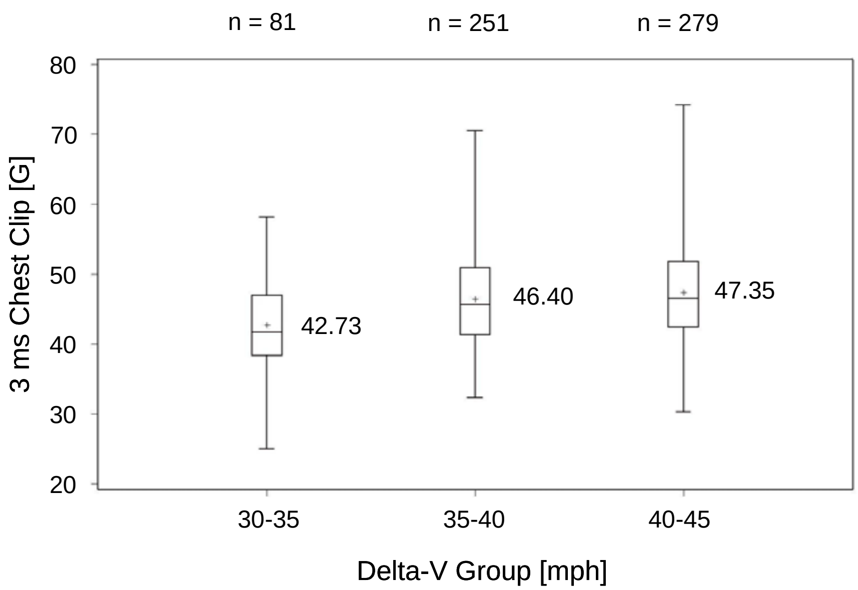


Figure 35. Average 3 ms Chest Clip by Delta-V

5.4.2 Model Selection

The results of the multiple linear regression (MLR) for all data and the belt and airbag subset are shown in Table 21 and Table 22, respectively. Only three parameter models are listed; each one includes one metric from each of the three categories. Only the top ten ranked models are listed in these tables with the unmodified delta-V model listed at the bottom for comparison purposes.

Table 21. Summary of MLR Results: All Cases

Crash Pulse	**Vehicle Structure**	**Restraint Performance**	**Adj. R^2**
Delta-V	μ	E_c	0.4175
Delta-V	t_c/t_m	E_c	0.4168
Delta-V	50 ms	E_c	0.4151
Delta-V	10 ms	E_c	0.4114
Delta-V	50 ms	RQ_c	0.3994
Delta-V	μ	RQ_c	0.3990
Delta-V	t_c/t_m	RQ_c	0.3970
Delta-V	10 ms	RQ_c	0.3948
$\Delta V/t_f$	μ	E_c	0.3793
$\Delta V/t_f$	50 ms	E_c	0.3454
Delta-V	-	-	0.0945

Table 22. Summary of MLR Results: Airbag and Belted Occupant Subset

Crash Pulse	**Vehicle Structure**	**Restraint Performance**	**Adj. R^2**
Delta-V	t_c/t_m	E_c	0.3665
Delta-V	μ	E_c	0.3661
Delta-V	50 ms	E_c	0.3640
Delta-V	10 ms	E_c	0.3606
Delta-V	μ	RQ_c	0.3559
Delta-V	t_c/t_m	RQ_c	0.3557
Delta-V	50 ms	RQ_c	0.3541
Delta-V	10 ms	RQ_c	0.3508
$\Delta V/t_f$	μ	E_c	0.3331
$\Delta V/t_f$	50 ms	E_c	0.3076
Delta-V	-	-	0.0775

5.4.3 Graphical Results

Based on the results shown in Table 21, the expanded delta-V models shown below were selected for further graphical analysis. Again, both incorporate a measure of vehicle structure and occupant restraint performance in addition to the traditional measure of crash severity.

Expanded DV-1:

3 ms Clip = f(DV, μ, E_c)

= -2.57 + 0.81*(DV) + 9.67*(μ) + 9.65*(E_c)

Expanded DV-2:

3 ms Clip = f (DV, 50 ms, RQ_c)

= -25.40 + 1.23*(DV) + 0.23*(50 ms) + 55.91*(RQ_c)

Expanded DV-1 produced the highest R^2 value for the entire data set and was ranked second based on the belted and airbag restrained subset. Expanded DV-2 was ranked 5th for the entire data set and 7th for the belted and airbag restrained subset. The baseline model for comparison used only delta-V to predict the crash test dummy 3 ms chest clip and is shown below:

Baseline DV Model:

3 ms Clip = f (DV) = 15.89 + 0.774*(DV)

Figure 36 shows the comparison of the 3 ms chest clip computed from each case to the value predicted by delta-V only. For a model that predicts the data perfectly, all points would be situated along the horizontal dashed line. Figure 37 and Figure 38 show the comparison of observed versus predicted 3 ms chest clip from Expanded DV-1 and Expanded DV-2, respectively. Both these models include a measure of vehicle structure and occupant restraint performance coupled with delta-V.

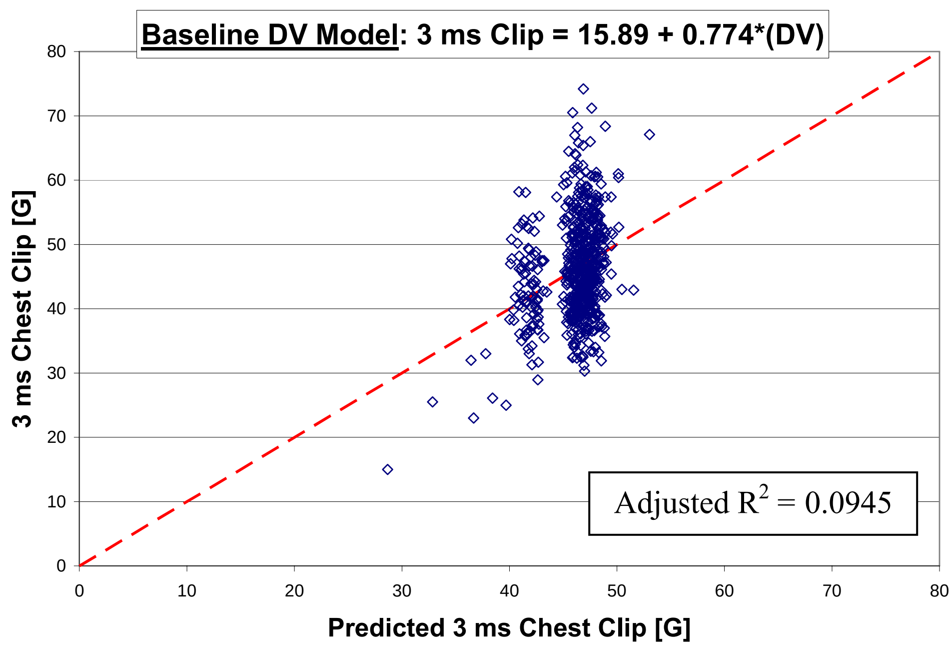


Figure 36. Comparison of Predicted and Actual 3 ms Chest Clip: Baseline DV Model, All Cases

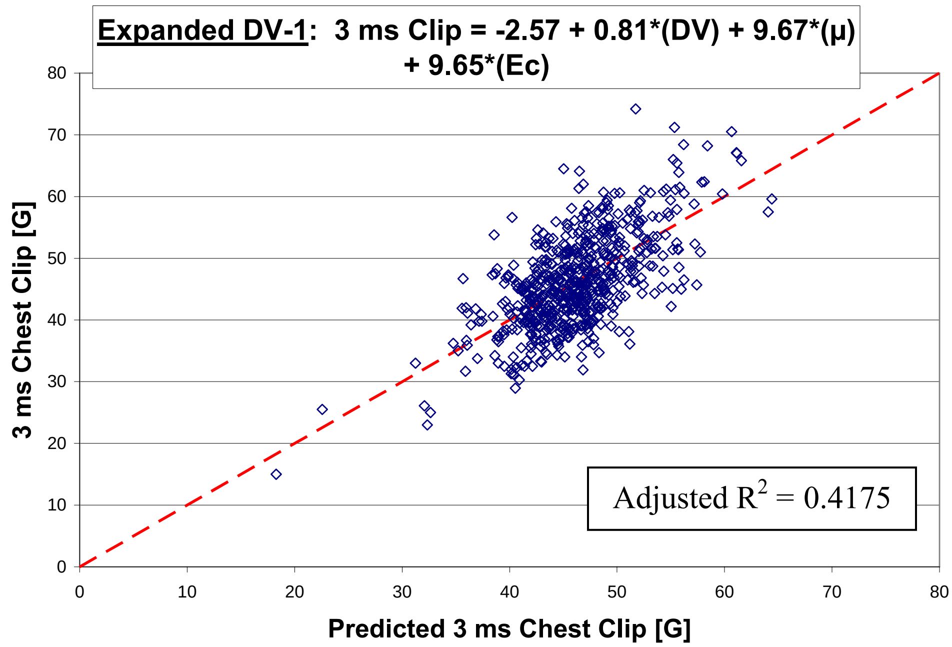


Figure 37. Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-1, All Cases

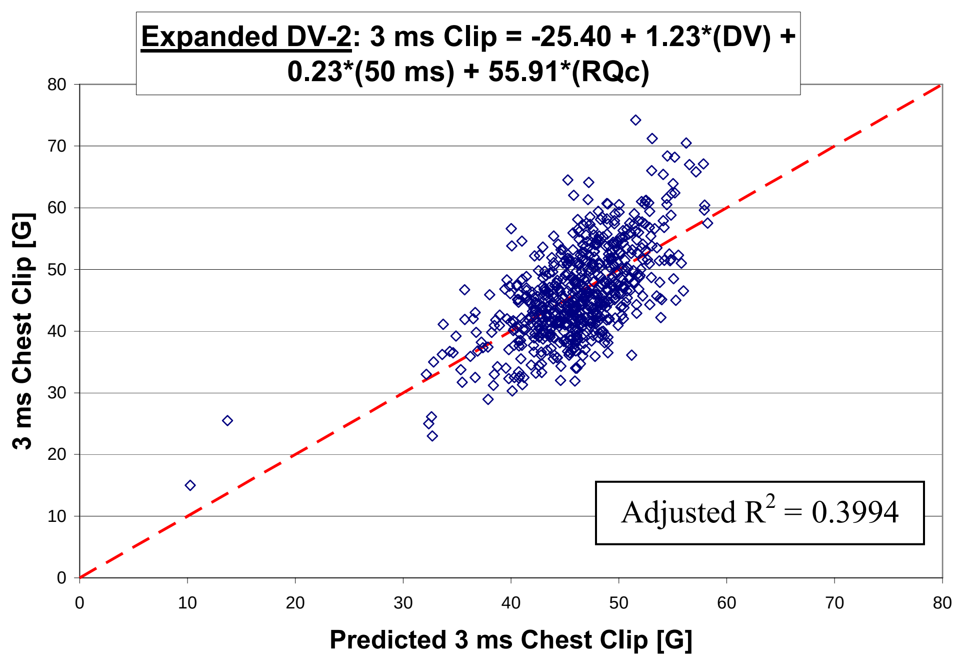


Figure 38. Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-2, All Cases

Figure 39 through Figure 41 shows the comparison of the observed versus predicted 3 ms chest clip for the airbag and belted data subset. Again, points along the dashed diagonal line indicate a model that predicts the data perfectly. Note that the constants in these models have been based on the subset data and are not identical to those presented in Figure 36 through Figure 38.

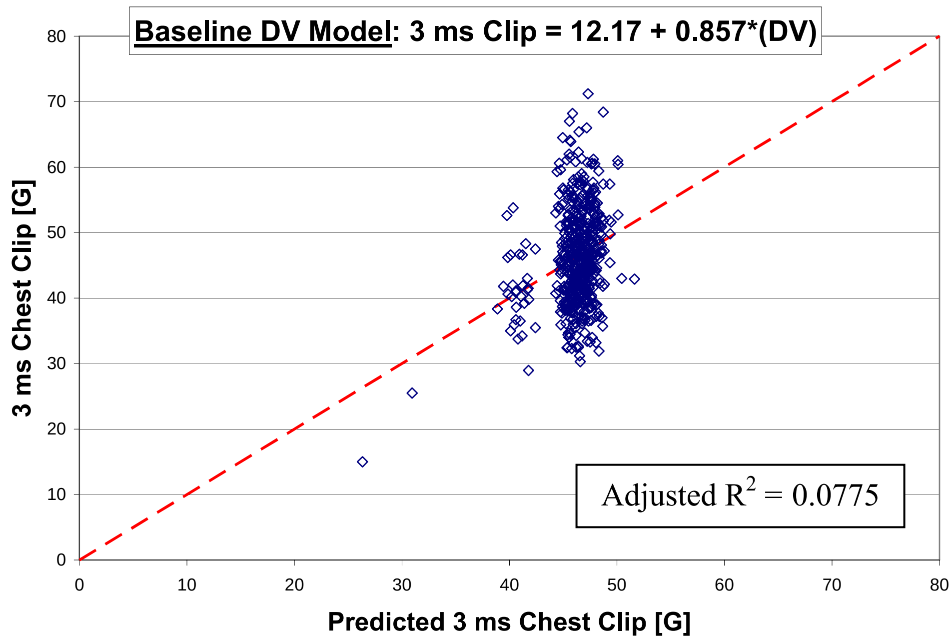


Figure 39. Comparison of Predicted and Actual 3 ms Chest Clip: Baseline DV Model, Belt and Bag Subset

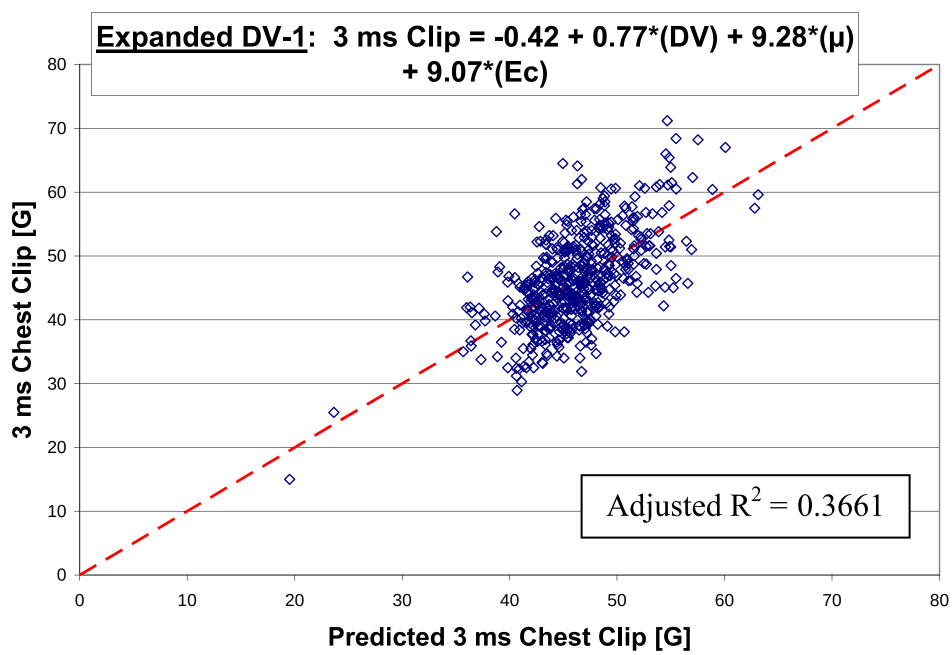


Figure 40. Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-1, Belt and Bag Subset

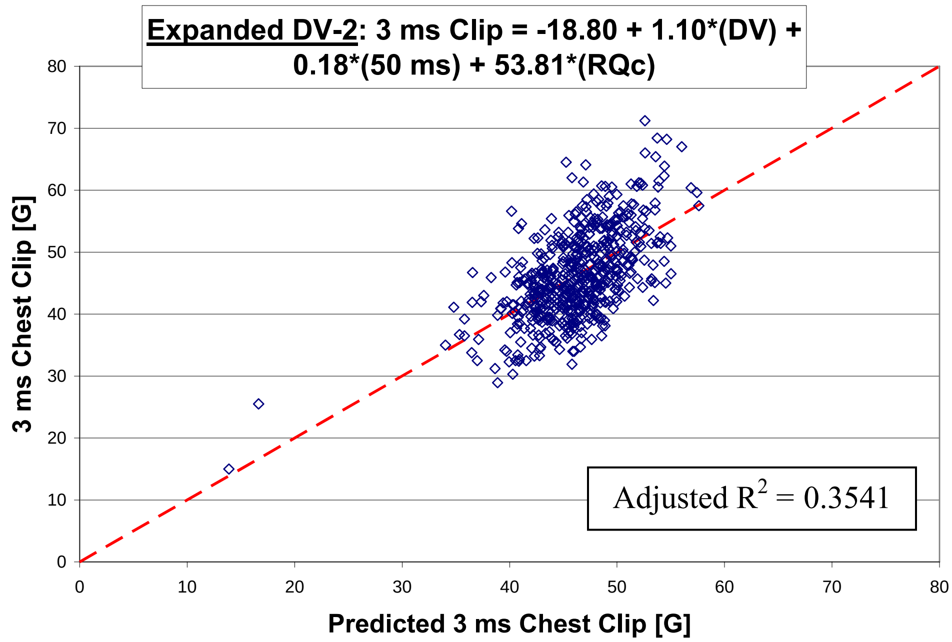


Figure 41. Comparison of Predicted and Actual 3 ms Chest Clip: Expanded DV-2, Belt and Bag Subset

5.5 Discussion

Based on the results shown in Table 21 and Table 22, the augmentation of delta-V with a measure of vehicle structure and occupant restraint performance dramatically improves the prediction of the 3 ms chest clip of an occupant involved in a frontal collision. This was evident both for all cases as well as the belt and airbag data subset. In both cases, the best models accounted for roughly 4 times the variation of the 3 ms chest clip when compared to the baseline model that used only the delta-V predictor. This is particularly evident in the graphical comparison of the predicted versus observed values of the 3 ms chest clip. With delta-V as the sole predictor, the data points are widely scattered about the diagonal. The incorporation of vehicle structure and occupant restraint performance reduces the scatter of the data points about the diagonal.

The combination of delta-V, ridedown efficiency, and the kinetic energy factor provide the best prediction of the occupant kinematics. There was not a large difference, however, between the predictive capabilities of the top ranked combination and the combination ranked 10^{th} based on adjusted R^2. For the entire data set, this difference was approximately 7 percent of the 3 ms chest clip variation (adjusted R^2 = 0.4175 versus adjusted R^2 = 0.3454). For the belt and airbag subset, this difference was approximately 6 percent (adjusted R^2 = 0.3665 versus adjusted R^2 = 0.3076).

There are also several observations that can be drawn regarding the predictive power of the individual metrics. Based on Figure 35, there is an increase in average driver peak chest acceleration with increasing vehicle delta-V; this increase was found to be statistically significant. Thus, at least for this relatively narrow range of delta-V values (30 to 45 mph), delta-V is a rudimentary predictor of average occupant chest acceleration. The variation about those means, however, is substantial based on the overlap present in Figure 35 and the low R-square value (0.041). Delta-V appears to be a stronger indicator of occupant chest acceleration than the other crash severity metric, the average vehicle acceleration. The delta-V metric was included in 8 of the top 10 ranked models in lieu of the average vehicle acceleration. There also appears to be an advantage to using the kinetic energy factor in lieu of the restraint quotient as this metric was a component of the top 4 models in both data sets. It should be noted that these metrics are highly correlated since they are based on the maximum velocity of the occupant with respect to the vehicle interior. The kinetic energy factor translates this velocity into energy and normalizes the energy based on a 5 m/s impact. In contrast, the restraint quotient simply normalizes the relative occupant velocity to the maximum change in velocity of the vehicle.

In comparison to the crash severity and occupant restraint performance descriptors, the vehicle structure metrics appear to be a smaller factor in the resulting occupant chest kinematics. The top 4 models for both data sets, for example, only differ by the vehicle structure performance metric. Changing this metric only changed the adjusted R^2 value by approximately 0.006. This suggests that these metrics only account for only a small percentage (less than 1 percent) of the variation in the 3 ms chest clip.

In addition to the crash severity, vehicle structure, and occupant restraint performance, occupant injury risk is influenced by occupant specific characteristics. These include but are not limited to occupant age, size, weight, gender, and physical condition. This analysis has been performed assuming constant occupant characteristics. For the prediction of occupant injury in real-world crashes, these occupant characteristics would need to be considered and could have a large influence on resultant occupant injury. Examining crash tests with the 5th, 50th, and 95th percentile crash test dummies may provide insight into how occupant restraint performance varies based on occupant size and weight.

5.6 Limitations

One limitation of this study was the narrow range of impact conditions across the available crash test data. Although the vehicle speed for the entire data set ranged from 14 to 42 mph, a majority of the available tests were conducted at 30 mph and 35 mph due to the FMVSS 208 regulations and New Car Assessment Program (NCAP) crash testing program, respectively. This resulted in approximately 98 percent of the cases having delta-V values between 30 and 45 mph. It is suspected that both vehicle structure and occupant restraint performance may vary with impact speed, degree of frontal engagement, and object struck.

Our study has been limited only to drivers. In addition, this study has only considered injury to one body region focusing on one specific injury mechanism, maximum chest acceleration. Several researchers have shown chest deflection to be more indicative of hard-tissue chest injury (Grosch, 1985; Kent et al, 2001a; Kent et al, 2001b). Injury to other body regions, such as the head or lower extremities, has not been included.

Only full-width frontal barrier crash tests have been included in the analysis. Vehicle front end design involves a trade-off between reducing maximum occupant chest acceleration in a full frontal engagement (i.e. a full-width barrier test) and providing sufficient stiffness to prevent large occupant compartment deformations in the frontal offset configuration. The correlation of occupant peak chest acceleration to crash severity, vehicle structure and occupant restraint performance are likely different for the frontal offset impact configuration. An analysis of full-scale frontal offset crash tests would be required to identify any potential differences. Also, this study only included vehicle structure metrics derived from measured vehicle kinematics or the vehicle and the occupant response combined. This excluded metrics such as maximum occupant compartment intrusion, which may play a larger role in occupant injury, especially to the lower extremities, in frontal offset tests.

5.7 Conclusions

The primary finding of this study is that adjustments to delta-V which reflect the vehicle structure performance and occupant restraint performance provide a better prediction of resultant occupant chest acceleration during a frontal crash. The combination of delta-V, ridedown efficiency, and the kinetic energy factor was found to provide the best prediction of the occupant chest kinematics accounting for approximately 4 times the variation in the maximum chest acceleration in comparison to a model based solely on vehicle delta-V.

6. EVALUATION OF VEHICLE-BASED METRICS ENHANCED WITH VEHICLE STRUCTURE AND RESTRAINT PERFORMANCE METRICS

6.1 Introduction

Chapter 5 presents potential modifications to delta-V to account for the performance of a particular vehicle structure and occupant restraints. Analysis of the occupant response in full-scale frontal crash tests indicated that these augmented versions of delta-V improve the ability to predict the peak driver chest acceleration. To determine the true effectiveness of these expanded delta-V metrics for predicting occupant injury, however, real-world crash data must be examined. The purpose of this exploratory study was to evaluate several candidate delta-V modifications using EDR data coupled with occupant injury data from real-world collisions.

6.2 Candidate Expanded Delta-V Metrics

In this analysis, three expanded delta-V metrics were evaluated as summarized in Table 23. These included Expanded DV-1 and Expanded DV-2 from Chapter 5 as well as an additional metric, Expanded DV-3, which modifies delta-V based on the 50 ms maximum acceleration and the kinetic energy factor. Recall that μ, E_c, RQ_c are the ridedown efficiency, kinetic energy factor, and restraint quotient, respectively. *DV* is the maximum vehicle delta-V and *50ms* is the 50 ms maximum vehicle acceleration.

Table 23. Summary of Candidate Expanded Delta-V Metrics Investigated

Metric	Computation
Expanded DV-1	$0.81*(DV) + 9.67*(\mu) + 9.65*(E_c) - 2.57$
Expanded DV-2	$1.23*(DV) + 0.23*(50ms) + 55.91*(RQ_c) - 25.40$
Expanded DV-3	$0.807*(DV) + 0.182*(50ms) + 7.60*(E_c) + 0.367$

The primary assumption is that these modifications to the traditional delta-V metric provide a better prediction of the maximum occupant chest acceleration during a crash event.

The hypothesis is that this estimate of occupant chest acceleration (as opposed to vehicle acceleration), will improve occupant injury prediction. Also, for the purpose of this study, the measures of restraint performance and vehicle structure performance used to modify delta-V (those computed from the available crash test data) were assumed to be both repeatable and to not vary significantly as a function of vehicle delta-V. The implications of these two latter assumptions are explored at a cursory level in this study.

6.3 Methods

The general methodology for this study included (1) matching real-world crashes involving EDR-equipped vehicles to available full-frontal barrier crash tests, (2) computing the candidate expanded delta-V metrics for each case, (3) fitting binary logistic regression models between each enhanced metric and occupant injury, and (4) comparing the injury predictive capability of the modified metrics to the traditional delta-V metric using ROC curve analysis.

Real-world crashes involving EDR-equipped vehicles have been selected for this analysis for two primary reasons. First, these devices are believed to provide an improved estimate of the true vehicle delta-V when compared to crush-based estimates (Niehoff and Gabler, 2006; Niehoff et al, 2005; Gabler, Hampton and Hinch, 2004). Second, EDR data can be used to compute a number of the vehicle structure metrics used in the development of the expanded delta-V metrics. For this study, EDR data was used to compute maximum 50 ms acceleration for the Expanded DV-2 and Expanded DV-3 metrics.

6.3.1 Case Selection and Matching

Two sources of data were used in this study: (1) the NASS/CDS cases with EDR data from crashes occurring between years 2000 and 2006 and (2) the database of full-scale vehicle crash tests maintained by the National Highway Traffic Safety Administration (NHTSA). The real world crashes and crash tests were selected based on the methodology similar to that presented in Chapter 3 and Chapter 5, respectively. These criteria have been summarized below in Table 24.

Table 24. Summary of Real-World and Crash Test Case Selection Criteria

Data Set	Case Selection Criteria	Available Cases
NASS/CDS + GM EDR Data (Chapter 3)	Crashes comprising a single event	214
	Crash occurred between 2000 and 2006, inclusive	
	Airbag Deployment	
	Complete GM EDR vehicle crash pulse data	
	Known driver injury information (including no injury data)	
	Frontal collision (no vehicle rollover or occupant ejection)	
NHTSA Crash Test Database (Chapter 5)	Vehicle impacting a flat rigid barrier	619
	Full frontal engagement	
	50th % male Hybrid III crash test dummy seated in the driver position	
	Occupant restrained by an airbag, seatbelt or both	
	Sensor data suitable for computation of vehicle structure and restraint performance metrics	

For each of the 214 available NASS/CDS cases, a matching process was used to determine if a suitable crash test with the same or similar vehicle was available in the NHTSA crash test database. Vehicles were matched based on make, model, production generation and, finally, vehicle model year. In order to be matched, the vehicle make, model, and production generation were required to match exactly. Production generation refers to multiple model years of the same vehicle that have similar structural, exterior, and interior features. If there were multiple matches within the same generation, then the vehicle with closest model year was selected. For multiple vehicles of the same model year, an effort was made to match body styles (e.g. 2-door, 4-door, etc.). An additional stipulation was that the crash test was run at an impact speed of 35 mph and the driver was restrained by both an airbag and seatbelt. The rationale for this stipulation was to evaluate the restraint performance of each vehicle under essentially the same impact and occupant restraint conditions.

The matching process produced 130 matched NASS/CDS cases with suitable full-scale vehicle crash test data. Of the NASS/CDS cases, there were 103 belted drivers and 27 unbelted drivers. The unbelted occupants have been excluded from this analysis as the restraint performance metrics are based on belted occupants. For the 103 cases suitable for analysis, the mean occupant age was 38.1, which is similar to the mean age of the entire 214 case data set. Approximately 91 percent of the crash test vehicles matched were within 3 model years of the corresponding NASS/CDS case vehicle. The remaining 9 percent had between 3 and 6 years of separation between the model years; the production generation, however, was always the same.

6.3.2 Computations

Regardless of the metric, the delta-V was computed by selecting the largest change in vehicle velocity value for the crash event, as recorded by the EDR. The restraint quotient, ridedown efficiency, and the kinetic energy factors were all computed using the data from the corresponding matched full-scale crash test data. Restraint quotient (RQ_c) was computed based on the crash test dummy thorax longitudinal and vertical accelerations using the following relation (Viano and Arepally, 1990):

$$RQ_c = \frac{V_c}{(\dot{x}_V)_{\max}}$$

where V_c is the resultant velocity of the thorax with respect to the moving vehicle reference frame. This is computed by subtracting the respective velocity from that of the vehicle occupant compartment. $(\dot{x}_V)_{\max}$ is simply the maximum velocity change of the vehicle during the crash test, which is constant for a particular crash. For each matched crash test, RQ_c was computed at each time step and the largest value was selected as a single measure of restraint performance.

The relative kinetic energy factor (Viano and Arepally, 1990) was computed by squaring the maximum value of V_c for the crash event and then dividing by 25 m^2/s^2, as shown in the relation below:

$$E_c = \frac{\max(V_c)^2}{25}$$

The ridedown efficiency (μ) was computed using the following relation (Huang et al, 1995):

$$\mu = \frac{e_{rd}\,|_{\max}}{\frac{1}{2}V_o^2}$$

where V_o is the initial velocity of the vehicle and e_{rd} is the vehicle ridedown energy density, defined as follows:

$$e_{rd} = \int \ddot{x}_o dx_v$$

where $\ddot{x}_o$ represents the acceleration of the crash test dummy and x_v is the displacement of the occupant compartment. The maximum absolute value of this integral was used as the numerator of the first equation to determine the ridedown efficiency.

Unlike the previous vehicle-specific metrics, the maximum 50 ms average accelerations was computed using the available EDR data based on a procedure tailored to the GM EDR. The procedure was 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.

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

2. Select the largest absolute 50-ms acceleration value and convert to G units.

After computation of each of these metrics, Expanded DV-1, Expanded DV-2, and Expanded DV-3 were computed using the equations shown in Table 23, which have been based on the analysis presented in Chapter 5.

6.3.3 Model Fitting and Comparison

Binary logistic regression models were fit to the available data using delta-V and the three candidate modified delta-V metrics 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). For this analysis, two injury threshold levels were used to define "serious" injury: (1) a maximum AIS value of 3 or greater (MAIS 3+), and (2) MAIS 2+. In the previous analyses presented in Chapter 3, injury risk curves were generated for all 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'). Only occupants that were restrained by a seat belt and airbag have been included in this analysis.

Each binary logistic model also accounted for the effects of occupant age. Several age classification schemes were investigated including a single threshold resulting in two age categories (e.g. age < 25 years or age ≥ 25) or a dual threshold resulting in three categories (e.g. age < 25 years, 25 ≤ age < 55, or age ≥ 55). Based on the available data, a single threshold of 35 years was selected for this analysis.

Note that since all of these vehicle-based metrics are correlated, their relative effect could not be examined by incorporating all metrics into a single model. The models were compared using a Receiver Operating Characteristic (ROC) curve analysis. All statistical analyses were completed with the SAS® v9.1.3 software. ROC curve analysis was conducted using the SAS macro *%ROC* (SAS® Institute) based on DeLong et al (1988).

6.4 Analysis of Results

6.4.1 Logistic Regression Models

Table 25 summarizes the age and belt-corrected MAIS logistic regression model results for the MAIS 2+ and MAIS 3+ injury levels. All tests for the global null hypothesis and Wald Chi Square values were significant to the 0.0021 level or better. As all of the vehicle-based metric predictors are continuous, the Hosmer and Lemeshow test is used to determine goodness-of-fit. With the exception of the MAIS 2+ Expanded DV-3 model (Hosmer and Lemeshow value of 0.0056), all models generated statistically adequate (>0.05) fits with Hosmer and Lemeshow values of 0.1915 or greater. It is not clear why the Hosmer and Lemeshow test indicates a lack of correlation in Expanded DV-3 model.

Table 25. Summary of Age-Corrected MAIS Logistic Regression Model Parameters, Belted Occupants

Injury Level	**Predictor**	**Model Parameter**			**Hosmer & Lemeshow**
		Estimate	**Std. Error**	**Wald χ^2 (p)**	
MAIS 3+	Delta-V	0.2893	0.0877	10.87 (0.0010)	0.3594
	Expanded DV-1	0.1249	0.0406	9.47 (0.0021)	0.9357
	Expanded DV-2	0.0866	0.0273	10.51 (0.0012)	0.7133
	Expanded DV-3	0.1215	0.0386	9.92 (0.0016)	0.7857
MAIS 2+	Delta-V	0.3190	0.0813	15.41 (<0.0001)	0.3039
	Expanded DV-1	0.1965	0.0485	16.43 (<0.0001)	0.1915
	Expanded DV-2	0.1142	0.0282	16.42 (<0.0001)	0.6594
	Expanded DV-3	0.1771	0.0432	16.84 (<0.0001)	0.0056

Figure 42 shows the MAIS 2+ injury risk curve based on the belted data available for this analysis. Figure 43 through Figure 45 show the MAIS 2+ injury risk curves for the Expanded

DV-1, Expanded DV-2, and Expanded DV-3 predictors, respectively. For clarity, these risk curves have not been age-adjusted. The remainder of the analysis, however, does provide a comparison of these metrics based on the age-corrected models.

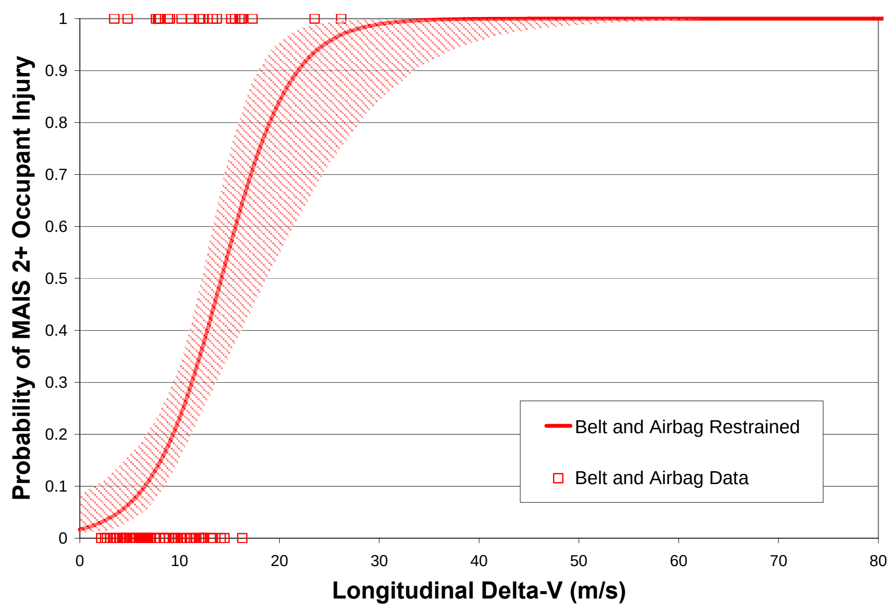


Figure 42. Belted Occupant MAIS 2+ Injury Risk Curve: Delta-V Predictor

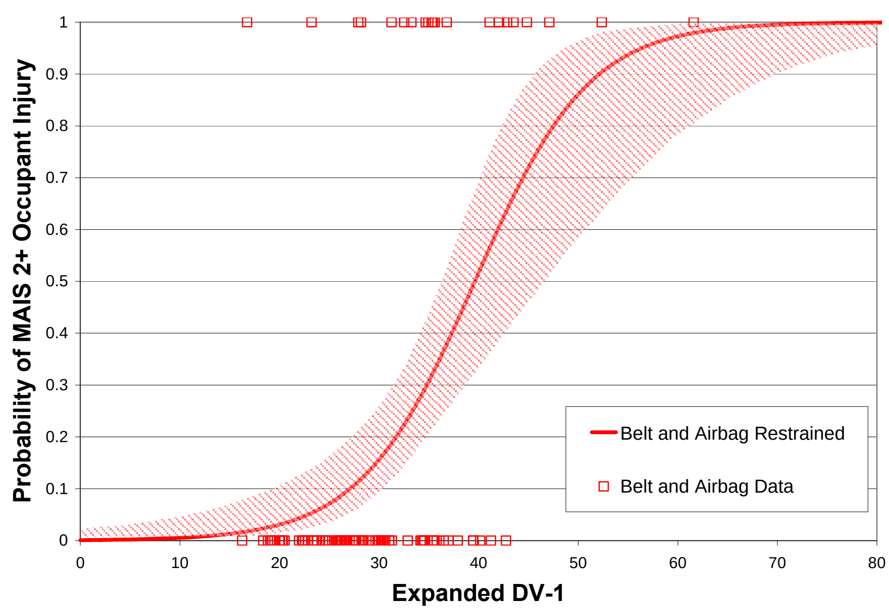


Figure 43. Belted Occupant MAIS 2+ Injury Risk Curve: Expanded DV-1 Predictor

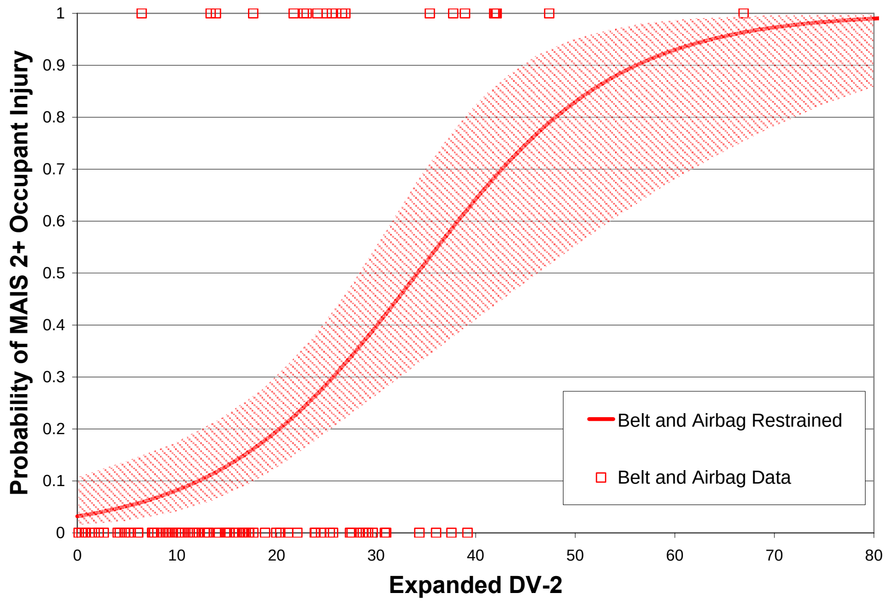


Figure 44. Belted Occupant MAIS 2+ Injury Risk Curve: Expanded DV-2 Predictor

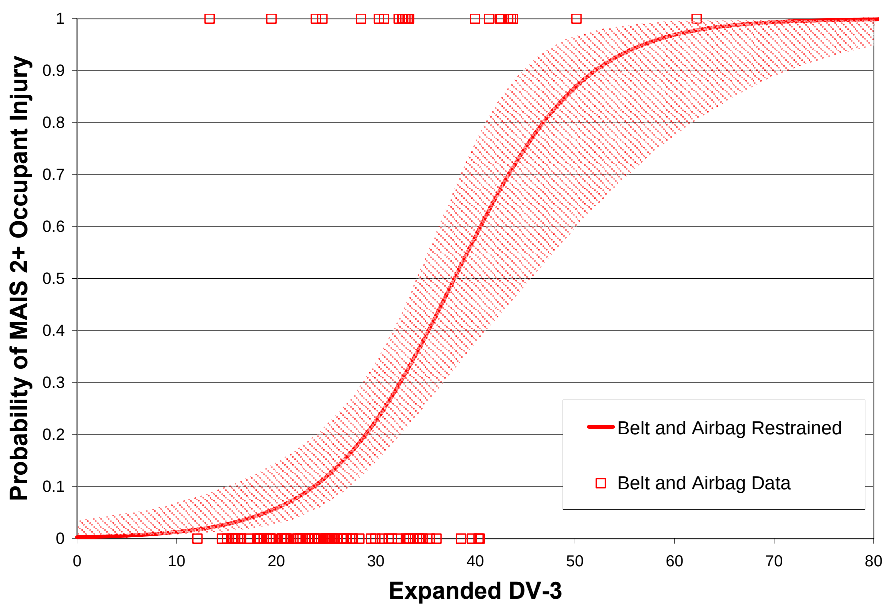


Figure 45. Belted Occupant MAIS 2+ Injury Risk Curve: Expanded DV-3 Predictor

6.4.2 ROC Comparison

To compare the modified delta-V metrics to the traditional delta-V metric, an ROC curve analysis was performed for the MAIS 2+ and MAIS 3+ logistic regression models. Figure 46 and Figure 47 provide a graphical comparison of the ROC curves for the MAIS 2+ and MAIS 3+ models, respectively.

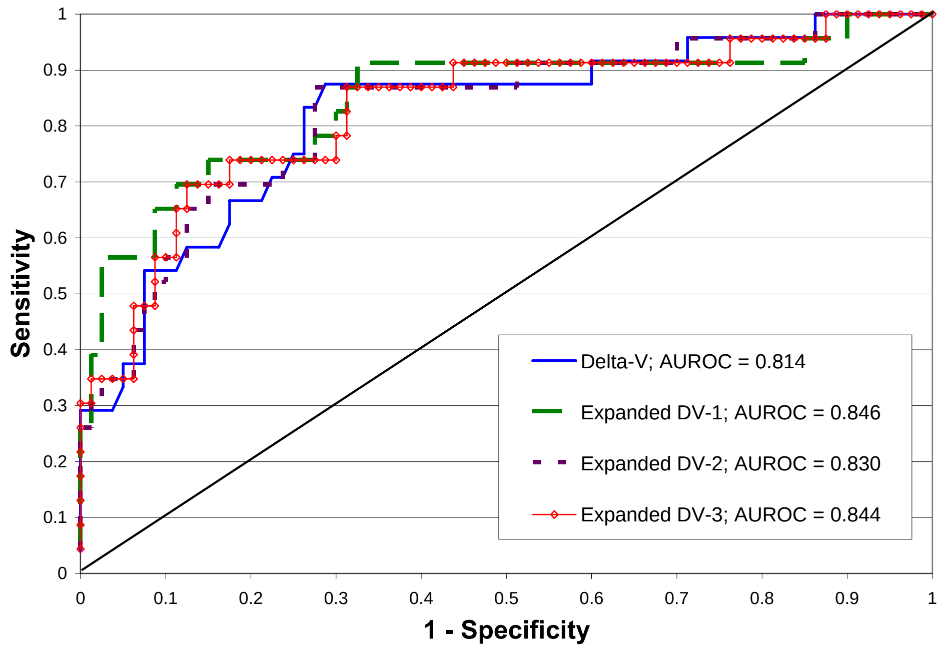


Figure 46. MAIS 2+ ROC Comparison: Belted Occupants, Age-Adjusted

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. The area under the ROC curve provides a means of statistically comparing different predictors. Table 26 summarizes the pairwise ROC curve area comparisons between each expanded delta-V metric and the unmodified delta-V metric. The overall comparison, between all metrics, is also shown. In all cases, the p-values exceeded 0.05 suggesting no statistically significant difference between the area under the respective ROC curves for any of the metrics. This implies that there is no statistically significant difference in injury predicting capability between any of the candidate expanded delta-V metrics and the traditional delta-V metric.

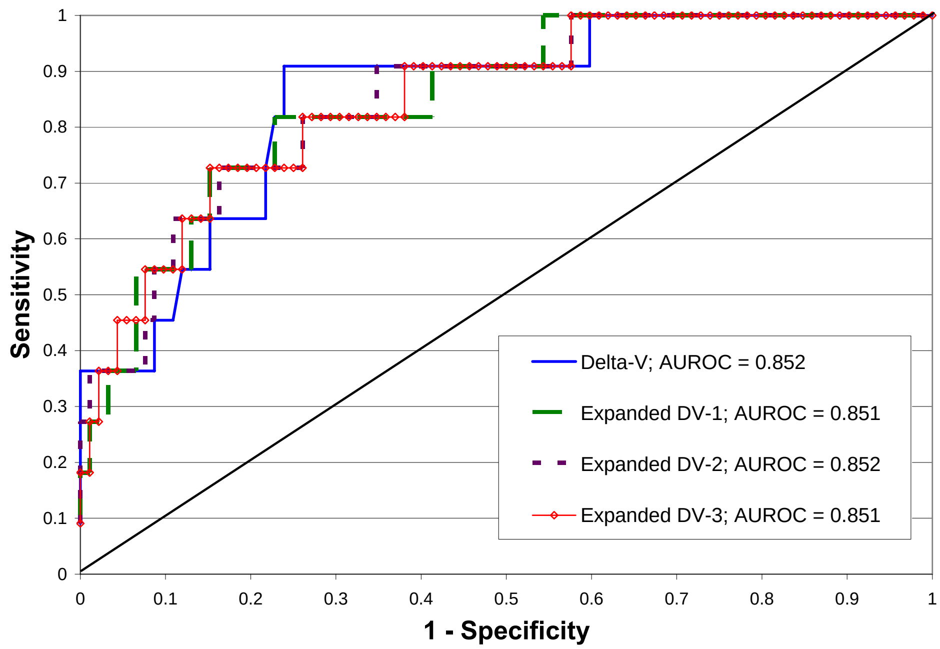


Figure 47. MAIS 3+ ROC Comparison: Belted Occupants, Age-Adjusted

Table 26. Delta-V and Candidate Expanded Delta-V ROC Pairwise Comparisons

Level	Data Subset	p	Overall p
MAIS 3+	Delta-V vs. Expanded DV-1	0.969	0.999
	Delta-V vs. Expanded DV-2	1.000	
	Delta-V vs. Expanded DV-3	0.963	
MAIS 2+	Delta-V vs. Expanded DV-1	0.169	0.5747
	Delta-V vs. Expanded DV-2	0.220	
	Delta-V vs. Expanded DV-3	0.169	

Based on the area under the ROC curves shown in Figure 46 and Figure 47, there does appear to be a slight injury predictive advantage to the expanded delta-V metrics, especially at the MAIS 2+ level. In the case of Expanded DV-1, the area under the ROC curve is increased from 0.814 to 0.846. This difference is highlighted graphically in Figure 48 where the solid shaded regions represent areas of injury prediction improvement over delta-V and the hatched shaded areas represent areas where prediction was not as accurate as delta-V alone.

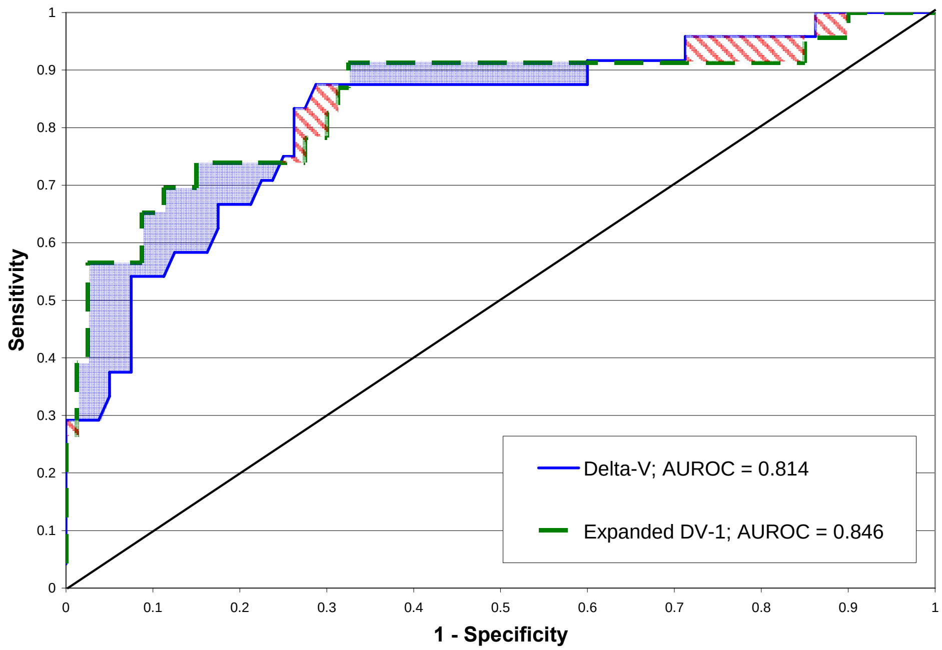


Figure 48. Comparison of Expanded DV-1 to Delta-V at the MAIS 2+ Level

6.5 Discussion and Limitations

Based on the available data examined in this study, modifying delta-V with a measure of vehicle structure and occupant restraint performance does not appear to result in a significantly improved prediction of occupant injury in frontal crashes. There is, however, some evidence of small increases in injury prediction capability. Several possible factors may have contributed to this outcome, including, but not limited to the following:

1. Vehicle and Restraint Performance Variation by Percent Offset. The development of the candidate expanded delta-V metrics presented in Chapter 5 have been based solely on frontal collisions with full-frontal engagement and did not include offset crashes. It is not known how the vehicle structure and occupant restraint performance measures studied vary with frontal offset percentage. The data set of matched NASS/CDS and EDR cases used in this analysis included all frontal collisions with a PDOF of 0 $\pm$ 10 degrees, regardless of frontal offset.

2. Occupant Characteristics. Due to the relatively small size of the data set, the analysis presented herein accounts only for a single confounding occupant factor, occupant age. There are other confounding factors, however, such as occupant gender, height and weight that affect occupant injury risk. Although these are not expected to have a larger effect than occupant age, they would be expected to affect occupant injury nonetheless.
3. Repeatability of the Vehicle Specific Metrics. Little is known regarding the repeatability of the measurements obtained from full-scale crash tests and there is some evidence that there is a large component of variability due to "uncontrolled and generally unknown factors" (Versace and Berton, 1975). The vehicle structure performance and occupant restraint performance metrics are subject to the variability of these crash tests. Large variations in these metrics would reduce the injury predicting capabilities of the proposed delta-V modifications. The size of this variation is unknown at this time.
4. Vehicle and Restraint Performance Variation by Crash Severity. The vehicle structure and restraint performance metrics for this study have all been computed for a vehicle impacting a barrier at a single speed. While this provides a snapshot of performance at a consistent crash severity level, it provides no information on performance at higher or lower crash severity levels which were present in the real-world cases used in the analysis. For the real world crashes, EDR delta-V ranged from 5 to 58 mph with a mean of 20 mph while the vehicle-specific metrics were computed for crash tests conducted at 35 mph with delta-V ranging from 37 to 42 mph. It is unknown how the vehicle structure, and perhaps more importantly, the occupant restraint performance metrics vary as a function of crash severity.

A brief examination of two of these potential concerns, the repeatability of the vehicle specific metrics and the variation with crash severity, are examined in more detail below.

6.5.1 Repeatability of Vehicle Structure and Occupant Restraint Metrics

A matching procedure similar to that used in this study to match crash tested vehicles to those involved in a real world crash was used to match vehicles within the available crash test data. Vehicles were matched based on make, model, production generation, and then vehicle model year. An exact match of make, model and production generation was a requirement for each matched pair. An additional stipulation was that the occupant restraint condition matched; all occupants were belted an airbag restrained in this analysis. A total of 24 suitable pairs of crash tests were identified with the average model year difference of approximately 2 years (a single matched pair had a difference of 4 years with the remainder at 3 years or less).

For each pair, the repeatability of two metrics was investigated graphically: the restraint quotient and the ridedown efficiency. The results are shown in Figure 49 and Figure 50. The diagonal represents perfect agreement between the metrics between the matched pairs. For reference, points falling within the shaded region are within 20 percent of one another. Points falling within the outer dashed diagonal lines are within 50 percent. The average error for the restraint quotient and ridedown efficiency for the matched tests was 15.0 and 19.9 percent, respectively. Based on the graphical results alone, the restraint quotient appears more consistent among the available cases with all falling within 50 percent error. It should be noted that there were 11 cases for the restraint quotient and 10 cases for the ridedown efficiency where the error was within 10 percent.

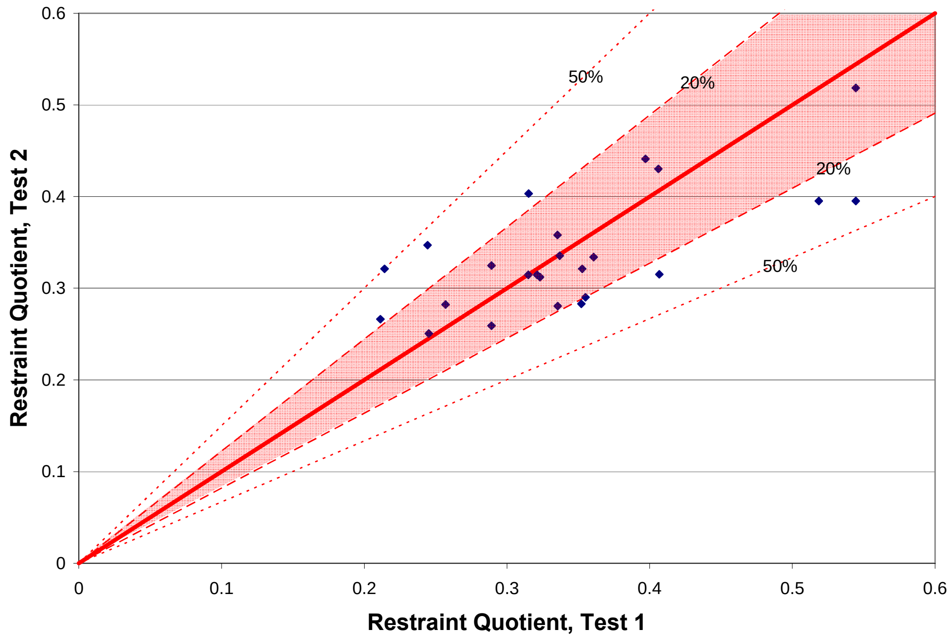


Figure 49. Repeatability of the Restraint Quotient Metric

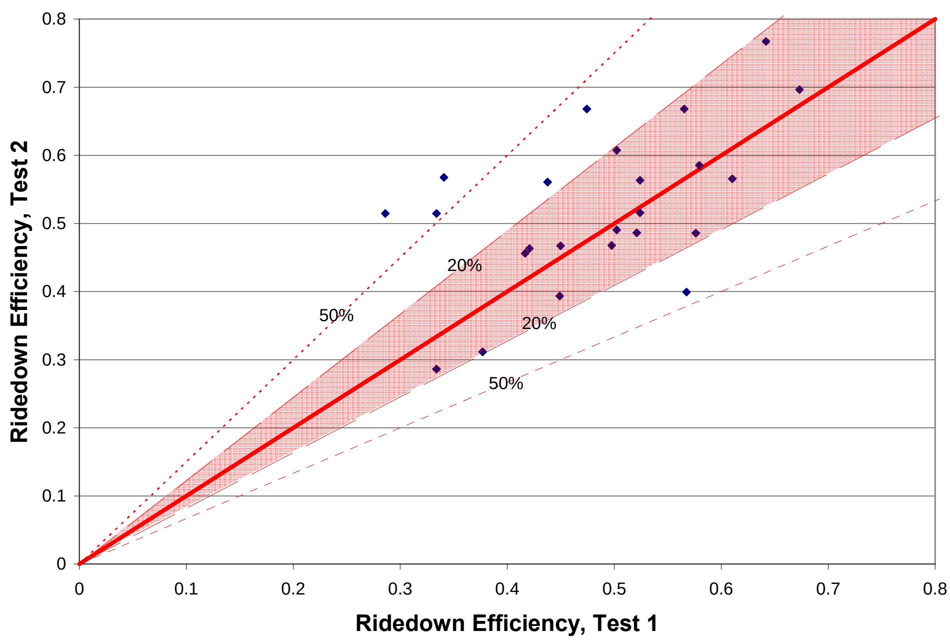


Figure 50. Repeatability of the Ridedown Efficiency Metric

6.5.2 Variation of Restraint Performance with Vehicle Delta-V

To investigate the variation of restraint performance with crash severity, full-scale crash tests of differing speeds were matched based on vehicle make, model, production generation and model year. Similar to the repeatability analysis above, an exact make, model and production generation was required as well as occupants with identical restraint conditions. Again, all occupants were drivers and restrained by an airbag and a seat belt. A total of 29 suitable pairs of crash tests were identified with the average model year difference of approximately 0.7 years. All matches had model years within 2 years of one another. With the exception of a single matched pair, the vehicle impact speeds were 30 and 35 mph, corresponding to the FMVSS 208 regulation and New Car Assessment Program (NCAP) crash test impact speeds, respectively.

Both the change in the restraint quotient and ridedown efficiency was investigated using a paired t-test analysis. With increasing vehicle delta-V, there was a statistically significant decrease in mean restraint quotient ($p = 0.0335$) and a statistically significant increase in ridedown efficiency ($p = 0.0299$). In terms of an average percentage, the restraint quotient increased by approximately 9 percent while the ridedown efficiency increased approximately 8 percent. The average increase in delta-V for the available matched cases was approximately 21 percent.

Based on this limited data, the vehicle structure and occupant restraint performance metrics appear to be dependent upon crash severity. However, the range of crash severity examined here was very narrow (30 to 35 mph impact speeds) and the changes in these metrics may not be applicable to other crash severity levels. It is likely that the correlation between crash severity and restraint performance and vehicle structure performance varies by vehicle type.

6.6 Conclusions and Future Directions

This study has provided a comparison of the newly developed modified delta-V metrics to the traditional delta-V injury metric based on their ability to predict injury in real-world collisions. The expanded delta-V metrics modified delta-V based on vehicle-specific structure and occupant restraint performance. While there was some evidence of an improved prediction with the expanded delta-V metrics, the increase in injury prediction was not found to be statistically significant.

There are several possible reasons for only a marginal increase in injury prediction. Perhaps the largest factor is the variation of vehicle structure and occupant restraint performance as a function of crash severity. For this study, these metrics were assumed to remain constant with respect to vehicle delta-V. A preliminary analysis of matched crash tests conducted at different speeds suggests that this assumption may not be valid. A better understanding of how the vehicle structure and occupant restraint performance metrics vary with delta-V would allow for a correction to be applied to these metrics, which may improve the ability of the expanded delta-V metrics developed herein.

7. Summary of Research Program and Contribution to the Field

7.1 Research Summary

The goal of this research was the development of an improved vehicle-based injury metric that accounts for the performance of the vehicle structure and occupant restraints during a crash event. Several important research objectives have been attained, including the following:

1. A comparison of vehicle-based and ATD-based injury criteria using full-scale crash tests.
2. An evaluation of current vehicle-based metrics for predicting injury in real-world crashes using Event Data Recorder (EDR) data coupled with detailed occupant injury information.
3. A determination of the effects of restraints on occupant injury in real-world crashes involving roadside hardware.
4. Evaluation of potential vehicle structure and restraint performance measures to be used to enhance current vehicle-based injury metrics.
5. An assessment of modified delta-V metrics in real-world crashes using EDR data.

A summary of the primary findings for each of these research objectives is detailed below.

7.1.1 Comparison of Vehicle-Based and ATD-Based Injury Criteria

Based on an analysis of crash test dummy responses in full-scale crash tests, vehicle-based occupant risk criteria, specifically the Flail Space Model, were not found to be an accurate measure of occupant risk for individual vehicles. The Flail Space Model algorithm was unable to predict the variation in occupant risk for unbelted, belted, airbag only, or belt and airbag restrained occupants. Also, at a given impact speed, variation in ATD-based risk between occupants in the same vehicle were found to be vastly different in some instances; all vehicle-based criteria, however, are the same for a particular vehicle and crash event.

The findings that the current vehicle-based occupant risk criteria do not fully capture occupant risk in these crash tests underscore the importance of considering occupant restraints when assessing occupant risk. During the early development of the Flail Space Model, the Occupant Impact Velocity criterion was checked against the responses of ATDs in similar crash conditions. Unfortunately, these checks were only performed during the development stages when advanced restraints such as airbags were not present in vehicles. This research provides a characterization of how the vehicle-based criteria compare to ATD-based criteria under the same crash conditions in light of current occupant restraints available in a modern vehicle fleet.

7.1.2 Evaluation of Vehicle-Based Metrics in Real-World Crashes

Through the use of EDR data coupled with occupant injury data for 214 real-world crashes, age-adjusted injury risk curves were developed relating the more complex vehicle-based metrics to occupant injury in real-world frontal collisions. Although a significant amount of research has developed injury risk curves with delta-V as the predictor of injury, there has been no definitive effort to date to provide these curves for the more complex vehicle-based injury criteria that require the entire crash pulse. In addition to delta-V, injury risk curves were developed for the Occupant Impact Velocity portion of the Flail Space Model, the Acceleration Severity Index, as well as the maximum 10 ms through 50 ms average acceleration metrics.

A comparison of these risk curves based on model fit statistics and an ROC curve analysis indicated that the more computationally intensive metrics that require knowledge of the entire crash pulse offer no statistically significant advantage over the simpler delta-V crash severity metric in discriminating between serious and non-serious occupant injury. This finding underscores the importance of developing an improved vehicle-based injury metric.

7.1.3 Occupant Restraints and Occupant Injury in Roadside Hardware Crashes

Based on an analysis of 915 real-world longitudinal barrier crashes, airbags were found to deploy in 70 percent of all tow-away collisions when the vehicle was equipped with an airbag. Seat belt usage rates in longitudinal barrier collisions were found to be 86 percent in airbag-equipped vehicles which was consistent with the national average.

When adjusting for other confounding factors, seatbelts and airbags are found to reduce the odds of occupant injury in single event longitudinal barrier crashes. Compared with completely unrestrained occupants, the odds of occupant injury were found to be between 1.75 and 3 times lower if the occupant is airbag-equipped, between 6.5 and 7 times lower if the occupant is not airbag-equipped but belted, and between 3.5 and 19 times lower if the occupant is belted and airbag-restrained. Although there have been several studies addressing occupant injury in crashes involving vehicles impacting longitudinal barriers, all have pre-dated the widespread implementation of airbags in vehicles and were unable to evaluate the effect of airbags on occupant injury in these collisions. This study has quantified the effect of occupant restraints in longitudinal barrier crashes for the modern vehicle fleet.

7.1.4 Enhancing Vehicle-Based Metrics

Based on an analysis of 619 full-scale crash tests, adjustments to delta-V that reflect the vehicle structure performance and occupant restraint performance are found to provide a better prediction of resultant occupant chest acceleration during a frontal crashes. The combination of delta-V, ridedown efficiency, and the kinetic energy factor was found to provide the best prediction of the occupant chest kinematics accounting for approximately 4 times the variation in the maximum chest acceleration in comparison to a model based solely on vehicle delta-V. This study provides the first comprehensive study examining previously developed methods to quantify the performance of the vehicle structure and the occupant restraints, including the ridedown efficiency and the restraint quotient.

7.1.5 Evaluation of Enhanced Vehicle-Based Metrics

Real-world crash data was used to evaluate modified delta-V metrics based on their ability to predict injury in real-world collisions. These expanded delta-V metrics modified delta-V based on vehicle-specific structure and occupant restraint performance. While there was some evidence of an improved prediction with the expanded delta-V metrics, the increase in injury prediction was not found to be statistically significant. Several possible reasons for this were explored, including the repeatability of the occupant restraint and vehicle structure performance metrics as well as how they vary as a function of crash severity.

7.2 Publication Summary

The research presented herein has answered several novel scientific questions that have never before been addressed. Upon completion of each of these research objectives, it is expected that the research findings will be published in various scientific journals and presented at appropriate scientific conferences. Table 27 summarizes the planned journal publications and scientific conference presentations. Those indicated with an asterisk (*) have already been presented, published, or are currently in press.

Table 27. Summary of Research Publications

Chapter	Topic	Journal Publication *(Supplementary Conference Presentation)*
2	Comparison of Vehicle-Based and ATD-Based Injury Criteria in Full-Scale Crash Tests	International Journal of Vehicle Safety* *(Transportation Research Board)**
3	Comparison of Roadside Crash Injury Metrics Using Event Data Recorders	Accident Analysis and Prevention* *(Association for the Advancement of Automotive Medicine)**
4	The Effects of Restraints on Occupant Injury in Roadside Hardware Crashes	Journal of Safety Research *(International ISA Biomedical Sciences Instrumentation Symposium)**
5	Enhancing Vehicle-Based Injury Metrics with a Metric of Restraint Performance	Traffic Injury Prevention *(Association for the Advancement of Automotive Medicine)** *(International ISA Biomedical Sciences Instrumentation Symposium)**
6	Evaluation of Restraint Performance-Enhanced Vehicle-Based Injury Metric	Transportation Research Record *(Transportation Research Board)*

* Indicates publication or accepted/'In Press' status

REFERENCES

AAAM. 2001. *The Abbreviated Injury Scale: 1990 Revision, Update 98*, Association for the Advancement of Automotive Medicine.

Bahouth GT, Digges KH, Bedewi NE, Kuznetsov A, Augenstein JS, Perdeck E. 2004. Development of URGENCY 2.1 for the Prediction of Crash Injury Severity. *Top Emerg Med* 26(2):157-165.

Baker SP, O'Neill B, Haddon W Jr., Long WB. 1974. The Injury Severity Score: A Method for Describing Patients with Multiple Injuries and Evaluating Emergency Care. *Journal of Trauma* 14(3):187-96.

Bilston LE, Yuen M, Brown J. 2007. Reconstruction of Crashes Involving Injured Child Occupants. *Traffic Injury Prevention* 8, pp 47-61.

Braver ER, Ferguson SA, Greene MA, Lund AK. 1997. Reductions in Deaths in Frontal Crashes among Right Front Passengers in Vehicles Equipped with Passenger Airbags. *Journal of the American Medical Association,* 278:1437-1439.

Bronstad ME, Michie JD. 1974. *Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances*, NCHRP Report No. 153, Washington, DC.

Carlson RD, Allison JR, Bryden JE. 1977. *Performance of Highway Safety Devices*. Report FHWA-NY-77-RR 57, New York State Department of Transportation, Albany, NY.

Coon BA, Reid JD. 2005. Crash Reconstruction Technique for Longitudinal Barriers. *Journal of Transportation Engineering 131*(1), pp. 54-62.

Coon BA, Reid JD. 2006. Reconstruction Techniques for Energy-Absorbing Guardrail End Terminals. *Accident Analysis and Prevention 38*, pp. 1-13.

Council FM, Stewart JR. 1993. Attempt to Define Relationship between Forces to Crash-Test Vehicles and Occupant Injury in Similar Real-World Crashes. *Transportation Research Record 1419*: 78-85.

Council FM, Stewart JR. 1996. Severity Indexes for Roadside Objects. *Transportation Research Record 1528*, 87-96.

Council FM, Mohamedshah YM, Stewart JR. 1997. Effects of Air Bags on Severity Indexes for Roadside Objects. *Transportation Research Record 1581*, 66-71.

Crandall CS, Olson LM, Skylar DP. 2001. Mortality Reduction with Air Bag and Seat Belt Use in Head-On Passenger Car Collisions. *American Journal of Epidemiology*, 153: 219-224.

DeLong ER, DeLong DM, Clarke-Pearson DL. 1988. Comparing the Areas Under Two or More Correlated Receiver Operating Characteristic Curves: A Nonparametric Approach. *Biometrics* 44, 837-845.

Derrig RA, Segui-Gomez M, Abtahi A. 2000. The Effect of Seat Belt Usage Rates on the Number of Motor Vehicle-Related Fatalities. *Proceedings of the 2000 Risk Theory Society Seminar*, April 14-16, Minneapolis, Minnesota.

Dischinger PC, Siegel JH, Ho SM, Kufera JA. 1998. Effect of Change in Velocity on the Development of Complications in Patients with Multisystem Trauma Sustained in Vehicular Crashes. *Accid Anal and Prev* 30(6):831-837.

Elvik R. 1995. The Safety Value of Guardrails and Crash Cushions: A Meta-Analysis of Evidence From Evaluation Studies. *Accident Analysis and Prevention 27*(4), pp 523-549.

Erinle O, Hunter W, Bronstad M, Council F, Stewart JR. 1994. *An Analysis of Guardrail and Median Barrier Accidents Using the Longitudinal Barrier Special Studies (LBSS) File, Volume I: Final Report*. Report FHWA-RD-92-098, Washington, DC: Scientex Corporation/Federal Highway Administration.

European Committee for Standardization (CEN). 1998. *Road Restraint Systems – Part 2: Performance Classes, Impact Test Acceptance Criteria and Test Methods for Safety Barriers*. European Standard EN 1317-2.

Evans L. 1986. The Effectiveness of Safety Belts in Preventing Fatalities. *Accident Analysis and Prevention 18*(3): 229-41.

Foret-Bruno JY, Trosseille X, Le Coz JY, Bendjellal F, Steyer C. 1998. Thoracic Injury Risk in Frontal Car Crashes with Occupant Restrained with Belt Load Limiter. SAE Paper No. 983166, *Proceedings of the Stapp Car Crash Conference*.

Gabler HC, Gabauer DJ, Newell HL, O'Neill M. 2004. *Use of Event Data Recorder (EDR) Technology for Highway Crash Data Analysis*. NCHRP Project 17-24 Final Report, Washington, DC: Transportation Research Board.

Gabler HC, Hampton CE, Hinch J. 2004. Crash Severity: A Comparison of Event Data Recorder Measurements with Accident Reconstruction Estimates, SAE 2004-01-1194, Society of Automotive Engineers.

Gabler HC, Hampton C, Roston T. 2003. Estimating Crash Severity: Can Event Data Recorders Replace Crash Reconstruction? *Proceedings of the Eighteenth International Conference on Enhanced Safety of Vehicles,* May 19-22, Paper 490.

Grzebieta RH, Zou R, Corben B, Judd R, Kulgren A, Tingval C, Powell C. 2002. Roadside Crash Barrier Testing. *Proceedings of the 3rd International Crashworthiness Conference*, Melbourne, Australia.

Grzebieta RH, Zou R, Jiang T, Cary A. 2005. Roadside Hazard and Barrier Crashworthiness Issues Confronting Vehicle and Barrier Manufacturers and Government Regulators. Paper No. 05-0149. *Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, Washington, DC.

German A, Dalmotas D, Comeau JL, Monk B, Contant P, Gou M, Carignan S, Lussier LP, Newman J, Withnall C. 1998. In-Depth Investigation and Reconstruction of an Airbag Induced Child Fatality. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*.

Geigl BC, Hoschopf H, Steffan H, Moser A. 2003. Reconstruction of Occupant Kinematics and Kinetics for Real World Accidents. International Journal of Crashworthiness 8 (1).

Grosch L. 1985. Chest injury Criteria for Combined Restraint Systems. *Proceedings of the 1985 Government/Industry Meeting*, SAE Technical Paper Number 851247.

Hiss JGF, Bryden JE. 1992. *Traffic Barrier Performance*. Report No. FHWA/NY/RR92/155,

New York State Department of Transportation, Albany, NY.

Holdridge JM, Shankar VN, Ulfarsson GF. 2005. The Crash Severity Impacts of Fixed Roadside Objects. *Journal of Safety Research 36*, pp. 139-147.

Huang M, Lawson GP, Powell BK, Walker JH. 1977. Characterization of Vehicle Deceleration Time Histories in the Analysis of Impact Dynamics. SAE Paper No. 770013, *SAE International Automotive Engineering Conference and Exposition*.

Huang M, Laya J, Ming L. 1995. A Study on Ride-Down Efficiency and Occupant Responses in High Speed Crash Tests. SAE Paper No. 950656.

Huelke DF, Sherman HW. 1987. Seat Belt Effectiveness: Case Examples from Real-World Crash Investigations. *Journal of Trauma 27*:750.

Huere JF, Foret-Bruno JY, Faverjon G, Le Coz JY. 2001. Airbag Efficiency in Frontal Real World Accidents. Paper 2001-S1-O-193, *Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles*.

Hunter WW, Stewart JR, Council FM. 1993. Comparative Performance of Barrier and End Treatment Types Using the Longitudinal Barrier Special Study File. *Transportation Research Record 1419*, pp. 63-77.

Jakobsson L, Lundgren K, Norin H, Svensson MY. 2004. Evaluation Criteria for AIS 1 Neck Injuries in Frontal Impacts – A Parameter Study Combining Field Data and MADYMO Modeling. Traffic Injury Prevention 5, pp 374-381.

Katoh H, Nakahama R. 1982. A Study on the Ride-Down Evaluation. *Proceedings of the 9th Experimental Safety of Vehicles (ESV) Conference*, Kyoto, Japan.

Kent RW, Crandall JR, Bolton J, Prasad P, Nusholtz GS, Mertz HJ. 2001a. The Influence of Superficial Soft Tissues and Restraint Condition on Thoracic Skeletal Injury Prediction. Stapp Car Crash Journal, Vol. 45, pp. 183-204.

Kent RW, Bolton J, Crandall JR, Prasad P, Nusholtz G, Mertz HJ, Kallieris D. 2001b. Restrained Hybrid II Dummy-Based Criteria for Thoracic Hard-Tissue Injury Prediction. *Proceedings of the International Research Conference on the Biomechanics of Impact,* pp 215-232.

McGwin G, Metzger J, Alonso JE, Rue LW. 2003. The Association between Occupant Restraint Systems and Risk of Injury in Frontal Motor Vehicle Collisions. *J. Trauma Inj. Infect. Crit. Care*, Vol. 54, No. 6, pp 1182-1187.

Mertz HJ. 2002a. Chapter 4: Anthropomorphic Test Devices. In *Accidental Injury: Biomechanics and Prevention* Second Edition; Nahum, AM and Melvin, JW; Springer: New York, 637 pp.

Mertz HJ. 2002b. Chapter 5: Injury Risk Assessments Based on Dummy Responses. In *Accidental Injury: Biomechanics and Prevention* Second Edition; Nahum, AM and Melvin, JW; Springer: New York, 637 pp.

Michie JD. 1981. Collision Risk Assessment Based on Occupant Flail-Space Model. *Transportation Research Record 796*: 1-9.

Michie JD, Bronstad ME. 1994. Highway Guardrails: Safety Feature or Roadside Hazard? *Transportation Research Record 1468*, pp. 1-9.

Moran SG, Key JS, McGwin G, Keeley JW, Davidson JS, Rue LW. 2004. The Applicability of a Computer Model for Predicting Head Injury Incurred During Actual Motor Vehicle Collisions. Journal of Trauma – Injury Infection & Critical Care: 57(1), pp 99-103.

Nance ML, Elliott MR, Arbogast KB, Winston FK, Durbin DR. 2006. Delta V as a Predictor of Significant Injury for Children Involved in Frontal Motor Vehicle Crashes. *Ann Surg* 243(1):121-125.

National Center for Statistics and Analysis (NCSA). 2005. *National Automotive Sampling System / Crashworthiness Data System: Analytical User's Manual, 2005 File*. Washington, DC: NHTSA.

National Center for Statistics and Analysis (NCSA). 2008. *National Automotive Sampling System / Crashworthiness Data System: Web Query System.*. Retrieved May 27, 2008, Web site: http://www-nass.nhtsa.dot.gov/BIN/NASSCASELIST.EXE/SETFILTER.

National Highway Traffic Safety Administration (NHTSA). 1999. Federal Motor Vehicle Safety Standards: Occupant Crash Protection – Supplemental Notice of Proposed Rulemaking. 49 CFR Parts 552, 571, 585, 595. NHTSA Docket 99-6407, US Department of Transportation.

National Highway Traffic Safety Administration (NHTSA). 2007. *Seat Belt Use in 2006: Use Rates in the States and Territories*. DOT HS 810 690.

National Highway Traffic Safety Administration (NHTSA). 2008a. *NHTSA Vehicle Crash Test Database*. Retrieved May 27, 2008, Web site: http://www-nrd.nhtsa.dot.gov/database/nrd-11/veh_db.html

National Highway Traffic Safety Administration (NHTSA). 2008b. *NHTSA Vehicle Safety Research Signal Analysis Software*. Retrieved May 27, 2008, Web site: http://www.nhtsa.gov/portal/site/nhtsa/menuitem.8027fe7cfb6e727568d07a30343c44cc/#Software

Niehoff P, Gabler HC. 2006. The Accuracy of WinSmash Delta-V Estimates: The Influence of Vehicle Type, Stiffness, and Impact Mode. *Proceedings of the 50th Annual Association for the Advancement of Automotive Medicine Conference*.

Niehoff P, Gabler HC, Brophy J, Chidester A, Hinch J, Ragland C. 2005. Evaluation of Event Data Recorders in Full Systems Crash Tests. *Proceedings of the 19th International Conference on the Enhanced Safety of Vehicles*, Paper 05-0271.

Ray MH, Michie JD, Hargrave M. 1986. Events that Produce Occupant Injury in Longitudinal Barrier Accidents. *Transportation Research Record 1065*: 19-30.

Ray MH, Michie JD, Hunter W, Stutts J. 1987. An Analysis of the Risk of Occupant Injury in Second Collisions. *Transportation Research Record 1133*, pp. 17-22.

Reinfurt D, Williams A., Wells J, Rodgman E. 1996. Characteristics of Drivers Not Using Seat Belts in a High Belt Use State. *Journal of Safety Research 27*(4), pp. 209-215.

Roberts VL, Compton CP. 1993. The Relationship between Delta-V and Injury. *Proceedings of the 37th Stapp Car Crash Conference*, pp. 35–41.

Ross HE, Sicking DL, Zimmer RA, and JD Michie. 1993. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. NCHRP Report 350, TRB, National Research Council, Washington, DC.

Segui-Gomez M. 2000. Driver Air Bag Effectiveness by Severity of the Crash. *American Journal of Public Health* 90(10), pp. 1575-1581.

Sharma D, Stern S, Brophy J, Choi EH. 2007. An Overview of NHTSA's Crash Reconstruction Software WinSMASH. *Proceedings of the 20th International Conference on the Enhanced Safety of Vehicles*, Paper 07-0211.

Shojaati M. 2003. Correlation Between Injury Risk and Impact Severity Index ASI. *Proceedings of the 3rd Swiss Transport Research Conference*, Monte Verita/Ascona, March 19-21.

Smith RA, Noga JT. 1982. *Accuracy and Sensitivity of CRASH*, SAE Paper 821169, Warrendale, PA: Society of Automotive Engineers.

Society of Automotive Engineers (SAE). 2007. Surface Vehicle Recommended Practice: Instrumentation for Impact Test – Part 1 – Electronic Instrumentation. SAE-J211, Revised July 2007.

TRC 191. 1978. *Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances.* Transportation Research Board, Transportation Research Circular No. 191, Washington, DC.

US Department of Transportation. 1999. *National Automotive Sampling System Crashworthiness Data System 1994-1996*. National Highway Traffic Safety Administration, DOT HS 808 985.

Versace J, Berton RJ. 1975. Determination of Restraint Effectiveness: Airbag Crash Test Repeatability. SAE Paper 750395, *Proceedings of the Automotive Engineering Conference and Exposition*, Detroit, Michigan.

Viano DC, Arepally S. 1990. Assessing the Safety Performance of Occupant Restraint Systems. SAE Transactions, Vol. 99, No. 6, pp. 1913-1939.

Viano DC. 1995. Restraint Effectiveness, Availability and Use in Fatal Crashes: Implications to Injury Control. *Journal of Trauma: Injury, Infection and Critical Care* 38(4): p 538.

Viner JG. 1995. The Roadside Safety Problem. *Transportation Research Circular #435*, Transportation Research Board, National Research Council, pp. 17-29.

Walz M. 2004. NCAP Test Improvements with Pretensioners and Load Limiters. *Traffic Injury and Prevention*, 5:18-25.

Winnicki J, Eppinger R. 1998. *A Method for Estimating the Effect of Vehicle Crashworthiness Design Changes on Injuries and Fatalities*. NHTSA Technical Report, Washington, DC: US Department of Transportation.

Zweden JV, Bryden JE. 1977. *In-service Performance of Highway Barriers*. Report No. NYSDOT-ERD-77-RR51, New York State Department of Transportation, Albany, NY.

APPENDIX A: VEHICLE-BASED AND ATD-BASED CRITERIA COMPARISON: ADDITIONAL GRAPHICAL RESULTS

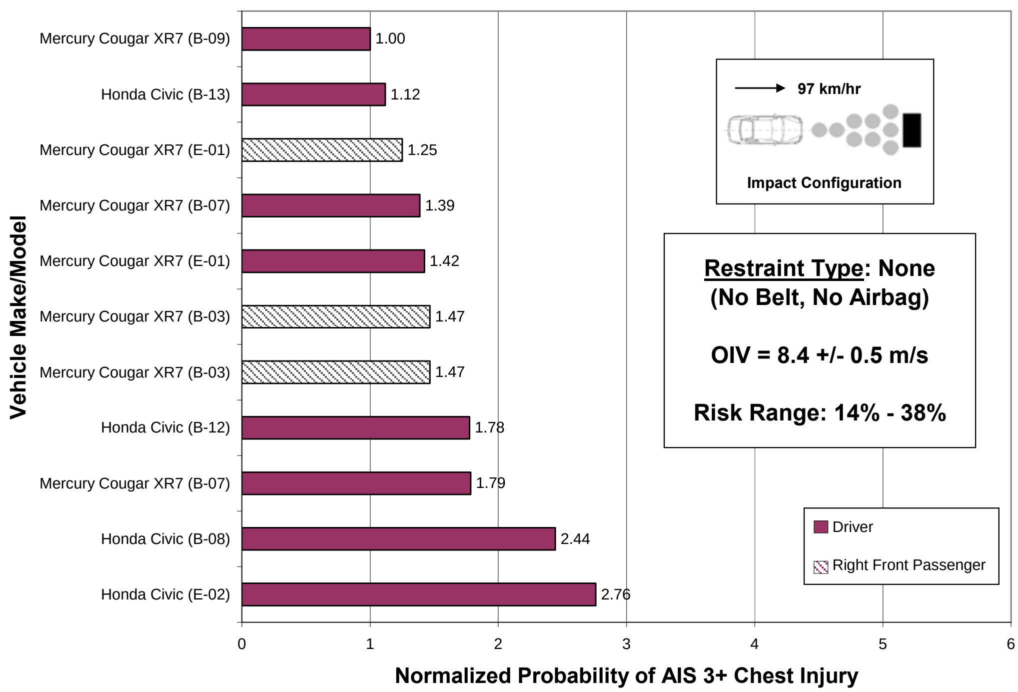


Figure 51. Normalized Probability of Acceleration-Based Chest Injury to Unrestrained Occupants

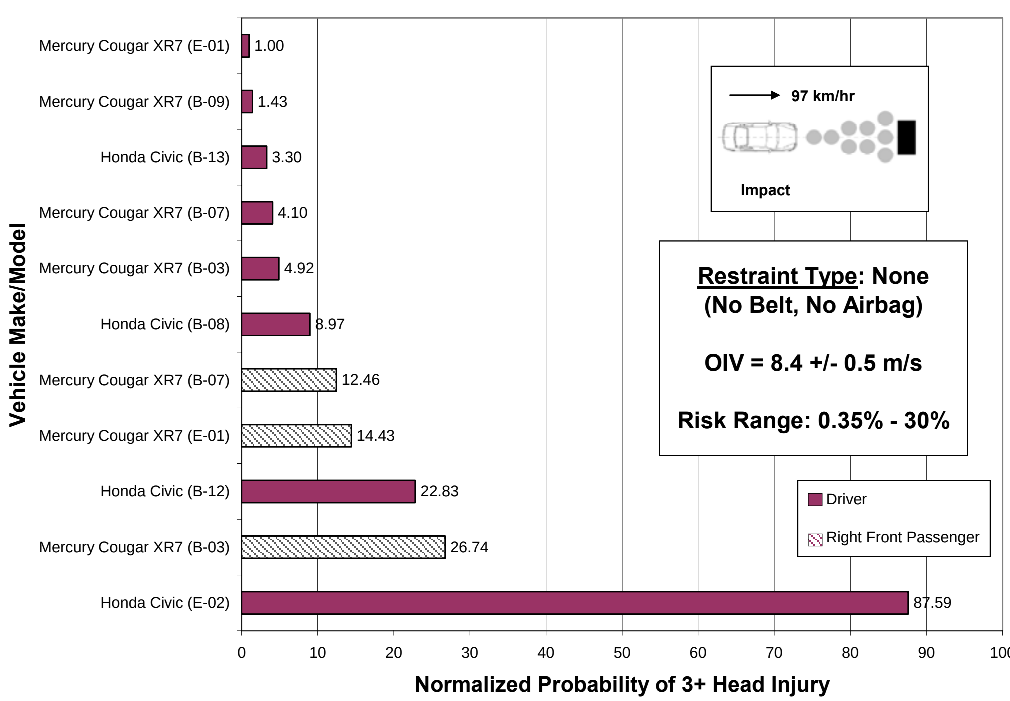


Figure 52. Normalized Probability of Head Injury to Unrestrained Occupants

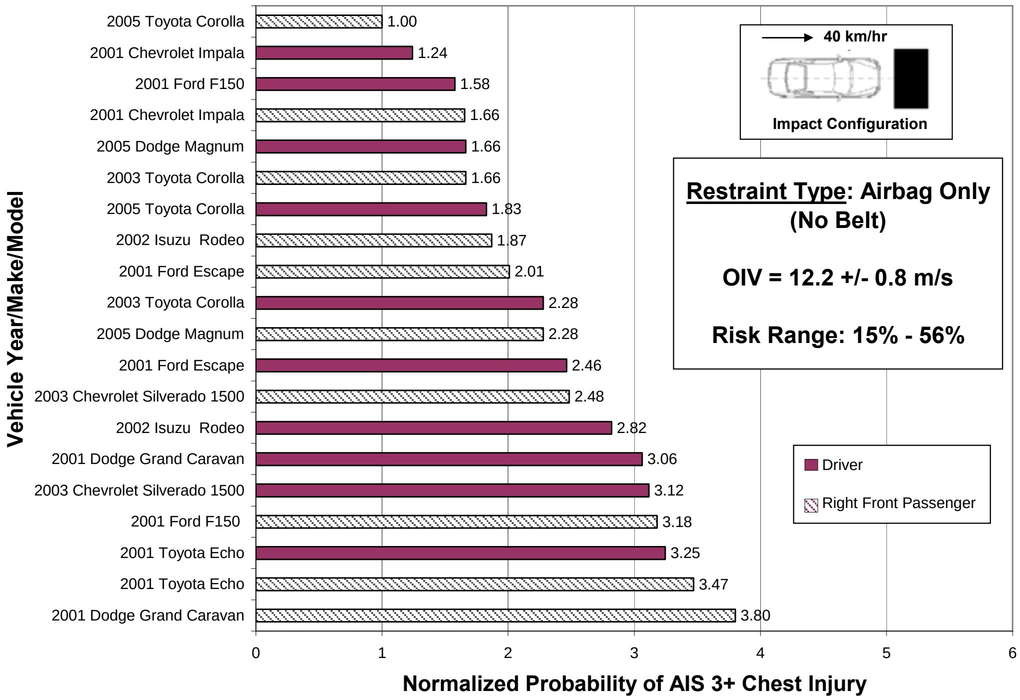


Figure 53. Normalized Probability of Acceleration-Based Chest Injury to Airbag-Restrained Occupants

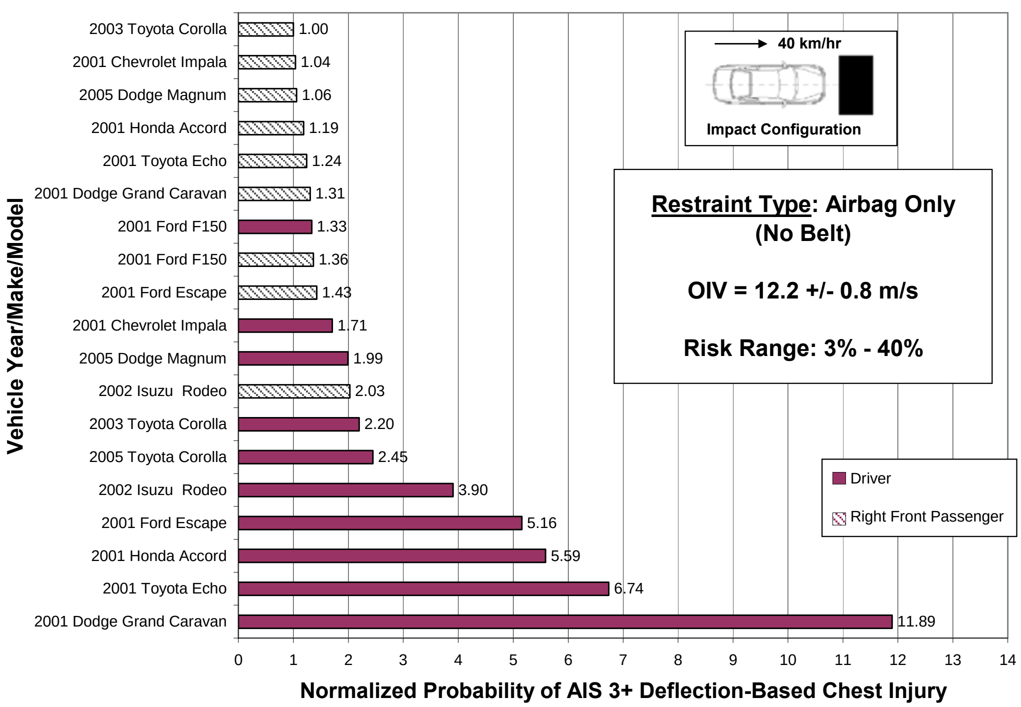


Figure 54. Normalized Probability of Deflection-Based Chest Injury to Airbag Restrained Occupants

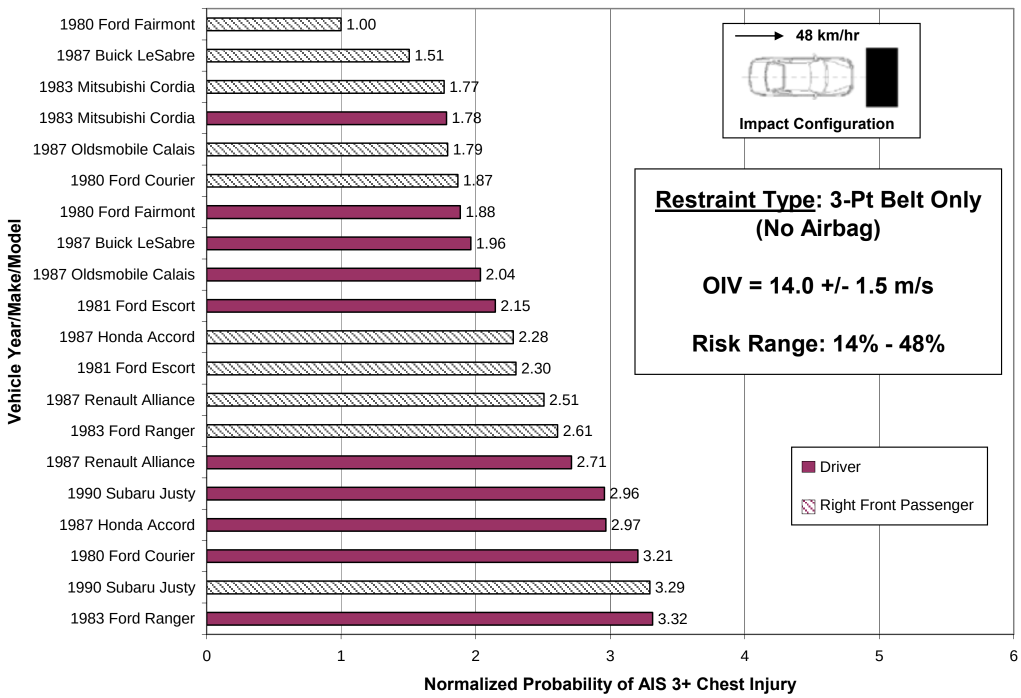


Figure 55. Normalized Probability of Acceleration-Based Chest Injury to Belt-Restrained Occupants

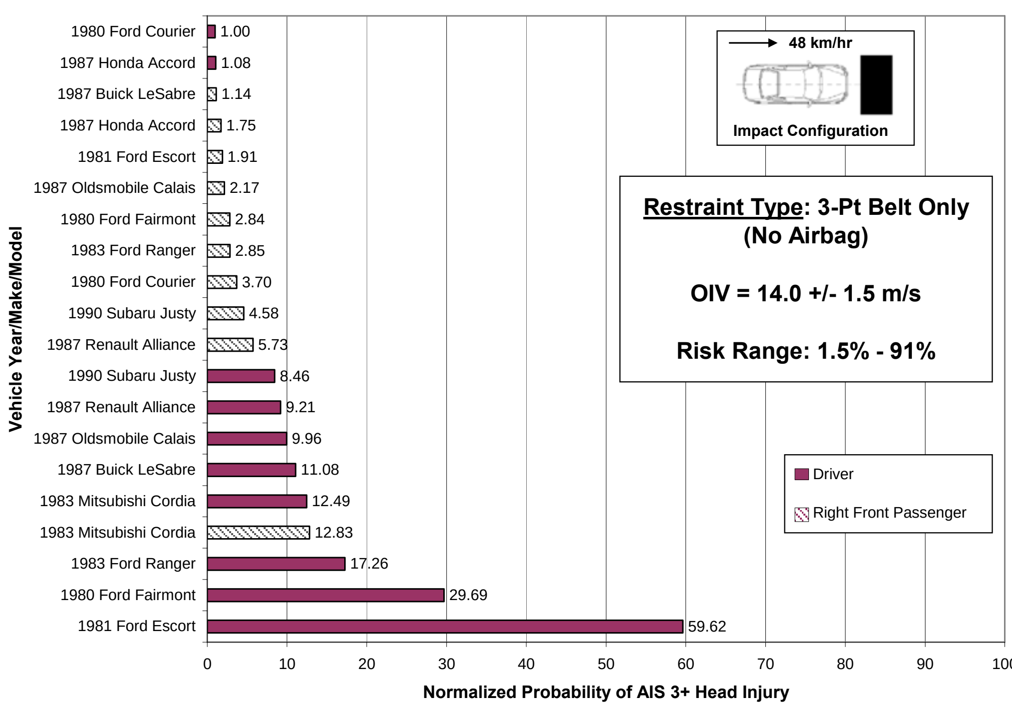


Figure 56. Normalized Probability of Head Injury to Belt-Restrained Occupants

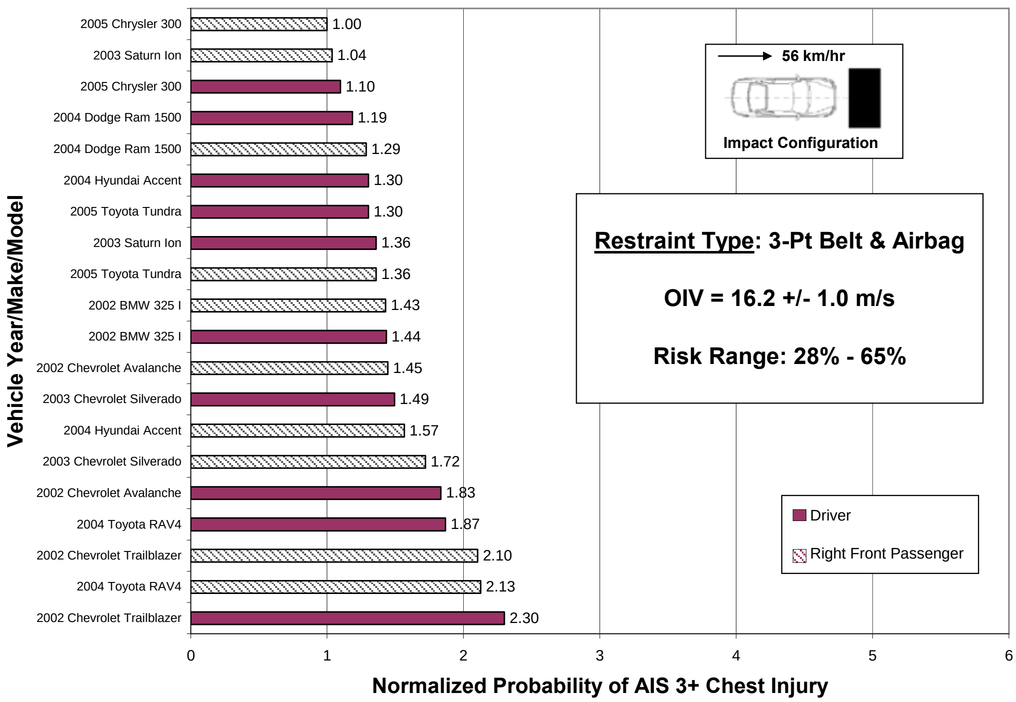


Figure 57. Normalized Probability of Acceleration-Based Chest Injury to Belt and Airbag Restrained Occupants

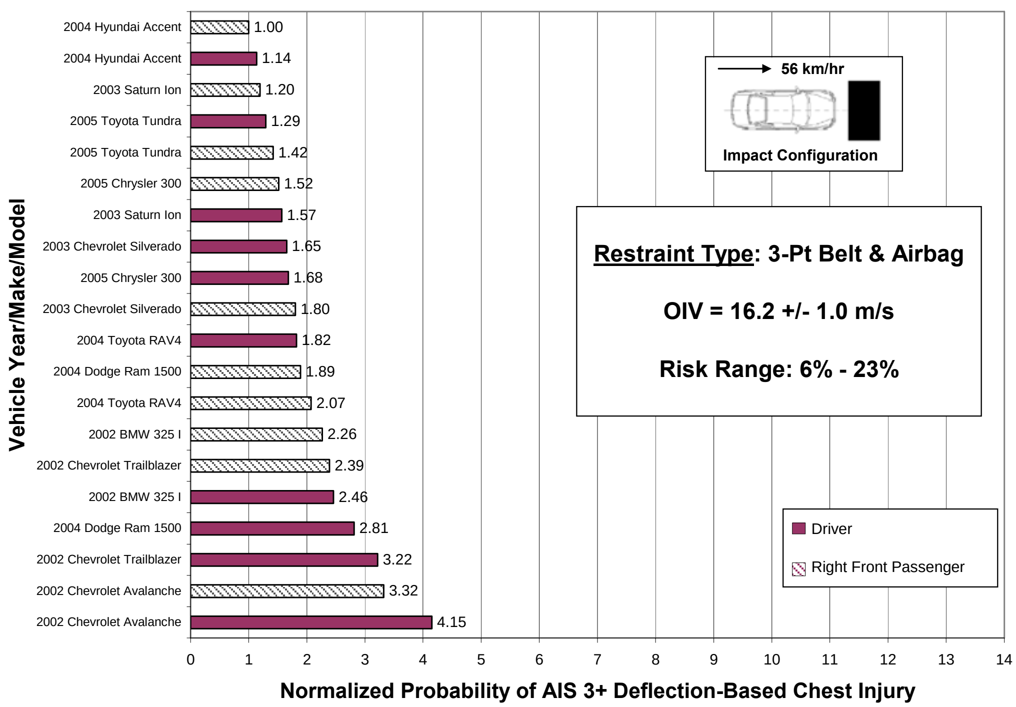


Figure 58. Normalized Probability of Deflection-Based Chest Injury to Belt and Airbag Restrained Occupants

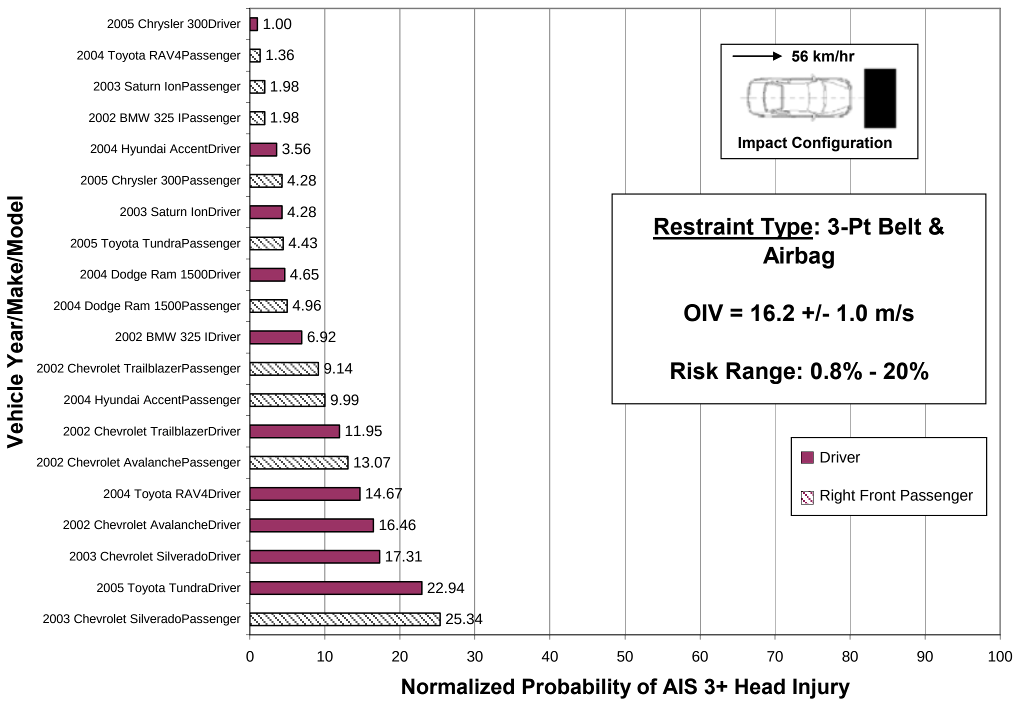


Figure 59. Normalized Probability of Head Injury to Belt and Airbag Restrained Occupants

APPENDIX B: ADDITIONAL MAIS AND ISS INJURY RISK CURVES

Additional MAIS 2+ and ISS 9+ injury risk curves as well as all MAIS 3+ injury risk curves are provided below. All figures show belted occupant risk on the right and unbelted occupant risk on the left.

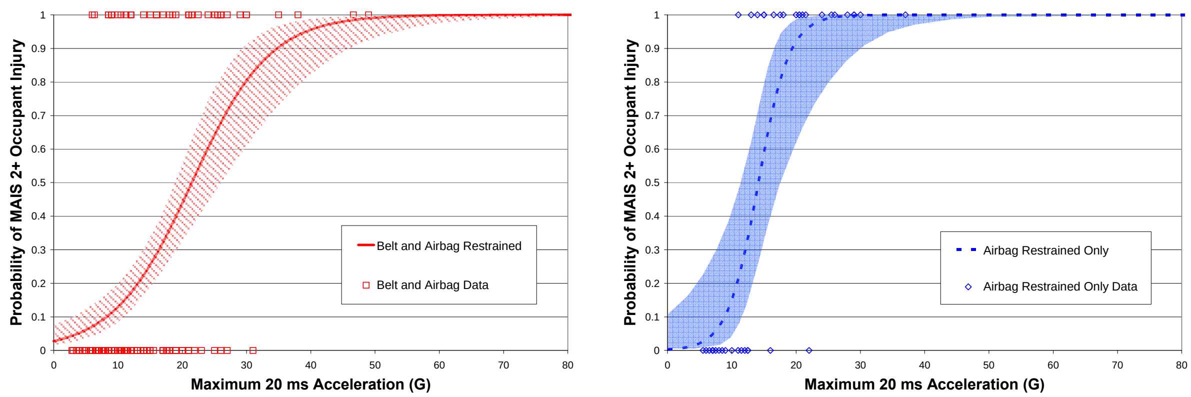


Figure 60. 20 ms Acceleration MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

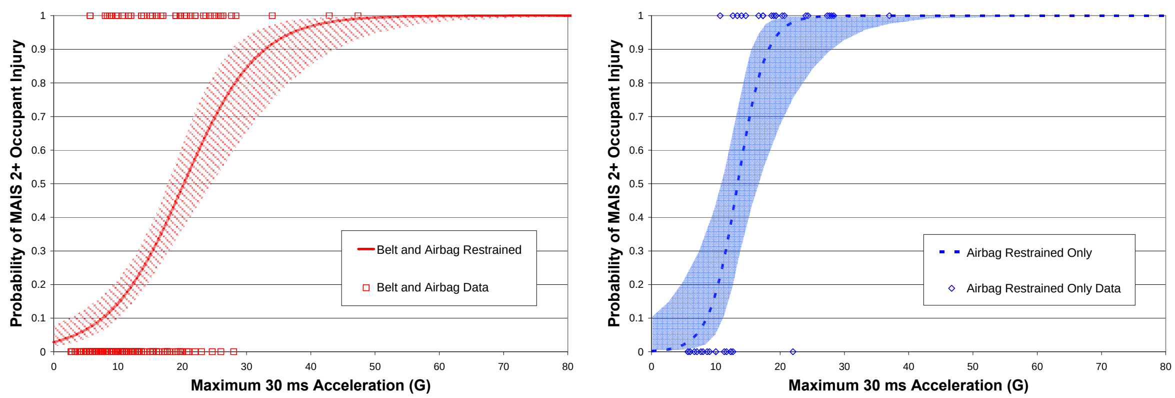


Figure 61. 30 ms Acceleration MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

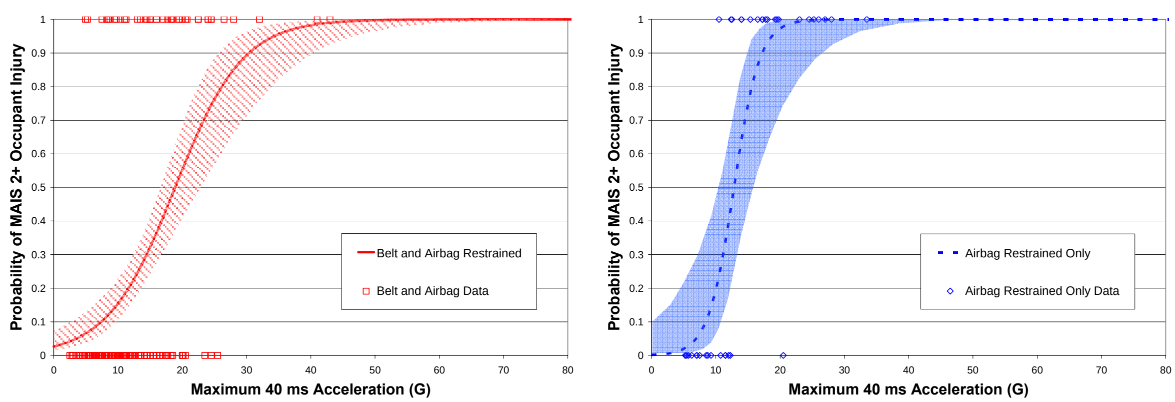


Figure 62. 40 ms Acceleration MAIS 2+ Injury Risk Curves: Belted (left) and Unbelted (right)

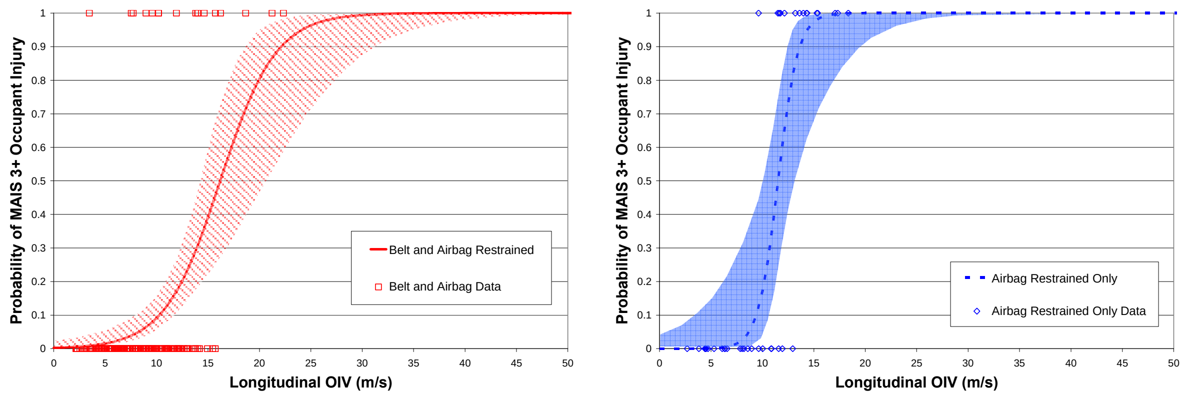


Figure 63. OIV MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)

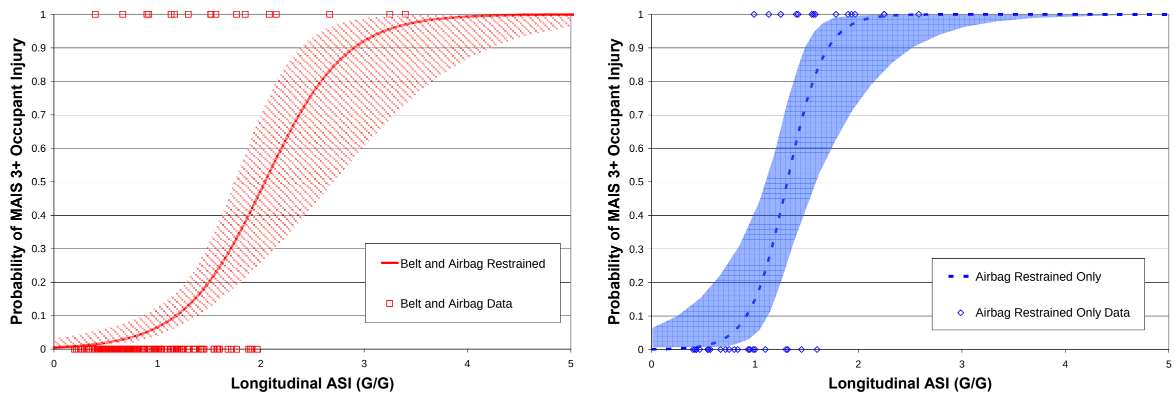


Figure 64. ASI MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)

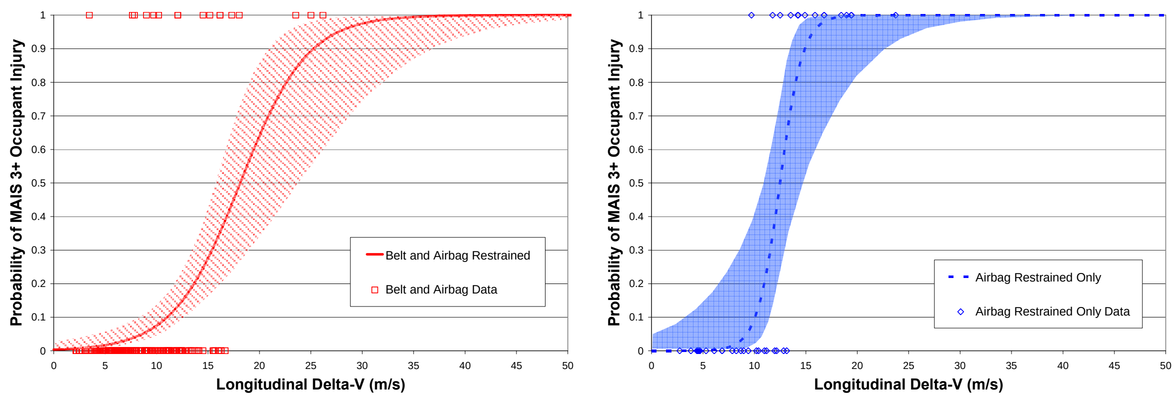
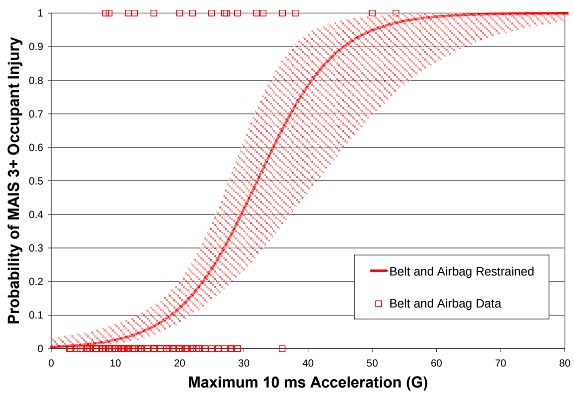


Figure 65. Delta-V MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)



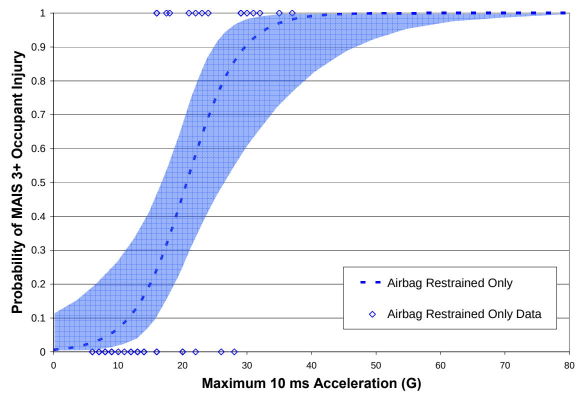
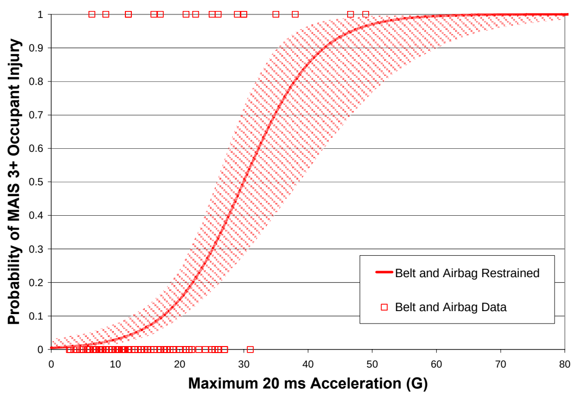


Figure 66. 10 ms Acceleration MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)



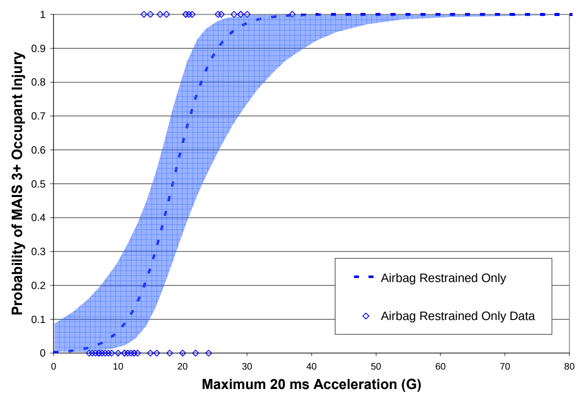
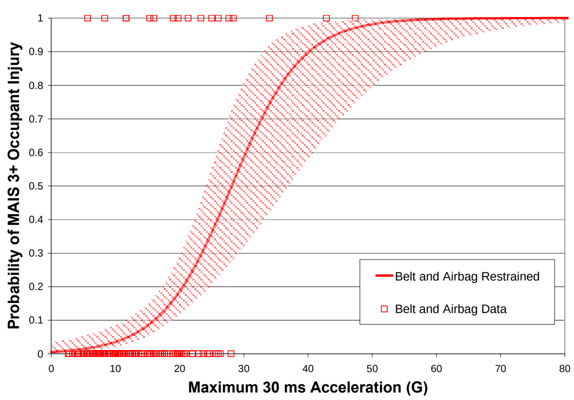


Figure 67. 20 ms Acceleration MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)



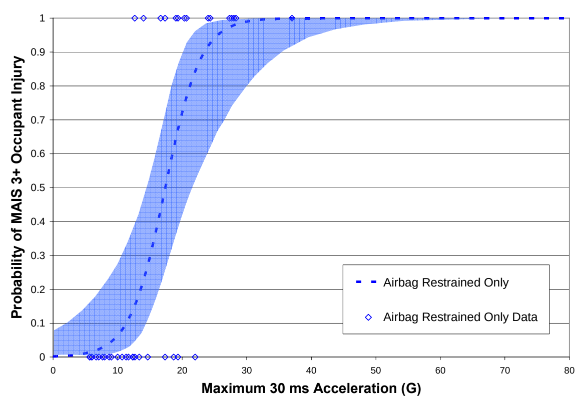
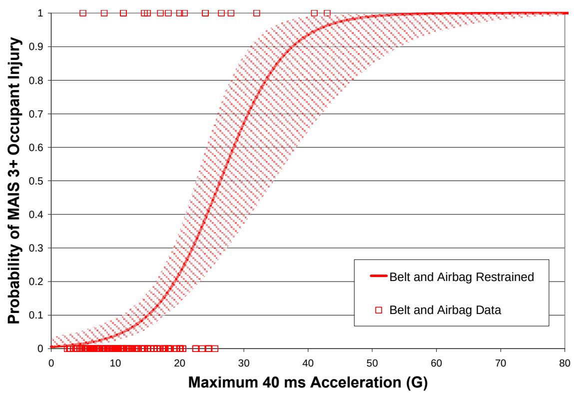


Figure 68. 30 ms Acceleration MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)



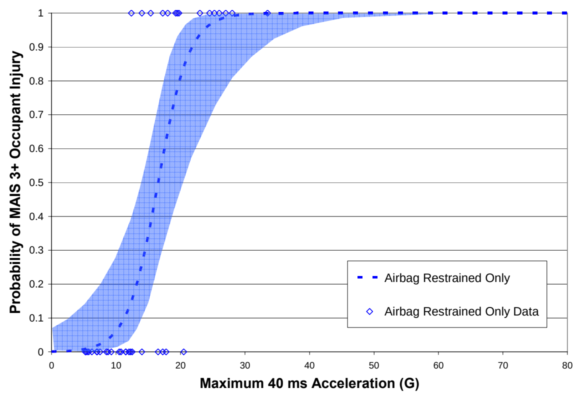
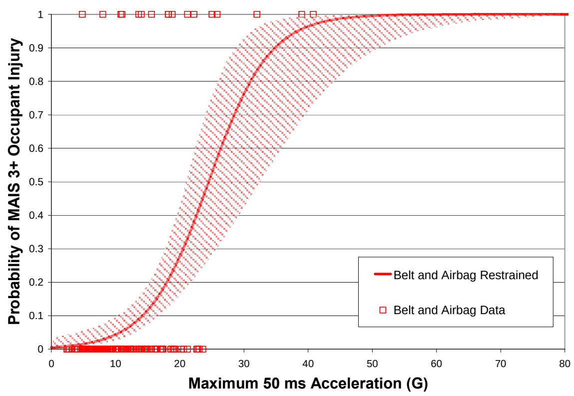


Figure 69. 40 ms Acceleration MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)



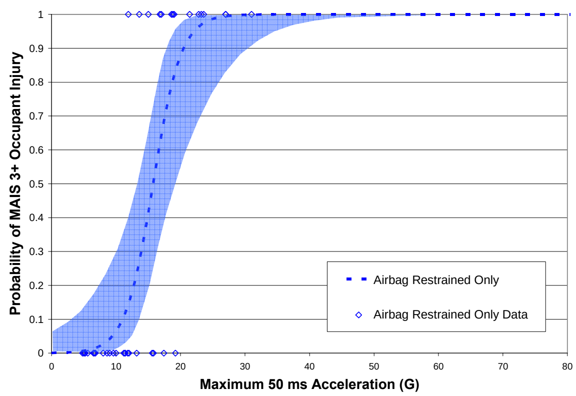
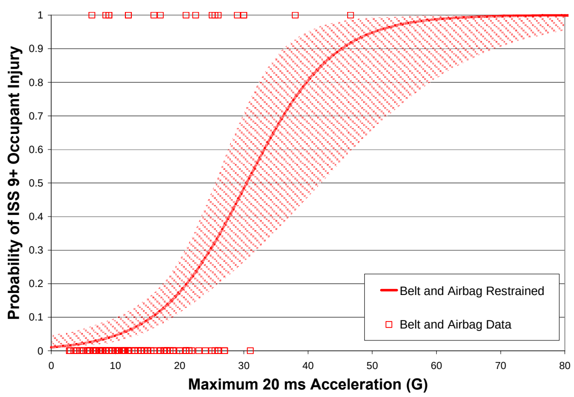


Figure 70. 50 ms Acceleration MAIS 3+ Injury Risk Curves: Belted (left) and Unbelted (right)



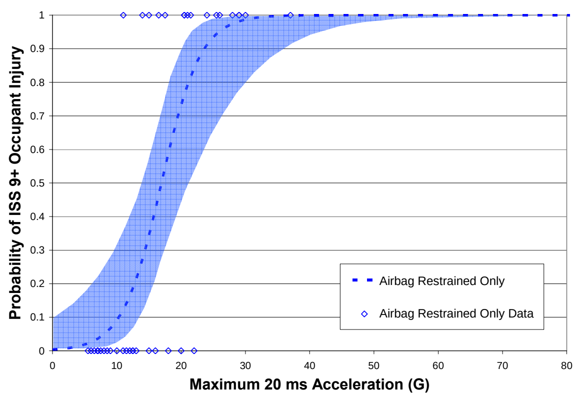
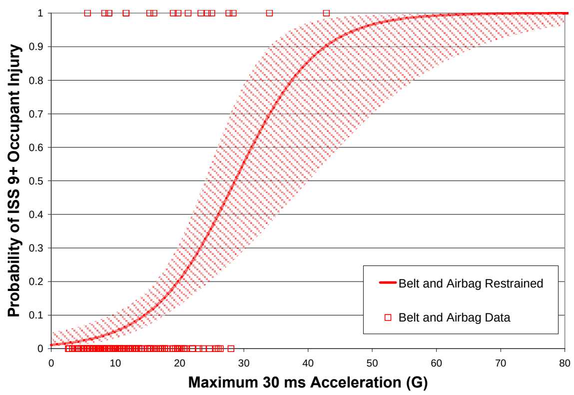


Figure 71. 20 ms Acceleration ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)



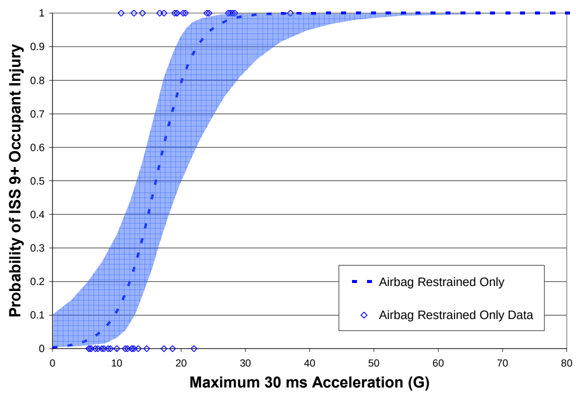
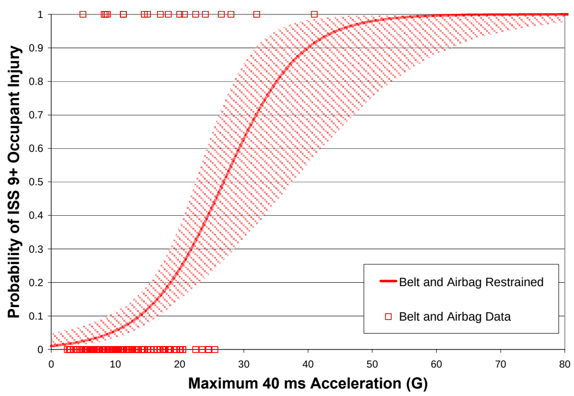


Figure 72. 30 ms Acceleration ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)



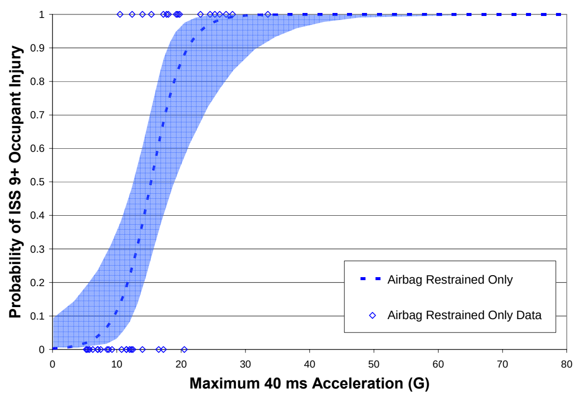


Figure 73. 40 ms Acceleration ISS 9+ Injury Risk Curves: Belted (left) and Unbelted (right)