Comparison of roadside and vehicle crash test injury criteria in frontal crash tests

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Abstract: The flail space model is widely used to assess occupant injury risk potential in full-scale crash tests of roadside safety hardware, e.g. guardrail. A fundamental assumption of this model is that the occupant is unbelted and not airbag restrained. In the early 1980s, these were valid assumptions in the US: cars were not airbag equipped and belt usage rates were around 11%. In today's US vehicle fleet, however, these assumptions are questionable: the belt usage rate is approximately 80% and airbags are required equipment. These changes have significant implications on injury risk computed using the original flail space model. The objective of this study is to contrast flail space model injury risk with the widely accepted dummy-based injury criteria in frontal crashes involving unbelted, belted or airbag restrained occupants. In an analysis of 39 frontal crash tests of speeds ranging from 40 to 97 km hour^{-1}, the flail space model was unable to account for variations in occupant risk due to the presence and performance of seatbelts and airbags.

Keywords: comparison; crash injury criteria; frontal crash tests; occupant restraints; roadside safety.

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1 Introduction

Full-scale crash testing is the traditional method of evaluating both vehicles and roadside safety hardware impact performance. A critical part of these evaluations is the assessment of occupant risk potential. Although the basic goal is the same, the vehicle and roadside crash safety communities approach the assessment differently. The vehicle safety community has developed impact configuration-specific crash test dummies to serve as a surrogate for the human response. Occupant risk procedures for vehicle crashworthiness are set forth in the Federal Motor Vehicle Safety Standards (FMVSS) (NHTSA, 2004a,b,c). Frontal crash tests, for example, are described by FMVSS 208 (NHTSA, 2004b).

Ideally, occupant risk in roadside barrier crash tests would be evaluated using an instrumented dummy. Several practical considerations, however, have led the roadside community to avoid this option. Crash testing of roadside hardware is more complex and must provide a structural evaluation of the device in addition to an assessment of occupant injury risk potential. Tests with longitudinal barriers, such as guardrail, are conducted at higher test speeds and oblique impact angles. As the roadside hardware is typically tested in soil, repeatability becomes a challenge. A vehicle impacting one of these devices must travel over a surface sufficiently uneven to bounce a dummy out of position prior to the impact with the roadside hardware. In addition, these crash tests often produce vehicle instability and overturn which could damage the dummy or its instrumentation. As a result, the roadside safety community has developed occupant risk models, namely the flail space model. Roadside hardware occupant risk guidelines are set forth in NCHRP Report 350 (Ross et al., 1993). The guidelines attempt to indirectly predict occupant injury risk based on vehicle kinematics.

Human surrogates 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 1980s as belt use rates in the US were roughly 11% (Derrig, Segui-Gomez and Abtahi, 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 in the US to 80% nationally. Despite the potentially large effect these shifts have on occupant risk, current roadside occupant risk criteria do not account for them.

2 Objective

The intent of this study is to illustrate the importance of developing roadside hardware crash test injury criteria that account for occupant restraints. Specifically, the study will provide a comparison of the relative variation between roadside injury criteria and injury risk, as measured by human surrogates, in full-scale vehicle crashworthiness tests for differing restraint conditions.

3 Background

Vehicle crashworthiness tests are intended to evaluate the performance of in-vehicle occupant restraints across the vehicle fleet spectrum. The idea is to provide a means of comparing occupant risk between vehicles for the same crash conditions. Development of roadside hardware is inherently more complex as both device performance and occupant protection must be considered. The result is a more complex set of tests, consisting of different combinations of vehicles and impact conditions and simplified methods of computing occupant risk. The limitation of the current roadside injury criterion, the flail space model, is that it is based exclusively on measured vehicle accelerations. The criterion is unable to account for variations in occupant risk due to the presence and performance of seatbelts and airbags.

3.1 Roadside injury criteria

3.1.1 Flail space model

Introduced by Michie (1981a), the flail space model assumes that occupant injury severity is related to the velocity at which the occupant impacts the interior and the subsequent acceleration forces. The occupant is assumed to be an unrestrained point mass that behaves as a 'free-missile' inside the occupant compartment in the event of a collision. The occupant is allowed to 'flail' 0.6 m in the longitudinal direction (parallel to the typical direction of vehicle travel) and up to 0.3 m in the lateral direction prior to impacting the vehicle interior. Measured vehicle kinematics are used to compute the difference in velocity between the occupant and occupant compartment at the instant the occupant has displaced either 0.3 m laterally or 0.6 m longitudinally. For ease of computations, the vehicle yaw and pitch motions are ignored, all motion is assumed to be in the horizontal plane, and the lateral and longitudinal motions are assumed to be independent. At the instant of occupant impact, the largest difference in velocity (lateral and longitudinal directions are handled independently) is termed the occupant impact velocity (OIV). Once the impact with the interior occurs, the occupant is assumed to remain in contact with the interior and be subjected to any subsequent vehicular acceleration. The maximum 10 msec moving average of the accelerations subsequent to the occupant impact with the interior is termed the occupant ridedown acceleration (ORA). Again, the lateral and longitudinal directions are handled separately producing two maximum ORAs.

Threshold values for the OIV and ORA are used to gauge occupant injury potential. Table 1 summarises the current threshold values, as prescribed in NCHRP 350 (Ross et al., 1993). Although values below the 'preferred' are desirable, values below the 'maximum' category are considered acceptable. Note that the 'maximum' thresholds correspond to serious but not life-threatening occupant injury (Michie, 1981b). The longitudinal OIV values in Table 1 were developed primarily from pure frontal head impacts into windshields (Kay, Pickard and Patrick, 1973; Begeman et al., 1978; Michie, 1981b). The lateral limits were based mainly on French accident statistics (Hartman et al., 1976) and research aimed at developing FMVSS 214 (NHTSA, 2004c), a US vehicle standard for side impact protection. As the threshold values are based independently on frontal and side impact directions, the flail space model should predict injury best in either of these directions. Note that the biomechanical data used to develop the flail space model did not include any oblique tests. The biomechanical validity of OIV in angled longitudinal barrier impacts has not been established.

Table 1 Flail space model thresholds

Occupant impact velocity limits		
Component direction	*Preferred value*	*Maximum value*
Lateral and longitudinal	9 m $\sec^{-1}$	12 m $\sec^{-1}$
Occupant ridedown acceleration limits		
Component direction	*Preferred value*	*Maximum value*
Lateral and longitudinal	15 g	20 g

Using crash reconstruction and crash test matching methods, early research (Ray, Michie and Hargrave, 1986; Council and Stewart, 1993) attempted to link the flail space model to occupant injury with limited success. More recently, Gabauer and Gabler (2004) evaluated OIV using crash pulse data from real-world frontal collisions coupled with occupant injury information. Although preliminary results suggested a reasonable correlation to occupant injury, the analysed data set was small (58 cases), dealt only with the longitudinal OIV, and included only General Motors vehicles.

European test procedures prescribe a variation of the flail space model (CEN, 1998), while other researchers have proposed various computational modifications (Ray, Michie and Calcote, 1987; Ross et al, 1988; Ray and Carney, 1989). All attempted to provide a more realistic model of unrestrained point mass motion within the occupant compartment by modifying the original model assumptions. Although the improved versions better characterise unrestrained occupant motion, none attempted to account for the presence of seatbelt or airbag restraints.

3.2 Vehicle crashworthiness injury criteria

3.2.1 The head injury criterion

A refinement of the Gadd Severity Index (Gadd, 1966), the Head Injury Criterion (HIC) was first defined in 1971 by Versace (1971) as follows:

$$\mathbf{HIC} = \frac{\left[\int_{T_1}^{T_2} a(t)\mathrm{d}t\right]^{2.5}}{(T_2 - T_1)},$$

where $a(t)$ is the resultant linear acceleration time history (G's) of the centre of gravity of the head, and T_1 and T_2 are two particular time values that maximise the above expression. Traditionally, the National Highway Traffic Safety Administration (NHTSA) has limited the separation between to T_1 and T_2 to no more than 36 msec. Based on this separation, the maximum value for the HIC for an adult mid-size male anthropomorphic test dummy is 1,000 (NHTSA, 2004b). In 2000, NHTSA changed this to require a 15 msec HIC with a corresponding limit of 700 (Eppinger et al., 2000).

3.2.2 Chest injury criteria

Several injury criteria have been developed to predict chest injury in full-scale vehicle crashworthiness tests. Currently, NHTSA mandates limits on maximum chest acceleration and maximum chest deflection. For chest acceleration, NHTSA prescribes a maximum of 60 G's, except in cases where the duration of the peak is less than 3 msec (often referred to as simply the '3 msec Clip'). For chest deflection, a maximum value of 76 mm (3 inches) was previously prescribed. This criterion is based on a study by Neathery (1975) that analysed cadaver data to estimate that a 33% chest deflection (or 76 mm in a 50th% male) would result in severe but not life threatening injury. In conjunction with the update to the HIC requirements, NHTSA reduced the maximum chest deflection value to 63 mm (2.5 inches) (Eppinger et al., 2000).

4 Methodology

The general methodology for this study included:

1 selection of suitable full-scale crash tests

2 computation of the roadside crash injury criteria for each test

3 computation of the injury risk based on the measured response of instrumented human surrogates

4 comparison of the roadside injury criteria and injury risk using both graphical and linear regression techniques.

4.1 Case selection

For frontal collisions, there are four primary occupant restraint scenarios:

1 no restraint

2 three-point belt restraint only

3 airbag restraint only

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. Roadside hardware crash tests using a fully instrumented Hybrid II ATD, however, have been reported by Hinch et al. (1988). The dummy was completely unrestrained in several high speed tests involving sand-filled crash cushions. Nine of these tests (11 occupant responses), as reported by Hinch et al. (1988), were selected to compare roadside injury criteria to human surrogate occupant risk for unrestrained occupants.

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 FMVSS compliance as well as various other research purposes. All cases selected from the NHTSA database were frontal barrier collisions and had an impact speed of 40, 48, or 56 km hour^{-1}. For the airbag only restraint and belt and airbag restraint scenarios, additional restrictions included airbag presence and proper deployment, vehicle model year 2000 or newer, and use of Hybrid III 50th% male ATDs. For the belted only restraint scenario, additional requirements included no frontal airbags and the use of Hybrid II 50th% male ATDs. Only cases in which the airbag properly deployed (if equipped) were included. 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 each of the three restraint conditions remaining, 10 tests were used to provide a comparison of roadside and ATD-based occupant risk. The airbag only restraint condition used tests with 40 km hour^{-1} (25 mph) impact speed and Hybrid III 50th% male ATDs. The airbag and belt restraint condition used tests with 56 km hour^{-1} (35 mph) impact speed and Hybrid III 50th% male ATDs. Finally, the belt only scenario used tests with a 48 km hour^{-1} (30 mph) impact speed and Hybrid II 50th% male ATDs.

4.2 Flail space model computations

The computation of OIV and ORA is identical to the longitudinal portion of the procedures outlined in NCHRP Report 350 (Ross et al., 1993). In the tests, both the dummies and vehicle structure are instrumented with accelerometers. For computation of OIV and ORA, accelerometer data was chosen as close to the vehicle centre of gravity as possible to best describe the occupant compartment movement. Sensors used in our calculation 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 centre 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 to ensure data accuracy; corrections for sensor bias were made as necessary. The raw acceleration data from the selected channel was filtered to CFC 180, as prescribed in NCHRP 350, prior to integrating for velocity or position. Numerical integration was accomplished via the trapezoidal rule, as recommended in NCHRP 350.

4.3 Vehicle injury criteria and injury risk computations

Injury criteria reported in the NHTSA database include 36 msec HIC and chest 3 msec clip. The 15 msec HIC and maximum chest deflection were computed using the Signal Browser software, available from NHTSA. All head centre of gravity acceleration traces were filtered at CFC 1,000 prior to computation of the 15 msec HIC, as prescribed by SAE-J211 (2007). Similarly, the chest deflection traces were filtered at CFC 600 prior to determining the maximum deflection. In addition, any sensor bias problems were corrected prior to analysis.

Table 2 summarises the relations used to compute human injury risk potential based on the ATD-based injury criteria values (NHTSA, 1999). The occupant risk probability is gauged by the abbreviated injury severity (AIS) scale (AAAM, 1990), which methodically rates injury on a discrete 0–6 scale based on threat to life. Injury levels are summarised in Table 3. The original intent of the flail space model is to indicate the transition between AIS 3 and AIS 4 level injury (Michie, 1981a). As such, injury risk computed for this analysis is the probability of AIS 3 or greater occupant injury.

Table 2 Computation of injury risk based on injury criteria values

Body region	*Injury criteria*	*Probability of AIS 3 + injury*
Head	15 msec HIC	$p(\text{AIS} \geq 3) = \frac{1}{1+e^{((3.39+200/\text{HIC})-0.00372\text{HIC})}}$
Chest	3 msec chest clip (G)	$p(\text{AIS} \geq 3) = \frac{1}{1+e^{(3.1493-0.0630Ac)}}$

Source: NHTSA (1999).

Table 3 Abbreviated injury severity scale summary

AIS value	*Injury description*
0	No injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum/fatal

Source: AAAM (1990).

4.4 Risk comparison

Roadside and ATD-based occupant risk is first compared graphically for each occupant restraint scenario. As roadside occupant risk is intended to predict overall occupant injury, the combined probability of AIS 3 + head and chest injury is used as an analogous ATD metric. The combined probability is computed by adding the AIS 3 + head and chest injury (based on 3 msec clip) probability and then subtracting the product, as shown below:

$$p(\text{Head / Chest Injury}) = p(\text{Head}) + p(\text{Chest}) - p(\text{Head}) * p(\text{Chest}).$$

The assumption is that risk of head and chest injury are independent of one another. NHTSA uses this same assumption in computing vehicle star safety ratings. Each plot is then normalised based to the probability of injury of the best performer (lowest injury risk assumes a value of unity). Since each restraint scenario uses crash tests of nearly identical impact speeds, there is only small variation in roadside occupant risk values, especially the OIV. The mean OIV value and approximate range are noted on each plot.

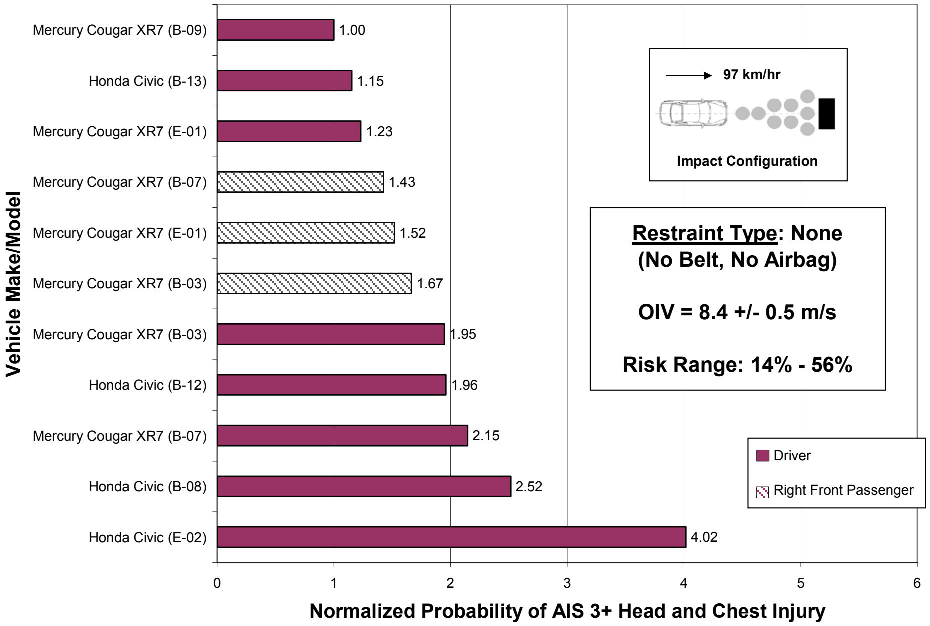
Linear regression analysis is used to provide further comparison. Ideally, if the roadside injury criteria are indeed good predictors of occupant risk, we would expect strong linear correlations to the ATD-based injury criteria. This should be especially evident in the unrestrained scenario, as the flail space model assumes this restraint condition. R^2 values are indicated for each available roadside-ATD criteria combination for each restraint condition.

5 Results

5.1 Unrestrained occupant risk comparison

Figure 1 is a chart showing AIS 3 + head and chest normalised injury risk for the selected 97 km hour^{-1} (60 mph) frontal crash cushion tests. The OIV was an essentially uniform 8.4 m $\sec^{-1}$ for all tests, but ATD-based injury varied dramatically. The vehicle make and model are shown with drivers indicated by solid bars and right front seat passengers indicated with hatched bars. All vehicles were model year 1979. The corresponding test designation reported by Hinch et al. (1988) is indicated in parentheses. All ATD occupants are Hybrid II 50th% males with no restraints. Probability of injury has been normalised to the best performer, the Mercury Cougar driver in test B-09, which has a combined head and chest injury probability of 14%. The OIV varies within a small 1 m $\sec^{-1}$ range suggesting a relatively constant risk whereas ATD occupant risk varies as much as four-fold in relation to the best performer. Note that the tests selected include 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.

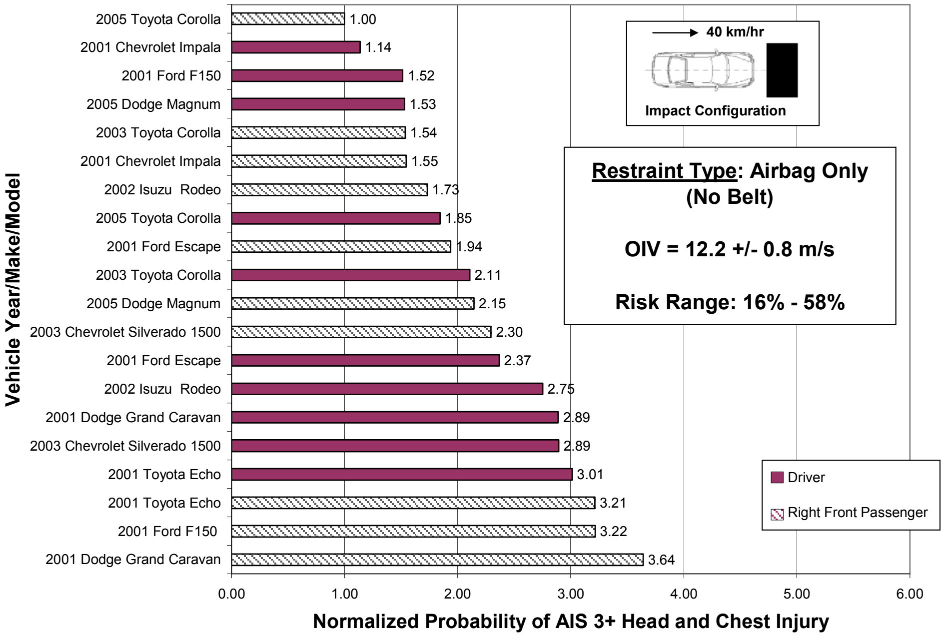
Figure 1 Probability of serious injury to unrestrained occupants normalised to best performer (see online version for colours)



5.2 Airbag-only restrained occupant risk comparison

Figure 2 is a chart showing AIS 3 + head and chest normalised injury risk in ten 40 km hour^{-1} (25 mph) frontal barrier vehicle crash tests. The OIV was approximately 12 m sec^{-1} for all of these tests, but actual injury risk varied widely. Again, drivers are indicated by solid bars and right front seat passengers are indicated with hatched bars. Both front seat ATD occupants are Hybrid III 50th% males with only an airbag restraint. Probability of injury has been normalised to the right front passenger of the 2005 Toyota Corolla, which has a combined head and chest injury probability of 16%. The OIV varies within a range of 1.5 m sec^{-1} whereas ATD occupant risk was as much as 3.6 times higher than 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 has an injury probability 1.5 times the best performer while the right front passenger risk was more than 3 times the best performer.

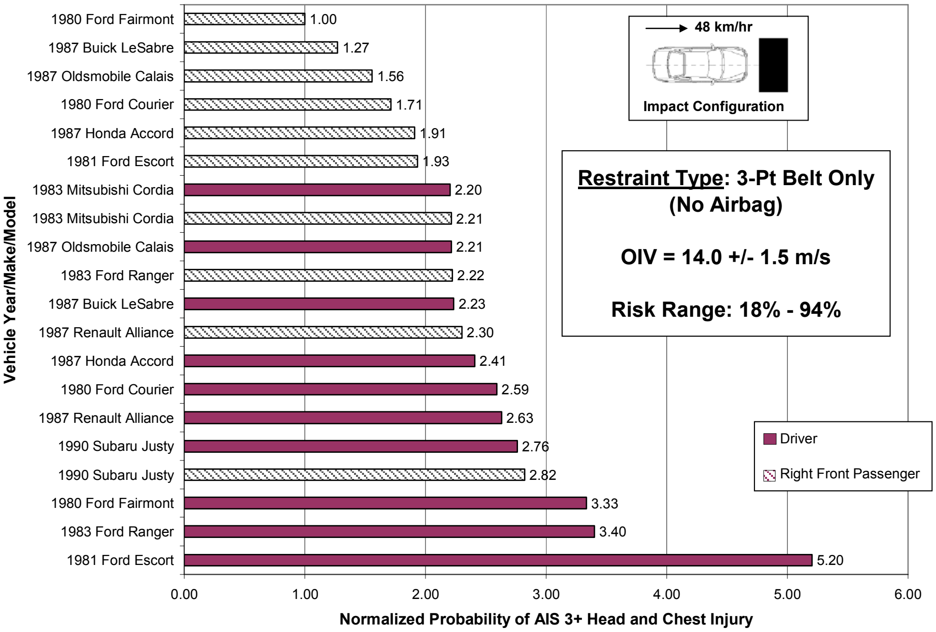
Figure 2 Probability of serious injury to airbag-restrained occupants normalised to best performer (see online version for colours)



5.3 Belt-only restrained occupant risk comparison

Figure 3 is a chart showing AIS 3 + head and chest normalised injury risk for ten 48 km hour^{-1} (30 mph) frontal barrier vehicle crash tests. The OIV was approximately 14 m sec^{-1} for all tests. Both front seat ATD occupants are Hybrid II 50th% males with only a three-point belt restraint. Probability of injury has been normalised to the right front passenger of the 1980 Ford Fairmont, which has a combined head and chest injury probability of 18%. The OIV varies within a range of 3 m sec^{-1} whereas ATD occupant risk varies 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 has more than a three-fold risk compared to the right front passenger.

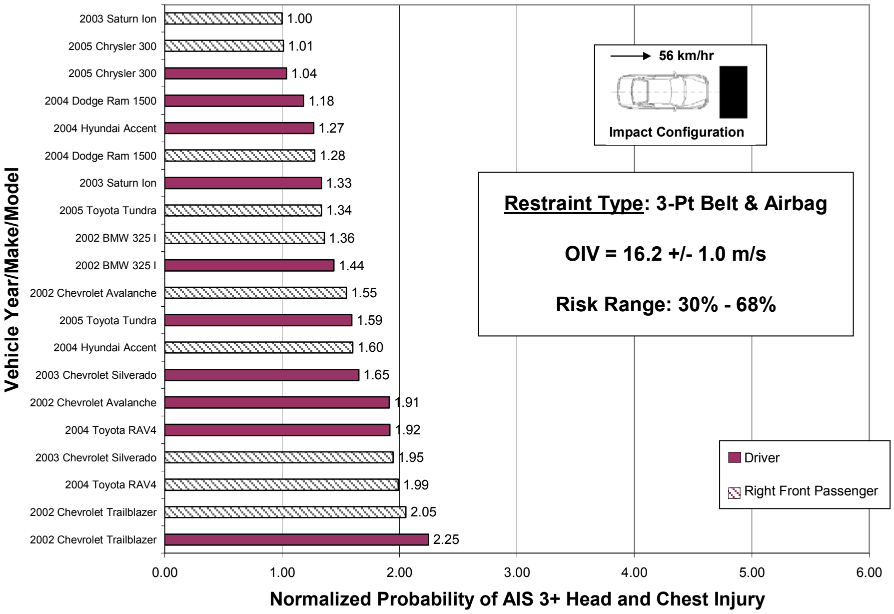
Figure 3 Probability of serious injury to belt-restrained occupants normalised to best performer (see online version for colours)



5.4 *Belt and airbag restrained occupant risk comparison*

Figure 4 is a chart showing AIS 3 + head and chest normalised injury risk for ten 56 km hour^{-1} (35 mph) frontal barrier vehicle crash tests. OIV was approximately 16 m sec^{-1} for each of these tests. Drivers are indicated by solid bars and right front seat passengers are indicated with hatched bars. Both front seat ATD occupants are Hybrid III 50th% males with airbag and three-point belt restraints. Probability of injury has been normalised to the right front passenger of the 2003 Saturn Ion, which has a combined head and chest injury probability of 30%. The OIV varies within a range of 2 m sec^{-1} whereas ATD occupant risk varies as much as two-fold.

Figure 4 Probability of serious injury to belt and airbag restrained occupants normalised to best performer (see online version for colours)



5.5 Linear regression comparison

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 4 provides a summary of the linear regression analysis for each of the restraint scenarios analysed. 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 and HIC and OIV and 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 4 Summary of linear regression analysis

		OIV		*ORA*	
Configuration	*Vehicle injury criteria*	R^2	*p*	R^2	*P*
No occupant restraint (97 km hour^{-1})	HIC	0.315 (+)	0.0711	0.079	0.4038
	3 msec clip	0.280 (+)	0.0904	0.094	0.3598
	Head/chest	0.326 (+)	0.0642	0.088	0.3757
Airbag only (40 km hour^{-1})	HIC	< 0.001	0.9414	< 0.001	0.9384
	3 msec 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 hour^{-1})	HIC	0.011	0.6534	0.006	0.7404
	3 msec clip	< 0.001	0.9708	0.122	0.1319
	Head/chest	0.007	0.7272	0.010	0.6714
Airbag and belt (56 km hour^{-1})	HIC	0.488 (–)	0.0006	0.025	0.5052
	3 msec 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

6 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 1 through Figure 4. 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% points for the 56 km hour^{-1} tests to 76% points for the 48 km hour^{-1} 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 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% 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.

7 Conclusions

This study highlights the importance of considering occupant restraints, from advanced passive restraints such as airbags to simpler active restraints such as seatbelts, in injury criteria used in full-scale crash tests with roadside hardware. Specific conclusions and recommendations include:

1. Current roadside crash injury criteria are out of step with current restraint usage in the US. In a fleet with 80% belt usage and 100% airbag installation, 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 article 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 crash test dummy-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.

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