

# COMPARISON OF OCCUPANT RESTRAINT PERFORMANCE MEASURES FOR CRASH INJURY PREDICTION

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## ABSTRACT

Current procedures for estimating occupant risk in real-world vehicle crashes do not account for the performance of the occupant restraints, such as seatbelts and airbags. This paper compares the ability of two restraint performance metrics, the ridedown efficiency and the restraint quotient, to predict occupant injury as measured by a crash test dummy. The responses of crash test dummies were analyzed in 25 full-frontal barrier crash tests. Ridedown efficiency was found to have an inverse relationship with respect to injury risk while the restraint quotient was found to have a positive relationship. Using linear regression analysis, the restraint quotient was found to offer an advantage over the ridedown efficiency for the prediction of head injury, chest injury, and combined head and chest injury.

**Keywords:** Restraint performance, ridedown efficiency, restraint quotient, injury risk

## INTRODUCTION

Occupant restraints, such as seatbelts and airbags, are used to reduce the potential for injury in automobile crashes. The effectiveness of these devices for reducing occupant injury in real-world crashes has been well established, especially for frontal crashes [1]-[4]. As evident in full-scale vehicle crash tests, however, the effectiveness of these restraint systems can vary considerably between vehicle manufacturers. These variations in restraint performance are not currently accounted for when reporting real-world crash severity. For real world crashes, crash severity is typically measured by delta- $v$ , which is defined as the maximum change in vehicle velocity during a collision event. Based on this metric, occupants exposed to a crash with the same change in vehicle velocity are assumed to have the same injury risk, irrespective of restraint performance. A metric that reflects occupant restraint performance for differing vehicles would be useful in adjusting traditional crash severity metrics for the effects of vehicle-specific occupant restraints as well as providing a better understanding of how restraint performance affects injury risk.

Although there is currently no universally accepted measure of restraint performance, there are several metrics available that provide a single numerical characterization of occupant restraint performance. The ridedown efficiency and the restraint quotient are two such metrics. The ridedown efficiency metric is an energy-based measure of how well the vehicle structure absorbs energy during a crash [5][6] while the restraint quotient is a ratio of occupant velocity change to the total vehicle change in velocity [7]. To date, however, there has been no comparison of the ability of these metrics to reliably characterize occupant restraint performance.

## OBJECTIVE

The purpose of this study is to compare the ridedown efficiency and restraint quotient restraint performance metrics based on their ability to predict occupant injury risk as measured by a crash test dummy.

## METHODS

The general approach for this study was to select suitable full-scale vehicle crash tests, compute the restraint performance metrics, estimate the occupant injury risk based on the response of the crash test dummy, and then compare the ability of the metrics to predict injury risk. Full-scale crash tests were selected from a database maintained by the National Highway Traffic Safety Administration (NHTSA) based on the following criteria: (1) vehicle impacting a rigid barrier with full frontal engagement, (2) a 35 mph impact speed, (3) a 50<sup>th</sup> percentile male Hybrid III seated in the driver position, (4) use of a seatbelt, (5) proper deployment of the airbag restraint, and (6) vehicle model year 1999 or newer. A particular emphasis was placed on the frontal configuration due to the availability of these test types. A vehicle model year cutoff of 1999 was chosen to provide a vehicle set similar to the current fleet. A total of 25 crash tests were randomly selected after applying the above constraints. Approximately forty percent of the vehicles chosen were passenger cars. The remaining sixty percent were light trucks and vans (LTVs) which include pickup trucks, sport utility vehicles and vans. Although vehicle type would not be expected to have a large impact on any correlation between the criteria, an effort was made to choose tests with varied vehicle types.

For each test, the restraint performance metrics were computed using vehicle and crash test dummy accelerations measured in the crash test. All data traces used were checked against redundant sensor traces to ensure data accuracy; corrections for sensor bias were made as necessary. Prior to computing the metrics, the vehicle accelerations and crash test dummy chest accelerations were filtered with a low pass filter of 180 Hz cutoff, according to SAE-J211 [8]. All integrations were computed numerically using the trapezoidal rule. The ridedown efficiency,  $\mu$ , was computed using the following relations [5]:

$$\mu = \frac{e_{rd}}{\frac{1}{2}V_o^2} \quad \text{[Equation 1]} \quad e_{rd} = \int \ddot{x}_o dx_v \quad \text{[Equation 2]}$$

where  $V_o$  is the initial velocity of the vehicle,  $e_{rd}$  is the ridedown energy density (computed over the entire crash pulse),  $\ddot{x}_o$  is the crash test dummy chest acceleration, and  $x_v$  is the displacement of the occupant compartment. The restraint quotient for the crash test dummy chest,  $RQ_c$ , was computed using following relation [7]:

$$RQ_c = \frac{V_c}{(\dot{x}_v)_{\max}} \quad \text{[Equation 3]}$$

where  $V_c$  is the resultant velocity (forward and vertical directions) of the dummy chest with respect to the moving vehicle reference frame. This was computed as a function of time by subtracting the resultant chest velocity from that of the vehicle occupant compartment. The maximum vehicle velocity change during the crash test,  $(\dot{x}_v)_{\max}$ , was computed by integrating the vehicle acceleration with respect to time. From Equation 3, a single measure of restraint performance was computed by selecting the maximum  $RQ_c$  value. Note that  $RQ_c$  can vary from 0 to 1, where a value of 0 represents an occupant rigidly coupled to the vehicle interior and a value of 1 indicates an occupant that attains the full velocity change of the vehicle prior to impacting the vehicle interior.

Injury criteria reported in the NHTSA database include chest 3 ms clip, a measure of the maximum crash test dummy chest acceleration. The 15 ms Head Injury Criterion (HIC), a measure of head acceleration severity, was computed using the Signal Browser software, available from NHTSA. Both of these standard crash test injury metrics were then used to compute occupant injury risk based on NHTSA-developed injury risk curves [9]. A summary of these correlations is shown in Table 1. Note that  $A_c$  indicates the maximum crash test dummy chest acceleration in gravity units. The occupant risk probability is gauged by the Abbreviated Injury Severity (AIS) scale [10], which methodically rates injury on a discrete 0 to 6 scale based on threat to life. Injury levels are summarized in Table 2. For this study, injury risk was computed in terms of the probability of AIS 3 or greater (AIS 3+) occupant injury.

Table 1. Computation of Injury Risk Based on Injury Criteria Values [9]

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)	$p(AIS \geq 3) = \frac{1}{1 + e^{(3.1493-0.0630Ac)}}$

Table 2. Abbreviated Injury Severity (AIS) Scale Summary

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

Linear regression analysis was used to compare the ability of the restraint metrics to predict occupant head injury risk and chest injury risk. In addition, these metrics were evaluated based on their ability to predict the combined probability of AIS 3+ head and chest injury. The combined probability was computed by adding the AIS 3+ head and chest injury probability and then subtracting the product; a procedure similar to how NHTSA determines vehicle star safety ratings. Ideally, if the restraint performance criteria are indeed good predictors of occupant risk, we would expect strong linear correlations to all of these crash test dummy-based injury criteria. Analysis of variance (ANOVA) was used to determine the significance of the linear regression fits via an F-test. For this analysis, statistical significance was assumed for an alpha less than 0.05. All statistical analyses were completed with the SAS<sup>®</sup> version 9.1 software.

## RESULTS

The results of the linear regression fits for head injury risk, chest injury risk, and combined head and chest injury risk are shown in Figure 1, Figure 2, and Figure 3, respectively. Each figure contains two plots; one with ridedown efficiency as the predictor (left) and the other with restraint quotient as the predictor (right). A dashed line represents the least squares regression fit to the available data and the unadjusted  $R^2$  value is

shown on each plot. Statistical parameters for each of the models are summarized in Table 3. As another measure of model fit, the adjusted  $R^2$  value is reported in the rightmost column of Table 3.

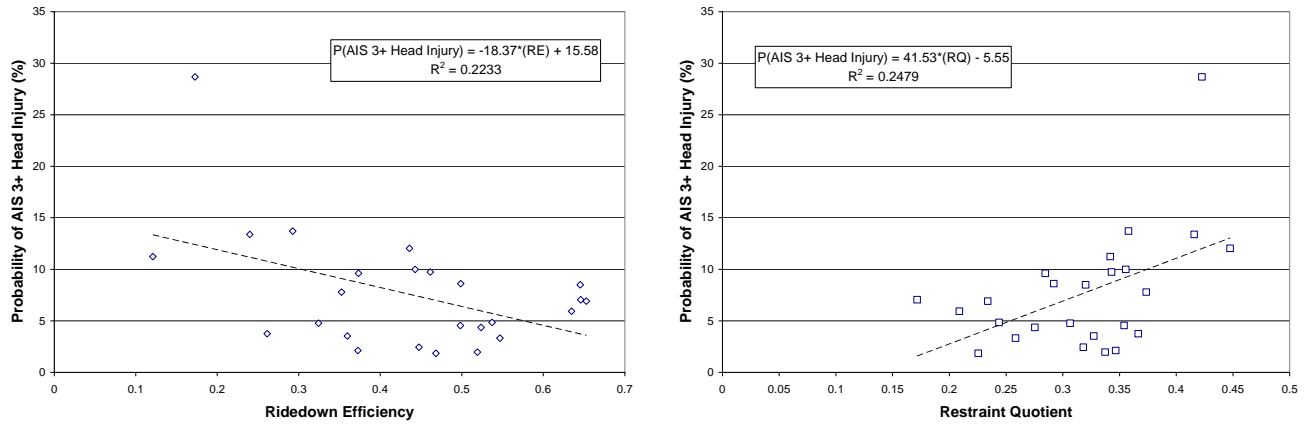


Figure 1. Probability of Serious Head Injury as a Function of Ridedown Efficiency (left) and Restraint Quotient (right)

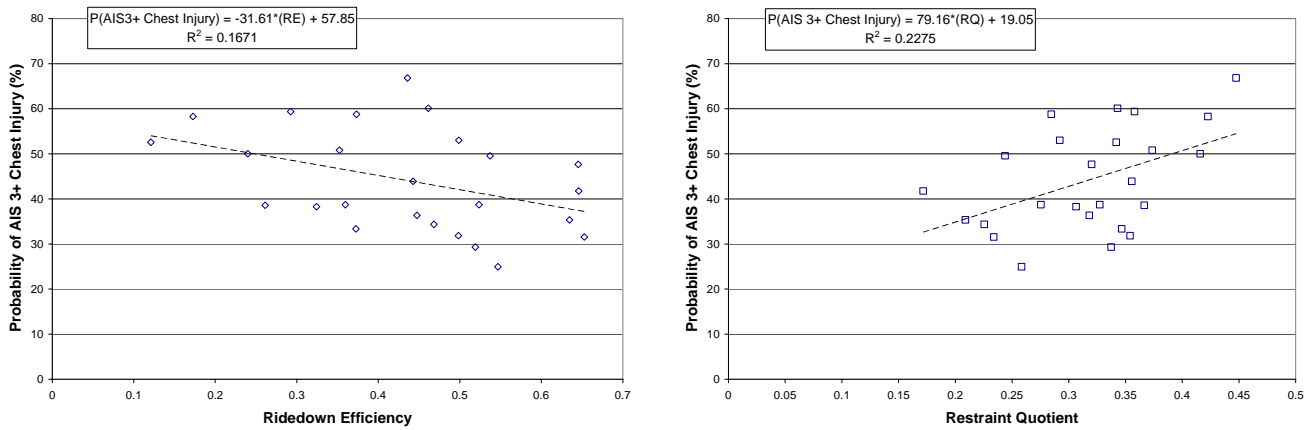


Figure 2. Probability of Serious Chest Injury as a Function of Ridedown Efficiency (left) and Restraint Quotient (right)

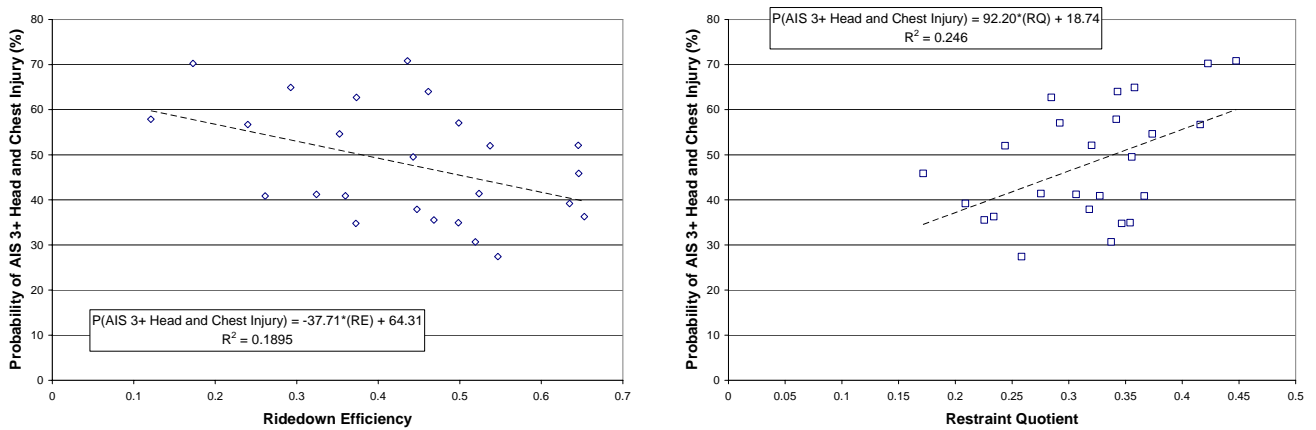


Figure 3. Probability of Serious Head and Chest Injury as a Function of Ridedown Efficiency (left) and Restraint Quotient (right)

Table 3. Summary of Linear Regression Statistical Parameters

Injury	Restraint Metric	F-Value	P	Adjusted R <sup>2</sup>
Head	Restraint Quotient	7.58	0.0113	0.2152
	Ridedown Efficiency	6.61	0.0171	0.1896
Chest	Restraint Quotient	6.78	0.0159	0.1940
	Ridedown Efficiency	4.61	0.0425	0.1309
Combined Head and Chest	Restraint Quotient	7.50	0.0117	0.2132
	Ridedown Efficiency	5.38	0.0296	0.1542

## DISCUSSION

As evident in Figure 1 through Figure 3, there is an inverse relationship between ridedown efficiency and occupant injury, with a general decrease in injury risk with increasing ridedown efficiency. For the restraint quotient, however, there appears to be a positive relationship as injury risk increases with increasing restraint quotient values. Both of these observed trends are logical. Larger ridedown efficiencies imply that the vehicle absorbs more of the crash energy and, thus, less is transferred to the occupant. Higher maximum restraint quotient values indicate that the occupant attains a larger percentage of the vehicle maximum change in velocity and, as such, would be more susceptible to injury.

For each linear regression model, the ANOVA indicated a statistically significant fit with the restraint quotient models having higher confidence (i.e. lower P values). Although the model parameters were similar, the restraint quotient metric had higher R<sup>2</sup> values than the ridedown efficiency predictor in each case. This suggests that the restraint quotient is a better predictor of chest injury risk, head injury risk, as well as combined head and chest injury risk in frontal crash tests. In each case, the restraint quotient was able to explain roughly one-fourth of the occupant injury risk variation, as measured by the crash test dummy.

One limitation of this study is the relatively small data set of 25 full-scale crash tests, all conducted at the same impact speed. Additional crash test data at varying speeds would be useful in more fully comparing these restraint performance metrics. This may also generate a larger range of head injury risk. In the current data set, head injury risk ranges from 2 to 15 percent, with the exception of one case at 28 percent injury risk. Also, this analysis applies only to drivers restrained both by an airbag and seatbelt. The effectiveness of these restraint performance metrics may be different for other occupant restraint scenarios. This would include a driver not wearing a seatbelt (i.e. restrained only by an airbag), a driver wearing a seatbelt in a non-airbag-equipped vehicle, as well as an occupant seated in the right front passenger position.

## CONCLUSIONS

This paper has compared the ability of two restraint performance metrics to predict occupant injury risk as measured by a crash test dummy. Ridedown efficiency was found to have an inverse relationship to injury risk while the restraint quotient was found to have a positive relationship. Using linear regression analysis, the restraint quotient was found to offer an advantage over the ridedown efficiency for the prediction of head injury, chest injury, and combined head and chest injury. Although limited to an analysis of 25 full-scale crash tests, we believe this analysis provides an important first look into how the ridedown efficiency and restraint quotient metrics compare in terms of ability to predict occupant injury risk.

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## REFERENCES

- [1] McGwin G, Metzger J, Alonso JE, Rue LW. 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, 2003, pp 1182-1187.
- [2] Huere JF, Foret-Bruno JY, Faverjon G, Le Coz JY. 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, 2001.
- [3] Evans L. 1986. The Effectiveness of Safety Belts in Preventing Fatalities. *Accident Analysis and Prevention* 18 (3): 229-241.
- [4] 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
- [5] 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.
- [6] Katoh H, Nakahama R. 1982. A Study on the Ride-Down Evaluation. *Proceedings of the 9th Enhanced Safety of Vehicles (ESV) Conference*, Kyoto, Japan.
- [7] Viano DC, Arepally S. 1990. Assessing the Safety Performance of Occupant Restraint Systems. *SAE Transactions*, Vol. 99, No. 6, pp. 1913-1939.
- [8] Society of Automobile Engineers. Surface Vehicle Recommended Practice: Instrumentation for Impact Test – Part 1 – Electronic Instrumentation. SAE-J211, Revised July 2007.
- [9] National Highway Traffic Safety Administration. 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, 1999.
- [10] Association for the Advancement of Automotive Medicine. *The Abbreviated Injury Scale*, 1990 Revision, Update 1998.