Relationship between Seat Rating Test Results and Neck Injury Rates in Rear Crashes

November 2008

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INTRODUCTION

Since 1969 motor vehicles in the United States have been required to have head restraints in front seats to mitigate neck injuries resulting from rear crashes. Simply equipping cars with head restraints reduced the incidence of these injuries by as much as 18 percent (Kahane, 1982; O'Neill et al., 1972; States and Balcerak, 1973). Further injury reductions were realized as head restraint designs evolved to be taller and closer to the backs of occupants' heads in response to seat ratings published by the Insurance Institute for Highway Safety (IIHS) and other members of the Research Council for Automobile Repairs (RCAR) (Chapline et al., 2000; Farmer et al., 1999; Farmer et al., 2003).   Led by Saab and Volvo in the 1990s, vehicle manufacturers began fitting more advanced seat designs specifically to address whiplash in rear crashes. These also were shown to be effective at reducing neck injury risk (Farmer et al., 2003; Jakobsson and Norin, 2004; Viano and Olson, 2001). Despite these improvements whiplash, or minor injury to the neck, is one of the most common consequences of motor vehicle crashes, affecting nearly 1 million people annually in the United States. Many of these injuries still occur in rear crashes (National Highway Traffic Safety Administration, 2004).

Several organizations have initiated vehicle rating programs to encourage wider adoption of seat designs better able to mitigate the risk and severity of neck injuries in rear crashes. The Allgemeiner Deutscher Automobil-Club (ADAC) published ratings of several seat designs based on simulated crash tests in 2001. The Swedish Road Administration (SRA) in cooperation with Folksam Insurance has been publishing ratings based on 3 simulated crash tests with BioRID since 2003 (Kullgren et al., 2007). IIHS and other RCAR members launched a rating program using a single dynamic test later the same year (Edwards et al., 2005). The European New Car Assessment Program (EuroNCAP) announced in 2008 that it too would add whiplash ratings to its well-known star ratings. Like the SRA ratings, the EuroNCAP whiplash ratings will be based on 3 tests.

In addition to the different number of tests on which the ratings are based, these programs use different test results to evaluate seat designs. The RCAR evaluation uses spine acceleration at the T1 vertebra, time from beginning of the test until the restraint contacts the dummy's head, and neck forces measured at the junction of the head and neck (IIHS, 2008). The SRA system uses the neck injury criterion (NIC), a combination of neck forces known as Nkm and head rebound velocity, whereas

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EuroNCAP will use all 7 criteria. Despite these differences, all of the programs aim to encourage manufacturers to fit vehicles with seat designs that provide protection against neck injury in rear crashes.

Studies by Folksam and IIHS indicate that vehicles with seats earning better ratings are providing better protection against whiplash in real crashes than lesser rated seats and earlier designs. Folksam researchers used 15,587 police-reported rear crashes to compare the risk of injury in struck cars versus striking cars by rating category for the seats in the struck cars (Kullgren et al., 2007). Using insurance data from 6,383 crashes to analyze whether initially reported neck injuries resulted in symptoms lasting 1 month or more, researchers found that seats with the best ratings in both the SRA and RCAR systems had lower injury risk (initial complaints and long-term injuries) than the worst rated seats. Relative risk for initial injury complaints was higher than expected for middle rating categories. Long-term injury risk was more orderly, with middle rated seats having risk between that of the best and worst rated seats.

Farmer et al. (in press) studied a sample of 4,178 rear crashes culled from 15,016 insurance claims for rated vehicle models from two large US insurers, State Farm Mutual and Nationwide. Vehicles with good rated seats had a rate of neck injuries per rear crash that was 15 percent lower than that for vehicles with poor rated seats. However, there essentially was no difference between neck injury rates for acceptable and poor rated seats. Good, acceptable, and marginal rated seats all had lower rates of neck injuries requiring treatment for 3 months or more, compared with poor rated seats. The difference in long-term neck injury rates was 35 percent lower for good rated seats compared to those rated poor. Farmer et al. also showed that applying the SRA rating system to the same seat designs (to the extent possible, with only one test) did not predict real injury rates better than the RCAR rating system.

The objective of the present study was to examine whether the variety of measurements from BioRID in simulated rear crashes can be combined so as to align better with observed neck injury rates than the rating system currently used by RCAR members.

METHODS

BioRID response measurements from simulated rear crash tests with 16 km/h velocity change and 10 g peak acceleration were available for 90 seat designs used in 105 different 2005-06 model vehicles. All tests were conducted at the IIHS Vehicle Research Center. Test measurements included in this analysis are shown in Table 1.

Rear crash data are from the same 4,178 insurance claims used in an earlier study of the relationship between RCAR ratings and neck injury rates (Farmer et al., in press). These data included information on the US state in which the crash occurred, damage severity of the struck vehicle, make/model of the striking vehicle, gender of the struck vehicle driver, and information about whether the driver was injured along with associated diagnostic and treatment information. Prices of the struck vehicles were from public sources.

Table 1
BioRID Response Parameters Analyzed

Location of measurement	Measurement
Head restraint to head	Height
	Backset
	Time to head restraint contact
	Time to head support[1]
Head	Maximum forward acceleration (+x)
	Head rebound velocity
Head relative to T1	Neck injury criterion (NIC)[2]
Upper neck	Maximum rearward force (+Fx)
	Minimum rearward force (-Fx)
	Maximum extension torque (+My)
	Maximum flexion torque (-My)
	Maximum tension (+Fz)
	Maximum compression (-Fz)
	Maximum Nkm
	Nkm (EA)
	Nkm (EP)
	Nkm (FA)
	Nkm (FP)
Lower neck (C7-T1 junction)	Maximum rearward force (+Fx)
	Minimum rearward force (-Fx)
	Maximum extension torque (+My)
	Maximum flexion torque (-My)
	Maximum tension (+Fz)
	Maximum compression (-Fz)
	Lower neck load criterion (LNL)[3]
	Forward acceleration of T1 vertebra (+x)

[1] Head support time is defined as the time that forward head acceleration and forward T1 acceleration first have equal values
[2] Boström et al., 1996
[3] Heitplatz et al., 2003

Correlations between the neck injury rates for 55 of the 90 seat designs and BioRID response parameters were calculated to identify the BioRID responses with the most promise for further analyses. This subset was defined as those for which at least 30 rear collision claims could be attributed to the specific seat design. When a single design was used in multiple vehicle models (e.g. Ford Fusion and Mercury Milan), the crash claims for all models with the same seat were combined.

Several alternate rating schemes were evaluated for their ability to predict neck injury rates better than the current RCAR system. These ranged from a simple modification of the current system to new systems based on statistical models of relationships between sled test response variables and odds of neck injury in the insurance claims database. The statistical modeling process necessarily identifies the best possible relationship among the variables, so all of the models fit the data better than the current RCAR rating system. Consequently, the alternate rating schemes cannot be judged only on whether they correlate with the injury rates better than the current system. They also must be evaluated on their robustness and on whether the indicated relationships among the variables can be supported by underlying biomechanics theory.

The first alternate rating scheme was based on the observation that time to restraint contact with the dummy's head had a low correlation with the injury rates associated with a seat design. Therefore, this criteria was dropped for the first alternate scheme. Logistic regression was used to model the odds of driver neck injury as a function of insurer, state group, vehicle type, vehicle damage severity, vehicle price, driver gender, and alternate seat ratings. The earlier analyses showed that these other nonsled test variables had a significant effect on neck injury rates, so they were included in all similar statistical analyses in the present study.

A second alternate rating scheme was based on the best linear combination of the 4 RCAR variables — time to restraint contact with the head, maximum forward acceleration of the T1 vertebra, and tension and shearing forces at the upper neck — as determined by a logistic regression model of the odds of a neck injury as a function of the 6 nonsled test variables and the 4 RCAR rating variables. A sled test index was defined as the linear combination of the RCAR rating variables multiplied by the associated coefficients from this model. New rating categories based on cutoff values for the sled test index also were compared with real neck injury rates.

A third alternate rating scheme, based on the best linear combination of the most promising BioRID response parameters, also was examined. Stepwise logistic regression was used to model the odds of driver neck injury as a function of the 6 nonsled test variables and 11 sled test variables. These 11 variables were those with the highest correlations to the seat design injury rates (> 0.1) and not highly correlated with one another. Variables were removed from the statistical model 1 at a time until the remaining variables were significant at the 0.15 level, leaving an index that was a function of 7 BioRID response parameters. Again, new rating categories based on cutoff values for the 7-variable index also were compared with real neck injury rates.

To define rating categories in the second and third alternate schemes, sled test index cutoff values were related to estimates of injury risk expressed as a function of the index alone. The log odds of neck injury were approximated as a function of sled test index using the coefficients from the regression model. Each nonsled test coefficient from the logistic regression model was multiplied by the mean of the corresponding variable. The sum of these products and the intercept coefficient plus the index, a function of sled variables, is approximately equal to the log odds of injury. Thus, values of the index associated with chosen risk levels could be computed.

RESULTS

Correlations between the 26 BioRID test parameters and seat design injury rates are shown in Table 2. Ten of the 26 BioRID test variables had very low correlations to seat design injury rates, and all but time to restraint contact with the head were dropped from further analyses.

Table 2
Pearson Correlation with Neck Injury Rate
(based on seat designs with at least 30 crash claims)

Variable	Coefficient	Variable	Coefficient
Upper neck compression	0.307	Lower neck load (LNL)	0.122
Nkm (EP)	-0.252	Upper neck tension	0.119
Head rebound velocity	-0.228	Lower neck forward force	0.111
Lower neck rearward force	0.226	Lower neck extension torque	-0.075
Lower neck flexion torque	-0.220	Head restraint height	0.069
T1 forward acceleration	0.200	Nkm maximum	0.046
Upper neck rearward force	0.172	Upper neck extension torque	0.045
Nkm (FA)	0.171	Lower neck tension	0.019
Head restraint backset	0.167	Time to head restraint contact	0.015
Head support time	0.156	Neck injury criterion (NIC)	0.015
Head forward acceleration	0.148	Nkm (FP)	-0.011
Upper neck flexion torque	0.144	Nkm (EA)	0.008
Upper neck forward force	0.126	Lower neck compression	-0.001

The first alternate rating scheme consisted of simply dropping the time to contact between head and restraint. Table 3 shows the rear crash claim data categorized by the first alternate rating scheme. Results of logistic regression modeling of the odds of driver neck injury as a function of the 6 nonsled test variables and these revised seat ratings are shown in Table 4. Good rated seats under this scheme had a 23 percent lower risk of initial neck injury than those rated poor. Although not statistically different from poor, the estimated risk for seats rated acceptable and marginal also was lower than for seats rated poor.

Table 3
Driver Neck Injury Rates by First Alternate Rating Scheme

Seat rating	Claims	Number with neck injury	Number with long-term neck injury	Percent with neck injury	Percent with long-term neck injury
Good	300	49	15	16.3	5.0
Acceptable	2,113	389	74	18.4	3.5
Marginal	3,981	719	163	18.1	4.1
Poor	3,790	744	219	19.6	5.8

Table 4
Relative Risk of Driver Neck Injury by First Alternate Rating Scheme

Comparison	Risk ratio	95% confidence interval	
		Lower limit	Upper limit
Insurer 1 vs. Insurer 2	0.94	0.77	1.13
Michigan vs. tort states	0.78	0.61	0.98
Car vs. SUV	1.15	0.98	1.32
Severe vs. minor or moderate damage	1.85	1.63	2.08
Vehicle price $30,000+ vs. lower	0.71	0.53	0.92
Female vs. male	1.45	1.25	1.66
Good vs. poor rating	0.77	0.60	0.97
Acceptable vs. poor rating	0.92	0.77	1.08
Marginal vs. poor rating	0.87	0.72	1.04

Results of the logistic regression modeling of the odds of a neck injury as a function of the 6 nonsled test variables and 4 RCAR evaluation variables are shown in Table 5. An index related to the risk of injury was defined as:

$$\text{INDEX} = (0.0503 \times \text{T1 X-accel}) + (0.0037 \times \text{Time to HR Contact}) +$$
$$(0.0074 \times \text{Fx}/100) + (0.0451 \times \text{Fz}/1000).$$

The log odds of injury risk can be approximated as:

Log odds = -2.487 + INDEX,

where the constant is the sum of the intercept and the nonsled test coefficients from Table 5 multiplied by the mean values of the nonsled test variables.

Table 5
Logistic Regression on Driver Neck Injury Rates

Variable	Coefficient	p-value
Intercept	-2.9450	0.0000
Insurer 1 (0 or 1)	-0.0997	0.4785
Michigan (0 or 1)	-0.3427	0.0344
Car (0 or 1)	0.1225	0.2673
Severe damage (0 or 1)	0.9552	0.0000
High price (0 or 1)	-0.4625	0.0135
Female driver (0 or 1)	0.5292	0.0000
T1 acceleration	0.0503	0.1822
Time to restraint contact	0.0037	0.3216
Upper neck Fx / 100	0.0074	0.9114
Upper neck Fz / 1000	0.0451	0.8875

The second alternate scheme uses the same index to define rating categories in terms of estimated injury risk values. Table 6 shows the injury claims for 4 categories using 17, 18, and 19 percent risk as the cutoffs for good, acceptable, and marginal, respectively. These risk levels were chosen so the good and acceptable categories would have lower risk than the average for the entire dataset. Results of logistic regression modeling of the odds of driver neck injury as a function of the 6 nonsled test variables, and these second alternate ratings are shown in Table 7.

Table 6
Driver Neck Injury Rates by Second Alternate Rating Scheme

Seat rating	Claims	Number with neck injury	Number with long-term neck injury	Percent with neck injury	Percent with long-term neck injury
Good	3,129	545	127	17.4	4.1
Acceptable	3,089	537	128	17.4	4.2
Marginal	1,336	244	70	18.3	5.2
Poor	2,629	575	147	21.9	5.6

Table 7
Relative Risk of Driver Neck Injury by Second Alternate Rating Scheme

Comparison	Risk ratio	95% confidence interval	
		Lower limit	Upper limit
Insurer 1 vs. Insurer 2	0.93	0.76	1.12
Michigan vs. tort states	0.78	0.60	0.98
Car vs. SUV	1.08	0.92	1.26
Severe vs. minor or moderate damage	1.85	1.63	2.07
Vehicle price $30,000+ vs. lower	0.71	0.53	0.92
Female vs. male	1.44	1.24	1.66
Good vs. poor rating	0.83	0.68	0.99
Acceptable vs. poor rating	0.88	0.70	1.07
Marginal vs. poor rating	0.93	0.70	1.19

The third alternate rating scheme was based on an examination of the other BioRID responses recorded in the IIHS tests. Variables with correlations less than 0.1 in Table 2 were excluded, as were those variables that were highly correlated with other ones. Upper neck tension and lower neck load (LNL) had a correlation of 0.94. Upper neck tension was excluded because it had the lower correlation with the injury rate. LNL and lower neck rearward force had a correlation of 0.88, so LNL was excluded. Upper neck rearward force and lower neck flexion torque had a correlation of -0.87, so upper neck rearward force was excluded. Upper neck flexion torque and Nkm (EP) had a correlation of -0.83, so upper neck flexion torque was excluded. Lower neck flexion torque and lower neck rearward force had a correlation of -0.81, so lower neck flexion torque was excluded. That left 11 variables: backset, T1 forward x-acceleration, upper neck forward force, upper neck compression, lower neck rearward force, lower neck forward force, Nkm (EP), Nkm (FA), forward head x-acceleration, head rebound velocity, and head support time. Absolute correlations between these variables all were less than 0.80. The results of the stepwise logistic regression eliminated 4 of these variables, leaving those shown in Table 8.

Table 8
Logistic Regression on Driver Neck Injury Rates

Variable	Coefficient	p-value
Intercept	-1.9280	0.0000
Insurer 1 (0 or 1)	-0.1029	0.4667
Michigan (0 or 1)	-0.3379	0.0387
Car (0 or 1)	0.0442	0.7130
Severe damage (0 or 1)	0.9460	0.0000
High price (0 or 1)	-0.3327	0.0968
Female driver (0 or 1)	0.5048	0.0000
Head restraint backset	0.0059	0.1039
T1 forward acceleration	0.1026	0.0041
Upper neck compression	0.0043	0.0204
Lower neck rearward force	0.0015	0.0488
Nkm (EP)	-1.8960	0.0757
Nkm (FA)	-1.0748	0.0364
Head forward acceleration	-0.0576	0.0719

A third alternate rating scheme was devised using the same method as the second but substituting 7 sled test variables and coefficients in Table 8 for the 4 RCAR variables and coefficients from Table 5. Again, injury risk levels of 17, 18, and 19 percent risk were used as the cutoffs for good, acceptable, and marginal, respectively. The dataset sorted by this scheme is shown in Table 9, and results of logistic regression modeling of the odds of driver neck injury as a function of the nonsled test variables and these third alternate ratings are shown in Table 10.

Table 9
Driver Neck Injury Rates by Third Alternate Rating Scheme

Seat rating	Claims	Number with neck injury	Number with long-term neck injury	Percent with neck injury	Percent with long-term neck injury
Good	4,728	697	179	14.7	3.8
Acceptable	974	193	36	19.8	3.7
Marginal	1,447	284	65	19.6	4.5
Poor	3,033	727	191	24.0	6.3

Table 10
Relative Risk of Driver Neck Injury by Third Alternate Rating Scheme

Comparison	Risk ratio	95% confidence interval	
		Lower limit	Upper limit
Insurer 1 vs. Insurer 2	0.93	0.76	1.12
Michigan vs. tort states	0.78	0.61	0.99
Car vs. SUV	1.07	0.91	1.24
Severe vs. minor or moderate damage	1.84	1.61	2.07
Vehicle price $30,000+ vs. lower	0.77	0.58	1.00
Female vs. male	1.43	1.23	1.64
Good vs. poor rating	0.71	0.59	0.85
Acceptable vs. poor rating	0.88	0.67	1.13
Marginal vs. poor rating	0.86	0.70	1.05

DISCUSSION

None of the 26 sled test variables was highly correlated with the neck injury rates for the 55 seat designs with the greatest rear crash exposure (at least 30 rear crashes). In fact, some variables that have long been associated with whiplash injury risk in biomechanics literature had the weakest relationships: neck extension torque, neck tension, NIC, and Nkm (max). Two components of Nkm, extension-posterior (EP) and flexion-anterior (FA), were more highly correlated. The correlation for Nkm (EP) was negative, suggesting that higher values of this variable were associated with lower injury risk. Similarly, forward shear forces and compression forces measured both at the upper and lower neck had correlations indicating that higher forces were less injurious. The ranges for these forces were well below levels that would be considered injurious: 2-63 N in the x-direction and 1-95 N compression. Although a positive correlation for the forward x-forces could be an indication that forward pushing by the head restraint is protective, the weak correlation does not strongly support this.

The weak correlations could result from the strong influence of the nonsled test variables in this dataset. As the first 6 rows of Tables 5 and 8 indicate, state group, crash damage, vehicle price, and driver gender had strong influences on neck injury risk.

The time to restraint contact with the head, an important criterion in the RCAR rating, also was not correlated with neck injury rates, which suggests that modifying RCAR ratings might provide a better correlation with neck injury risk than reported in our earlier analysis. When time to restraint contact with the head was left out of the rating system, the resulting ratings had a better fit to the dataset than the current RCAR ratings. After adjusting for the effects of the nonsled test variables, seats rated good, accepted, and marginal had lower odds of neck injury than seats rated poor. Only the difference between good and poor ratings was significant.

It is not clear why leaving the time to restraint contact variable out of the rating system improves the fit of the ratings to the dataset. This variable is related to the principle by which head restraints are intended to work. That is, by supporting the mass of the head as the body is accelerated forward during a rear crash, a restraint relieves the neck of stress associated with moving the head forward. A head that is

supported from the beginning of a crash is a best case scenario. Therefore, the earlier a restraint that is not initially in contact with the head moves to support the head, the better it can do its intended job. During development of the RCAR rating system, this variable was shown to be a distinguishing test measurement among proven active head restraint designs and their nonactive predecessors. Consequently, although this simple modification of the RCAR rating system fits the dataset somewhat better, it lacks the theoretical underpinnings of the original.

The second alternate ratings scheme was based on modeling neck injury risk as a function of the nonsled test and evaluation variables alone. As expected, ratings based on this model showed an improved fit to the data, and each of the RCAR evaluation variables related in the predicted way to injury risk. However, none of the coefficients for the RCAR variables was statistically significant, which suggests the second alternate scheme would be unlikely to stand the test of another dataset.

The third alternate rating scheme considered all sled test measurements with significant, independent relationships to injury risk, whether or not they are used in a current rating scheme. The resulting scheme was based on 7 sled test variables: backset, T1 forward x-acceleration, upper neck compression, lower neck rearward shear force, Nkm (EP and FA), and head forward x-acceleration. As expected from the statistical procedure used to derive this scheme, the ratings fit the injury data better. However, the coefficients for 4 of these variables indicated that higher values of the measured response are associated with lower neck injury risk. This is counter to the theory of injury biomechanics, which associates higher forces and stresses with higher injury risk. Thus, the findings for these 4 variables likely only reflect random associations in this dataset. The other 3 variables — backset, T1 x-acceleration, and lower neck rearward shear force — contribute to the model in ways that are consistent with biomechanics theory. T1 x-acceleration already is part of the RCAR rating system, and lower neck rearward shear force is highly correlated with upper neck rearward shear force, which also is part of the current RCAR rating system. Thus, despite its better fit to the injury data, the third alternate scheme is not an improvement over the current RCAR system because the contributions of 4 of the variables do not make sense, and 2 of the other variables already are considered.

IIHS and Folksam analyses have shown that the current RCAR rating system promotes seat designs associated with lower whiplash injury risk in rear crashes. Good rated designs have significantly lower rates of initial and long-term injuries than those rated poor. The lack of correlation between initial injury rates and the middle seat ratings of acceptable and marginal is a curiosity, but because the good rating was set up to promote the types of designs already shown to represent improvement, the lack of correlation among these ratings is not a major impediment to this goal.

The present study examined 3 alternate rating schemes to explore the possibility of improving the correlation between seat ratings and injury rates. A different combination of the RCAR rating variables

and a combination of other sled test variables were examined. Although these schemes correlated with injury rates somewhat better than the current RCAR scheme, all 3 schemes lack the theoretical underpinnings of the RCAR system. Previous work indicates that using NIC, Nkm, and head rebound velocity as employed by SRA and Folksam does not provide a better correlation with neck injury rates in this dataset than the RCAR system. Based on these results, the RCAR working group charged with monitoring the effectiveness of its rating system agreed to maintain the current system without modifications.

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