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Research Note

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Roof Strength Testing and Real-World Roof Intrusion in Rollovers

Summary

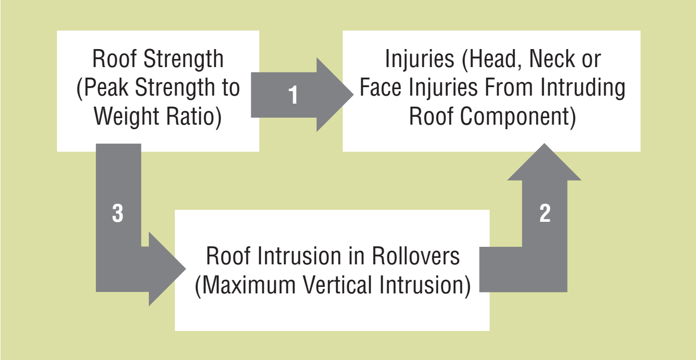
This Research Note demonstrates a statistically significant relationship between the peak strength-to-weight ratio (SWR) obtained through laboratory roof strength testing and the maximum vertical roof intrusion in real-world rollovers from the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS). The results from both categorical analysis of vehicles with similar SWR measures and linear regression support the hypothesis that passenger vehicles with a higher SWR measured in a roof crush test are likely to experience less vertical roof intrusion in rollover crashes than vehicles with a lower SWR. Support for the hypothesis also remains when controlling for other possible factors that may explain roof intrusion and in a sensitivity analysis focused on the variance in the sampling weights. This finding complements NHTSA's previous work that demonstrated a relationship between vertical roof intrusion and injury risk in rollovers and supports the validity of SWR as a measure of roof strength.

Background

The question of whether greater roof strength as measured by the SWR is correlated to less real-world roof intrusion is part of the larger question of whether greater roof strength is correlated with lower injury severity in rollovers. The hypothesized relationship between roof strength and injury severity can be described as either a direct or an indirect relationship. Figure 1 demonstrates these hypothesized relationships between roof strength and injury.

One hypothesis, indicated by Arrow 1 in Figure 1, is that roof strength is directly correlated with injuries. Studies that have attempted to correlate roof strength and overall injury severity have reached differing conclusions regarding whether such a relationship exists

Figure 1
Hypothesized Relationships Between Roof Strength and Injuries



(for example, IIHS, 2008; Padmanaban, Moffatt, and Marth, 2005). Part of the difficulty in statistically establishing this direct relationship may be that roof strength is only one of several factors that determine the degree of roof intrusion in rollovers and that intrusion may be only one of several factors that determine whether intrusion is related to injury severity. Rollovers are complex events with complicated injury mechanisms. Establishing the direct connection may be problematical because of the additional factors for which it may be difficult to control in a single statistical model, and the direct relationship may be obfuscated by these numerous confounding variables.

NHTSA took a different approach by examining the relationship between the maximum vertical intrusion of a roof component (over a particular seating position) and the severity of injuries to the head, neck, or face from the intrusion (Austin, Hicks, and Summers, 2005; Strashny, 2007). These studies provided support for the hypothesis indicated by Arrow 2 in Figure 1 by demonstrating a statistically significant relationship between greater roof intrusion and more severe injuries. However, these studies only provide partial support for the hypothesis that stronger roof structures reduce injury severity because they do not establish a relationship between roof strength and roof intrusion in rollovers.

The hypothesis that stronger roofs are related to less roof intrusion in real-world rollovers, indicated by Arrow 3 of Figure 1, is the focus of this analysis. The measure of roof strength used in this analysis is the peak SWR obtained from NHTSA laboratory testing conducted from 2001 through 2008. The measure of roof intrusion is the maximum vertical intrusion of a roof component over either front outboard seat in real-world rollovers obtained through NHTSA's NASS-CDS from 1997 through 2008. This Research Note describes these two measures, the methods used to match the two sources of information, and the statistical results that provide support for the hypothesis that greater roof strength as measured by the SWR is correlated to less vertical roof intrusion in real-world rollovers.

Real-World Roof Intrusion in Rollovers

The study uses NASS-CDS data for years 1997 through 2008. NASS-CDS is a nationally representative sample of crashes where at least one passenger vehicle was towed due to damage. There are 24 field research teams that study about 5,000 crashes a year involving passenger vehicles. Trained crash researchers obtain data and photographs from crash sites collecting scene evidence such as skid marks, fluid spills, broken glass, and bent guardrails. They locate the vehicles involved, photograph them, measure the crash damage, and identify interior locations that were struck by the occupants. Unlike NHTSA's other crash systems that rely predominantly on Police Accident Reports, NASS-CDS has precise intrusion measures that are needed for this analysis. The choice to begin the study with 1997 reflects both the availability of the exact intrusion measures in NASS-CDS and the fact that the earliest model year tested was 1997.

Study vehicles were nonconvertible passenger cars, light trucks (pickups and SUVs), and vans that overturned or rolled two or more quarter turns along the longitudinal axis. All vehicles were towed due to damage. This search produced a total sample of 7,535 rollover vehicles. However, for some sampled vehicles the intrusion measures are not available, which reduced the sample to 6,372 rollover vehicles.

The next step involved assigning these vehicles to analytical groups based upon the Vehicle Identification Number (VIN) for matching to the laboratory test results. NHTSA staff developed a series of programs to identify a vehicle's make, model, model year, general body type, and air bag availability based upon the VIN. This analysis uses the latest version of these programs, which decode VINs of passenger vehicles from model years 1985 through 2006. The programs assign a four-digit code that identifies a fundamental vehicle group. These vehicle groups contain all of a manufacturer's vehicles of the same type and wheelbase and run for several model years until the vehicles are redesigned. For example, Chevrolet Cavalier and Pontiac Sunfire for model years 1995 through 2005 comprise a single vehicle group. These vehicle groups are important for identifying when a vehicle parameter for one model year may be applied to other model years of the same make-model (carryovers) as well as across similar vehicles with different names (corporate twins). These programs were able to assign a vehicle group to 6,058 vehicles. (The remaining vehicles were either outside of the relevant model years or had unknown VINs.)

To compute the real-world intrusion, all vertical intrusions of roof components (roof, roof rails, and other components attached to the roof) assigned to the front left and right (outboard) seats were selected. The maximum vertical intrusion over either front outboard seat was retained as a vehicle level measure of the maximum real-world roof intrusion. Note also that the measure of intrusion does not require that the passenger seat be occupied.

For 1,242 vehicles, there were no intrusions of a roof component over either seat, and the maximum vertical intrusion was set to zero. For another 4,369 vehicles, the maximum vertical intrusion of a roof component over either seat, ranging from 3 to 130 cm, was retained. For the remaining 447 vehicles, the maximum vertical roof intrusion was a range rather than an exact measure. In these instances the measure of roof intrusion was imputed by replacing the range with the estimated average intrusion of known values within the same range.

The estimated average intrusion for these 6,058 cases was 12 cm. However, many of these cases could not be used in the final analysis because they were either a vehicle that was not among the laboratory tested vehicles or because it was of a model year that was fundamentally different from that of the tested model. The next section describes the roof strength laboratory tests and how they were matched to the NASS-CDS cases.

Roof Strength

The measure of roof strength was obtained from NHTSA's Office of Vehicle Safety Research roof crush test data. Roof crush testing of one side of the vehicle (one-sided testing) was performed from April 2001 through March 2008 on 75 passenger vehicles. The model years of the tested vehicles ranged from 1997 through 2008. The test procedure that was used to measure roof strength involved securing a vehicle on a rigid horizontal surface, placing a flat steel rectangular plate on the vehicle's roof, and using the plate to apply force to the roof. Strength was measured as the peak or maximum force required to reach 127 mm (5 inches) of platen displacement. In a one-sided test the SWR is thus defined as the peak force divided by the unloaded vehicle weight. (Note that the roof crush test data is available in NHTSA's Component Test Database under test type "FMVSS 216 Roof Crush Resistance." The database may be queried at http://www-nrd.nhtsa.dot.gov/database/aspx/comdb/querytesttable.aspx.)

The first step in merging the roof strength data to the crash data was to use the VIN programs described above to assign a fundamental vehicle group to each of the 75 tested vehicles. There were 56 tests that were assigned a vehicle group. The remaining 19 tests were not assigned a group due to the vehicles being model years 2007 or 2008. In cases where there was more than one test result within the vehicle group (such as tests of the GMC Sierra and the Chevrolet Silverado), the average SWR was calculated for the group. In the end there were 50 vehicle groups with one or more peak SWR measure. These 50 measures represent the 56 tested vehicles assigned a vehicle group because three vehicle groups contained two tested vehicles, and one vehicle group contained four tested vehicles.

The 50 measures of vehicle roof strength were then merged with the 6,058 NASS-CDS rollover vehicles using the fundamental vehicle group. In the end, 38 of the vehicle groups were matched to 931 rollovers in NASS-CDS. The number of NASS-CDS cases per vehicle group ranged from 1 (for the Ford 500 and the Volvo XC90) to 112 (for the 1995-2005 Chevrolet Cavalier/Pontiac Sunfire). The estimated average intrusion for these 931 vehicles was 11 cm. (While not directly used in the analysis, rollovers that did not match to a tested vehicle were assigned their own domain and were retained for the computation of survey standard errors.)

Statistical Analysis of Relationship

As described above, the research hypothesis for this note is that vehicles with a higher SWR in the roof crush test are likely to experience less vertical roof intrusion in rollover crashes than vehicles with a lower SWR. This hypothesis is tested using two methods. The first method compares the average maximum vertical roof intrusion across groups of vehicles with similar SWRs. The second method uses linear regression to establish the correlation between SWR and the maximum vertical roof intrusion.

Table 1 divides the SWR measures into four categories and compares the estimated mean (average) maximum vertical intrusion for each category. In addition to the estimated mean, Table 1 also provides the 95-percent confidence interval for the estimate as well as the coefficient of variation (estimated standard error divided by mean) to capture sampling variability. One practical concern can be seen from the distribution of the number of cases by categories of SWR; the bulk of the cases involve an SWR of 2.0 to 2.9. The relatively small number of cases with an SWR of 3.0 or greater did not enable the creation of finer categories between 3.0 and 5.2.

Table 1
Mean Maximum Vertical Roof Intrusion by SWR Categories

Strength to Weight Ratio (SWR)	Mean Maximum Vertical Intrusion (cm)	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound	Coefficient of Variation for Estimated Mean	Number of Cases
1.7 – 1.9	24.8	14.4	35.3	0.20	50
2.0 – 2.4	11.7	6.2	17.1	0.22	308
2.5 – 2.9	11.7	9.1	14.4	0.11	505
3.0 – 5.2	2.4	0.1	4.7	0.44	68
All tested	**10.8**	**8.2**	**13.4**	**0.11**	**931**

Sources: NASS-CDS 1997-2008, NHTSA Vehicle Safety Research roof crush test data

Table 2

Mean Maximum Vertical Roof Intrusion by SWR Categories for Vehicles With One Roof-to-Ground Exposure

Strength to Weight Ratio (SWR)	Mean Maximum Vertical Intrusion (cm)	95% Confidence Interval lower Bound	95% Confidence Interval Upper Bound	Coefficient of Variation for Estimated Mean	Number of Cases
1.7 – 1.9	24.5	12.2	36.9	0.24	35
2.0 – 2.4	10.9	4.9	16.8	0.26	215
2.5 – 2.9	11.4	8.2	14.6	0.13	364
3.0 – 5.2	1.7	0.1	3.2	0.43	48
All tested	**10.2**	**7.1**	**13.2**	**0.14**	**662**

Sources: NASS-CDS 1997-2008, NHTSA Vehicle Safety Research roof crush test data

Overall, Table 1 provides evidence in support of the hypothesis. Vehicles with a SWR less than 2.0 experienced the greatest average vertical roof intrusion, and vehicles with a SWR of 3.0 or greater experienced the least average vertical roof intrusion. However, the average intrusion in the categories of 2.0 to 2.4 and 2.5 to 2.9 appear similar.

Table 1 considers only SWR and intrusion. The exclusion of crash factors in the statistical model could be an issue if there are particular factors that are correlated with both SWR and intrusion. For example, if vehicles with a higher SWR tend to be in less severe crashes, then the relationship between SWR and intrusion could be spurious. While there is no universally accepted measure of rollover severity, the number of roof-to-ground exposures has frequently been used as a proxy (Strashny, 2007). Following Eigen (2005), the number of roof-to-ground exposures in a lateral rollover is defined as the number of times that the vehicle roof faced downward, toward the ground, regardless of the number of times that the roof physically contacted the ground. The number of roof-to-ground exposures is computed as 0.25 times the number of quarter turns, rounded to the nearest unit. Thus, 2, 3, 4, and 5 quarter turns correspond to 1 roof-to-ground exposure; 6, 7, 8, and 9 quarter turns correspond to 2 roof-to-ground exposures, etc.

Rather than attempt directly to control for the number of roof-to-ground exposures, the data used for Table 1 was reanalyzed by excluding the more severe crashes with more than one roof-to-ground exposure. Table 2 provides the results for the remaining 662 rollovers that only involved one roof-to-ground exposure.

Overall, the results in Table 2 appear similar to the results in Table 1. The estimated mean maximum roof intrusion decreased, which is expected given the positive relationship between intrusion and the number of roof-to-ground contacts. The large difference between average maximum roof intrusion for the vehicles with an SWR less than 2.0 and those with an SWR of 3.0 or greater remains and continues to lend support to the hypothesized relationship. The categories of 2.0 to 2.4 and 2.5 to 2.9 are again similar.

The second statistical method involved estimating the effect of SWR on the maximum vertical roof intrusion using linear regression. The analysis used statistical procedures that account for the complex survey design from which the NASS-CDS cases are selected. The estimated linear equation describing the relationship between roof intrusion and roof strength is as follows:

*Vertical Roof Intrusion (cm) = 25.2 – 5.6 * SWR*
(t=-4.00, Pr>|t|=0.0012, F=16.01, Pr>F=0.0012,
R^2=0.04, N=931)

The results indicate that a one-unit increase in the SWR predicts a 5.6 cm decrease in roof intrusion. This effect is statistically significant at less than the 0.01 level. The R^2 appears low, but it is not expected to be high. There are many crash specific factors that are not accounted for in this model, and the model is not designed to explain all of the variation. The model applies the same laboratory measure to each vehicle in the vehicle group even though it is likely that the crash characteristics vary from vehicle to vehicle.

In an attempt to control for some of these crash characteristics, a second linear regression was performed by including the SWR as well as three control variables. The control variables included in the linear regression model as independent variables were the number of roof-to-ground contacts, an indicator variable for whether the vehicle was in a single-vehicle crash,

Table 3
Linear Regression of Roof Intrusion on SWR and Other Crash Factors

Variable	Coefficient	Standard Error	t-test	*Pr*>|t|
Intercept	20.01	5.32	3.76	0.002
Strength to Weight Ratio	-5.94	1.48	-4.01	0.001
Roof to Ground Exposures	6.46	1.36	4.74	0.000
Fixed Object Collision to Roof (1 = yes, 0 = no)	9.79	3.98	2.46	0.027
Single Vehicle Crash (1 = yes, 0 = no)	-1.83	1.58	-1.16	0.262

N=859, R^2 = 0.11, F = 101.13, *Pr*>F = 0.0001
Sources: NASS-CDS 1997-2008, NHTSA Vehicle Safety Research roof crush test data

Table 4
Sensitivity Analysis for Linear Regression of SWR and Roof-to-Ground Exposure on Maximum Vertical Roof Intrusion

SWR Coefficient	Sample Weight Trimming	Number of Trimmed Cases	Design Effect
-5.9	None	0	2.85
-8.1	Max of 10,000	3	1.17
-8.7	Max of 5,000	5	1.00
-9.2	Max of 1,000	53	1.04

Sources: NASS-CDS 1997-2008, NHTSA Vehicle Safety Research roof crush test data

and an indicator variable for whether the rollover was interrupted by a fixed object collision to the top of the vehicle. (Events where the fixed object was the ground, a culvert, an embankment, or a bush were not considered.) The total number of cases in the analysis was 859 since the number of roof-to-ground exposures was unknown for 72 rollover vehicles. Table 3 summarizes the results of the linear regression analysis.

The results indicate that SWR, roof-to-ground exposures, and fixed object collisions to the roof have a statistically significant effect on vertical roof intrusion at the conventional level of 0.05. The coefficient for SWR (-5.9) was similar to the coefficient in the previous estimated linear model (-5.6) even when controlling for other rollover characteristics and suggests that the observed relationship between higher SWR and lower intrusion is not spurious.

Testing for the Statistical Robustness of the Observed Relationship

One concern when using the NASS-CDS sample design for statistical analysis is the high degree of variation in the sample weights. This concern is magnified when performing an analysis of subpopulations, such as rollover vehicles, because one or more cases with a very large sample weight may have a significant amount of influence on the results. Examining the distribution of the sample weights for the 931 cases in the analysis indicated that the sample weights ranged from 1.3 to 40,634. While the median weight was 78.5, the mean weight was 355 due to the presence of a few cases with very large sample weights.

Based upon statistical theory, the best estimate is derived from the full sample and the weights provided on the file. Furthermore, the survey standard errors account for the variance in the weights and the effect of the sample design. That said, it is still sometimes helpful to empirically explore the effect of the sample weights on the estimates as a sensitivity analysis. One method of exploring these potential effects is by conducting a sensitivity analysis where the largest weights are reduced to a maximum (trimmed) value and then the analysis is rerun with the trimmed weights. Table 4 indicates how the results change when the weights are trimmed to successively smaller values for the regression of SWR and roof-to-ground exposure on roof intrusion.

All coefficients in Table 4 are statistically significant from zero at less than the 0.01 level using complex survey standard errors. Table 4 also reports the design effect, which is the ratio of the estimated variance for the coefficient under the sample design compared to the estimated variance computed under the assumption of simple random sampling. The design effect for the estimated SWR coefficient in the original model (no trimming) indicates that the sample design inflates the standard error of the estimate almost by a factor of 3 compared to simple random sampling. This finding reflects the influence of the high variance in sample weights on the precision of the estimates and suggests the need to perform the sensitivity analysis. However, the more important point is that the statistically significant negative relationship between SWR and maximum vertical roof intrusion remains in each of the analyses using different values for trimming. Therefore, the results of this sensitivity analysis continue to support the hypothesis.

Conclusions

The various statistical analyses in this Research Note support the hypothesis that passenger vehicles with a higher SWR in the roof crush test are likely to experience less vertical roof intrusion in rollover crashes than vehicles with a lower SWR. This finding in combination with NHTSA's previous research demonstrating a relationship between roof intrusion and head, neck, or face injuries confirms a relationship between greater roof strength and fewer injuries. This finding also supports the validity of SWR as a measure of roof strength because it was found to be a statistically significant predictor of vertical roof intrusion in real-world rollovers.

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