ROOF STRENGTH AND INJURY RISK IN ROLLOVER CRASHES OF PASSENGER CARS AND SUVS

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ABSTRACT

A 2009 study by the Insurance Institute for Highway Safety found that midsize SUVs with stronger roofs, as measured in quasi-static tests, had lower risk of ejection and lower risk of injury for nonejected drivers. The objective of the present study was to determine whether a similar association exists for other vehicle groups.

Twelve small passenger cars were evaluated according to Federal Motor Vehicle Safety Standard 216 test conditions extended to 10 inches of plate displacement. Crash databases in 14 states provided more than 20,000 single-vehicle rollover crashes involving these vehicles. Logistic regression analyses were used to evaluate the effect of roof strength on the rate of driver injury while assessing and controlling for the effects of driver age, vehicle stability, state, and other factors where necessary.

Small cars with stronger roofs had lower overall rates of serious injury, lower rates of ejection, and lower rates of injury for nonejected drivers. Although the effect on ejection was somewhat smaller for cars than for SUVs, the overall pattern of injury results was consistent. For roof strength-to-weight ratio measured at 5 inches (SWR_5), a one-unit increase (e.g., from 2.0 to 3.0) was associated with a 22% reduction in risk of incapacitating or fatal driver injury in single-vehicle rollovers. This compares with a 24% reduction estimated for a similar change in roof strength among midsize SUVs.

The association between vehicle roof strength and occupant injury risk in rollover crashes appears robust across different vehicle groups and across roof SWR_5 values, varying from just more than 1.5 to just less than 4.0. If roofs were to increase in strength by one SWR_5, a 20-25% percent reduction in risk of serious injury in rollovers would be expected. Still, even if all vehicle roofs were as strong as the strongest roof measured, many rollover injuries still would occur, indicating the need for additional research and countermeasures.

INTRODUCTION

In 1971 the National Highway Traffic Safety Administration (NHTSA) promulgated Federal Motor Vehicle Safety Standard (FMVSS) 216 to "reduce deaths and injuries due to the crushing of the roof into the passenger compartment in rollover accidents" [1]. Even as the standard was coming into effect, some researchers were questioning the relationship between roof strength and injury risk [2,3]. However, very few rollover crashworthiness analyses have combined roof strength measures with real-world crash data. Instead, most studies either have been based on observations of anthropometric test devices (ATDs) in rollover tests that may be overly severe and for which ATDs are not well suited [4-6], or have compared roof crush with injury outcome in field data without controlling for vehicle structure differences [2,7-9]. The question of roof strength's influence on injury causation cannot be resolved by these studies.

Prior to 2009 only two studies had compared the measured roof strengths of certain vehicles with the injury experience in real-world rollover crashes involving those vehicles [10,11]. Neither study found a relationship between roof strength and injury risk. However, a 2009 study reached the opposite conclusion, finding that stronger roofs reduce the risk of injury in rollover crashes [12]. The authors suggested that earlier research may have failed to detect this relationship due to a combination of factors including the use of roof strength tests of nonproduction vehicles, uncontrolled differences between vehicle types and state reporting practices, and the inclusion of variables such as police-reported belt use and alcohol involvement whose coding is biased with respect to injury outcome.

FMVSS 216 evaluates roof strength using a quasi-static test in which a metal plate is pushed into the roof at a fixed angle. The reaction force against the plate is divided by the weight of the vehicle to produce a strength-to-weight ratio (SWR). For the midsize SUVs studied, Brumbelow et al. [12] found that a one-unit increase in peak SWR measured within 5 inches of plate displacement (SWR_5) was associated with a 24% reduction in risk of fatal or incapacitating injury, a 32% reduction in fatality risk, and a 41% reduction in ejection risk. Restricting to nonejected occupants showed a 16% reduction in risk of fatal or incapacitating injury for the same roof strength increase. The authors concluded that stronger roofs are beneficial by reducing both ejection risk and injury risk for occupants remaining in the vehicle.

Brumbelow et al. [12] restricted their study to 12 midsize SUV roof designs. This restriction more tightly controlled for differences in driver demographics, vehicle use patterns, and crash kinematics than did previous research. However, evaluating only one vehicle type made it impossible to estimate the magnitude of the benefit of increased roof strength for other portions of the vehicle fleet, especially passenger cars. There was no reason to expect that stronger roofs would not benefit occupants of other vehicle types, but the specific effects could not be inferred from the SUV analysis.

The purpose of the present study was to investigate the relationship between roof strength and injury risk for passenger cars and to compare this relationship with that previously found for SUVs.

METHODS

The methods employed by Brumbelow et al. [12] were applied to this study. Logistic regression was used to estimate the effect of roof strength on driver injury risk in rollover crashes while controlling for potential confounding variables. The effect of roof strength on ejection risk also was estimated. Roof strength data were obtained for 12 small four-door passenger cars in quasi-static tests with 10 inches of plate displacement. Crash data consisted of police-reported single-vehicle rollovers in 14 states.

Vehicle Selection and Roof Strength Testing

Small four-door passenger cars were chosen because this segment had a greater number of unique roof designs with substantial rollover counts than midsize or large cars. The 12 designs selected for testing were those with the largest sample of rollover crashes in the state databases used for the study. None of these vehicles were sold with side curtain airbags or electronic stability control (ESC) as standard equipment. One model was sold with ESC as optional equipment for three of the eight model years studied, but the installation rate during these three years was less than 2% [13]. These model years were not excluded because any potential effect on the results for this vehicle would be minimal. Another model was sold with side curtain airbags as optional equipment for two of the eight model years, and the installation rate during these years was unknown. Because most of the state databases do not record the presence of curtain airbags, and their deployment may affect injury and ejection risk, these two model years were excluded from analysis.

Roof strength tests were conducted using the quasi-static procedure outlined in FMVSS 216, with the exception that tests were extended beyond the 1.5 SWR compliance level to 10 inches of plate displacement to obtain peak roof strength values. Although the standard requires compliance within 5 inches of displacement, extending the tests to 10 inches allowed roof performance beyond the regulated level to be compared with field experience. In addition to the SWR metric, other evaluated metrics were peak roof strength, energy absorption, and equivalent drop height (EDH). EDH is energy absorption normalized by curb weight. Because some of the 12 roof designs were shared by trim levels with differing curb weights, calculations of SWR and EDH using these weights resulted in more than 12 unique values. Roof strength values for the study vehicles are listed in Appendix A.

Rollover Crash Data

Data on rollover crashes were obtained from the State Data System of police-reported crashes. NHTSA maintains this database of police crash records from certain states. States with data available for some part of the calendar years 1997-2006 were included, provided there were event and/or impact codes allowing identification of single-vehicle rollovers, and coded vehicle identification numbers (VINs). Without sufficient VIN information it is not possible to be certain of a vehicle's make, model, and model year. Because these qualifications were identical to the previous study of midsize SUVs, the same 14 states were used: Florida, Georgia, Illinois, Kansas, Kentucky, Maryland, Missouri, New Mexico, North Carolina, Ohio, Pennsylvania, Utah, Wisconsin, and Wyoming.

Logistic Regression

Logistic regression was used to assess the effect of roof strength on the likelihood of fatal or incapacitating injury, fatal injury, and ejection for drivers in single-vehicle rollover crashes. Injury risk for non-ejected drivers also was evaluated. Separate models were fit for each of these outcomes using each of the four roof strength metrics as measured at three plate displacements: 2, 5, and 10 inches. The final models controlled for state, driver age, and static stability factor (SSF).

Controlling for state is necessary because of state-to-state variation in injury rates possibly resulting from differences in reporting methods, terrain, urbanization, and other factors.

Vehicle stability may be indirectly related to rollover injury risk because the average rollover crash severity could be greater for more stable vehicles. This study attempted to control for variations in stability among the study vehicles by using SSF. SSF is calculated by dividing half the average track width by the center of gravity height, so it does not account for stability differences due to wheelbase or suspension and tire properties. However, it is the most widely used stability metric and is the basis for NHTSA's rollover resistance ratings. Data for all but three of the study vehicles were publicly available. The remaining vehicles were measured at SEA, Ltd., using the same vehicle inertial measurement facility utilized by NHTSA. SSF values are included in Appendix A.

Preliminary models included other factors when coded in the state data files. These were vehicle age, vehicle weight, driver gender, and rural versus urban crash environment. Coded belt use was not included as a covariate in an overall model because police reporting of belt use in crashes has been found to be biased by injury outcome [14]. However, several studies have found that belt use affects injury likelihood in rollovers [15-17]. Because the effect of belt use has the potential to confound the effect observed for roof strength, separate models were fit for drivers coded by police as belted and as unbelted.

Rollovers resulting in fatal or incapacitating injuries were fairly rare events, and ejection was an even less common outcome. Consequently, the odds ratios resulting from these models are reasonable approximations of relative risks and are interpreted accordingly.

A sensitivity analysis was conducted to determine whether roof strength test variability could be confounding the results of the logistic regression models. A random number generator was used to select roof strength values that varied up to 10% from the actual value measured for each vehicle, and these new values were used in the regression analyses. This was repeated with 10 sets of roof strength data, and the different outcomes were compared with the final model outcome.

Rollover Propensity

The main results estimate the risk of injury given a rollover crash occurrence, so they do not account for any changes in rollover likelihood that may be caused by increasing roof strength. Two additional analyses evaluated whether there was a relationship between roof strength and rollover propensity. First, the proportion of all police-reported crashes that were single-vehicle rollover was calculated for each unique SWR_5 value. Logistic regression was used to estimate the effect of a one-unit increase in SWR_5 on this proportion. Crash data came from the same state data files included in the main analyses.

The second analysis was intended to evaluate the combined effect of roof strength on rollover propensity and crashworthiness. Data were extracted from the Fatality Analysis Reporting System (FARS) for years 2003-07 to determine the proportion of driver deaths that resulted from single-vehicle rollover crashes. Again, the effect of a one-unit SWR_5 increase was estimated using logistic regression.

Estimated Lives Saved

In addition to the estimates of effects on driver injury and fatality risks, study results are presented in terms of the estimated number of lives that could have been saved with stronger roofs. Two target roof strength levels were investigated: 2.5 SWR_5 and 3.9 SWR_5. The lower SWR target was chosen because it is the level of strength included in NHTSA's 2005 notice of proposed rulemaking to upgrade FMVSS 216 [18]. The higher SWR target represents the strongest roof among the study vehicles. For each vehicle, the increase in roof strength required to achieve the target SWR, if any, was used to scale the estimated effect of roof strength on injury risk from the logistic regression model. Because there were too few fatalities in the state databases to make precise effect estimates of roof strength on fatality risk alone, results of the logistic regression model that included incapacitating injuries were used for this exercise. To obtain the estimated number of lives saved, the scaled effectiveness estimates were applied to the total number of drivers and right-front passengers who were killed in single-vehicle rollover crashes in the United States during 2007 for each of the study vehicles. These data were obtained from FARS.

RESULTS

Study vehicles were involved in 1,232,990 police-reported crashes in the 14 states studied. Of these, 20,459 were single-vehicle rollovers, resulting in 328 driver fatalities and 2,113 drivers with incapacitating injuries. Figure 1 shows the relationship between peak SWR_5 and the rate of fatal or incapacitating driver injury, before adjusting for potential confounding factors. The circle sizes represent the number of rollover crashes of each vehicle. The slope of the weighted linear regression line in Figure 1 represents a 17% reduction in the rate of fatal or incapacitating injury for a one-unit SWR_5 increase from the average roof strength of these vehicles. Logistic regression analyses were used to investigate whether this relationship was due to roof strength differences or to confounding factors.

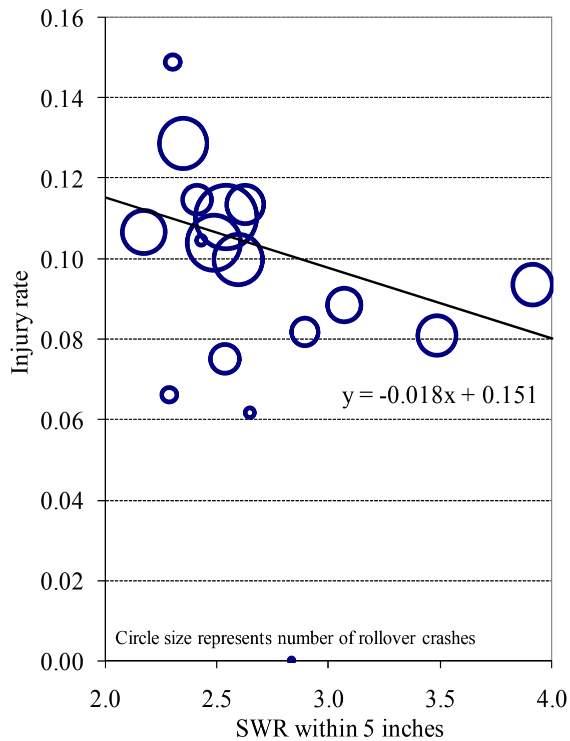

Figure 1. Rates of fatal or incapacitating driver injury by peak SWR_5

Vehicle age, vehicle weight, and driver gender did not have significant effects on the risk of injury or ejection. Furthermore, their inclusion did not substantially change the estimated effect of roof strength. These variables were excluded from the final models.

Urban versus rural crash environment was coded in 72% of the crashes in the dataset. Analyses limited to these cases did not find a statistically significant relationship between crash environment and injury risk. In addition, inclusion of crash environment did not substantially change the effect of roof strength on injury outcome. Crash environment was excluded from the final models.

The final injury risk logistic regression models controlled for the state where each crash occurred, vehicle SSF, and driver age. Each combination of the four roof strength metrics and three displacement distances required a separate model, and all 12 of these models estimated reductions in the risk of fatal or incapacitating driver injury for increases in roof strength. These risk reductions were all statistically significant at the 0.05 level. A one-unit increase in SWR_5 was estimated to reduce the risk of fatal or incapacitating injury by 22% (95% confidence interval: 13-30). Table 1 lists the odds ratios for all the roof strength metrics, as well as those for the estimated effects of vehicle SSF and driver age.

Table 1
Results of logistic regression models for risk of fatal or incapacitating driver injury

		Roof strength	**SSF**	**Driver age**
Strength metric and plate displacement		**Odds ratio for 1-unit increase**	**Odds ratio for 0.1-unit increase**	**Odds ratio for 10-year increase**
Peak force (tons)	2 in	0.83*	1.18*	1.16*
	5 in	0.83*	1.17*	1.15*
	10 in	0.86*	1.08	1.15*
SWR	2 in	0.77*	1.21*	1.16*
	5 in	0.78*	1.20*	1.16*
	10 in	0.83*	1.10	1.15*
Energy absorbed (kJ)	2 in	0.58*	1.17*	1.15*
	5 in	0.77*	1.16*	1.16*
	10 in	0.87*	1.03	1.16*
EDH (in)	2 in	0.82*	1.18*	1.15*
	5 in	0.92*	1.18*	1.16*
	10 in	0.96*	1.05	1.16*

*Statistically significant at 0.05 level

In most cases, increases in SSF were associated with statistically significant injury risk increases. In every case, increases in injury risk with increasing driver age were statistically significant. The model using SWR_5 data predicted injury risk increases of 20% for a 0.1-unit increase in SSF and 16% for a 10-year increase in driver age. There were differences in injury risk between states, with Florida having the highest overall rate of fatal or incapacitating injury at 20% and North Carolina having the lowest at 5%. Table 2 lists the odds ratios for fatal or incapacitating driver injury from the final model of all states relative to Florida.

Table 2
Odds ratio estimates by state, relative to Florida, for model estimating effect of SWR_5 on risk of fatal or incapacitating driver injury

State	Odds ratio
Georgia	0.25*
Illinois	0.72*
Kansas	0.39*
Kentucky	0.54*
Maryland	0.66*
Missouri	0.64*
New Mexico	0.87
North Carolina	0.20*
Ohio	0.20*
Pennsylvania	0.20*
Utah	0.97
Wisconsin	0.41*
Wyoming	0.74*

*Statistically significant at 0.05 level

There was no evidence that differences in belt use among the vehicles confounded the effect observed for roof strength because all injury risk models limited by coded belt use status estimated reduced injury risk for stronger roofs (Table 3). For the 16,426 drivers coded as belted, the estimated risk reductions were less than those for all drivers, and all but two were significant at the 0.05 level. For the 2,589 drivers coded as unbelted, most of the risk reductions were greater than those for all drivers, and two were significant at the 0.05 level.

Table 3
Results of logistic regression models for risk of fatal or incapacitating driver injury by coded belt use and ejection status

Strength metric and plate displacement		Odds ratios for 1 unit increases in roof strength, by police-reported belt use or ejection status		
		Belted	Unbelted	Nonejected
Peak force (tons)	2 in	0.86*	0.75	0.84*
	5 in	0.87*	0.76*	0.85*
	10 in	0.90*	0.89	0.89*
SWR	2 in	0.83*	0.68	0.81*
	5 in	0.85*	0.71	0.83*
	10 in	0.89	0.88	0.88*
Energy absorbed (kJ)	2 in	0.62	0.38	0.54*
	5 in	0.83*	0.65*	0.79*
	10 in	0.90*	0.88	0.89*
EDH (in)	2 in	0.86*	0.74	0.83*
	5 in	0.95*	0.89	0.94*
	10 in	0.97*	0.97	0.97*

*Statistically significant at 0.05 level

There were 15,506 cases with known ejection status. Of these, 158 drivers were coded as being partially ejected and 714 as fully ejected. Figure 2 shows the relationship between peak SWR_5 and the unadjusted rates of partial or full ejection. Logistic regression models limited to cases with known ejection status estimated reductions in ejection risk for increasing roof strength while controlling for crash state, vehicle SSF, and driver age. Results are listed in Table 4. Seven of the twelve ejection risk reductions were statistically significant at the 0.05 level, including the 24% reduction in ejection risk associated with a one-unit SWR_5 increase (95% confidence interval: 11-36). Increased vehicle SSF was estimated to increase ejection risk given a rollover, and increased driver age was estimated to reduce ejection risk. The increases associated with SSF were all statistically significant at the 0.05 level, but none of the driver age risk reductions were. The reduction in ejection risk with increasing age is opposite the finding for injury risk. This suggests that older drivers have higher belt use rates, thus lower ejection risk, but that reduced

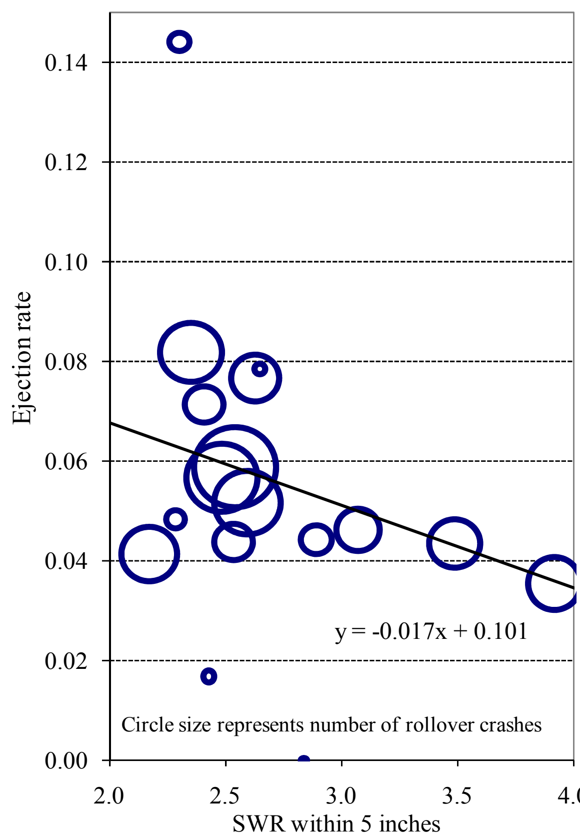

Figure 2. Rates of partial or complete driver ejection by peak SWR_5

Table 4
Results of logistic regression models for risk of driver ejection

Strength metric and plate displacement		Roof strength: Odds ratio for 1-unit increase	SSF: Odds ratio for 0.1-unit increase	Driver age: Odds ratio for 10-year increase
Peak force (tons)	2 in	0.87*	1.32*	0.95
	5 in	0.84*	1.30*	0.95
	10 in	0.97	1.32*	0.95
SWR	2 in	0.77*	1.34*	0.95
	5 in	0.76*	1.32*	0.95
	10 in	0.91	1.29*	0.95
Energy absorbed (kJ)	2 in	0.72	1.32*	0.95
	5 in	0.78*	1.28*	0.95
	10 in	0.94	1.25*	0.95
EDH (in)	2 in	0.84	1.31*	0.95
	5 in	0.91*	1.29*	0.96
	10 in	0.97*	1.23*	0.95

*Statistically significant at 0.05 level

Table 5
Results of logistic regression models for risk of driver fatality

Strength metric and plate displacement		Roof strength: Odds ratio for 1-unit increase	SSF: Odds ratio for 0.1-unit increase	Driver age: Odds ratio for 10-year increase
Peak force (tons)	2 in	0.88	1.18*	1.16*
	5 in	0.84	1.17*	1.15*
	10 in	0.87	1.08	1.15*
SWR	2 in	0.83	1.21*	1.16*
	5 in	0.79	1.20*	1.16*
	10 in	0.83	1.10	1.15*
Energy absorbed (kJ)	2 in	0.74	1.17*	1.15*
	5 in	0.75	1.16*	1.16*
	10 in	0.85*	1.03	1.16*
EDH (in)	2 in	0.90	1.18*	1.15*
	5 in	0.92	1.18*	1.16*
	10 in	0.96*	1.05	1.16*

*Statistically significant at 0.05 level

injury tolerance offsets this in all single-vehicle rollovers as their overall injury risk is still higher.

Logistic regression models restricted to the 14,634 drivers coded as nonejected estimated statistically significant reductions in injury risk for stronger roofs (Table 3). This indicates that the reduction in ejection risk does not fully explain the overall injury risk reduction associated with stronger roofs.

The main results of this study are based on the risk of fatal or incapacitating driver injury. However, separate models estimated the effects of roof strength on fatality risk to determine whether police judgment of injuries as incapacitating or nonincapacitating confounded the results. Table 5 lists the results of these models, all of which estimated reductions in fatality risk for stronger roofs. There was no indication that the inclusion of incapacitating injuries confounded the main results; the magnitudes of most of the fatality risk reductions were similar to the main results that included incapacitating injury. However, fewer were statistically significant at the 0.05 level due to the smaller number of fatal injuries.

The study findings did not appear sensitive to roof strength test variability. Ten additional models used roof SWR_5 values randomly altered by up to 10% of the measured values. These models produced injury risk odds ratios ranging from 0.75 to 0.81, compared with 0.78 for the model using actual roof strengths. The effect of SWR_5 on injury risk was statistically significant at the 0.05 level for all ten models.

The two analyses of rollover propensity indicated that vehicles with stronger roofs were not more likely to be involved in rollover crashes. Single-vehicle rollovers as a proportion of all police reported crashes were estimated to decline by 11% for a one-unit increase in SWR_5 (95% confidence interval: 9-14). Using FARS data, the same roof strength increase was estimated to reduce the number of driver fatalities in single-vehicle rollovers relative to other crash types by 16%, although this was not significant at the 0.05 level (95% confidence interval: 2% increase to 31% decrease).

According to FARS data, 228 drivers and right-front passengers died in single-vehicle rollover crashes of the study vehicles in 2007. A minimum roof strength requirement of 2.5 SWR_5 would have had minimal impact because most of the study vehicles exceeded this level of strength; an estimated 3 deaths could have been prevented (95% confidence interval: 2-5). If all vehicles had roofs with SWRs of 3.9, equal to the strongest roof tested for this study, 75 deaths could have been prevented (95% confidence interval: 46-100).

DISCUSSION

Brumbelow et al. [12] found that stronger roofs benefit drivers of SUVs involved in single-vehicle rollover crashes. The authors hypothesized that drivers of other vehicle types also benefit but that the magnitude of the effects of roof strength could vary. The present study confirms that roof strength is effective in reducing injury risk and ejection risk for passenger car drivers in single-vehicle rollovers. There was some variation between the estimated risk reductions produced by the logistic regression models in the two studies. However, other factors may explain some of this variation, as discussed below. Overall, results indicate that roof strength has similar benefits for drivers in single-vehicle rollover crashes involving vehicles in these two segments. The biggest difference was a larger reduction in ejection risk for SUV drivers with a given increase in roof strength.

Figure 3 shows that most of the overall injury odds ratios were similar for SUVs and passenger cars. The largest differences were for the SWR, energy absorption, and EDH metrics measured at 2 inches, and for the SWR metric at 10 inches. In all of these cases, the injury risk reductions associated with each strength increase were greater for SUV drivers than for car drivers. (Effect estimate magnitudes in Figure 3 should not be compared across metrics because the amounts of increased roof strength described by each are not equivalent.) For all metrics, the passenger car results followed the expected trend with plate displacement distance: a given increase in roof strength had a greater effect at lower displacement distances, when it was proportionally larger. The SUV results based on peak strength and SWR at 10 inches of plate displacement did not follow this trend.

Vehicle geometry is one reason the correlation between roof strength metrics at different plate displacement distances could vary by vehicle type. Because small cars have shorter roof pillars, other structural components become involved and contribute added strength more quickly as the quasi-static test progresses. Almost all of the passenger car roofs required a substantially higher peak force to crush the roof from 5 to 10 inches of plate displacement than from 0 to 5 inches, but this was true only for a few of the SUVs. Conversely, when drop-offs in the load sustained by the roof did occur, these drop-offs tended to be greater for cars. This could be explained by the larger contact patch between the test plate and the SUVs late in the test, given their longer roofs. Thus, SUVs had more available load paths, such as D-pillars, to compensate when a single component reached a failure point. It is difficult to know if these

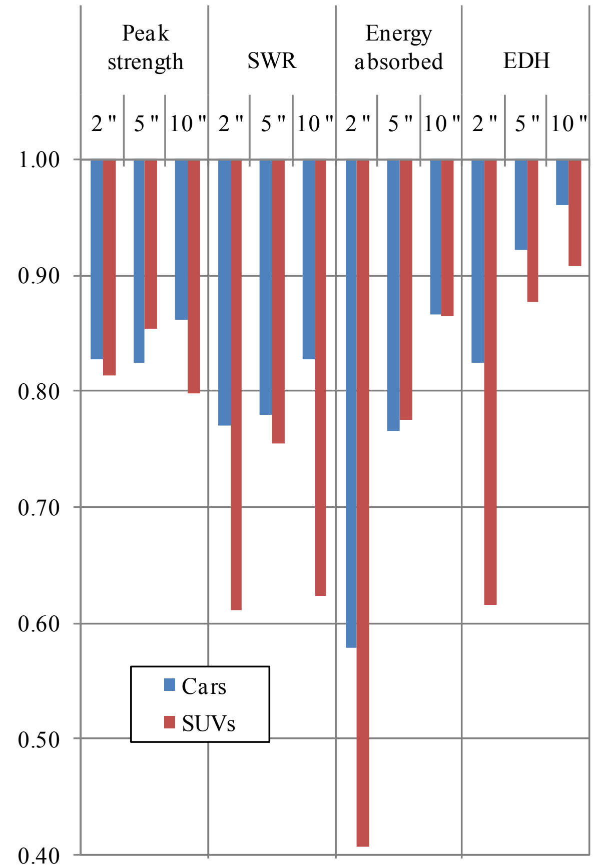

Figure 3. Odds ratios for risk of fatal or incapacitating driver injury with increasing roof strength, as measured with four strength metrics at three plate displacement distances.

geometrical differences are meaningful because the impact conditions in real-world rollovers depend on many other factors.

Ejection

Differences in ejection risk between cars and SUVs also may have contributed to the variation in injury odds ratios. For the study vehicles, the overall ejection rate was 14% lower for cars than for SUVs. This may have been due in part to the fact that, on average, cars had stronger roofs in terms of SWR. However, for a more diverse group of vehicle models, Bedewi et al. [7] also found higher rates of complete ejection for unbelted occupants in SUVs compared with passenger cars during 1997-2000. Again, geometric differences may be a factor. For example, side windows are the most frequent ejection path in rollovers [19], and midsize SUVs have larger side windows than small passenger cars. If geometric differences result in differing ejection risks for SUV and car drivers, it is plausible the effect of strong roofs on ejection risk would vary.

Because of these potential differences in ejection risk, a comparison of injury risk ratios for nonejected drivers was undertaken (Figure 4). For peak strength and energy absorption metrics, which do not account for vehicle weight, risk reductions were larger for passenger cars than for SUVs given the same strength increase. However, when strength was expressed relative to curb weight with the SWR and EDH metrics, most of the risk reductions had very similar magnitudes. Relative to curb weight, roof strength appeared equally important in reducing injury risk to nonejected drivers of SUVs and passenger cars in rollover crashes.

Effect of Stability

The previous study involving midsize SUVs found mixed results for the effect of SSF on rollover injury risk [12]. The authors hypothesized that stability differences among the vehicles studied were too small to produce meaningful results, because nearly three-quarters of the crashes occurred among vehicles with SSF values between 1.06 and 1.09. The distribution of rollover crashes involving the current set of vehicles was more evenly distributed among the full range of SSF values, spanning from 1.33 to 1.46. Results of the logistic regression models showed that more stable vehicles had higher injury risk during rollovers. This is consistent with the hypothesis that higher travel speeds or more severe tripping forces are required to initiate rollover in these vehicles than in less stable ones.

Strength Metrics

The earlier study of SUVs found that none of the four strength metrics clearly stood out as a better predictor of injury risk than others at every plate displacement distance. As shown in Figure 5, this also was the case for the passenger cars studied. The odds ratios plotted on the graph were scaled to represent the injury risk change associated with a roof strength increase equal in magnitude to the difference between the strongest

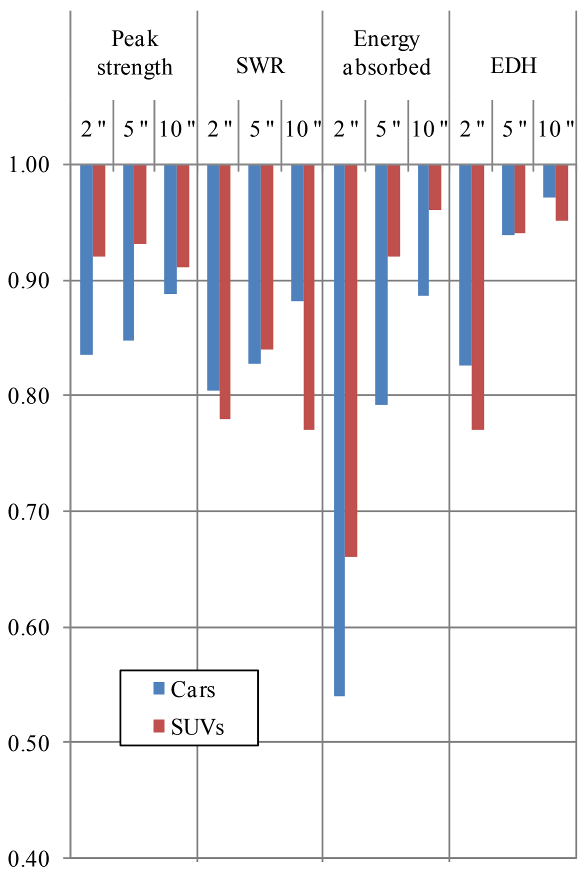

Figure 4. Odds ratios for risk of fatal or incapacitating injury for nonejected drivers with increasing roof strength, as measured with four strength metrics at three plate displacement distances.

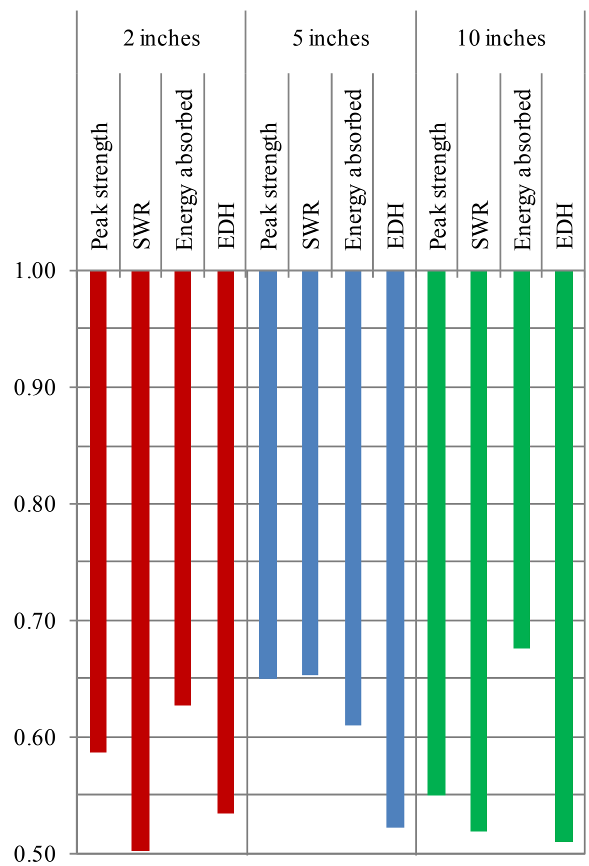

Figure 5. Odds ratios for risk of fatal or incapacitating driver injury with increasing roof strength in small passenger cars, adjusted to represent strength increases equal to range of strengths using each metric for small car study vehicles.

and weakest roof measured at each plate displacement. This allows some comparison between metrics despite their different units. Effects at different displacement distances may not be comparable because a single outlier at either end of the strength range could create disproportionate scaling differences.

Figure 6 presents the scaled estimates for the SUVs studied. Together with Figure 5, it is apparent that injury risk reductions predicted by roof strength at each level of plate displacement are only slightly different between the two strength metrics that make use of curb weight and the two that do not. However, this likely is because of the small range of curb weights of both sets of study vehicles. For the purpose of evaluating roof strength across the vehicle fleet, there are at least two indications that SWR or EDH are preferred to peak strength or energy absorption. First, the similarity in the odds ratios for the two vehicle types in Figure 4 for SWR and EDH, discussed above, suggests the benefits of roof strength

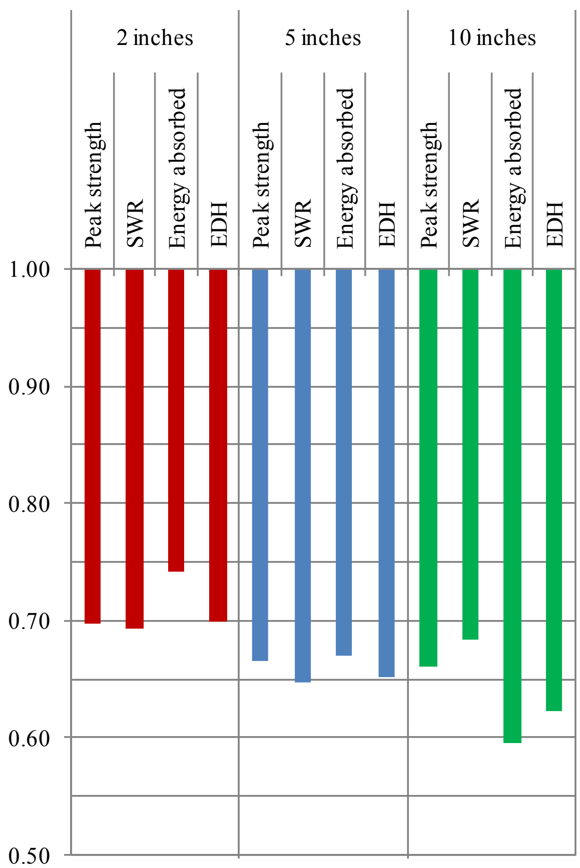

Figure 6. Odds ratios for risk of fatal or incapacitating driver injury with increasing roof strength in midsize SUVs, adjusted to represent strength increases equal to range of strengths using each metric for midsize SUV study vehicles.

are more homogeneous when expressed with these metrics. Second, SWR and EDH better explain the higher overall average raw rate of incapacitating or fatal injury for SUVs (12.3% compared with 10.3% for small passenger cars). Although other factors contribute, the difference in these rates likely would be even larger without the higher SSF values of the passenger cars and the resulting increased injury risk discussed previously. For the vehicles studied, overall injury rates are consistent with the average SWR and EDH values, which are higher for passenger cars. SUVs have higher average peak strength and energy absorption.

Roof Strength Regulation

Occupants of the passenger cars studied would have benefitted less than the SUV occupants from a regulation with a minimum SWR_5 of 2.5. Only 4 of the 12 roof designs would have required additional strength to meet such a standard, and these strength increases would have been relatively small. As a result, it was estimated that only 1% of the 228 drivers and right-front passengers killed in single-vehicle rollovers of these vehicles in 2007 could have been saved by a standard similar to that proposed by NHTSA in 2005. Increasing the minimum SWR_5 level to 3.9 would have had a much greater effect, with around one-third of the 228 fatalities prevented.

This disparity highlights the need for an upgraded regulation based on an accurate evaluation of the risk reductions associated with stronger roofs. NHTSA estimated that, fleet-wide, a minimum SWR_5 requirement of 3.0 would prevent up to 135 of 9,942 annual rollover fatalities [18], and that these reductions were too small to justify the cost of the necessary vehicle redesigns. These conclusions appear overly conservative in light of the current findings. At the same time, the large number of fatalities that still would occur with stronger roofs confirms that a comprehensive approach to rollover crash avoidance and crashworthiness is important.

CONCLUSIONS

For nonejected occupants, benefits of roof strength in single-vehicle rollover crashes are similar for drivers of midsize SUVs and small passenger cars. Increased roof strength is associated with reduced risk of ejection for drivers of both vehicle types, but the reduction may be greater for SUV drivers. The quasi-static FMVSS 216 test is a meaningful structural assessment of real-world rollover crashworthiness for occupants of passenger cars and SUVs.

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APPENDIX A

Roof strength and SSF values for study vehicles. Some models had trim levels with other curb weight values, leading to multiple values of SWR and EDH. Curb weight of most common trim level was used to calculate the SWR and EDH values reported here.

				Peak roof strength (lb_f)			SWR			Energy absorbed (J)			EDH (in)		
Model years	**Make**	**Model**	**SSF**	**2 in**	**5 in**	**10 in**	**2 in**	**5 in**	**10 in**	**2 in**	**5 in**	**10 in**	**2 in**	**5 in**	**10 in**
1995-2000	Saturn	SL	1.35	5,470	6,159	9,530	2.30	2.59	4.01	678	2,625	6,932	2.5	9.8	25.8
2000-2005	Dodge	Neon	1.41	6,673	6,893	7,305	2.54	2.63	2.78	776	2,753	6,023	2.6	9.3	20.3
2000-2001	Plymouth	Neon	1.41	6,673	6,893	7,305	2.54	2.63	2.78	776	2,753	6,023	2.6	9.3	20.3
1995-1999	Dodge	Neon	1.44	4,990	5,755	6,369	2.00	2.30	2.55	644	2,428	4,953	2.3	8.6	17.5
1995-1999	Plymouth	Neon	1.44	4,990	5,755	6,369	2.00	2.30	2.55	644	2,428	4,953	2.3	8.6	17.5
1998-2002	Toyota	Corolla	1.42	8,212	9,590	9,590	3.35	3.91	3.91	934	3,774	7,504	3.4	13.6	27.1
1998-2002	Chevrolet	Prizm	1.42	8,212	9,590	9,590	3.35	3.91	3.91	934	3,774	7,504	3.4	13.6	27.1
1995-1999	Volkswagen	Jetta	1.33	5,351	7,808	8,853	1.98	2.89	3.28	593	2,826	6,569	1.9	9.3	21.5
1995-1999	Nissan	Sentra	1.40	6,085	7,414	7,414	2.52	3.07	3.07	637	2,726	6,074	2.3	10.0	22.3
1995-2000	Ford	Contour	1.39	6,646	7,017	9,225	2.35	2.48	3.27	849	2,896	6,705	2.7	9.1	21.0
1995-2000	Mercury	Mystique	1.39	6,646	7,017	9,225	2.35	2.48	3.27	849	2,896	6,705	2.7	9.1	21.0
1997-2002	Ford	Escort	1.37	5,224	5,371	5,977	2.11	2.17	2.41	668	2,379	5,035	2.4	8.5	18.0
1997-1999	Mercury	Tracer	1.37	5,224	5,371	5,977	2.11	2.17	2.41	668	2,379	5,035	2.4	8.5	18.0
1995-1997	Nissan	Altima	1.41	6,437	7,346	8,206	2.22	2.53	2.83	761	3,054	6,765	2.3	9.3	20.6
1996-2000	Honda	Civic	1.46	5,060	5,783	8,714	2.11	2.41	3.63	566	2,274	5,628	2.1	8.4	20.8
1995-2005	Chevrolet	Cavalier	1.35	5,712	6,798	8,654	2.14	2.54	3.24	715	2,821	6,537	2.4	9.3	21.6
1995-2002	Pontiac	Sunfire	1.35	5,712	6,798	8,654	2.14	2.54	3.24	715	2,821	6,537	2.4	9.3	21.6
2000-2007	Ford	Focus	1.33	8,805	9,063	11,490	3.39	3.49	4.42	1,114	3,558	8,554	3.8	12.1	29.1