Statement before the US Senate Committee on Commerce, Science, and Transportation

IIHS research on vehicle roof crush

Stephen L. Oesch

June 4, 2008

INSURANCE INSTITUTE
FOR HIGHWAY SAFETY

1005 NORTH GLEBE ROAD ARLINGTON, VA 22201
PHONE 703/247-1500 FAX 703/247-1678
www.iihs.org

The Insurance Institute for Highway Safety is a nonprofit research and communications organization that identifies ways to reduce the deaths, injuries, and property damage on our nation's highways. We are sponsored by US automobile insurers. Thank you for inviting IIHS to testify on the findings of our recent research on the relationship between roof strength and injury risk in rollover crashes.

Principles of vehicle crashworthiness

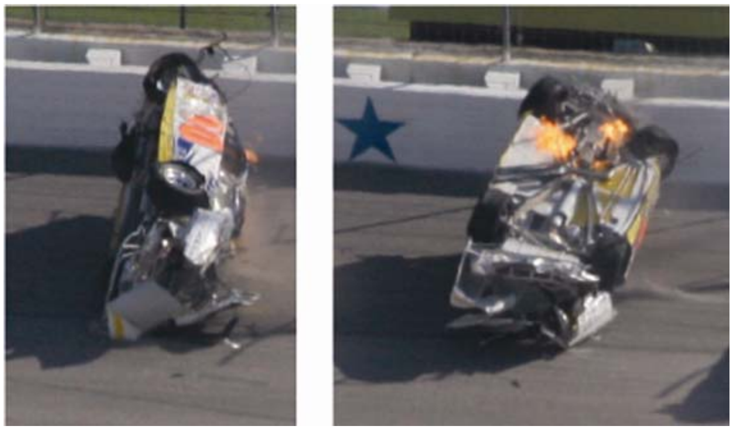
A key to protecting occupants in front, side, rear, or rollover crashes is ensuring that compartments, or "safety cages," surrounding the occupants remain intact so lap/shoulder belts and airbags can provide protection during the crashes. If an occupant compartment allows excessive intrusion of the door, instrument panel, footwell, roof, or other vehicle structure, it compromises the ability of vehicle restraint systems to protect the occupants.


1997 Pontiac Transport


2005 Chevrolet Uplander

This is demonstrated by comparing 2 vehicles IIHS evaluated in 40 mph frontal offset crash tests. The occupant compartment in the 1997 Pontiac Transport was compromised, thus increasing the potential for occupant injury. In sharp contrast is the occupant compartment in the 2005 Chevrolet Uplander, which withstood the forces of the frontal impact and remained intact, allowing the lap/shoulder belt and airbag to provide good occupant protection.

Prior to our recent research on roof strength, several studies had reported no relationship between roof strength and injury risk in rollover crashes. These earlier findings defy logic because, as I just explained, in every other crash configuration — whether front, side, or rear — the basic principles of occupant protection dictate that the compartment be designed to resist intrusion so lap/shoulder safety belts and airbags can provide protection to occupants. There is no logical reason to assume that in a rollover crash, you would design a vehicle to permit excessive intrusion. This is the reason NASCAR vehicles are equipped with roll bars to prevent roof crush in violent rollover crashes such as the one experienced by Michael McDowell at the Texas Motor Speedway in 2008. He walked away from this crash uninjured.


Michael McDowell’s rollover crash

Findings of IIHS’s study of SUV roof strength

Our study, described in the attached documents,[1-3] is a 2-part analysis involving vehicle testing and examination of the outcomes of real-world rollover crashes. Eleven midsize 4-door SUV roof designs were subjected to a test similar to the one conducted by automakers to comply with federal roof strength requirements. Researchers applied force to the roofs until crush reached 10 inches, measuring the peak force required for 2 inches of crush, 5 inches of crush, and 10 inches. There was a range of performance among the SUVs tested, and 2 demonstration tests illustrate the differences.


2000 Nissan Xterra

These photographs show what happened when the 2000 Nissan Xterra, the SUV with the strongest roof in IIHS tests, and the 2000 Ford Explorer, which has one of the weakest roofs, were subjected to a force of up to 10,000 pounds. The Xterra resisted a force of 10,000 pounds after only 2 inches of crush, while the Explorer crushed all the way to 10 inches without reaching this level of resistance. Such a striking difference in the amount of roof crush illustrates why higher injury risk would be expected in SUVs with weaker roofs.


2000 Ford Explorer

Having established the range of roof strength among the SUVs in the IIHS study, the researchers then focused on almost 23,000 rollover crashes of the same SUVs that occurred in the real world during 1997-2005. Logistic regression was used to assess the effect of roof strength on the likelihood of serious or fatal driver injury in the on-the-road rollover crashes of the SUVs. The regression controlled for state-to-state differences, vehicle stability, and driver age, and the results denote the injury risk, given the strength of an SUV's roof. No matter what measure of roof strength the researchers used, a consistent relationship emerged: SUVs with stronger roofs had lower injury risks.

There are important strengths of our study. We looked only at midsize SUVs because they are similar vehicles with similar drivers and a high risk of rolling over. This allowed researchers to limit the number of variables in the analysis and concentrate on the ones that would ensure that results were not biased by factors such as differences in driver age, types of use, etc. Another strength is that we used several different measures of roof strength, all of which confirmed that injury risk is lower among vehicles with stronger roofs. This makes logical sense, and the data confirm it.

Based on our research, we expect that the study's finding of reduced injury risk with increased roof strength will hold for other types of vehicles, although the magnitude of the injury risk reductions may differ among vehicle groups. To further establish this, we plan to conduct another series of roof crush tests involving a different class of vehicles — small passenger cars — that also has a high rollover rate.

Dynamic rollover test

A dynamic rollover test using instrumented test dummies would be a gold standard for assessing occupant protection in rollover crashes. However, we are not certain that the procedures for a dynamic test are reasonably repeatable, and we are not sure how to conduct such a test to obtain the most relevant information. Real-world rollover crashes vary widely. They often are preceded by violent events as vehicles leave the road and begin to roll over. The positions of occupants at the time a rollover begins are uncertain, so it is difficult to position test dummies to represent where occupants would be in real-world rollover crashes. Current dummies designed for front, side, and rear testing have not been shown to behave in a human-like manner in rollover crashes.

Proposed federal roof crush standard

IIHS's study clearly shows the relationship between increased roof strength and reduced injury risk in rollover crashes. We support the continued use of the current roof crush procedures set forth in the existing federal standard on roof crush resistance. However, our study supports requiring vehicles to have a strength-to-weight ratio of at least 3.0. We estimate that a 1-unit increase in peak strength-to-weight ratio — for example, from 1.5 times vehicle weight, as specified in the existing federal standard, to 2.5 times, as proposed by the National Highway Traffic Safety Administration — would reduce the risk of serious or fatal injury in a rollover crash by 28 percent. Increasing roof strength requirements beyond 2.5 times vehicle weight would reduce injury risk even further.

Attachments/references

1. Brumbelow, M.L.; Teoh, E.R.; Zuby, D.S.; and McCartt, A.T. 2008. Roof strength and injury risk in rollover crashes. Arlington, VA: Insurance Institute for Highway Safety.
2. Insurance Institute for Highway Safety. 2008. Comment to the National Highway Traffic Safety Administration in response to comments by Padmanaban and Moffatt on the Institute's study, "Roof Strength and Injury Risk in Rollover Crashes," May 13. Arlington, VA.
3. Insurance Institute for Highway Safety. 2008. Strength of roofs on SUVs influences risk of occupant injury in rollover crashes, new Institute study finds. *Status Report* 43:1. Arlington, VA.

Roof Strength and Injury Risk in Rollover Crashes

Matthew L. Brumbelow
Eric R. Teoh
David S. Zuby
Anne T. McCartt

March 2008

INSURANCE INSTITUTE
FOR HIGHWAY SAFETY
1005 NORTH GLEBE ROAD ARLINGTON, VA 22201
PHONE 703/247-1500 FAX 703/247-1678
www.iihs.org

ABSTRACT

Vehicle rollover is a major cause of fatality in passenger vehicle crashes. Rollovers are more complicated than planar crashes, and potential injury mechanisms still are being studied and debated. A central factor in these debates is the importance of having a strong vehicle roof. Minimum roof strength is regulated under Federal Motor Vehicle Safety Standard (FMVSS) 216, but no study to date has established a relationship between performance in this or any other test condition and occupant protection in real-world rollover crashes. The present study evaluated the relationship between roof strengths of 11 midsize SUV roof designs and the rate of fatal or incapacitating driver injury in single-vehicle rollover crashes in 12 states. Quasi-static tests were conducted under the conditions specified in FMVSS 216, and the maximum force required to crush the roof to 2, 5, and 10 inches of plate displacement was recorded. Various measures of roof strength were calculated from the test results for evaluation in logistic regression models. In all cases, increased measures of roof strength resulted in significantly reduced rates of fatal or incapacitating driver injury after accounting for vehicle stability, driver age, and state differences. A one-unit increase in peak strength-to-weight ratio (SWR) within 5 inches of plate displacement, the metric currently regulated under the FMVSS 216 standard, was estimated to reduce the risk of fatal or incapacitating injury by 28 percent.

INTRODUCTION

During the past two decades automobile manufacturers have made important advances in designing vehicle structures that provide greater occupant protection in planar crashes (Lund and Nolan 2003). However, there has been little consensus regarding the importance of roof strength in rollover crashes, as well as the best method for assessing that strength. In 2006 one-quarter of fatally injured passenger vehicle occupants were involved in crashes where vehicle rollover was considered the most harmful event (Insurance Institute for Highway Safety, 2007). Many fatally injured occupants in rollovers are unbelted, and some are completely or partially ejected from the vehicle (Deutermann 2002). There is disagreement concerning how structural changes could affect ejection risk or the risk of injury for occupants who remain in the vehicle, regardless of belt use.

Some researchers have concluded there is no relationship between roof crush and injury risk as measured by anthropometric test devices (ATDs) (Bahling et al. 1990; James et al. 2007; Moffatt et al. 2003; Orlowski et al. 1985; Piziali et al. 1998), whereas others have reached the opposite conclusion using data from the same crash tests (Friedman and Nash, 2001; Rechnitzer et al. 1998; Syson 1995). These disparate conclusions have led to distinct hypotheses about the primary source of rollover injury: either a diving mechanism in which injury occurs independently of roof crush, or a roof intrusion mechanism in which injury is caused by structural collapse. These hypotheses often are seen as being mutually exclusive, but both assume that keeping occupants in the vehicle and preventing head-to-roof contact reduces injury risk. According to Bahling et al. (1990), "the absence of deformation may benefit belted occupants if it results in the belted occupant not contacting the roof."

Federal Regulation of Roof Strength

Although many researchers have studied potential rollover injury mechanisms, evaluation of the federal regulation governing roof strength has been lacking. Federal Motor Vehicle Safety Standard (FMVSS) 216 was introduced in 1971 to establish a minimum level of roof strength and is the only regulation governing rollover crashworthiness for passenger vehicles (Office of the Federal Register 1971). FMVSS 216 specifies a quasi-static test procedure that measures the force required to push a metal plate into the roof at a constant rate. It requires a reaction force equal to 1.5 times the weight of the vehicle be reached within 5 inches of plate displacement. In 1991 the standard was extended to apply to light trucks and vans with gross vehicle weight ratings less than 6,000 pounds (Office of the Federal Register 1991).

In 2005 NHTSA issued a notice of proposed rulemaking (NPRM) announcing its intent to upgrade the roof strength standard (Office of the Federal Register 2005). According to the proposal the test procedure would remain largely unchanged but the level of required force would be increased to a strength-to-weight-ratio (SWR) of 2.5. The maximum 5-inch plate displacement limit would be replaced by a requirement that the minimum strength be achieved prior to head-to-roof contact for an ATD positioned in the front outboard seat on the side of the vehicle being tested. Using two different analysis methods, NHTSA estimated 13 or 44 lives per year would be saved by the proposed standard, equivalent to less than 1 percent of rollover fatalities. These estimates were based on an evaluation of 32 crashes in the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS), after assuming that the following occupants, among others, would not benefit from the proposed upgraded standard: occupants in arrested rolls, ejected occupants, unbelted occupants, occupants in rear seats, and occupants without coded intrusion above their seating positions.

In 2008 NHTSA issued a supplemental notice of proposed rulemaking announcing the results of additional research tests (Office of the Federal Register 2008). The proposal indicated the agency may consider adopting a sequential two-sided test. Final decisions about the minimum SWR for either a one- or two-sided test are pending results of an updated benefits analysis.

Previous Research Relating Roof Strength to Crash Injury Outcomes

NHTSA's benefits analysis in the 2005 NPRM assumed that roofs designed to meet a higher strength requirement in the quasi-static test are better able to maintain occupant headroom during rollover crashes in the field. This link has never been shown, nor has any measure of roof strength been found to predict injury risk. The agency's own assessment found most vehicles "easily exceeded" the requirements of FMVSS 216, even vehicles produced before introduction of the standard (Kahane 1989). Demonstrating that a test promotes crashworthy designs is difficult without either a sample of vehicles not meeting the test requirements or a range of performance among vehicles that pass. Kahane found that some hardtop roof designs without B-pillars sustained more crush before meeting the minimum strength requirement, and that fleet-wide fatality risk in non-ejection rollover crashes declined during the 1970s, a time period corresponding to a shift towards roof designs with B-pillars. These findings did not establish a relationship between roof strength and injury because test results for specific vehicles were not compared with injury rates for those vehicles.

Only two studies directly investigated the relationship between peak roof strength and injury outcome for occupants in real-world rollover crashes (Moffatt and Padmanaban 1995; Padmanaban et al. 2005). Vehicles were evaluated using the quasi-static procedure outlined in FMVSS 216, but every vehicle was tested to a full 5 inches of plate displacement to measure roof strength in excess of the minimum SWR. An earlier study by Plastiras et al. (1985) did not incorporate measures of peak roof strength and used a severely limited sample of crashes.

Moffatt and Padmanaban (1995) constructed a logistic regression model to investigate the effects of age, gender, belt use, alcohol use, crash environment (rural/urban), number of vehicle doors, vehicle aspect ratio (roof height divided by track width), vehicle weight, roof damage, and roof strength on the likelihood of fatal or incapacitating driver injury in single-vehicle rollover crashes. Crash data consisted of single-vehicle rollovers in databases of police-reported crashes in four states. Multiple vehicle types were included. The study reported no relationship between roof strength and the likelihood of fatal or incapacitating injury. Although more severe roof damage was associated with higher likelihood of injury, the study found roof strength did not predict the likelihood of severe roof damage.

Padmanaban et al. (2005) conducted a follow-up study that expanded the vehicle sample and differed in a few other respects, but the findings were similar. Driver factors such as belt use, age, and alcohol use were reported as important predictors of injury risk, whereas roof strength was not related to the risk of fatal or incapacitating injury, or to the risk of fatal injury alone. Both studies also found that vehicles with higher aspect ratios had lower rates of fatal or incapacitating injury.

These findings call into question the effectiveness of the FMVSS 216 regulation. The standard was established to "reduce deaths and injuries due to the crushing of the roof," but according to this research, roof strength assessed under the regulated test conditions has no relationship to injury likelihood. Furthermore, the Moffatt and Padmanaban (1995) study found no relationship between roof strength and roof damage in rollover crashes. This finding suggests two possibilities: either the federal standard is not evaluating roof strength in a mode relevant to real-world rollovers, or the methods used in these studies have allowed other factors to obscure this relevance. Differences among vehicle types and state reporting practices are two examples of factors that may have confounded the results for roof strength.

The purpose of the present study was to investigate whether there is any relationship between performance in the quasi-static test specified by FMVSS 216 and injury risk in rollover crashes. By restricting the analysis to midsize four-door SUVs the study sought to minimize other factors that may confound an analysis of roof strength, such as the differences in crash severity, vehicle kinematics, occupant kinematics, and driver demographics associated with vehicles of different types. Vehicle stability, occupant age effects, and differences between states were controlled statistically in the analyses. The study estimated the effects of raising the minimum SWR requirement and also compared alternative strength metrics calculated from the roof test data.

METHODS

Logistic regression was used to evaluate the effect of roof strength on driver injury risk in single-vehicle rollover crashes involving midsize four-door SUVs. Roof strength data for 11 SUV models were obtained from quasi-static tests in which roofs were crushed with up to 10 inches of plate displacement. Using data from police-reported crashes in 12 states, driver injury rates by make/model were calculated as the proportion of drivers in single-vehicle rollover crashes who were coded as having fatal or incapacitating injury.

Vehicle Selection and Roof Strength Testing

Certain vehicle safety features might affect the rate of injuries in rollover crashes and thereby confound the analyses of roof strength. Side curtain airbags and electronic stability control (ESC) are two such features. In a single-vehicle rollover crash the presence of side curtain airbags may reduce the risk of full or partial occupant ejection or reduce the risk of injury for occupants remaining in the vehicle. ESC does not influence injury risk once a rollover has begun, but it most likely affects the type of rollover crashes in which ESC-equipped vehicles are involved. All models with side curtain airbags or ESC as standard features were excluded. None of the remaining vehicles had optional ESC installation rates exceeding 3 percent, and only one had an optional curtain airbag installation rate higher than 5 percent (Ward's Communications, 2006). Potential confounding from the inclusion of 2002-04 Ford Explorers, 15 percent of which had curtain airbags, was addressed in a manner described below. Although it would have been desirable to evaluate roof strength effects for vehicles with these safety features, which soon will be standard across the fleet, there were insufficient data to do so.

Roof strength data from vehicle manufacturers typically do not enter the public domain and therefore are not readily available to independent researchers. Additionally, compliance testing rarely is extended beyond the crush distance required to demonstrate the minimum SWR of 1.5. To study the range of roof strengths in the vehicle fleet, testing must continue beyond this level to measure peak force. The required test data were available for three midsize SUVs from NHTSA research related to the proposed standard upgrade. These data were included in the study.

Roof strength data for additional vehicles were obtained from tests conducted by General Testing Laboratories, under contract with the Insurance Institute for Highway Safety. The eight midsize SUVs with the most rollover crashes in the state databases used for the study were tested. Six of these models were not current designs, so it was necessary to test used vehicles. Tested vehicles had no previous crash damage and were equipped with the original factory-installed windshield and side windows. It has been suggested that the windshield and its bond to the vehicle frame can contribute up to 30 percent of the strength measured in the test (Friedman and Nash 2001).

In total, tests of 11 roof designs provided the data for the study. Some of these designs were shared by corporate twins, so the number of vehicle models in the study exceeds 11.

Static Stability Factor

Moffatt and Padmanaban (1995) and Padmanaban et al. (2005) found that vehicles with larger aspect ratios had lower rates of serious driver injury. The authors did not discuss the implications of this finding, although the 2005 study suggested it was not due to any increased headroom of taller vehicles. Assuming identical suspension properties, taller and narrower vehicles are less stable than wider shorter ones, leading to rollovers at lower speeds and with less severe tripping events. It is possible that these lower speed rollovers are less likely to cause serious injury, meaning that when rollovers do occur, less stable vehicles may have lower severe injury rates simply because they roll more easily. Harwin and Emery (1989) reported this from a sample of 3,000 rollover crashes in Maryland. The present study included static stability factor (SSF) as a predictor in the logistic regression. SSF is a better measure of stability than aspect ratio because the height of the center of gravity is measured instead of the height of the roof. NHTSA uses SSF to assign rollover risk ratings to the vehicle fleet, and these publicly available data were used in this study.

Roof Strength Metrics

Because performance in the FMVSS 216 test has not been shown to affect injury risk, it is not clear that a baseline SWR within 5 inches of plate displacement better predicts injury outcome than other strength metrics that can be calculated from the same test data. The energy absorbed by the roof may be more relevant to injury risk than the peak force it can withstand, or the roof’s performance over a plate displacement other than 5 inches could better predict injury risk. The contribution of vehicle mass to rollover crashworthiness also is unknown.

In the present study the following metrics were evaluated: peak force, SWR, energy absorbed, and equivalent drop height. SWR is peak force divided by vehicle curb weight, and equivalent drop height is energy divided by curb weight converted to inches. The term “equivalent drop height” is used because this metric can be considered the height from which the vehicle could be dropped on its roof to produce the same level of crush as observed in the test (under an ideal condition where the roof deforms identically in the dynamic and quasi-static conditions). Each of the metrics was calculated within 2, 5, and 10 inches of plate displacement. Two inches was chosen based on the highly linear characteristic of the force-deflection curves up to this displacement. Ten inches represented the maximum deflection in 10 of the 11 tests.

Because there were 11 tested roof designs, the evaluations using peak force and energy absorption had 11 available values for comparison. The use of curb weight for calculating SWR and equivalent drop height produced many more unique values. Corporate twins were separated where curb weights differed, and two-wheel drive vehicles were separated from four-wheel drive versions due to their lower weights and varying SSF values. These 31 vehicles produced 28 unique values of SWR and equivalent drop height. Table 1 lists the vehicle test data used in the analysis. Appendix A reports the other metrics for these vehicles as well as the other models for which these data can be applied. The results for the 1996-2001 Ford Explorer and Mercury Mountaineer reflect the use of averaged values obtained from two tests. The Mitsubishi Montero Sport was omitted from the 10-inch displacement evaluations because NHTSA’s test of this vehicle did not continue beyond 7.4 inches. This omission did not substantially affect the results; the Montero Sport had the smallest exposure of all vehicles in the study.

Table 1
FMVSS 216 roof strength test results

			Peak roof strength (lb_f)		
Model years	**Make**	**Model**	**2 in**	**5 in**	**10 in**
1996-2004	Chevrolet	Blazer	4,293	7,074	7,337
2002-2005	Chevrolet	TrailBlazer	6,896	8,943	8,943
1998-2003	Dodge	Durango	6,409	9,138	9,138
1996-2001	Ford	Explorer	5,901	7,072	8,196
2002-2004	Ford	Explorer	6,895	9,604	12,372
1996-1998	Jeep	Grand Cherokee	5,497	8,455	8,455
1999-2004	Jeep	Grand Cherokee	5,073	6,560	7,090
2002-2005	Jeep	Liberty	8,226	10,374	10,544
1997-2004	Mitsubishi	Montero Sport	6,063	10,069	N/A
2000-2004	Nissan	Xterra	9,431	11,996	11,996
1996-2000	Toyota	4Runner	5,269	8,581	8,581

Rollover Crash Data

Data for single-vehicle rollover crashes were obtained from the State Data System. The system is maintained by NHTSA and consists of data from police-reported crashes submitted to the agency by certain states. Qualifying states had data available for some part of calendar years 1997-2005, had event and/or impact codes allowing single-vehicle rollovers to be identified, and had available information on vehicle identification numbers sufficient for determining vehicle make, model, and model year. Twelve states met these criteria: Florida, Georgia, Illinois, Kentucky, Maryland, Missouri, New Mexico, North Carolina, Ohio, Pennsylvania, Wisconsin, and Wyoming. All of these states use the KABCO injury coding system, where "K" represents fatal injuries and "A" represents incapacitating injuries as assessed by the investigating police officer.

Logistic Regression

Logistic regression was used to assess the effect of roof strength on the likelihood of fatal or incapacitating driver injury. The final models controlled for state, SSF, and driver age. Controlling for state is necessary because of differences in reporting methods, terrain, urbanization, and other factors that could result in state-to-state variation in injury rates. The potential influence of SSF on rollover crash severity was discussed previously, and age has been found to affect injury risk (Li et al. 2003). A separate model was fit for each roof strength metric at each plate displacement distance, yielding 12 models. The effect of roof strength was assumed to be constant across all states. Because rollovers resulting in fatal or incapacitating injuries are fairly rare events, the odds ratios resulting from these models are reasonable approximations of relative risks and are interpreted accordingly.

Other covariates initially were examined in the models. These included coded belt use, driver gender, vehicle drive type (two- vs. four-wheel drive), and vehicle age. Driver gender, drive type, and vehicle age did not have significant effects on injury likelihood and were excluded from the final model. Coded belt use did affect injury risk in rollover crashes, and there was concern that belt use may confound the observed effects of roof strength. To study this possibility, separate models were fit for drivers coded as belted, unbelted, and unknown despite the unreliability of this information from police reports.

Tests that provided data for the 2002-04 Ford Explorer and 2000-04 Nissan Xterra were conducted with an alternative tie-down procedure that NHTSA was investigating for a change to the laboratory test procedure specified by the Office of Vehicle Safety Compliance (NHTSA 2006). At least one manufacturer has expressed concern that this tie-down procedure produces different results than the procedures used in its own compliance tests (Ford Motor Company 2006). The test procedure employed by General Testing Laboratories for this study differed from both the alternative being investigated by NHTSA and the procedure used by Ford. Two supplemental analyses addressed these procedural variations. First, results for the Explorer and Xterra were excluded and the data were modeled again. This also addressed any potential confounding resulting from the 15 percent installation rate of side curtain airbags in the 2002-04 Explorer. Second, a sensitivity analysis was conducted. This consisted of 10 separate regression models in which the roof strength inputs to the model varied by up to 10 percent above or below the measured strength. These values were sampled from a distribution using a random number generator.

One difficulty associated with using fatal and incapacitating injury counts as the measure of crash outcome is the subjectivity with which police can code incapacitating injuries. To check potential error from police judgment, separate models were fit for fatal injuries alone to ascertain that they followed the same pattern as models including incapacitating injuries.

Estimated Lives Saved

The present study has direct bearing on any future upgrades to FMVSS 216. Most of the study vehicles would require stronger roofs if the SWR requirement increased from 1.5 to 2.5 without any other modifications to the test procedure. To estimate the number of lives saved by such a change, data were extracted from the Fatality Analysis Reporting System for 2006. Fatalities were counted for occupants in front outboard seating positions in single-vehicle rollover crashes for each of the study vehicles. For vehicles with SWRs below 2.5, the increase required to achieve this level of strength was used to scale the effectiveness estimates of the final logistic regression model, producing vehicle-specific effectiveness values. These values were applied to the number of fatalities in each vehicle to produce an estimate of total lives saved. A second estimate was calculated using a target SWR of 3.16, the highest level achieved by any of the study vehicles. No compliance margin was included in these estimates; it was assumed that the roof strength values would not be greater than the target strength value.

RESULTS

Figure 1 shows the unadjusted relationship between the rate of fatal or incapacitating driver injury and peak SWR within 5 inches of plate displacement, the metric used in FMVSS 216. The circles represent the raw injury rate data; circle sizes are proportional to the total number of rollover crashes in the state databases for each study vehicle, and hence to that vehicle's contribution to the weighted regression line that is plotted. The slope of the line represents an injury rate 24 percent lower than average for an SWR one unit higher than average, but no adjustment was made for potentially confounding factors.

After controlling for state effects, SSF, and driver age the logistic regression models estimated changes in the odds of fatal or incapacitating driver injury for greater roof strength. Lower injury rates were associated with higher values of peak force, SWR, energy absorption, and equivalent drop height at 2, 5, and 10 inches of plate displacement. All of these findings were statistically significant at the 0.05 level. The model for peak SWR within 5 inches predicted that a one-unit increase in SWR would reduce the risk of fatal or incapacitating driver injury by 28 percent. These findings were based on 22,817 rollover crashes in the 12 states.

Figure 1
Rates of fatal or incapacitating driver injury by peak strength-to-weight ratio (SWR) within 5 inches of plate displacement

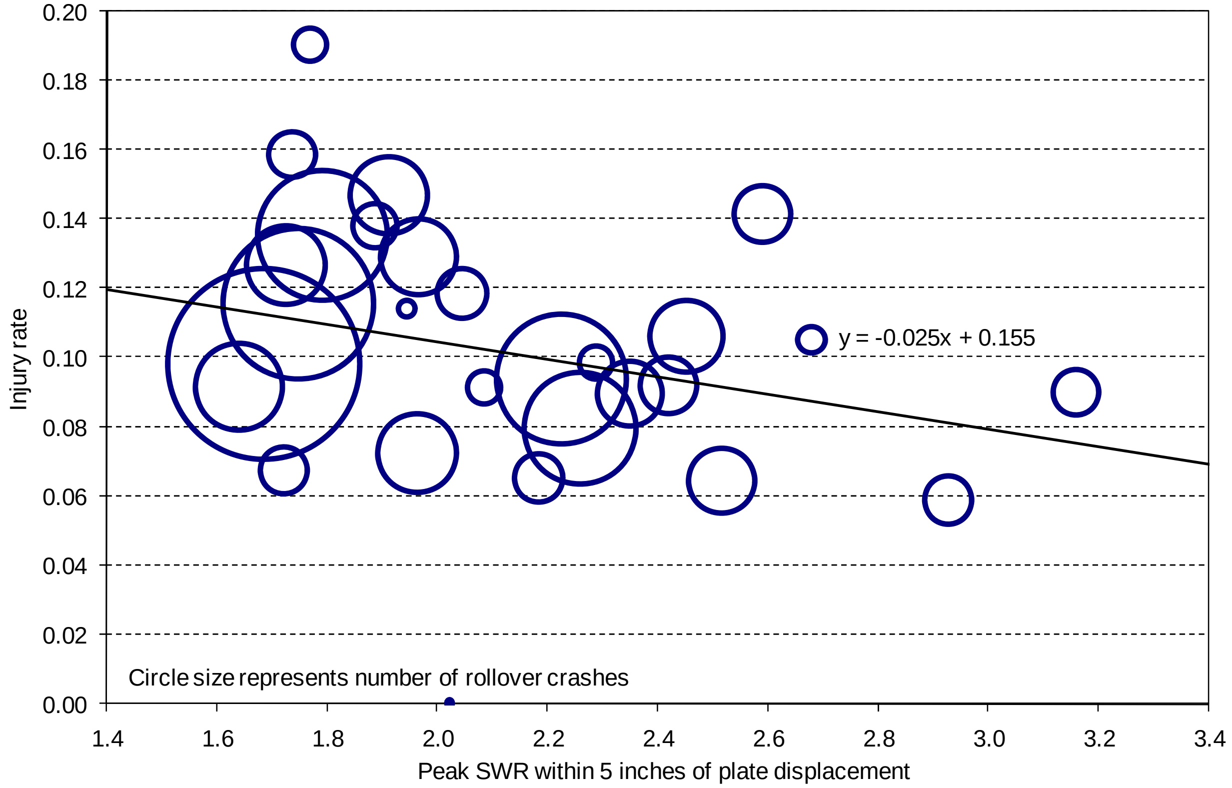


Table 2 lists the odds ratios for fatal or incapacitating driver injury for higher roof strength values. Odds ratios less than one indicate that greater roof strength is associated with lower injury risk. The units vary by metric. Peak force is given in English tons, SWR in increments of vehicle weight, energy absorption in kilojoules, and equivalent drop height in inches. One-unit differences in these metrics do not represent equivalent changes in roof strength, so the point estimates in the first column should not be directly compared against one another. To facilitate comparison, the second column lists the range of roof strength test performance for the study vehicles, and the third column lists the effect associated with a difference of this amount. For example, the lowest peak force within 2 inches of plate displacement was 4,293 lb_f (2.15 tons), observed in the test of the Chevrolet Blazer. The highest peak force was 9,431 lb_f (4.72 tons) for the Nissan Xterra, or 2.57 tons greater than the force in the Blazer test. A strength difference of 2.57 tons was associated with a 49 percent lower injury risk for the stronger roof.

The effects of driver age and SSF also are listed in Table 2. SSF values ranged from 1.02 to 1.20 for the study vehicles, so the effect of a 0.1 unit increase in SSF was evaluated. Results did not show a clear trend in injury risk by SSF. The effect of age was very consistent and statistically significant. Each 10-year increase in driver age was estimated to increase injury risk, given a single-vehicle rollover had occurred, by 12-13 percent.

Table 2
Results of logistic regression models for risk of fatal or incapacitating driver injuries

		Roof strength			SSF	Driver age
Strength metric	**Plate displacement**	**Odds ratio for 1 unit increase**	**Range**	**Odds ratio for observed range**	**Odds ratio for 0.1 unit increase**	**Odds ratio for 10 year increase**
Peak force (tons)	2 in	0.77*	2.15-4.72	0.51*	1.05	1.13*
	5 in	0.82*	3.28-6.00	0.58*	1.06	1.12*
	10 in	0.74*	3.55-6.19	0.46*	1.06	1.13*
SWR	2 in	0.55*	1.05-2.48	0.43*	0.98	1.13*
	5 in	0.72*	1.64-3.16	0.61*	0.96	1.12*
	10 in	0.57*	1.77-3.16	0.45*	0.93	1.13*
Energy absorbed (kJ)	2 in	0.34*	0.45-0.97	0.57*	1.01	1.13*
	5 in	0.71*	2.58-4.51	0.52*	1.08	1.13*
	10 in	0.82*	6.28-8.96	0.59*	1.06	1.13*
Equivalent drop height (in)	2 in	0.56*	0.96-2.25	0.48*	0.95	1.13*
	5 in	0.85*	5.56-10.5	0.45*	0.98	1.13*
	10 in	0.89*	13.6-20.5	0.44*	0.93	1.13*

*Statistically significant at 0.05 level

Eighty-three percent of drivers in the study were coded as belted. Logistic regression models using only these drivers produced estimates for the effectiveness of roof strength in preventing injury that were very similar to those of the regression models for all drivers. All estimates were statistically significant. Ten percent of drivers were coded as unbelted, and regression models restricting to these crashes found small effects of roof strength on injury risk that were not statistically significant. Police reported unknown belt use for the remaining 7 percent of drivers. Roof strength effect estimates for these crashes were similar to the overall model, although not all were statistically significant at the 0.05 level. Results are listed in Table 3.

Table 3
Results of logistic regression models for risk of fatal or incapacitating driver injuries by police-reported belt use

		Odds ratios for 1 unit increases in roof strength, by police reported belt use			
	Plate displacement	**All drivers**	**Belted**	**Unbelted**	**Unknown**
Peak force (tons)	2 in	0.77*	0.79*	0.93	0.79
	5 in	0.82*	0.82*	1.00	0.90
	10 in	0.74*	0.76*	0.94	0.81
SWR	2 in	0.55*	0.59*	0.85	0.54*
	5 in	0.72*	0.73*	0.99	0.78
	10 in	0.57*	0.59*	0.90	0.59
Energy absorbed (kJ)	2 in	0.34*	0.40*	0.64	0.34
	5 in	0.71*	0.73*	0.95	0.79
	10 in	0.82*	0.85*	0.95	0.86
Equivalent drop height (in)	2 in	0.56*	0.62*	0.79	0.54*
	5 in	0.85*	0.86*	0.98	0.86
	10 in	0.89*	0.91*	0.97	0.88*

*Statistically significant at 0.05 level

The two supplemental analyses addressing test procedure differences produced results comparable with the overall results in Table 2. The odds ratio for fatal or incapacitating driver injury associated with a one-unit higher SWR at 5 inches of plate displacement, originally 0.72, was 0.74 for the regression model excluding the Explorer and Xterra and ranged from 0.67 to 0.78 for the 10 regression models with varying roof strengths. These results remained statistically significant at the 0.05 level.

Of the 22,817 rollover crashes in the state data set, 1,869 drivers sustained incapacitating injuries and 531 sustained fatal injuries. Because these injuries were split among 12 different states and up to 28 unique SWR values, fatality counts were quite small. Nevertheless, results from the fatality models were similar to results from the models that also included incapacitating injury, and in 11 of 12 cases were statistically significant at the 0.05 level. Results are presented in Table 4.

Table 4
Results of logistic regression models of risk of driver fatality

	Plate displacement	Odds ratio for 1 unit increase
Peak force (tons)	2 in	0.61*
	5 in	0.80*
	10 in	0.58*
SWR	2 in	0.36*
	5 in	0.76
	10 in	0.43*
Energy absorbed (kJ)	2 in	0.11*
	5 in	0.54*
	10 in	0.62*
Equivalent drop height (in)	2 in	0.35*
	5 in	0.79*
	10 in	0.80*

*Statistically significant at 0.05 level

In 2006, 668 occupants in front outboard seating positions were killed in single-vehicle rollover crashes involving the study vehicles. It was estimated that 108 of these lives (95 percent confidence interval: 63-148) could have been saved by increasing the minimum SWR required by FMVSS 216 from 1.5 to 2.5. Increasing the minimum SWR to 3.16 could have saved 212 lives (95 percent confidence interval: 130-282).

DISCUSSION

The present study demonstrates that roof strength has a strong effect on occupant injury risk. This is in contrast to previous research relating roof test results to injury rates in field rollover crashes (Moffatt and Padmanaban 1995; Padmanaban et al. 2005). To fully investigate these differences, the detailed roof strength data from the previous studies would need to be compared with the data reported here. Unfortunately, these earlier data are confidential and a precise reason for the difference in results cannot be established. Nevertheless, the differing methods employed by the studies offer some potential explanations.

One of the biggest differences is that confounding effects associated with vehicle type largely were ignored in earlier research. Passenger cars, minivans, pickups, and SUVs all were included, and vehicles were classified by aspect ratio (roof height divided by track width). The substantial differences in driver demographics, rollover kinematics, and other factors associated with these vehicle types were unlikely to be captured with a measurement based solely on two exterior vehicle dimensions.

The only consideration of vehicle type was a secondary analysis in the Moffatt and Padmanaban (1995) study in which sports cars were grouped with pickups and SUVs, while non-sports cars were grouped with minivans. This attempted to control for the likelihood of drivers engaging in risky driving maneuvers, but likely only served to exacerbate differences in rollover crashes. Sports cars typically are the least rollover prone of all vehicles, with low centers of gravity and wide track widths. By grouping sports cars with SUVs and pickups, the authors combined vehicles requiring very severe roll-initiation events with vehicles requiring less severe initiation. Calculations using data reported by Digges and Eigen (2003) showed that for belted non-ejected occupants in rollover crashes, more than 20 percent of those in passenger cars were exposed to two or more roof impacts, whereas less than 10 percent of SUV and pickup occupants were in rollovers this severe.

Another difference was that these two previous studies did not control for differences among the states used in the analysis. NHTSA analyses of rollover crashes using state data controlled for these differences (Office of the Federal Register 2000), and the present study did so as well.

Belt Use and Ejection

Schiff and Cummings (2004) found that police reports overestimate belt use as compared with NASS/CDS, which is regarded as a more reliable source of this information. The authors found the most disagreement in cases where occupant injuries were least severe; for uninjured occupants coded as unbelted in NASS/CDS, police reported positive belt use 47 percent of the time. Because of this discrepancy, including restraint use as a predictor of injury would produce regression models that overestimate the true effect of belt use and reduce the apparent effect of other variables, such as roof strength.

The present study did not include police-reported belt use in the final regression model. Preliminary models separately analyzed drivers coded as belted and unbelted. Regression models for drivers with reported belt use estimated roof strength effects nearly identical to the effects estimated for all drivers. This is not surprising given the high percentage of reported belt use, but it does imply that belt use is not confounding the results of the final regression model. The models for drivers reported as unbelted did not find a significant relationship between roof strength and injury risk. Roof strength may have less of an effect on injury risk for unbelted drivers, but results are inconclusive given the limited sample of drivers reported as unbelted and the inaccuracy of restraint use from police reports.

Thirty-eight percent of drivers who police said were unbelted also were reported as ejected. Digges et al. (1994) reported that 42 percent of unrestrained occupants who were ejected exited the vehicle through a path other than the side windows, such as the door opening or the windshield. Increased roof strength potentially can reduce the integrity loss that can lead to doors opening or windshields being displaced. As the number of vehicles with side curtain airbags increase, the likelihood of ejection through the side windows should decrease. However, weak roofs could compromise the protection afforded by these airbags if they allow the roof rails to shift laterally and expose occupants to contacts with the ground.

Injury Causation

In finding that vehicles with stronger roofs are more protective of occupants, this study does not directly address injury mechanisms. It is possible the occupant protection provided by increased roof strength mitigates crush injuries by maintaining head clearance, reduces diving injuries by changing vehicle kinematics, or some combination of the two.

The possibility that roof strength influences vehicle kinematics was identified by Bahling et al. (1990). The authors observed substantial differences in rollover tests of production and rollcaged sedans. The production vehicles had a greater “velocity and duration of the roof-to-ground impact of the trailing roofrail” due to more roof deformation earlier in the roll. In addition, the actual number of far-side roof impacts among the rollcaged vehicles was less than half the number among the production vehicles. For far-side occupants, these changes produced a dramatic reduction in the number and average magnitude of neck loads surpassing 2 kN.

Various Roof Strength Metrics

The present study evaluated roof strength with multiple metrics calculated from NHTSA’s quasi-static test data. Logistic regression analyses found rollover injury risks were significantly lower for vehicles with stronger roofs, regardless of which strength assessment was used. Based on this finding, it is difficult to determine whether any one metric may be more predictive of injury outcome than the others. To permit an indirect comparison of the metrics, the one-unit effect estimates were converted to estimates for strength level increases equal to the range of study vehicle roof strengths. However, it is not known how much the relationship between these ranges would change with samples of other vehicles. For the vehicles in this study, such comparisons showed a range of predicted injury risk reductions but did not reveal any single combination of strength metric and plate displacement distance that stood out above the others.

For the study vehicles, higher peak roof strengths and SWRs within 2 and 10 inches of plate displacement predicted greater reductions in injury risk than roof strengths within 5 inches of displacement. The federally regulated metric of SWR evaluated within 5 inches predicted the smallest reduction in injury risk of all 12 metric and displacement combinations. Across all three displacement distances, higher values of equivalent drop height predicted the most consistent reductions in injury risk but the differences from other metrics were not large. Future analyses of the quasi-static test condition's relevance to real-world rollovers should further evaluate the equivalent drop height metric.

The metrics that accounted for vehicle curb weight were somewhat better predictors of injury risk than the metrics that did not. The importance of weight may be stronger across the entire vehicle fleet, where the range of curb weights is much wider than for the study vehicles. More than 80 percent of the rollover crashes in this study occurred among vehicles with curb weights between 3,800 and 4,200 pounds.

Other Covariates

All of the logistic regression models estimated significant injury risk increases of 12-13 percent for each 10-year increase in driver age. The findings for SSF were not statistically significant. Although the full range of SSF values for the study vehicles was 1.02-1.20, 74 percent of the rollover crashes in this study involved vehicles with SSF values between 1.06 and 1.09. This could explain the inconclusive injury risk estimates because such small variation in SSF values may be outweighed by other differences that affect vehicle stability and cannot be captured in SSF calculations, such as wheelbase or suspension and tire properties. A stronger trend may exist across the wider range of SSF values found in the entire fleet, with the most stable vehicles typically having values of 1.50 (Robertson and Kelley 1989).

Implications of Testing Used Vehicles

The analyses required vehicle models that have been in the fleet for enough years to accumulate sufficient crash data, so it was necessary to test used vehicles. According to vehicle manufacturers and NHTSA, roof strengths of used vehicles may not be equivalent to those of new vehicles (Office of the Federal Register 2006). Vehicles in the present study had no crash damage or corrosion that could have affected test results. Factory-installed windshields and side glazing still were present. However, it is possible that different results would have been obtained for new models. To some extent, this concern was addressed with the sensitivity analysis. The injury risk findings did not vary substantially when roof strength values were varied up to 10 percent.

Test results for the study vehicles may better represent the roof strengths of vehicles involved in rollover crashes than results for vehicles used in compliance testing and those used in earlier research. Previous studies included tests of production vehicles, prototypes, and vehicles "representative of production" that were "deemed satisfactory for compliance…[based on] engineering judgment" (Moffatt and Padmanaban 1995). The authors did not specify how many values were obtained from production vehicles.

Relevance to Proposed FMVSS 216 and Estimated Lives Saved

The estimated number of lives saved by increasing the regulated SWR to 2.5 is considerably higher than the estimated 13 and 44 lives saved indicated in NHTSA's 2005 NPRM, despite the fact the agency's estimates cover the entire passenger vehicle fleet. Estimates presented here are limited to the 11 study vehicles for two reasons: peak roof strength values for other vehicles mostly are unknown, and the effectiveness of roof strength in reducing injury may vary across vehicle types. Another difference in the estimates comes from the NPRM's modified plate displacement criterion, which allows roof intrusion for each vehicle until head contact with an ATD. The NPRM details 10 research tests in which plate displacement ranged from 3.2 to 7.3 inches at roof contact with the ATD. Because the present study looked at midsize SUVs with a narrow range of headroom values relative to the entire fleet, results could not directly address the headroom criterion proposal.

The number of rollover fatalities in the future will be affected by other changes to the vehicle fleet in addition to roof strength, such as wider availability of ESC and side curtain airbags, especially those designed to inflate in rollovers. Nevertheless, an upgraded standard requiring an SWR value of 2.5 likely would produce much greater reductions in fatal and incapacitating injuries than estimated by NHTSA. Further increasing the minimum SWR requirement beyond 2.5 would prevent even more deaths and serious injuries.

CONCLUSIONS

Increased vehicle roof strength reduces the risk of fatal or incapacitating driver injury in single-vehicle rollover crashes. This finding contradicts those from two previous studies on the topic, but the present study more tightly controlled potential confounding factors. The study focused on midsize SUVs, but there is no obvious reason similar relationships would not be found for other vehicle types, although the magnitudes of injury rate reductions may differ. Any substantial upgrade to the FMVSS 216 roof strength requirement would produce reductions in fatal and incapacitating injuries that substantially exceed existing estimates.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

REFERENCES

Bahling, G.S.; Bundorf, R.T.; Kaspzyk, G.S.; Moffatt, E.A.; Orlowski, K.F.; and Stocke, J.E. 1990. Rollover and drop tests – the influence of roof strength on injury mechanics using belted dummies. *Proceedings of the 34th Stapp Car Crash Conference*. SAE Technical Paper Series 902314. Warrendale, PA: Society of Automotive Engineers.

Digges, K.H. and Eigen, A.M. 2003. Crash attributes that influence the severity of rollover crashes. *Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles*. Paper 231-O. Washington, DC: National Highway Traffic Safety Administration.

Digges, K.H.; Malliaris, A.C.; and DeBlois, H.J. 1994. Opportunities for casualty reduction in rollover crashes. *Proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles.* Paper 94-S5-O-11. Washington, DC: National Highway Traffic Safety Administration.

Deutermann, W. 2002. Characteristics of fatal rollover crashes. Report no. DOT HS-809-438. Washington, DC: US Department of Transportation.

Ford Motor Company. 2006. Comment to the National Highway Traffic Safety Administration concerning Federal Motor Vehicle Safety Standard 216, Roof Crush Resistance. Docket Document No. NHTSA-2005-22143-191, January 11, 2006. Washington, DC: US Department of Transportation.

Friedman, D. and Nash, C.E. 2001. Advanced roof design for rollover protection. *Proceedings of the 17th International Technical Conference on the Enhanced Safety of Vehicles.* Paper 01-S12-W-94. Washington, DC: National Highway Traffic Safety Administration.

Harwin, E.A. and Emery, L. 1989. The crash avoidance rollover study: a database for the investigation of single vehicle rollover crashes. *Proceedings of the 12th International Technical Conference on the Enhanced Safety of Vehicles*, 470-477. Washington, DC: National Highway Traffic Safety Administration.

Insurance Institute for Highway Safety. 2007. Analysis of 2006 data from the Fatality Analysis Reporting System. Arlington, VA.

James, M.B.; Nordhagen, R.P.; Schneider, D.C.; and Koh, S.W. 2007. Occupant injury in rollover crashes: a reexamination of Malibu II. SAE Technical Paper Series 2007-01-0369. Warrendale, PA: Society of Automotive Engineers.

Kahane, C.J. 1989. An evaluation of door locks and roof crush resistance of passenger cars, Federal Motor Vehicle Safety Standards 206 and 216. Report no. DOT HS-807-489. Washington, DC: US Department of Transportation.

Li, G.; Braver, E.R.; and Chen, L. 2003. Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analysis and Prevention* 35:227-35.

Lund, A.K. and Nolan, J.M. 2003. Changes in vehicle designs from frontal offset and side impact crash testing. SAE Technical Paper Series 2003-01-0902. Warrendale, PA: Society of Automotive Engineers.

Moffatt, E.A.; Cooper, E.R.; Croteau, J.J.; Orlowski, K.F.; Marth, D.R.; and Carter, J.W. 2003 Matched-pair rollover impacts of rollcaged and production roof cars using the controlled rollover impact system (CRIS). SAE Technical Paper Series 2003-01-0172. Warrendale, PA: Society of Automotive Engineers.

Moffatt, E.A. and Padmanaban, J. 1995. The relationship between vehicle roof strength and occupant injury in rollover crash data. *Proceedings of the 39th Annual Conference of the Association for the Advancement of Automotive Medicine,* 245-267. Des Plaines, IL: Association for the Advancement of Automotive Medicine.

National Highway Traffic Safety Administration. 2006. Laboratory test procedure for FMVSS 216 roof crush resistance. Report no. TP-216-05. Washington, DC: US Department of Transportation.

Office of the Federal Register. 1971. *Federal Register*, vol. 36, no. 236, pp. 23299-23300. National Highway Traffic Safety Administration – Final rule. Docket no. 2-6, Notice 5; 49 CFR Part 571 – Motor Vehicle Safety Standards. Washington, DC: National Archives and Records Administration.

Office of the Federal Register. 1991. *Federal Register*, vol. 56, no. 74, pp. 15510-15517. National Highway Traffic Safety Administration – Final rule. Docket no. 89-22, Notice 03; 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Roof Crush Resistance. Washington, DC: National Archives and Records Administration.

Office of the Federal Register. 2000. *Federal Register*, vol. 65, no. 106. pp. 34998-35024. National Highway Traffic Safety Administration – Request for comments. Docket no. NHTSA-2000-6859; 49 CFR Part 575 – Consumer Information Regulations, Federal Motor Vehicle Safety Standards, Rollover Prevention. Washington, DC: National Archives and Records Administration.

Office of the Federal Register. 2005. *Federal Register*, vol. 70, no. 162, pp. 49223-49248. National Highway Traffic Safety Administration – Notice of proposed rulemaking. Docket no. NHTSA-2005-22143; 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Roof Crush Resistance. Washington, DC: National Archives and Records Administration.

Office of the Federal Register. 2006. *Federal Register*, vol. 71, no. 168, pp. 51663-51665. National Highway Traffic Safety Administration – Denial of petition for compliance investigation. Docket no. NHTSA-2005-22904, Notice 1; 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Roof Crush Resistance. Washington, DC: National Archives and Records Administration.

Office of the Federal Register. 2008. *Federal Register*, vol. 73, no. 20, pp. 5484-5493. National Highway Traffic Safety Administration – Supplemental notice of proposed rulemaking. Docket no. NHTSA-2008-0015; 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Roof Crush Resistance. Washington, DC: National Archives and Records Administration.

Orlowski, K.F.; Bundorf, R.T.; and Moffatt, E.A. 1985. Rollover crash tests-the influence of roof strength on injury mechanics. Proceedings of the *29th Stapp Car Crash Conference.* SAE Technical Paper Series 851734. Warrendale, PA: Society of Automotive Engineers.

Padmanaban, J; Moffatt, E. A.; and Marth, D.R. 2005. Factors influencing the likelihood of fatality and serious/fatal injury in single-vehicle rollover crashes. SAE Technical Paper Series 2005-01-0944. Warrendale, PA: Society of Automotive Engineers.

Piziali, R.; Hopper, R.; Girvan, D.; and Merala, R. 1998. Injury causation in rollover accidents and the biofidelity of Hybrid III data in rollover tests. SAE Technical Paper Series 980362. Warrendale, PA: Society of Automotive Engineers.

Plastiras, J.K.; Lange, R.C.; McCarthy, R.L.; and Padmanaban, J.A. 1985. An examination of the correlation between vehicle performance in FMVSS 216 versus injury rates in rollover accidents. SAE Technical Paper Series 850335. Warrendale, PA: Society of Automotive Engineers.

Rechnitzer, G.; Lane, J.; McIntosh, A.S.; and Scott, G. 1998. Serious neck injuries in rollovers – is roof crush a factor? *International Journal of Crashworthiness* 3:286-94.

Robertson, L.S. and Kelley, A.B. 1989. Static stability as a predictor of overturn in fatal motor vehicle crashes. *The Journal of Trauma* 29:313-19.

Schiff, M.A. and Cummings, P. 2004. Comparison of reporting of seat belt use by police and crash investigators: variation in agreement by injury severity. *Accident Analysis and Prevention* 36:961-65.

Syson, S.R. 1995 Occupant to roof contact: rollovers and drop tests. SAE Technical Paper Series 950654. Warrendale, PA: Society of Automotive Engineers.

Ward's Communications. 2006. Ward's Automotive Reports, 2003-06. Southfield, MI.

APPENDIX A

Table A1
All study vehicle make and model combinations with roof strength and SSF data; vehicles grouped by FMVSS 216 test result; only 4 door models were included in the study

First model year	Last model year	Make	Model	Drive type	SSF	SWR			Energy absorbed (J)			Equivalent drop height (in)		
						2 in	5 in	10 in	2 in	5 in	10 in	2 in	5 in	10 in
1996	2004	Chevrolet	Blazer	2wd	1.02	1.16	1.91	1.98	447	2575	6282	1.1	6.2	15.0
1996	2004	Chevrolet	Blazer	4wd	1.09	1.06	1.75	1.81	447	2575	6282	1.0	5.6	13.7
1996	2001	GMC	Jimmy	2wd	1.02	1.14	1.89	1.96	447	2575	6282	1.1	6.1	14.8
1996	2001	GMC	Jimmy	4wd	1.09	1.05	1.73	1.79	447	2575	6282	1.0	5.6	13.6
1996	2001	Oldsmobile	Bravada	4wd	1.09	1.05	1.74	1.80	447	2575	6282	1.0	5.6	13.6
2002	2005	Chevrolet	TrailBlazer	2wd	1.16	1.58	2.04	2.04	729	3482	7647	1.5	7.0	15.5
2002	2005	Chevrolet	TrailBlazer	4wd	1.18	1.52	1.97	1.97	729	3482	7647	1.4	6.8	14.9
2002	2005	GMC	Envoy	2wd	1.16	1.58	2.04	2.04	729	3482	7647	1.5	7.0	15.5
2002	2005	GMC	Envoy	4wd	1.18	1.52	1.97	1.97	729	3482	7647	1.4	6.8	14.9
2002	2004	Oldsmobile	Bravada	2wd	1.16	1.56	2.02	2.02	729	3482	7647	1.5	7.0	15.3
2002	2004	Oldsmobile	Bravada	4wd	1.18	1.50	1.94	1.94	729	3482	7647	1.4	6.7	14.7
1998	2003	Dodge	Durango	2wd	1.20	1.46	2.08	2.08	694	3405	7483	1.4	6.9	15.1
1998	2003	Dodge	Durango	4wd	1.16	1.39	1.98	1.98	694	3405	7483	1.3	6.5	14.3
1996	2001	Ford	Explorer	2wd	1.06	1.50	1.79	2.07	710	2966	7064	1.6	6.6	15.8
1996	2001	Ford	Explorer	4wd	1.06	1.40	1.68	1.96	710	2966	7064	1.5	6.3	14.9
1997	2001	Mercury	Mountaineer	2wd	1.06	1.48	1.77	2.05	710	2966	7064	1.6	6.6	15.6
1997	2001	Mercury	Mountaineer	4wd	1.06	1.40	1.68	1.96	710	2966	7064	1.5	6.3	14.9
2002	2004	Ford	Explorer	2wd	1.10	1.64	2.29	2.95	838	3713	8780	1.8	7.8	18.5
2002	2004	Ford	Explorer	4wd	1.14	1.57	2.18	2.81	838	3713	8780	1.7	7.5	17.7
1996	1998	Jeep	Grand Cherokee	2wd	1.07	1.53	2.35	2.35	577	2971	6443	1.4	7.3	15.8
1996	1998	Jeep	Grand Cherokee	4wd	1.07	1.45	2.23	2.23	577	2971	6443	1.3	6.9	15.0
1999	2004	Jeep	Grand Cherokee	2wd	1.09	1.33	1.72	1.86	661	2645	6376	1.5	6.1	14.8
1999	2004	Jeep	Grand Cherokee	4wd	1.11	1.27	1.64	1.77	661	2645	6376	1.5	5.9	14.1
2002	2005	Jeep	Liberty	2wd	1.10	2.12	2.68	2.72	962	3896	8959	2.2	8.9	20.5
2002	2005	Jeep	Liberty	4wd	1.12	1.99	2.51	2.56	962	3896	8959	2.1	8.4	19.2
1997	2004	Mitsubishi	Montero Sport	2wd	1.07	1.56	2.59	N/A	667	3473	N/A	1.5	7.9	N/A
1997	2004	Mitsubishi	Montero Sport	4wd	1.11	1.46	2.42	N/A	667	3473	N/A	1.4	7.4	N/A
2000	2004	Nissan	Xterra	2wd	1.09	2.48	3.16	3.16	967	4514	8708	2.3	10.5	20.3
2000	2004	Nissan	Xterra	4wd	1.12	2.30	2.93	2.93	967	4514	8708	2.1	9.7	18.8
1996	2000	Toyota	4Runner	2wd	1.08	1.51	2.45	2.45	612	2896	6618	1.5	7.3	16.7
1996	2000	Toyota	4Runner	4wd	1.06	1.39	2.26	2.26	612	2896	6618	1.4	6.7	15.4

INSURANCE INSTITUTE
FOR HIGHWAY SAFETY

May 13, 2008

The Honorable Nicole R. Nason
Administrator
National Highway Traffic Safety Administration
1200 New Jersey Avenue, SE, West Building
Washington, DC 20590

Supplemental Notice of Proposed Rulemaking; 49 CFR Part 571, Federal Motor Vehicle Safety Standards, Roof Crush Resistance; Docket No. NHTSA-2008-0015

Dear Administrator Nason:

The Insurance Institute for Highway Safety (IIHS) has conducted a study that demonstrates a direct relationship between roof strength and injury risk reduction in rollover crashes (Brumbelow et al., 2008). We included this study in our previous comment to the docket (IIHS, 2008) because of its relevance to the National Highway Traffic Safety Administration's (NHTSA) rulemaking under Federal Motor Vehicle Safety Standard (FMVSS) 216.

Finding that stronger roofs reduce the risk of injury in rollover crashes, the IIHS study contradicts two previous studies on the topic (Moffatt and Padmanaban, 1995; Padmanaban et al., 2005). Two authors of these earlier studies have submitted a comment and additional analysis to NHTSA (Padmanaban and Moffatt, 2008), questioning the IIHS study and concluding that "stronger roofs are not safer roofs."

The comments by Padmanaban and Moffatt (2008) contain misleading statements about the IIHS study that are detailed in item 6 of the attached document, "Logical and Statistical Errors in Comments by Padmanaban and Moffatt on the Insurance Institute for Highway Safety Study, 'Roof Strength and Injury Risk in Rollover Crashes.'" In addition, the analytical tactics recommended and used by Padmanaban and Moffatt depart in fundamental ways from appropriate use and interpretation of statistical results (see item 4). Of most concern is their insistence on including ejection, belt use, and alcohol use as control variables in their analysis when, in fact, these variables are either direct outcomes of roof crush strength or affected by the dependent variable, injury risk. Inclusion of them in the analysis obfuscates the real effects of roof strength on injury risk (see items 1-3).

These concerns are detailed in the attachment. We would be happy to discuss the issues further if NHTSA has questions.

Sincerely,

Adrian K. Lund, Ph.D.
President

cc: Docket Clerk, Docket No. NHTSA-2008-0015

1005 N. GLEBE RD., ARLINGTON, VA 22201 TEL. 703/247-1500 FAX 703/247-1678 www.iihs.org

Logical and Statistical Errors in Comments by Padmanaban and Moffatt on the Insurance Institute for Highway Safety Study, "Roof Strength and Injury Risk in Rollover Crashes"

1. **Ejection is an outcome of rollover and is influenced by roof strength. Including ejection as a predictor of death or serious injury in a rollover crash masks a major benefit of roof strength.**

   Padmanaban and Moffatt argue that IIHS should have included a number of additional variables in the predictive model of injuries and deaths in rollovers. One of these variables is ejection. Their argument is that ejection greatly increases the risk of injury while "ejection is…likely to be unrelated to roof strength" (pg. 1).

   a. This argument is illogical. Roof strength may not affect injury risk once a person is ejected, but a strong roof may prevent occupants from being ejected in the first place. Preventing an occupant compartment from collapsing obviously can reduce ejection risk by preventing broken glazing and deformed structure, which create ejection paths.

   b. This argument is testable. Using the midsize SUVs in the IIHS study, IIHS researchers investigated the relationship between roof strength and ejection risk with an additional analysis. The risk of ejection was 31 percent lower for each 1-unit increase in peak roof strength-to-weight ratio (SWR) measured within 5 inches of plate displacement (p-value of 0.004). Appendix A reports details of this analysis. Clearly, ejection risk is not "unrelated to roof strength."

   c. By treating ejection as a risk factor unrelated to roof strength, when reduced ejection risk is one of the benefits of stronger roofs, Padmanaban and Moffatt bias their analysis against finding a relationship between roof strength and injury risk.

   d. Padmanaban and Moffatt's concern about ejection implies that roof strength does not matter if ejected occupants are not counted. However, a new IIHS analysis limited to drivers coded by police as not having been ejected reveals that stronger roofs reduced injury risk among these drivers. Many of the fatal and incapacitating injuries in the overall analysis were sustained by ejected drivers, but risk reductions for drivers not ejected were statistically significant and very similar to the overall analysis. Appendix B reports the full results.

2. **Belt use cannot be used in a model evaluating roof strength and injury likelihood because information about belt use in crashes is inaccurate, incomplete, and subject to influence by the injury outcomes.**

   Another variable that Padmanaban and Moffatt argue should be included as a control (predictor) variable in the IIHS study is police-reported belt use. According to Padmanaban and Moffat, "It is well known that the majority of rollover KA injuries and fatalities are to unbelted occupants, mostly ejectees" (pg. 2) and, later, "… 56% of the fatalities and 28% of the serious/fatal injuries were unbelted and completely ejected" (pg. 5). As a result, Padmanaban and Moffat conclude that belt use should have been a predictor variable. However, because this variable is difficult to know with precision, inclusion as a predictor variable can bias any analysis of roof strength.

   a. The principal source of bias in belt use codes is that police-coded belt use is subject to distortion by crash outcomes. No official typically is present to observe belt use prior to a crash. Instead, police must *judge* belt use based on information gathered after the crash including statements by occupants about their own belt use, statements by witnesses to the crash and, significantly, the presence of injuries and whether police believe they are consistent or inconsistent with belt use. In other words, Padmanaban and Moffat include in their analysis a variable that is itself subject to influence by the outcome (injury severity and pattern) to be predicted. In addition, occupant statements about belt use are influenced by the fact that it is illegal in most states to be unbelted. A result of these twin biases is that belt use in crashes can be overestimated, especially for occupants with lesser injuries whose claims of belt use are more believable (Schiff and Cummings, 2004). Models including belt use as a predictor of injury severity not only introduce general inaccuracy but also overestimate the effect of belt use on reducing injury, simultaneously masking the effects of any other variables.

Evidence of the bias toward overestimating belt use in the dataset used in the IIHS study is provided by comparisons with NHTSA's National Occupant Protection Use Survey (NOPUS), which records rates of belt use for the general population observed during daylight hours. During the calendar years of the IIHS study, NOPUS data show driver belt use averaging 70-75 percent, which is lower than the 83 percent recorded by police for drivers in the rollover crashes in the IIHS study. It is unlikely that drivers involved in single-vehicle rollover crashes, many of which occur at night when belt use rates are lower (NHTSA, 2005, 2007), were wearing belts more often than the general population during daylight hours.

b. Because of these problems, IIHS did not include belt use as a predictor. However, IIHS did examine whether the effects varied by coded belt use. As reported in the study, additional statistical models were run for occupants coded as belted (83 percent), for those coded as unbelted (10 percent), and for those coded as unknown (7 percent).

   i. For those coded as belted, the pattern of effects of roof strength varied little from the overall analysis. This is not surprising because most drivers in the study were coded as belted. In addition, if belt use is miscoded, as argued above, then many of the drivers actually were unbelted, again meaning that this analysis is very similar to the overall analysis.

   ii. For those coded as unknown, the pattern also was quite similar to the overall analysis. Again, this is not surprising because the unknown group also included both belted and unbelted occupants.

   iii. Effects estimated for those coded as unbelted were much smaller, but this would be expected from the twin biases noted in item 2.a. It is likely many of those coded as unbelted received their codes because their injuries were serious and inconsistent with belt use. This bias would occur for both weak and strong roofs, masking the effect of roof strength by assigning higher weight to the (overestimated) effect of belt use.

The conclusion from these separate analyses is that coded belt use does not affect the estimated effect of roof strength on injury severity, except in a way that would be expected from the biases and inaccuracies inherent in police-coded belt use.

3. **Like police-coded belt use, police-coded alcohol involvement in crashes is incomplete, inaccurate, and may be related to the injury severity. Besides, Padmanaban and Moffatt offer no justification other than the empirical relationship, which could be spurious, for including alcohol use codes in the prediction equation.**

a. Results of blood alcohol concentration (BAC) tests are the most objective measures of the presence of alcohol, but only a small percentage of crash-involved drivers typically are tested. Queries of the state databases used in the IIHS study show that about 11 percent of the drivers studied were tested. Padmanaban and Moffatt report using a combination of BAC test results and "had been drinking" codes. They do not specify in their comments to NHTSA what percentage of the codes resulted from actual BAC tests, what codes were used for those not tested, or the extent of missing data. In response to an IIHS inquiry, they provided this additional information:

i. Of drivers identified in their analysis as positive for alcohol use, about 18 percent were tested. About 13 percent tested positive, and 5 percent were coded as having positive alcohol use despite negative BAC tests. Thus 5 percent were coded as positive for alcohol despite chemical tests to the contrary.

ii. For drivers without BAC test results, Padmanaban and Moffatt determined alcohol use from a variety of codes regarding police judgment of alcohol use or factors contributing to the crashes. When alcohol was not listed as a factor, alcohol use was coded as negative.

b. It is incorrect to assume that all of the drivers not tested were alcohol-free based on police not listing alcohol as a contributing factor to the crashes. According to Moskowitz et al. (1999), police most often cite breath odor in determining alcohol involvement in traffic offenses, but the ability to detect this odor is unreliable even under controlled laboratory conditions.

c. It is likely that reported alcohol use is spuriously related to injury outcome because more seriously injured people are more likely to undergo close examination. About half of the states included in the IIHS study mandate BAC testing of fatally injured drivers (NHTSA, 2004), creating inherent reporting bias because the likelihood of testing is correlated with injury outcome. Padmanaban and Moffatt do not report or account for this bias.

d. It is likely that factors such as crash severity, vehicle damage, and driver age and gender have some influence on whom police choose to test for alcohol as well as which crashes they judge to be influenced by alcohol. Previous research has found that driver age and gender affect which drivers at sobriety checkpoints are judged not drinking (Wells et al., 1997).

e. Although alcohol clearly increases crash likelihood, Padmanaban and Moffatt offer no explanation of how alcohol increases the likelihood of K/A injury, given that a crash already has occurred. Absent convincing evidence that alcohol increases the susceptibility of human tissue and bones to injury, the primary determinants of whether an injury occurs to alcohol-impaired or sober occupants are the forces experienced during the crash. It might be argued that sober drivers' rollover crashes would be more severe, and their injurious forces greater, than those of drinking drivers because more extreme circumstances would be required for the sober drivers to lose control of their vehicles or leave the road. But this argument leads to the opposite of the effect claimed by Padmanaban and Moffatt. Any empirical relationship to the contrary observed between alcohol and K/A injury likelihood is likely to be spurious and related to the absence of objective evidence of alcohol involvement after a crash has occurred.

4. Padmanaban and Moffatt's docket submission is based on unsound and inconsistent statistical treatment. It contains numerous misstatements and omissions that undermine its conclusions.

a. They either misunderstand or misconstrue the fundamental concepts of statistical estimation and significance testing. The object of a study of roof strength is to obtain the best estimate permitted by the data. In this context, statistical significance is only a way of representing how often one expects to be wrong in concluding that the observed estimate is indicative of a real non-zero effect. Padmanaban and Moffatt claim that if the estimated effect of roof strength on injury risk is found to be "not significant, then the lives saved [by strengthening roofs] could just as well be zero or negative" (pg. 2). This trivializes the process of statistical estimation in a way that is fundamentally misleading.

i. It is misleading to treat any estimate with a p-value slightly above 0.05 as if it were drastically different from estimates with p-values slightly below 0.05. For example, among the effects estimated for reductions in the likelihood of driver death with increased roof strength, the p-value for SWR within 5 inches of crush was slightly greater than 0.06. This means that if one were to conclude that an effect this large is different from zero, one would expect to be wrong about 6 times out of 100 (a p-value of 0.05 would lower the error risk only slightly, to 5 times in 100). This 6 percent error risk also means that the likelihood of seeing effects as large as that estimated for roof strength when the true effect is zero or negative is only about 3 in 100. Padmanaban and Moffatt misrepresent the logic of statistical estimation and misconstrue the implications of significance testing.

ii. This illogical approach leads them to ignore the overwhelming consistency of the results of the IIHS study. Their docket submission suggests that a single IIHS estimate for injury risk reduction that was not significant at the 0.05 level contradicts and invalidates the overall finding that stronger roofs reduce injury risk. Of the 12 estimates for K/A injury risk related to roof strength measured in 4 different ways and at 3 different crush distances, all were significant at $p<0.0001$. For the 12 estimates for K injury risk, 9 were significant at $p<0.0001$, 2 at $p<0.05$, and 1 at $p<0.07$. Robustness of an empirical pattern when measured in different ways is much more important than the fact that 1 of 24 tests did not meet an arbitrary level of $p<0.05$.

b. The docket submission does not include sample sizes for any of Padmanaban and Moffatt's 7 statistical models. In response to subsequent requests by IIHS, they indicated sample sizes ranging from 1,352 to 20,010. These details should have been included in the discussion of their statistical modeling, especially given their ill-advised reliance on levels of statistical significance for interpretation of results. For example, they emphasize that odds ratios in the IIHS study were not statistically significant for the subset of drivers that police coded as unbelted, asserting that this means roof strength is not beneficial for these occupants. However, these drivers account for only 10 percent of the total sample, limiting the power to detect statistically significant effects.

c. Padmanaban and Moffatt do not give parameter estimates for the predictors of injury risk they chose to include in their comment. Without these, it is unknown whether the effects being estimated by their models are consistent or realistic relative to some underlying reasonable theory. Subsequent IIHS inquiries produced some, but not all, of the parameter estimates (see item 5.a.i. below).

d. Padmanaban and Moffatt do not present p-values for their additional parameters in the model that looked at fatality risk, saying only that roof SWR was not significant at a p-value of 0.10. It is possible that some variables previously claimed to be major factors (alcohol, belt use, ejection status) in injury outcome were not significant in this model.

5. Padmanaban and Moffatt's docket submission is based on questionable engineering judgment.

a. They stress the importance of aspect ratio (height divided by track width) in previous research and criticize IIHS for excluding it. In their reproduction of the IIHS study, they find it statistically significant. This is problematic for 4 reasons:

i. Based on data provided to IIHS, their models predict greater injury risk in SUVs with larger aspect ratios. This directly contradicts their previous studies, which reported decreased injury risk for vehicles with larger aspect ratios. Padmanaban and Moffatt do not explain or even disclose this fact in their submission to NHTSA.

ii. They do not offer a hypothesis for how the shape of these SUVs, as defined by aspect ratio, would affect injury risk. This also is true of their previous research, although they have stated that it is unrelated to differences in headroom. If the small geometric differences between these midsize SUVs are important in the rollover crash dynamics, more meaningful measurements would include maximum vehicle width or vehicle width at the height of the roof.

iii. The range of aspect ratios given for these vehicles is very small. Height and track width vary by up to only about 2 inches.

iv. There is enough variation in the specified height and track width measurements between model years of several of the study vehicles to invalidate whatever data were used.

b. Padmanaban and Moffatt do not seem to understand the IIHS motivation for including static stability factor (SSF) in the statistical models, stating that “the purpose of the IIHS study and of ours was to evaluate the likelihood of serious/fatal injuries given a rollover and not the likelihood of rollovers.” The IIHS study clearly explains why SSF may be correlated to crash severity: By definition, more stable vehicles require more severe events to cause them to roll over.

c. Padmanaban and Moffatt do not explain why vehicle weight should be included in two different places in their statistical models. They include it both as an independent variable and in the calculation of SWR.

6. Padmanaban and Moffatt misrepresent the IIHS study.

a. They say they “agree [with the IIHS study] that SWR within 5 inches is the most useful and universally accepted roof strength metric,” but the IIHS study makes no such claim. Its calculations of lives saved use this metric simply because FMVSS 216 uses the same metric. SWR within 5 inches of plate displacement is 1 of 12 roof strength metrics IIHS evaluated, and several of the other metrics predict greater reductions in injury risk across the range of tested vehicles. Even with their problematic predictors, it is possible that Padmanaban and Moffatt would have found statistically significant results with different roof strength metrics.

b. Padmanaban and Moffatt claim that the regression line in Figure 1 of the IIHS study is the “primary finding” and later in their submission to NHTSA dedicate much time to discussing this line. However, they separately state their understanding that the plot is included “solely to present a visual representation of their raw data. [IIHS does] not rely upon it in any way for their conclusions.” This second statement is correct, and it is disingenuous to criticize the statistical fit of a plot presented for visualization and understood to be uncorrected for known confounding factors.

c. They claim IIHS used the estimate for the reduction of fatal and incapacitating injury in the lives-saved calculations because the fatality estimate alone was not statistically significant (see items 4.a.i. and 4.a.ii. above). However, the former estimate was used because it is based on more observations (of injuries) and therefore likely to be more accurate. For the other 11 roof strength metrics, little variation was observed between effect estimates for K/A injury and for fatal injury, so the choice was well founded.

d. Padmanaban and Moffatt say their analysis does not "differ significantly from [IIHS] raw data counts" but do not give any details. Responses to subsequent requests from IIHS indicate their analysis includes 2,807 fewer drivers overall and 100 more drivers with fatal or incapacitating injuries. These differences are not explained. Padmanaban and Moffatt fail to demonstrate that their data and analysis replicate the IIHS study before including additional predictor variables. If their initial analysis cannot replicate IIHS's, then none of their subsequent claims are applicable to the current discussion.

7. Padmanaban and Moffatt's docket submission and associated analysis cannot be fully evaluated due to the lack of detailed information about data sources, methods, and results.

In contrast, IIHS methods and findings are fully described in the study. IIHS staff further assisted JP Research in understanding the construction of the statistical models used in the study. All information necessary to reconstruct the IIHS study is available to the public.

a. For some additional predictor variables, unexplained discrepancies exist between the data counts in the state files and the counts JP Research reported to IIHS. For example, JP Research reports that ejection status was known for all but 2,198 drivers, whereas IIHS observed that ejection status was coded as unknown or completely missing for 8,713 drivers in the state data files. It would be useful to know how JP Research obtained the ejection status for their analyses.

b. The docket submission includes statements about the methods used in their two previous studies that were not disclosed in that research. For example, the submission claims that both earlier studies controlled for ejection and rural/urban land use, but their 2005 study mentions neither among the factors included in the logistic regression models. The docket comment says "all our previous models also controlled for states, though it was not explicitly stated in the reports" (pg. 3). It is impossible to judge the credibility of any study when important details are omitted about how the research was conducted.

c. Padmanaban and Moffatt report access to the results of other roof strength tests of the IIHS study vehicles that differ substantially from the IIHS results. These other results are not public, so it is impossible to determine their relevance. Previous research by Padmanaban and Moffatt included confidential tests conducted by vehicle manufacturers on non-production vehicles (Moffatt and Padmanaban, 1995; Padmanaban et al., 2005), and we do not know the nature of any additional test data on IIHS study vehicles.

d. As detailed above, Padmanaban and Moffatt exclude several important facts that were revealed to IIHS only after follow-up inquiries to JP Research (see items 3.a., 4.b., 4.c., 5.a.i., 6.d., and 7.a.).

Appendix A – Relationship between roof strength and ejection risk

To address Padmanaban and Moffatt's claim that ejection is "likely to be unrelated to roof strength," IIHS conducted a logistic regression analysis of ejection likelihood based on roof strength. Vehicle and crash data were the same as in IIHS's analysis of vehicle roof strength and injury risk (Brumbelow et al., 2008). Figure 1 shows the relationship in the raw data between peak roof SWR within 5 inches of plate displacement and ejection rate before adjusting for any potentially confounding factors. Of 22,817 rollover crashes of study vehicles, police coded 13,086 drivers as not ejected, 1,018 as fully or partially ejected, and the rest were coded as unknown or had missing values. Only the drivers with known ejection status were included in this analysis. Table 1 presents results of the logistic regression model controlling for the effects of state, driver age, and vehicle SSF. For a 1-unit increase in peak SWR, ejection risk was reduced 32 percent. For each 10-year increase in driver age, there was an 11 percent decrease in ejection risk. Both of these results are statistically significant at the 0.05 level. An increase in SSF of 0.1 was predicted to increase ejection risk by 4 percent, but this result was not statistically significant at the 0.05 level.

Figure 1 – Rates of full or partial driver ejection by peak SWR within 5 inches of plate displacement

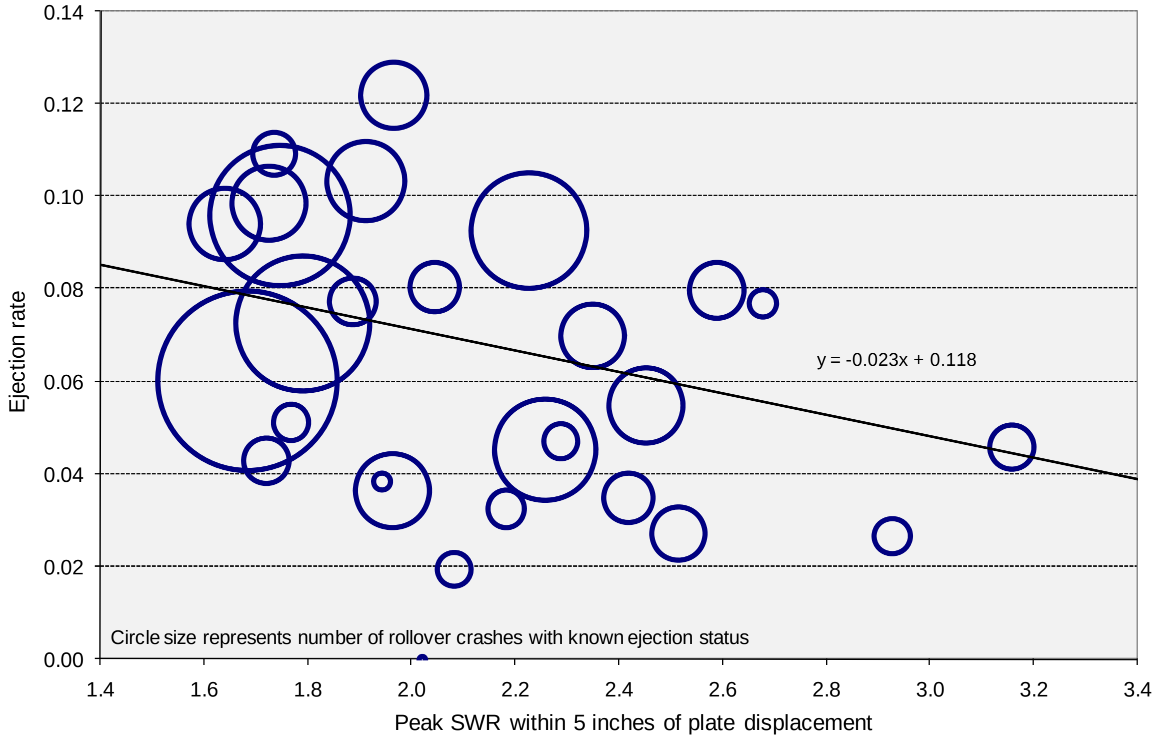


Table 1 – Results of logistic regression model for risk of ejection

Parameter	Odds ratio
Roof SWR within 5 inches (1-unit increase)	0.68*
Driver age (10-year increase)	0.89*
SSF (0.1-unit increase)	1.04

*Statistically significant at 0.05 level

Appendix B – Relationship between roof strength and injury risk for drivers coded as not ejected

The logistic regression model described in Appendix A demonstrates that reducing the risk of driver ejection is one benefit of stronger roofs. Also of interest is how stronger roofs benefit drivers who remain inside a vehicle during a rollover crash. Police coded 13,086 drivers in the IIHS study as not ejected. Figure 2 shows the relationship between the rate of fatal or incapacitating injury among the nonejected drivers and the peak roof SWR measured within 5 inches of plate displacement for each of the vehicles. The figure plots the raw data before adjusting for any confounding factors. Controlling for state effects, SSF, and driver age, a logistic regression model estimated a 27 percent reduction in the risk of fatal or incapacitating driver injury for a 1-unit increase in peak SWR within 5 inches of plate displacement. Nearly identical to the risk reduction estimated for all drivers in the IIHS study (see Table 2), this result is not surprising because nonejected drivers represent 93 percent of all drivers with known ejection status. A 10-year increase in driver age was predicted to increase the risk of K/A injury by 18 percent. A 0.1-unit increase in SSF was associated with a 6 percent increase in K/A injury risk. The odds ratios for SWR and driver age were significant at the 0.05 level, but the odds ratio for SSF was not.

Figure 2 – Rates of fatal or incapacitating driver injury by peak SWR within 5 inches of plate displacement

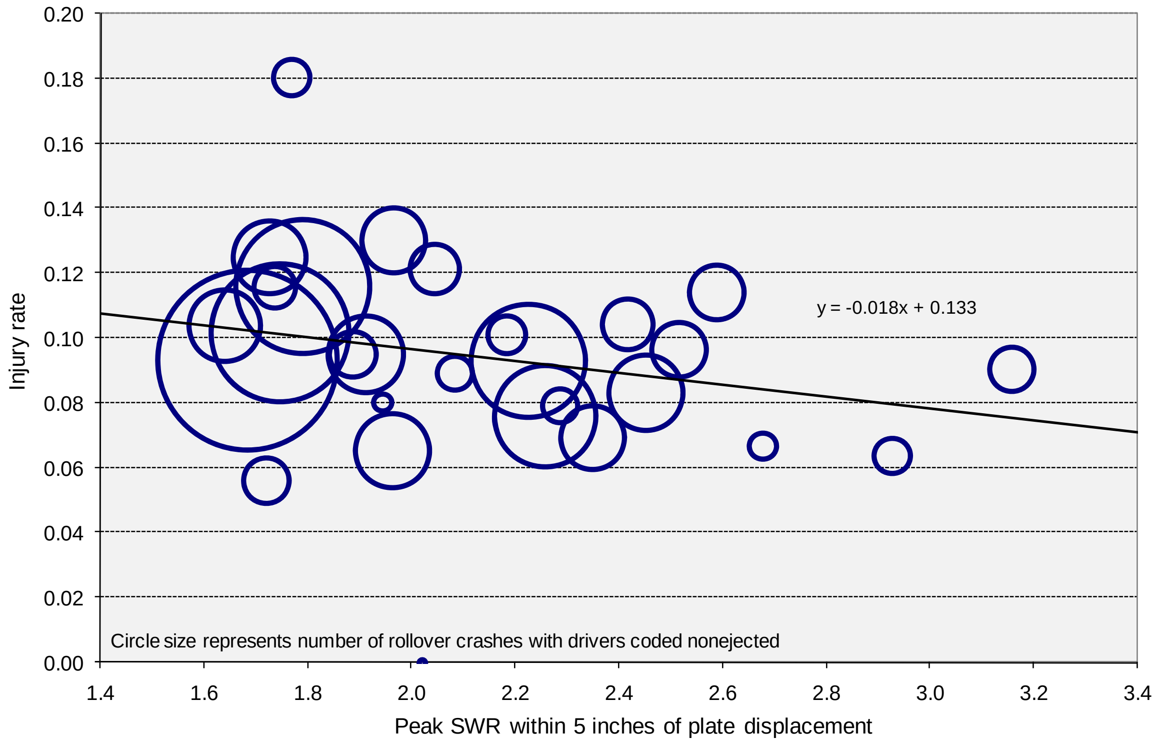


Table 2 – Results of logistic regression model for risk of fatal or incapacitating injuries for drivers coded as nonejected by police and for all drivers

Parameter	Odds ratio for drivers coded as nonejected	Odds ratio for all drivers
Roof SWR within 5 inches (1-unit increase)	0.73*	0.72*
Driver age (10-year increase)	1.18*	1.12*
SSF (0.1-unit increase)	1.06	0.96

*Statistically significant at 0.05 level

References

Brumbelow, M.L.; Teoh, E.R.; Zuby, D.S.; and McCartt, A.T. 2008. Roof strength and injury risk in rollover crashes. Arlington, VA: Insurance Institute for Highway Safety.

Insurance Institute for Highway Safety. 2008. Comment to the National Highway Traffic Safety Administration concerning proposed changes to Federal Motor Vehicle Safety Standard 216, Roof Crush Resistance; Docket No. NHTSA-2008-0015, March 27. Arlington, VA.

Moffatt, E.A. and Padmanaban, J. 1995. The relationship between vehicle roof strength and occupant injury in rollover crash data. *Proceedings of the 39th Annual Conference of the Association for the Advancement of Automotive Medicine*, 245-67. Des Plaines, IL: Association for the Advancement of Automotive Medicine.

Moskowitz, H.; Burns, M.; and Ferguson, S. 1999. Police officers' detection of breath odors from alcohol ingestion. *Accident Analysis and Prevention* 31:175-80.

National Highway Traffic Safety Administration. 2004. State laws and practices for BAC testing and reporting drivers involved in fatal crashes. Report no. DOT HS-809-756. Washington, DC: US Department of Transportation.

National Highway Traffic Safety Administration. 2005. Connecticut's day and night safety belt use. Report no. DOT HS-809-954. Washington, DC: US Department of Transportation.

National Highway Traffic Safety Administration. 2007. Daytime and nighttime seat belt use at selected sites in New Mexico. Report no. DOT HS-810-705. Washington, DC: US Department of Transportation.

Padmanaban, J. and Moffatt, E.A. 2008. Comment to the National Highway Traffic Safety Administration concerning proposed changes to Federal Motor Vehicle Safety Standard 216, Roof Crush Resistance; Docket No. NHTSA-2008-0015, March 27. Mountain View, CA.

Padmanaban, J; Moffatt, E. A.; and Marth, D.R. 2005. Factors influencing the likelihood of fatality and serious/fatal injury in single-vehicle rollover crashes. SAE Technical Paper Series 2005-01-0944. Warrendale, PA: Society of Automotive Engineers.

Schiff, M.A. and Cummings, P. 2004. Comparison of reporting of seat belt use by police and crash investigators: variation in agreement by injury severity. *Accident Analysis and Prevention* 36:961-65.

Wells, J.K.; Greene, M.A.; Foss, R.D.; Ferguson, S.A.; and Williams, A.F. 1997. Drinking drivers missed at sobriety checkpoints. *Journal of Studies on Alcohol* 58:513-17.

STATUS REPORT

INSURANCE INSTITUTE FOR HIGHWAY SAFETY

Vol. 43, No. 2, March 15, 2008

ROLL OVER

IN YOUR SUV, AND YOU WANT THE ROOF TO HOLD UP SO YOU'RE PROTECTED

from injury, including harm from the roof caving in on you. Every passenger vehicle meets federal requirements for roof strength, measured in a test, and some exceed the requirements by substantial amounts. The question has been whether stronger roofs actually reduce injury risk in real-world rollover crashes. Some studies have concluded that the strength of a vehicle's roof has little or no effect on the likelihood of injury, but a new Institute study indicates that roof strength definitely influences injury risk.

Researchers tested SUVs in a procedure similar to what the government requires automakers to conduct to assess roof strength and then related the findings to the real-world death and injury experience of the same SUVs in single-vehicle rollover crashes. The main finding is that injury risk went down as roof strength increased.

Injury rates vary considerably among vehicles in rollovers, and there's still a lot researchers don't know about these crashes. For example, is injury risk primarily from the sudden crushing of the roof? Is it because people crash into the roof when the vehicle is upside down? Or does the main risk come from full or partial ejection of occupants when vehicle doors and windows break open during rollover crashes?

"We don't know just what happens to people in these crashes or what the injury mechanisms are. What we do know from the new study is that strengthening a vehicle's roof reduces injury risk, and reduces it a lot," says Institute president Adrian Lund.

Extent of the rollover problem: About 35 percent of all occupant deaths occur in crashes in which vehicles roll over. This problem is worse in some kinds of vehicles than others. About 25 percent of occupant deaths in crashes of cars and minivans involve rolling over. The proportion jumps to 59 percent in SUVs.

Of course, the best way to prevent these deaths is to keep vehicles from rolling over in the first place, and electronic stability control is helping. It's reducing rollover crashes, especially fatal single-vehicle ones, by significant percentages.

"But until these crashes are reduced to zero, roof strength will remain an important aspect of occupant protection," Lund points out.

What the US government requires: Federal Motor Vehicle Safety Standard 216 establishes minimum roof strength for passenger vehicles. Compliance testing involves the application of a metal plate to one side of a roof at a constant speed. The roof must withstand a force of 1.5 times the weight of the vehicle before reaching 5 inches of crush. Thus, a vehicle weighing 4,000 pounds has to withstand 6,000 pounds of force while sustaining 5 or fewer inches of crush.

This requirement, in effect since 1973 for cars and 1994 for other passenger vehicles, is in the process of an upgrade. One of the government's main proposals, issued in 2005, is to boost the specified force to 2.5 times vehicle weight (see *Status Report*, Jan. 28, 2006; on the web at iihs.org). Last month the government indicated it may consider further altering the standard by testing both sides of vehicle roofs instead of applying the force to one side only. When the changes were proposed in 2005, the Institute voiced general support but noted the "surprising lack of evidence" connecting the requirements of the standard to real-world rollover crash outcomes.

The new Institute study provides some missing evidence. Across 11 SUVs at 3 different degrees of roof crush — 2, 5, and 10 inches — the strongest roofs are associated with injury risks 39 to 57 percent lower than the weakest roofs. Peak roof strength at 2 and 10 inches of crush is more highly related to injury risk than at 5 inches. Based on these findings, the researchers estimate that if the roofs on every SUV the Institute tested were as strong as the strongest one, about 212 of the 668 deaths that occurred in these SUVs in 2006 would have been prevented.

"These are big risk reductions, bigger than what the government or anybody else has established," Lund says.

The researchers estimate that a 1-unit increase in peak strength-to-weight ratio — for example, from 1.5 times vehicle weight to 2.5, as the government proposed in 2005 — reduces the risk of serious and fatal injury in a rollover crash by 28 percent. Increasing roof strength requirements beyond 2.5 times vehicle weight would reduce injury risk even further.

IMPORTANCE OF ESC AND SIDE AIRBAGS

Vehicle roof strength is crucial to occupant protection in rollover crashes. Other features are effective, too, in both preventing such crashes in the first place and protecting people when their vehicles do roll. Researchers estimate that electronic stability control, or ESC, reduces the risk of a fatal single-vehicle rollover by about 69 percent for all passenger vehicles and 72 percent for SUVs in particular. Side curtain airbags are expected to reduce the risk of death in the rollovers that still occur.

"These technologies are essential," Institute president Adrian Lund points out, "but electronic stability control doesn't completely eliminate rollover crashes, and side airbags aren't the only protection occupants need if they do roll over. This is why we have to pay attention to the roof. If a vehicle's roof is strong enough to absorb the energy of a rollover without caving in on its occupants, injury risk goes down."

Electronic stability control monitors vehicle response to driver steering and applies the brakes on individual wheels to maintain the path that's indicated by the steering wheel position (see *Status Report*, June 13, 2006; on the web at iihs.org). This technology is standard or optional on about two-thirds of all current passenger vehicle models. Side airbags are standard or optional in about 80 percent.

STRONG VS. WEAK

The difference in roof strength was obvious when the Nissan Xterra and Ford Explorer, both 2000 models, were subjected to a crushing force of up to 10,000 pounds. The Xterra's roof crushed about 2 inches, and damage is hardly visible except for a cracked windshield. Meanwhile the Explorer's roof crushed 10 inches, caving far into the occupant compartment even before reaching 10,000 pounds of force.

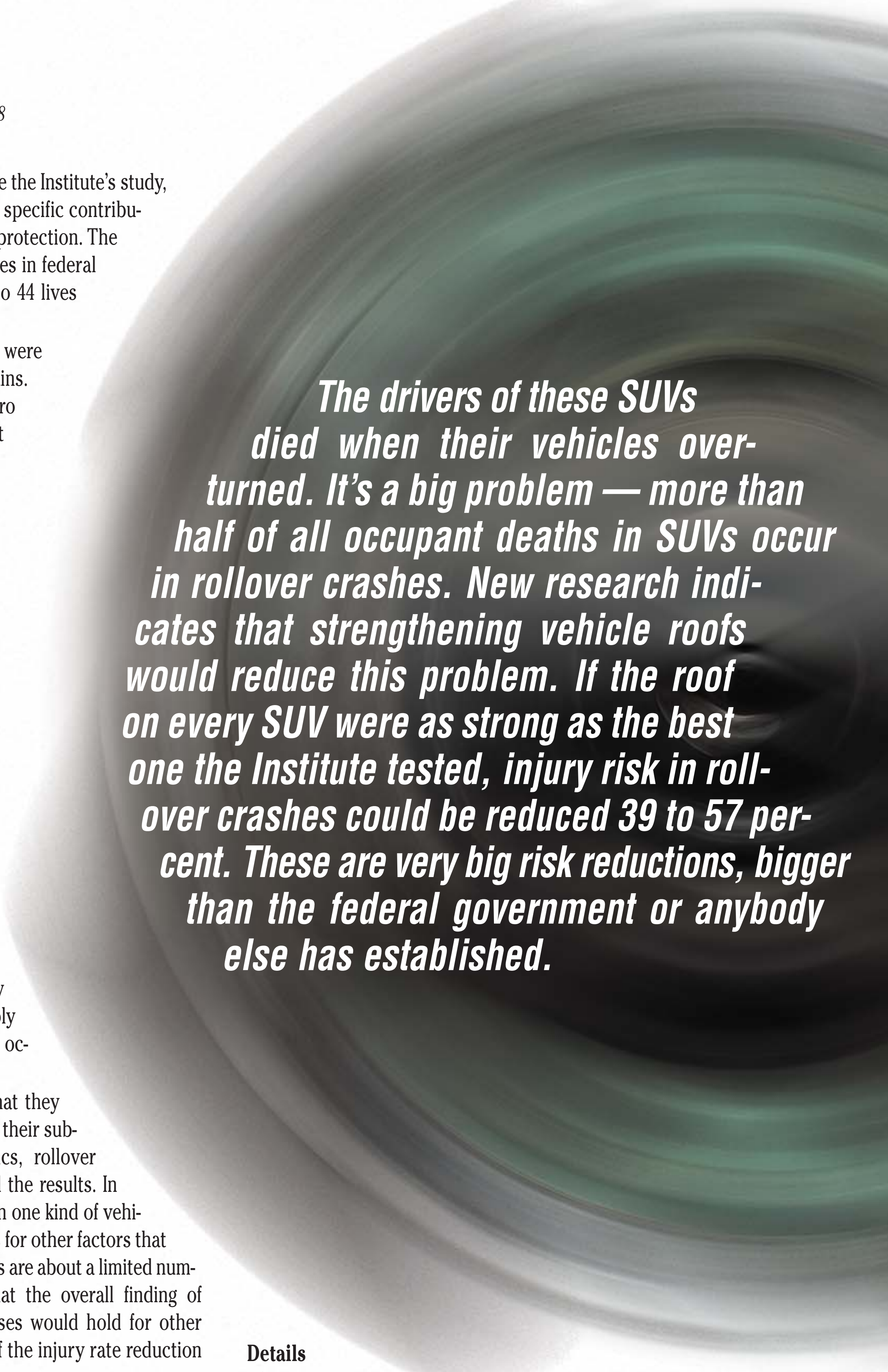
New findings vs. previous studies: Before the Institute's study, there was no conclusive evidence about the specific contribution of a vehicle's roof strength to occupant protection. The government estimated that proposed changes in federal roof strength requirements would save 13 to 44 lives per year.

"This was based on assumptions that were conservative in the extreme," Lund explains. "For example, the government assumed zero benefit for unbelted occupants. We don't know exactly what the benefit of an upgraded roof strength standard would be for these occupants, but it would be likely to exceed zero."

Meanwhile two studies sponsored by automakers, one in 1995 and the other a decade later, found no relationship at all between roof strength and injury risk in rollovers. Findings of the first study prompted General Motors to tell *The Detroit News* in 2002, "Good science, long established and well reviewed in the technical literature, has conclusively demonstrated that there is no relationship between roof strength and the likelihood of occupant injury given a rollover." Four years later, Ford told the government that "substantial and compelling real-world crash data and laboratory testing have confirmed that simply increasing roof strength will not measurably reduce the risk of injury or death to vehicle occupants in rollovers."

A main problem with these studies is that they included all kinds of passenger vehicles with their substantial differences in driver demographics, rollover propensity, and other factors that confound the results. In contrast, the Institute's new study focuses on one kind of vehicle, midsize 4-door SUVs, and tightly controls for other factors that could confound the results. While the findings are about a limited number of SUVs, the researchers conclude that the overall finding of reduced injury risk as roof strength increases would hold for other kinds of vehicles, although the magnitude of the injury rate reduction may differ among vehicle groups.

Lund adds that the findings "prompt us to expand our research on roof strength with an eye to supplying consumers with comparisons of how well vehicles protect people in rollover crashes. A dynamic test with dummies instrumented to measure injury risk in rollovers would be desirable, but there's a sticking point. First we have to understand how the movement of dummies in controlled tests could reflect how real people move in real-world rollovers. Meanwhile, simpler roof strength measurements could provide useful consumer information."



The drivers of these SUVs died when their vehicles overturned. It's a big problem — more than half of all occupant deaths in SUVs occur in rollover crashes. New research indicates that strengthening vehicle roofs would reduce this problem. If the roof on every SUV were as strong as the best one the Institute tested, injury risk in rollover crashes could be reduced 39 to 57 percent. These are very big risk reductions, bigger than the federal government or anybody else has established.

Details of the study: The Institute study is a two-part analysis involving vehicle testing and examination of the outcomes of real-world rollover crashes. Eleven midsize 4-door SUVs were subjected to a test similar to the one run by automakers to comply with federal roof strength requirements (the manufacturers' own test data aren't public information). The 11 SUVs exclude features that might affect injury rates in rollovers such as side curtain airbags and electronic stability control (see p.2). To

assess the range of roof strength among the SUVs, researchers applied force to the roofs until crush reached 10 inches, measuring the peak force required for 2 inches of crush, 5 inches, and 10 inches. Because crush in a rollover can depend on vehicle weight as well as roof strength, the researchers calculated strength-to-weight ratios for each degree of crush. They also measured the amount of energy absorbed by each roof at each degree of crush and, again taking vehicle weight into account, the height from which the vehicle would have to be dropped to produce equivalent energy absorption.

By almost any of these measures, the strongest roof was on the 2000-04 Nissan Xterra while one of the weakest was on the 1999-2004 Jeep Grand Cherokee. Within 5 inches of crush, the Jeep withstood a force as high as 6,560 pounds, which amounts to 1.64 times the weight of the 4-wheel-drive version and 1.72 times the weight of the 2-wheel-drive. The corresponding figure for the Xterra was 11,996 pounds, or 2.93 times the weight of the 4-wheel-drive and 3.16 times the 2-wheel-drive.

Having established the range of roof strength among the SUVs, the researchers studied almost 23,000 real-world rollovers of the same 11 SUVs during 1997-2005. This information was collected from 12 states with sufficient data on police-reported crashes to comply with study criteria.

Logistic regression was used to assess the effect of roof strength on the likelihood of driver injury in the rollover crashes of the 11 SUVs. The regression controlled for state-to-state differences in methods of reporting crashes, terrain, urbanization, etc.; vehicle stability; and driver age. Results indicate the various injury risks given the various SUV roof strengths.

"No matter what measurement of roof strength we used or whether we measured at 2 or 5 or 10 inches of crush, we found a consistent relationship between roof strength and injury risk," Lund points out.

The relationship between roof strength-to-weight ratio and injury risk was stronger at 2 inches than at 5 inches, the crush specified for testing under the federal standard (the government doesn't require automakers to assess roof strength at 2 or 10 inches). At 5 inches, the predicted injury risk for people in SUVs with roof strength-to-weight ratios as strong as the Xterra's would be 39 percent lower than for people in vehicles with roof strength like the Grand Cherokee's. At 2 inches of crush, the difference in predicted injury risk is 51 percent.

The 11 SUV designs in the study include the 1996-2004 Chevrolet Blazer, 2002-05 Chevrolet TrailBlazer, 1998-2003 Dodge Durango, 1996-2001 Ford Explorer, 2002-04 Ford Explorer, 1996-98 Jeep Grand Cherokee, 1999-2004 Jeep Grand Cherokee, 2002-05 Jeep Liberty, 1997-2004 Mitsubishi Montero Sport, 2000-04 Nissan Xterra, and 1996-2000 Toyota 4Runner.

For a copy of "Relationship between roof strength and injury risk in rollover crashes" by M.L. Brumbelow et al., write: Publications, Insurance Institute for Highway Safety, 1005 N. Glebe Rd., Arlington, VA 22201, or email publications@iihs.org.

NECK INJURY RISK IS LOWER IF SEATS AND HEAD RESTRAINTS ARE RATED GOOD

The rate of neck injury complaints is 15 percent lower in cars and SUVs with seat/head restraint combinations rated good compared with poor. The results for serious injuries are more dramatic. Thirty-five percent fewer insurance claims for neck injuries lasting 3 months or more are filed for cars and SUVs with good seat/head restraints than for ones rated poor.

These are the main findings of a new Institute study of thousands of insurance claims filed for damage to vehicles, all 2005-06 models, that were struck in front-into-rear impacts. Conducted in cooperation with State Farm and Nationwide, the study is the first time seat/head restraint ratings based on dynamic tests conducted by the Institute have been compared with real-world neck injury results.

"In stop and go traffic, you're more likely to get in a rear-end collision than any other kind of crash, so you're more likely to need your seat and head restraint than any other safety system in your vehicle," says David Zuby, the Institute's senior vice president for vehicle research. "This is why it's so important to fit vehicles with seats and head restraints that earn good ratings for saving your neck."

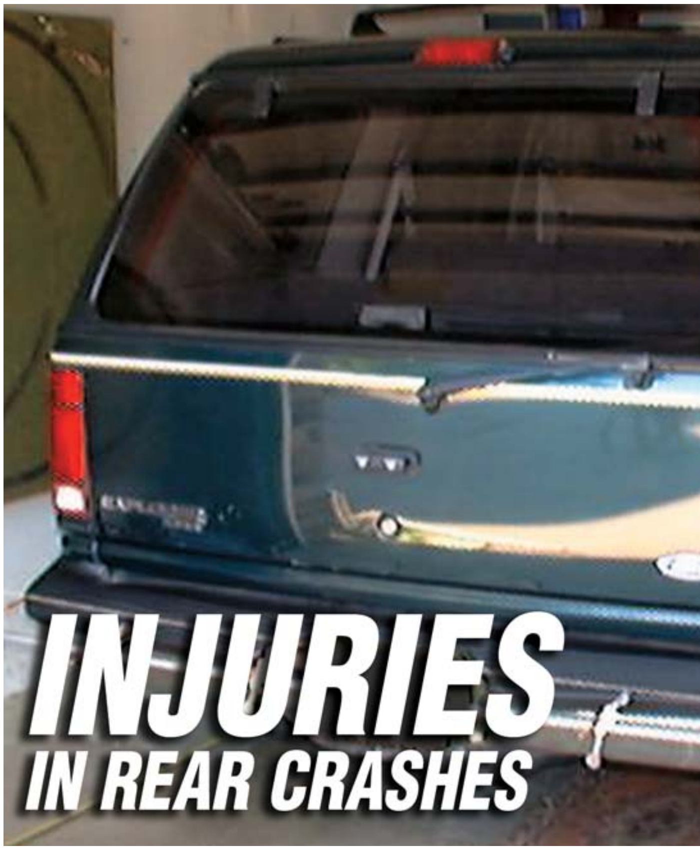
The Institute has been measuring and rating head restraint geometry since 1995. The higher and closer a restraint is, the more likely it will be to prevent neck injury in a rear collision. In 2004 the Institute added a dynamic test simulating a rear crash to refine the ratings. Vehicles are rated good, acceptable, marginal, or poor based on both restraint geometry and test results (see *Status Report*, Nov. 20, 2004; on the web at iihs.org). The same rating system is used internationally by a consortium of insurer-sponsored organizations, the International Insurance Whiplash Prevention Group.

An estimated 4 million rear collisions occur each year in the United States. Neck sprain or strain is the most serious injury in one-third of insurance claims for injuries in all kinds of crashes. The annual cost of these claims exceeds $8 billion annually.

While findings about real-world neck injury in vehicle seats rated good and poor are clear, those for seats rated acceptable and marginal aren't as clear. There wasn't any reduction in initial neck injury complaints for acceptable and marginal seats, compared with poor, though long-term neck injuries were reduced.

"The long-term injuries are the very ones we want to reduce because they're the most serious," Zuby points out. "While many neck injuries involve moderate discomfort that goes away in a week or so, about one of every four initial complaints still was being treated three months later. These longer term injuries involve more pain and cost more to treat. They're being reduced about one-third in vehicles with seat/head restraints rated good compared with poor. Serious neck injuries also are being reduced in seats that are rated acceptable or marginal.

Improvements: More and more passenger vehicles are being equipped with seats and head restraints rated good. When the Institute started evaluating and comparing the geometry of the head re-



These vehicles didn't sustain a lot of damage when they were struck from behind, but the drivers were treated for injuries suffered in the impacts. Neck sprains and strains are the most serious problems reported in about 1 of 3 insurance claims for injuries. This problem could be reduced by equipping vehicles with seat/head restraints rated good, based on Institute tests. Twenty-nine of all recent model cars and 22 perent of other passenger vehicles have systems rated good for protection against neck injury.

straints in 1995 model cars, only a handful were rated good and 80 percent were poor. Then the automakers responded, and by 2004 about 4 of every 5 head restraints had good or acceptable geometry (see *Status Report*, Nov. 20, 2004; on the web at iihs.org). Similarly, the dynamic performance of seat/head restraint combinations is improving. Only 12 percent of 2004 model cars had combinations rated good, but by the 2007 model year the proportion had increased to 29 percent (see *Status Report*, Aug. 4, 2007; on the web at iihs.org).

These improvements are being driven not only by ratings of seat/head restraints published by the Institute and other insurer-sponsored groups but also by a US standard that will require the restraints to extend higher and fit closer to the backs of people's heads by the 2009 model year. In the United States, automakers also have been spurred by the Institute's *TOP SAFETY PICK* award. To win this designation, a vehicle has to earn good ratings in all three tests — front, side, and rear.

How the injuries occur: When a vehicle is struck in the rear and driven forward, its seats accelerate occupants' torsos forward. Unsupported, an occupant's head will lag behind this forward torso movement, and the differential motion causes the neck to bend and stretch. The higher the torso acceleration, the more sudden the motion, the higher the forces on the neck, and the more likely a neck injury is to occur.

Factors that influence neck injury risk include gender and seating position in addition to the designs of seats and head restraints. Women are more likely than men to incur neck injuries in rear crashes, and front-seat occupants, especially drivers, are more likely to incur such injuries than people riding in back seats.

The key to reducing whiplash injury risk is to keep an occupant's head and torso moving together. To accomplish this, the geometry of a head restraint has to be adequate — high enough and near the back of the head. Then the seat structure and stiffness must be designed to work in concert with the head restraint to support an occupant's neck and head, accelerating them with the torso as the vehicle is pushed forward.

About the study: To correlate seat/head restraint ratings with real-world neck injury risk, researchers studied about 3,000 insurance claims associated with rear crashes of 105 of the 175 passenger vehicles (2005-06 models) for which the Institute has ratings based on both restraint geometry and seat performance in dynamic tests. The claims were filed with State Farm Mutual Insurance and Nationwide Insurance, which together account for more than 20 percent of the personal auto insurance premiums paid in the United States in 2005. The researchers modeled the odds of a neck injury occurring in a rear-struck vehicle as a function of seat ratings (good, acceptable, marginal, or poor), while controlling for other factors that also affect neck injury risk, such as vehicle size and type and occupant age and gender.

The percentage of rear-struck drivers with neck injury claims was 16.2 in vehicles with seats rated good, based on dynamic testing. Corresponding percentages were 21.1 for seats rated acceptable, 17.7 for marginal seats, and 19.2 for poor ones. Neck injuries lasting 3 months or more were reported by 3.8 percent of drivers in good seats, 4.7 percent in acceptable seats, 3.6 percent in marginal seats, and 5.8 percent in seats rated poor.

"What these data show is that we're pushing seat designs in the right direction," Zuby says, "Results for acceptable and marginal seats weren't as clear as for good seats. Initial neck injury claims weren't significantly lower than for poor seats. Still we saw reductions in claims for serious neck injuries in acceptable and marginal seats as well as in good ones."

This is the third study the Institute has conducted that indicates the superiority of seat/head restraint combinations rated good for reducing neck injury risk. In 1999 the Institute found that head restraints rated good for geometry alone had lower insurance claims for neck injuries. In 2003 Institute researchers expanded the data, finding that modern features such as head restraints that automatically adjust in rear-end collisions and seats that absorb energy also reduce insurance claims.

The key to reducing whiplash is to keep occupants' heads and torsos moving forward together when their vehicles are struck from behind.

For a copy of "Relationship of dynamic seat ratings to real-world neck injury rates" by C.F. Farmer et al., write: Publications, Insurance Institute for Highway Safety, 1005 N. Glebe Rd., Arlington, VA 22201, or email publications@iihs.org.

STATUS REPORT

INSURANCE INSTITUTE FOR HIGHWAY SAFETY

1005 N. Glebe Rd., Arlington, VA 22201
Phone 703/247-1500 Fax 247-1588
Internet: www.iihs.org
Vol. 43, No. 2, March 15, 2008

The Insurance Institute for Highway Safety is a nonprofit scientific and educational organization dedicated to reducing deaths, injuries, and property damage from crashes on the nation's highways. The Institute is wholly supported by auto insurers:

21st Century Insurance
AAA Mid-Atlantic Insurance Group
Affirmative Insurance
AIG Agency Auto
AIG Direct
Alfa Insurance
Alfa Alliance Insurance Corporation
Allstate Insurance Group
American Family Mutual Insurance
American National Property and Casualty
Ameriprise Auto & Home
Amerisure Insurance
Amica Mutual Insurance Company
Auto Club Group
Auto Club South Insurance Company
Bituminous Insurance Companies
Bristol West Insurance
Brotherhood Mutual
California State Automobile Association
Capital Insurance Group
Chubb Group of Insurance Companies
Concord Group Insurance Companies
Cotton States Insurance
COUNTRY Insurance & Financial Services
Countrywide Insurance Group
Erie Insurance Group
Esurance
Farm Bureau Financial Services
Farm Bureau Mutual Insurance Company of Idaho
Farmers Insurance Group of Companies
Farmers Mutual of Nebraska
Florida Farm Bureau Insurance Companies
Frankenmuth Insurance
The GEICO Group
Gainsco
General Casualty Insurance Companies
GMAC Insurance
Grange Insurance
The Hartford
Hanover Insurance Group
High Point Insurance Group
Homeowners of America
ICW Group
Indiana Farm Bureau Insurance
Kemper, a Unitrin Business
Kentucky Farm Bureau Insurance
Liberty Mutual
The Main Street America Group
Markel Corporation
Mercury Insurance Group
MetLife Auto & Home
Michigan Insurance Company
MiddleOak
MMG Insurance
Mutual of Enumclaw Insurance Company
Nationwide Insurance
N.C. Farm Bureau Mutual Insurance Company
Nodak Mutual Insurance
Norfolk & Dedham Group
Ohio Casualty Group
Oklahoma Farm Bureau Mutual Insurance Company
Oregon Mutual Insurance
Palisades Insurance
Pekin Insurance
PEMCO Insurance
The Progressive Corporation
Response Insurance
Rockingham Group
Safeco Insurance
Samsung Fire & Marine Insurance Company
S.C. Farm Bureau Mutual Insurance Company
SECURA Insurance
Shelter Insurance
Sompo Japan Insurance Company of America
State Auto Insurance Companies
State Farm Insurance
Tennessee Farmers Mutual Insurance Company
Tokio Marine Nichido
The Travelers Companies
Unitrin
USAA
Virginia Farm Bureau Mutual Insurance
West Bend Mutual Insurance Company
Zurich North America

FUNDING ASSOCIATIONS
American Insurance Association
National Association of Mutual Insurance Companies
Property Casualty Insurers Association of America