

INSURANCE INSTITUTE FOR HIGHWAY SAFETY

March 27, 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 purpose of Federal Motor Vehicle Safety Standard (FMVSS) 216 is to reduce deaths and serious injuries when vehicle roofs crush into occupant compartments during rollover crashes. The National Highway Traffic Safety Administration (NHTSA) has issued a supplemental notice of proposed rulemaking (SNPRM) for this standard, asking for comments on additional tests conducted by the agency since the 2005 notice of proposed rulemaking (NPRM). The Insurance Institute for Highway Safety (IIHS) does not believe the additional tests provide meaningful information for a standard requiring two-sided testing. However, more important, we support an increase in the minimum strength-to-weight ratio (SWR) beyond the level of 2.5 initially proposed, based on new research conducted by IIHS.

New study results justify increased minimum roof strength

IIHS's (2005) comment on the NPRM noted the "surprising lack of evidence" that the quasi-static test method used to measure compliance with FMVSS 216 could predict performance in real-world rollover crashes. In fact, the only research published on the subject had not found a connection between roof strength and roof damage or between roof strength and injury risk in rollover crashes (Moffatt and Padmanaban, 1995; Padmanaban et al., 2005).

In 2007 IIHS initiated a research program to evaluate what effect, if any, roof strength has on injury risk in rollover crashes. The resulting study demonstrates a very strong relationship between injury risk and performance under the test conditions used in FMVSS 216 (Brumbelow et al., 2008, attached). Increasing a vehicle's roof strength from 1.5 to 2.5 times vehicle weight within 5 inches of plate displacement would be expected to reduce the risk of fatal or incapacitating injury by 28 percent.

The findings of the new study suggest NHTSA has greatly underestimated the number of lives that could be saved by raising the minimum roof strength required by FMVSS 216. Using 11 midsize SUVs in the analysis, IIHS estimates that a minimum requirement of 2.5 times vehicle weight would have prevented 108 of 668 deaths of front-seat occupants in these vehicles in 2006. NHTSA's NPRM estimated 13 or 44 lives per year would be saved by a new standard requiring this strength level for the entire fleet, and the SNPRM suggested new estimates could be even lower. Although many vehicles in the modern fleet have higher roof strengths than the vehicles evaluated in the IIHS study, NHTSA's benefits estimates are overly conservative; more appropriate estimates would justify a stronger rule.

Two-sided testing

NHTSA has requested comments on the merits of a standard requiring vehicles to meet strength requirements in sequential tests of both sides of the roof. The agency has suggested that the minimum strength level in a final rule involving one-sided testing may differ from the level mandated if the final rule

requires two-sided testing. IIHS supports any changes that would increase the level of roof strength of the vehicle fleet. However, we have no real-world data to address the potential benefits of two-sided testing. Furthermore, the procedure employed in the two-sided research tests conducted by NHTSA makes these tests essentially irrelevant to the process of updating the standard.

As outlined by NHTSA, a two-sided test requirement would involve testing the first side of a vehicle to some minimum strength level, at which point the first test would be stopped and the second side of the vehicle evaluated. However, none of NHTSA's research tests were conducted in this fashion. Instead, the first side test was continued beyond any predetermined strength level until the roof made contact with the dummy, the windshield cracked, or 5 inches of crush had occurred. This compromises NHTSA's effort to use these data to project the effect of two-sided testing. For example, NHTSA stated that four of the tested vehicles met 2.5 SWR on the first side but not on the second side. However, the damage to these vehicles in the first test was much greater than would have been the case under a standard requiring only 2.5 times vehicle weight in the test (the table lists the distances that testing continued beyond the level where it should have stopped in the first side tests of these four vehicles). It is inappropriate to make calculations of the fleet's failure rate based on these evaluations.

NHTSA two-sided roof crush tests – crush measures from first side test

Vehicle	Total crush distance (mm)	Crush distance at 2.5 SWR (mm)	Crush distance beyond 2.5 SWR (mm)	Crush percentage exceeding 2.5 SWR
2005 Lincoln LS	94	74	20	27
2007 Saturn Outlook	127	67	60	90
2005 Buick LaCrosse	127	71	56	79
2004 Lincoln LS	93	64	29	45

More generally, a single-sided test with a higher SWR target may be even more effective at promoting robust roof designs than a two-sided test with a lower SWR requirement. A lower SWR target under a two-sided evaluation means the initial test would be stopped sooner and there would be less difference in the subsequent test, if any. For example, the agency tested a 2007 Scion tC, which had a peak SWR of 4.6 in the first side test. However, under a two-sided test standard requiring 2.5 SWR, the first side test would have been stopped at around 2 inches of crush, and the performance of the roof beyond this point would not be meaningful. At such low levels of crush, it is unlikely a roof would be compromised to the extent that a second side test would be affected. The end result would be a fleet of vehicles with unknown roof strengths beyond very low deformation levels.

Headroom criterion

Relating the allowable amount of roof crush in the quasi-static test to the headroom in specific vehicles is a good concept. In practice, however, NHTSA's research tests have not shown that replacing the 5 inch plate displacement criterion with the headroom requirement would be a meaningful change to the standard and may not justify the added complications to the test procedure. The NPRM and SNPRM have reported results of 45 single-sided tests conducted with dummies, 14 of which indicated failure to reach 2.5 SWR before head contact. However, the same 14 vehicles also would fail 2.5 SWR before 5 inches of plate displacement. This is because roof strength almost always peaks prior to both head contact and 5 inches of plate travel, regardless of which distance criterion occurs first. Only 2 of the 35 tests released in the SNPRM had different peak strengths by these 2 criteria, and in both of these cases the roofs actually showed slightly higher peak strength before head contact. For these 2 vehicles, a rule based on head contact would be more relaxed than one based on 5 inches of plate displacement.

Summary

Neither the headroom criterion nor the two-sided testing alternative have any demonstrated safety benefit, and both would be more burdensome than the current single-sided test using a plate displacement criteria. Under the current test procedure, vehicle manufacturers can test a roof to its peak strength within 5 inches and later calculate the SWR values based on the final curb weights of the vehicles sharing that roof design. Under a two-sided test procedure, the final curb weight of a vehicle would need to be known prior to testing to calculate the force level at which the first side test should be stopped. The headroom restriction would require specific dummy seating information to be determined before testing the roof.

Based on the evidence currently available, IIHS supports a single-sided test requiring SWR of 3.0 to 3.5 to be reached within 5 inches of plate travel. Even stronger roofs might be justified, but there are no data on their effectiveness. The IIHS study shows that significant safety benefits exist for strengthening roofs beyond 2.5 SWR, but the highest SWR measured for the vehicles studied was 3.2. If the choice is between 3.0 and 3.5, it is noteworthy that, in the SNPRM, the agency estimated 85.5 percent of the fleet would fail a single-sided test requiring 3.5 SWR, compared with an 82.5 percent failure rate for a 3.0 requirement. The potential increased protection offered by stronger roofs outweighs the very slight increase in failure rate. Furthermore, 12 of the 35 vehicles tested for the SNPRM had SWR values exceeding 3.5, indicating this level of strength is a realistic target for new vehicle designs. The sooner all vehicle roofs are this strong, the more deaths and serious injuries will be prevented. Whatever target is adopted should apply to all vehicles, as no data suggest that occupants in heavier vehicles have less benefit from strong roofs.

Sincerely,



Adrian K. Lund, Ph.D.
President

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

Attachment

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.

References

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**Roof Strength and Injury Risk
in Rollover Crashes**

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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; Orłowski 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

Model years	Make	Model	Peak roof strength (lb _f)		
			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

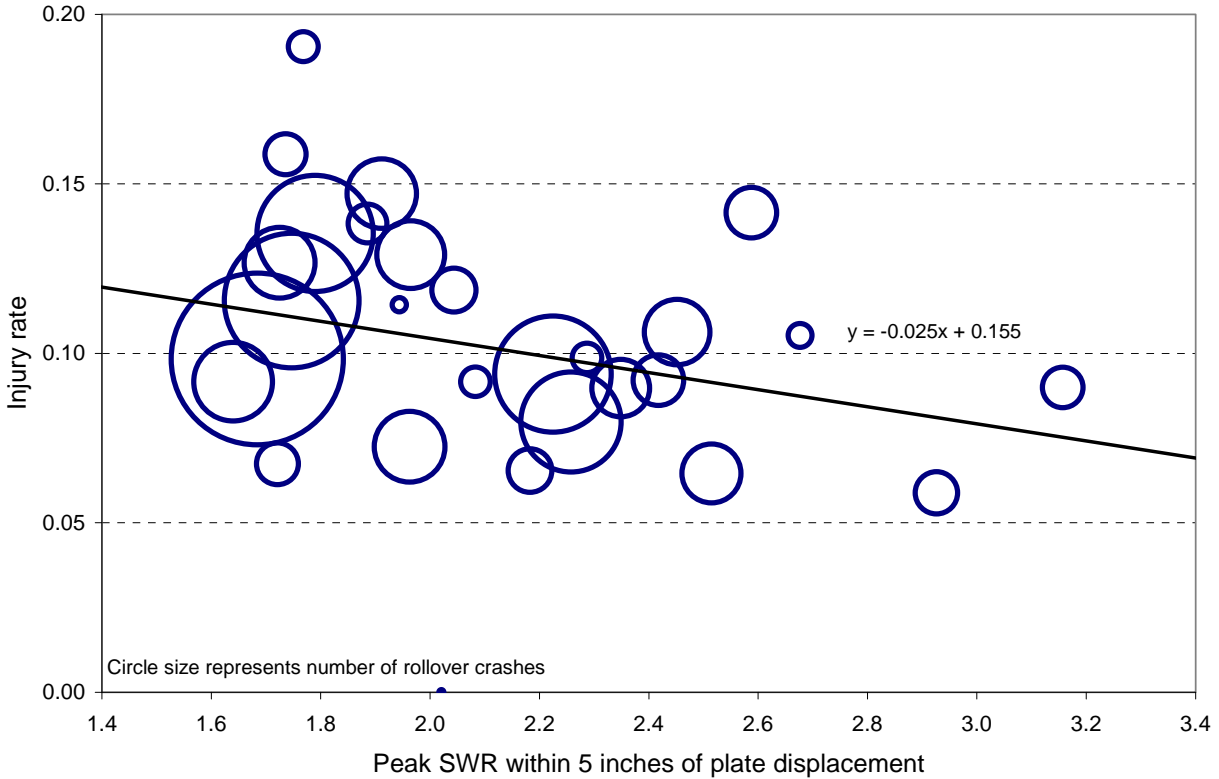


Table 2 lists the odds ratios for fatal or incapacitating driver injury for higher roof strength values. Odds ratios less than one indicate that greater roof strength is associated with lower injury risk. The units vary by metric. Peak force is given in English tons, SWR in increments of vehicle weight, 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

Strength metric	Plate displacement	Roof strength		SSF	Driver age	
		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

	Plate displacement	Odds ratios for 1 unit increases in roof strength, by police reported belt use			
		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.

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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