

RESULTS FROM TWO SIDED QUASI-STATIC (M216) AND REPEATABLE DYNAMIC ROLLOVER TESTS (JRS) RELATIVE TO FMVSS 216 TESTS

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ABSTRACT

In an attempt to find a test protocol that characterizes the rollover occupant protection capability of a passenger vehicle better than the test used in Federal Motor Vehicle Safety Standard 216, we developed equipment and protocols for a modified, quasi-static roof crush test (M216, a test conducted sequentially on both sides of the roof over the A pillars at a pitch angle of 10° and roll angles of 25° and 40° respectively) and for a repeatable, dynamic rollover test called the Jordan Rollover System (JRS).

We have conducted M216 and JRS tests on 17 production vehicles to determine roof crush and crush velocities at a number of points in the interior. These tests included complete production vehicles, body bucks at reduced weight to increase the effective roof strength-to-weight ratio, and pairs of identical vehicles where one has had the roof reinforced in a manner that is entirely hidden by the vehicle's sheet metal and upholstery. Data from the JRS tests and the M216 tests are compared with the results of FMVSS 216 tests.

Analyses of the data highlight the relative value and validity of each test methodology, its ability to predict roof performance in actual rollovers, its use in vehicle roof structure design, and its potential contribution to regulation or consumer information. Based on the roof crush and crush speed in the vicinity of front seat occupants' heads, we propose a rollover crashworthiness ranking system. While static tests measure the force and deformation of the roof on the outside, the dynamic tests measure the crush on the inside during the sequence of rollover roof impacts, where it is directly related to the occupant's survival space and injury potential.

INTRODUCTION

One third of all light vehicle fatalities are in rollovers. In rollovers, roof crush causes side window failures creating ejection portals. The largest number of casualties in rollovers are from ejection. Roof crush also causes a significant number of head and neck injuries: typically the most severe consequences of rollovers. These two key issues in rollover were recognized by auto safety specialists in the 1960s. They were formally recognized in 1970 when NHTSA established the FMVSS 208 unbelted dolly rollover test[1] (ejection) and proposed FMVSS 216 (roof crush).[2] Current accident statistics which are a basis for this research are shown in Figures 1, 2 and 3.

SUVs have the highest rollover rate and rollover fatality rate. The unbelted front seat dummy in the FMVSS 208 dolly rollover test was intended to be contained by passive means, such as with laminated side window glazing, as was demonstrated in the 1978 Minicars Research Safety Vehicle[3]. A popular misconception, created to encourage belt usage, is that ejection injury is an inevitable consequence for unbelted occupants. The fact is that in typical weak roof vehicles, roof crush creates ejection portals by breaking tempered glass side windows, allowing partial or complete ejection. In addition, weak roof vehicles make belted occupants more vulnerable to serious head, face and spinal injuries from intruding roof components in rollovers. On the other hand, serious injuries to other body parts such as thorax, pelvis, limbs and soft tissue injuries may be the result of an unbelted body position in close proximity to the roof at the moment of roof impact, crush and crush speed.

The U.S. Rollover Injury Problem

- Annual Number of Rollovers 258,000
- Number of Occupants Involved 467,000
- Number of Fatalities 10,000 (2.1%)
Severe to Critical injuries** 12,000 (2.6%)
- Serious Injuries** 18,000 (3.9%)
(90% of serious to fatal injuries occur within two rolls.)*
- Not Seriously Injured 427,000 (91.4%)

*NHTSA 2003 estimates. **estimated distribution from Ciren and GWU

Figure 1. Rollover Accident Statistics.

Crash type	Total occupants	Fatalities	Fatalities per total occupants	Fatal and serious injuries	Injuries per fatal and serious occupants
Rollover	418,371	10,149	0.0243	27,057	0.0647
Frontal	2,921,864	12,384	0.0042	62,536	0.0214
Side	1,359,538	8,169	0.0060	33,646	0.0247
Rear	467,559	1,023	0.0022	2,701	0.0058
Other	36,978	43	0.0012	568	0.0153
Totals	5,204,309	32,157	0.0062	126,484	0.0243

*Adjusted for unknowns

Crash Type	Total Occupants	Injury Rate per Occupant	Fatality Rate per Occupant
Rollover	418,371	0.065	0.024
Frontal	2,921,864	0.021	0.004
Side	1,359,538	0.025	0.006
Rear	467,559	0.006	0.002
Other	36,978	0.016	0.012
Totals	5,204,309	0.024	0.006

Figure 2. Rollover Injury and Fatality Rates (2001).

Still another quantitative misconception is that accident severity is the cause of injury. NASS data makes clear that 80% of rollovers and 65% of serious to fatal injuries occur in less than 4 quarter turns and 95% of rollovers and 95% of serious to fatal injuries occur in 8 quarter turns as shown in Figure 4. Rollovers of less than 4 quarter turns involve trip speeds of less than 15 mph and 8 quarter turn rollover trip speeds are in the range of 20+ mph. Further more many of these low speed rolls are the result of pre-rollover collision as indicated in another companion paper in this conference “What NASS Rollover Cases Tell Us” by Nash[4]. This data makes clear that if there are serious injury consequences in 15 to 20+ mph, one or two roll accidents, something is wrong with the occupant protection system and the number of additional rolls adds opportunity but is irrelevant.

	Rollover	Planar	Total
Complete Ejection	3,295	1,516	4,812
Partial Ejection	1,476	1,348	2,824
Total	4,772	2,864	7,636

	Partial Ejection	Complete Ejection	All Ejections	All Occupants in Crashes	Glazing Ejections per 1,000 Occupants
passenger car	9,917	8,501	18,417	3,782,316	5
utility vehicle	2,326	3,182	5,508	449,353	12
vans	468	1,772	2,340	409,336	6
pickups	4,014	5,023	9,036	531,590	17
other/unknown	60	31	91	12,365	7
total	16,784	18,509	35,293	5,209,380	7

Figure 3. Ejections in the United States.

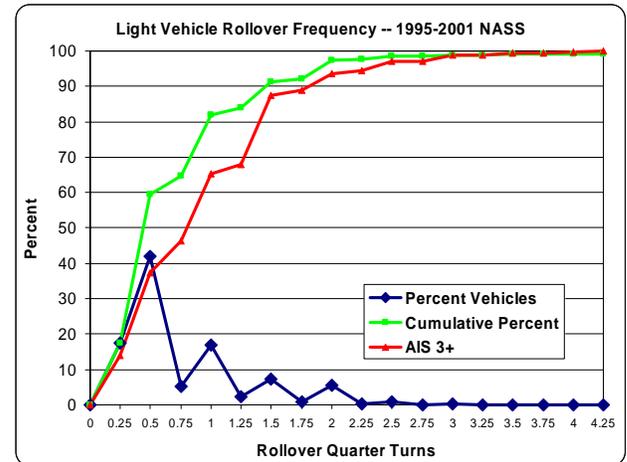


Figure 4. Rollover Frequency and Fatalities.

The most common perception about injury in a rollover accident is that injury increases with the amount of roof crush damage. Actually injury, as in all other accident modes, is caused by the speed of the occupant’s second collision with the vehicle interior. In a rollover, that second collision speed is a combination of the structural intrusion or crush speed in combination with the occupants falling (or as manufacturers like to say “diving”) speed creating a much higher contact speed at the injury site. This subject is discussed in some detail in a companion paper at this conference “Human/Dummy Rollover Falling (Excursion) Speeds” by Friedman, et. al.[5]

Another misconception comes from the lack of reliable data from accident statistics separating serious (non-permanently debilitating) injury and severe to fatal (permanently debilitating) injury. Several attempts from NASS data suggests (with

substantial uncertainty) that serious injury accounts for about 45% (of the 40,000 serious to fatal injuries) or 18,000 and severe to fatal about 55% or 22,000 (including 10,000 known fatalities) of what otherwise are considered “serious to fatal” injuries. These numbers are important since the economic loss and emotional consequences of these two levels of injury differ greatly. This subject is discussed in some detail in two companion papers in this conference “A Rollover Human/Dummy Head/Neck Injury Criteria” by Friedman and Nash,[6] and “What NASS Rollover Cases Tell Us” by Nash[4].

Crash tests and accident data have clearly shown that the greatest roof damage in a rollover is typically on the initially trailing or far side of a vehicle in a rollover. This coincides with the frequency of head, neck and spinal injuries to occupants seated on the far side of the vehicle. Roof strength designs which limit dynamic roof crush to less than 4” avoid creating side window ejection portals and reduce the potential for complete and partial ejection as well as exposure to external injury.

This paper addresses the issue of head impact on head, neck and thoracic spine injury from roof crush. We will present new data from dynamic rollover tests conducted on the Jordan Rollover System (JRS) on a selection of vehicles that show the mechanisms of roof crush in contemporary vehicles, the mechanisms of injury, and the criteria that can be used to assess the injury potential in dynamic rollover tests. Properly designed vehicles that show the portal creation ejection problem are also discussed. The vehicles tested included those with typical contemporary roof structures and with structures that have been reinforced to improve crush resistance.

SELECTION OF VEHICLES FOR TESTING

Because of their substantial overrepresentation in rollover crash statistics and their use as private passenger vehicles, we instrumented and tested eleven different SUVs. We also tested four different passenger cars and two pick-ups. Their FMVSS 216 Strength to Weight Ratios (SWR) ranged from 1.6 to 3.6.

There have been three series of tests. The first series of six vehicles was for general and regulatory SWR research and was documented in a paper “Observations from Repeatable Dynamic Rollover Tests” in the proceedings of the International Journal of Crashworthiness [7]. Some of those vehicles were tested on the two-sided M216 static roof crush fixture

and then on the JRS. Photos of the M216 and JRS fixtures are shown in Figures 5 and 6.



Figure 5. Vehicle in M216 test fixture.



Figure 6. Vehicle in JRS fixture.

Some of the SUVs that were tested were equipped with roof racks. Testing vehicle bucks at reduced weight simulated testing vehicles with higher SWRs. The tests were conducted at a low severity 15 mph and most at 5 degrees of pitch. For comparison purposes we also tested three similar vehicles with reinforced roofs.

A second series of 10 vehicles were tested only on the JRS with a similar low severity 15 mph, 5 degree of pitch protocol. A third series of vehicles is in process to develop a real world protocol suitable for regulatory compliance or NCAP testing with the 15 mph low severity protocol but with the pitch increased to 10 degrees. Three pre-tested vehicles were retested to preliminarily investigate this protocol

The reinforced vehicles and the production XC90 might be considered as the current state of the art reference standard roof: one that performs well and doesn't buckle under known rollover conditions.

DESCRIPTION OF M216 TESTING

The M216 test presses a 30.5 cm wide 61 cm long platen into the corner of the roof over the A-pillar at 10° pitch and 25° roll. It is pressed to a depth of 12.7 cm while measuring roof resistance. Then a similar platen is pressed into the opposite corner of the roof over the A-pillar at 10° pitch and 40° roll to a depth of 12.7 cm.

The test on the second side emulates the impact of the far side of the roof (after a near side impact in an actual rollover) because when the far side is in contact with the ground, the vehicle is rolling onto its side. This test provides a measure of roof strength which is expressed as the strength-to-weight ratio (SWR) which is the ratio of the maximum roof resistance force to the curb weight of the vehicle. Figure 7 compares the second side forces of tested vehicles as a percentage of weight (strength to weight ratio).

The generic effect of these measurements in comparison to FMVSS 216 measurements are shown

in Figure 8. The far side strength of the roof is about half of that indicated in the FMVSS 216 test and therefore often only comparable to the weight of the vehicle. This results from the increased pitch angle of the loading platen (which exerts force primarily on the A-pillar) and the fracturing of the windshield which acts as a shear web between A-pillars and header.

The large size of the FMVSS 216 platen and the shallow 5 degree pitch angle combine to transfer the initial loading of the A-pillar to the roof rail and B-pillar within a couple of inches of platen displacement. Since the SWR requirement must be reached in five inches, the A-pillar design strength can be limited in spite of the fact that when the vehicle is rolling with 10 degrees of pitch the A-pillar takes most of the load (2 to 3 times the vehicle weight) to about 5 inches by which time the roof panel buckles from far side lateral forces. Unfortunately we can't predict the way and the extent to which the buckle will propagate from a static test.

A further limitation of the FMVSS 216 test is that roof racks and other appurtenances are removed before the test because they interfere with the large

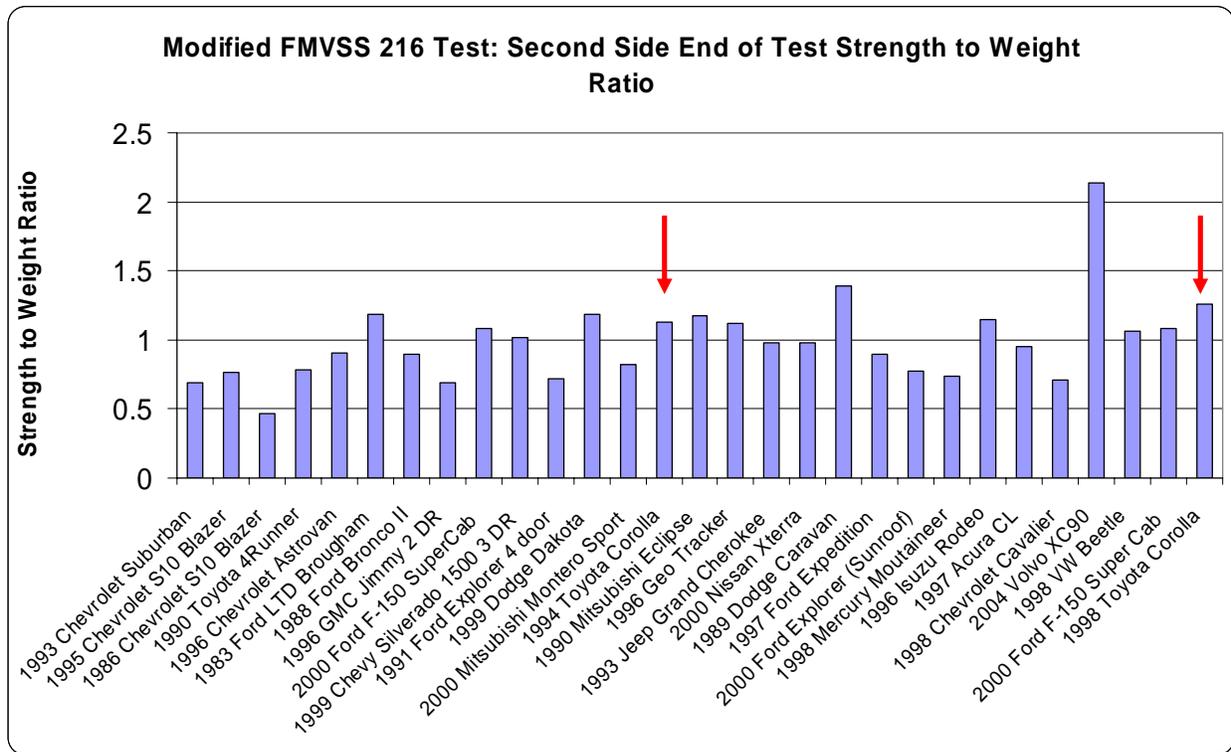


Figure 7. Second side M216 Strength to weight ratio highlighting 2 generations of Toyota Corollas

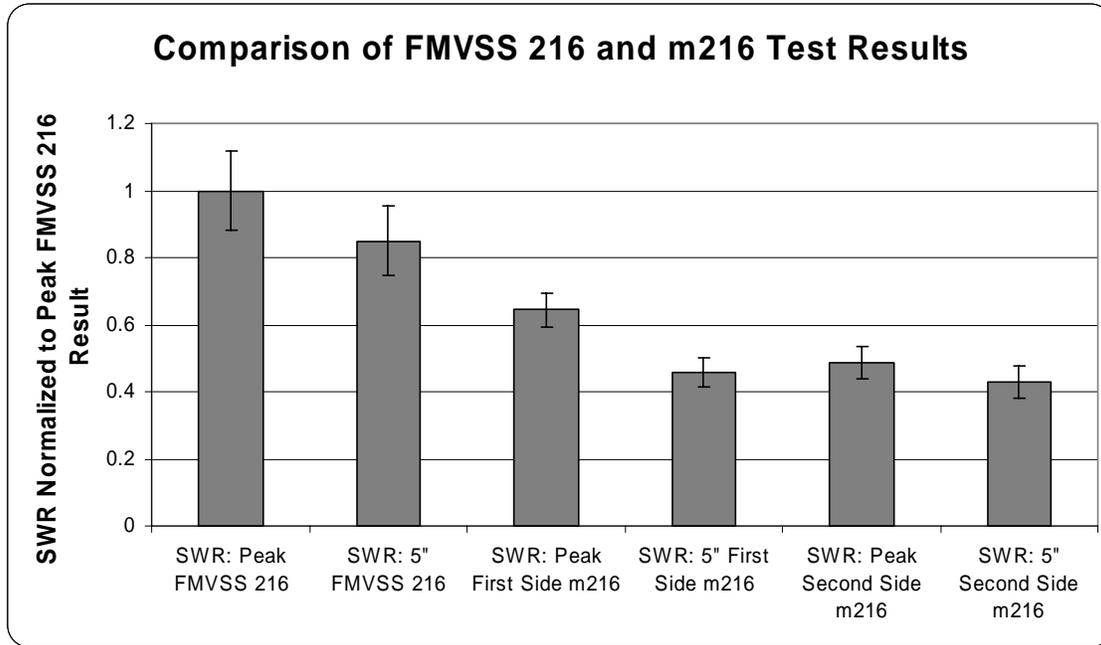


Figure 8. Comparison of FMVSS 216 and M216 tests at peak and 5" of displacement.

platen and shallow angle. In a crash or a dynamic test these things are pushed into the roof panel by the ground and precipitate a buckle whose intrusion speed is then amplified by lateral forces.

The size of the M216 platen was chosen to limit bending loads on the single hydraulic cylinder which provides the platen force. We have run a validation test using a standard FMVSS 216 machine in which the vehicle was attached and supported to the ground at 5 degrees pitch to create a 10 degree platen pitch angle. The conclusion was that the platen size can be as large as is convenient as long as it doesn't compromise the measurement of roof strength in an orientation representing contact with the ground of modern front wheel drive vehicles which roll with increased pitch.

M216 and FMVSS 216 performance has been roughly correlated through XC90 JRS testing. Volvo had an objective to achieve, but did not achieve, a SWR of 3.5 in 2" of platen displacement and at least maintain it to 5" in a FMVSS 216 test. This is roughly equivalent to increasing A-pillar strength as required to resist 10 degree pitch forces. Had it achieved its objective the M216 SWR would have been 2.5 and the ability to maintain structural integrity and low injury potential in 10 degree pitch rollovers would be significantly enhanced. Should NHTSA in its final FMVSS 216 rulemaking require such performance, roof buckles are unlikely and

quasi-static test performance can continue as a regulatory requirement. Such static tests could then be verified by dynamic repeatable NCAP tests using the JRS.

HEAD AND NECK INJURIES

The current compressive neck injury criteria value is based on studies by Mertz and Nyquist conducted in 1978.[8] That study examined two high school football practice cervical spine injuries from contact with a tackling block that had 15 cm of foam padding. Based on 1990 and more recent Hybrid III dummy experiments, the consensus catastrophic level of force neck injury measures of 2003 authored by Mertz and Prasad [9], correspond to a Hybrid III dummy impact speed of 3 mph, a level which no one currently claims is seriously injurious.

Accordingly the authors have used six different studies as the basis for head and neck injury potential and criteria in these repeatable dynamic rollover (JRS) experiments. Those studies and conclusions are in a companion paper at this conference [6].

From these studies, we concluded that for rollover research, design and occupant protection evaluation tests the following Injury Criteria should be used:

The onset of serious neck injury occurs at a head impact speed of 3.1 m/sec (7 mph) which produces a force of 7,000 N at the base of a Hybrid III dummy's

head. The onset of severe to fatal neck injury is 4.5 m/sec (10 mph) which produces a force of 10,000 N at the base of a Hybrid III dummy's head. The onset of head and brain injury occurs at an impact speed of around 7 m/sec (16 mph).

DESCRIPTION OF REPEATABLE DYNAMIC JRS ROLLOVER TESTING

The test conditions for the original JRS research test series [10] were derived from various sources. The conditions of a typical next-to-last and last roll of dolly rollover tests (which, in the Malibu tests produced the most serious head/neck injuries) as recorded from instruments and on film suggested testing parameters. Examination of the conditions of actual rollovers from the National Accident Sampling System (NASS) and other sources also suggest aspects of test conditions.

The vehicle to be tested (either the complete vehicle or just the occupant compartment with weighting to emulate a complete vehicle) is balanced around its longitudinal roll axis with the approximately correct roll moment of inertia. It is suspended from drop towers at a fixed pitch and yaw above tracks supporting a mobile roadbed segment that can move under the vehicle as shown in Figure 6.

When the test is initiated, the vehicle is rotated at a fixed speed, freely falling a fixed distance to contact the near side of the roof at a given roll angle on the roadbed moving at a fixed speed under it. The vehicle continues to roll, moving freely as the roadbed moves beneath it so that the far side of the roof strikes the roadbed. After the far side impact, the roadbed moves beyond and the vehicle is caught by the drop towers so that it suffers no further damage.[10] The roadbed is instrumented to record vertical and lateral impact loads. String potentiometers record resultant roof displacement and speed during roof impacts at several roof locations inside the vehicle. A number of high speed and real time cameras record the impact.

Qualification tests in the range and at the limits of the various angles and speeds of the flexible impact parameters were conducted. Since the basic functions are controlled by coordinated mechanical linkages and triggers, repeatability of impact conditions are very good [11]. Repeatability of injury measure potential however is governed by the non-linearity of typical weak roof designs which buckle in unpredictable ways. Based on the research results (with underweight compartment bucks), roofs with M216 far side SWRs in the range of about 2.5

and/or FMVSS 216 SWRs in the range of 3.5 within 2 inches of platen displacement would not be expected to buckle and should be highly repeatable in JRS measured injury potential.

Preliminary examples are the XC90, Xterra and Corolla tests of Table 1. Although these are sequential tests on the same vehicle notice that the first two XC90 and Corolla tests are within about 30% of each other and well under the injury criteria. Both suffer from inadequate A-pillar strength when sequentially subjected to a 10 degree of pitch test although the geometry of the XC90 causes it to roll at 5 degrees while the geometry of the Corolla causes it to roll at 10 degrees. The Xterra when M216 and JRS tested, buckled at the roof rack panel mounting and performed consistently poorly independent of pitch, indicating that the buckle rather than the pillar strength caused the injury potential.

**Table 1
JRS Tests at 5 and 10 degrees of pitch.**

Vehicle	FMVSS 216 SWR	Initial Pitch Angle (deg)	Dynamic Maximum Crush (in)	Maximum Residual Crush (in)	Maximum Crush Speed (mph)
2004 Volvo XC90 Roll 1	3.6	5	1.5	0.4	2.3
2004 Volvo XC90 Roll 2	3.6	5	2.6	0.7	3
2004 Volvo XC90 Roll 3	3.6	10	7.0	4.1	7.0
2000 Nissan Xterra Roll 1	3.3	5	5.8	2.8	10.4
2000 Nissan Xterra Roll 2	3.3	10	5.9	2.9	10.2
2000 Nissan Xterra Roll 3	3.3	5	5.2	2.0	9.1
2002 Toyota Corolla Roll 1	4.2	5	3.0	1.6	4.1
2002 Toyota Corolla Roll 2	4.2	5	3.5	1.0	5.1
2002 Toyota Corolla Roll 3	4.2	10	5.1	1.8	7.1
2002 Toyota Corolla Roll 4	4.2	10	6.7	2.9	10.2

These research tests were not all conducted with identical protocols. The tests were designed to maximize the collection of experimental data. The road speed, drop height and roll rate were kept the same but the impact angle and weight were varied as was the sequence and number of rolls. Some judgment therefore was involved in combining and generalizing the results.

An occupant's head position and the location of roof crush buckles are relatively unpredictable. The preferred protocol therefore was to study the over-the-seat potential injury environment with an array of several string potentiometers measuring the crush of roof elements relative to the rotational axis of the vehicle. Even so, the measurements were usually not at the peak of the buckles.

BASIC RESEARCH RESULTS FROM JRS TESTING

An examination of the early test results gives insight into the rollover protection capabilities of several roof structures over a variety of test conditions. The data includes the crush and crush speed at several points on both the near and far side of the roof

structure and the vertical loads as measured on the roadway.

Although there were some differences in the test protocol for each of the seventeen vehicle tests, a comparison can be made between peak roof crush speed and roof strength for the same point on each vehicle. Figure 9 and 10 illustrates these analyses respectively.

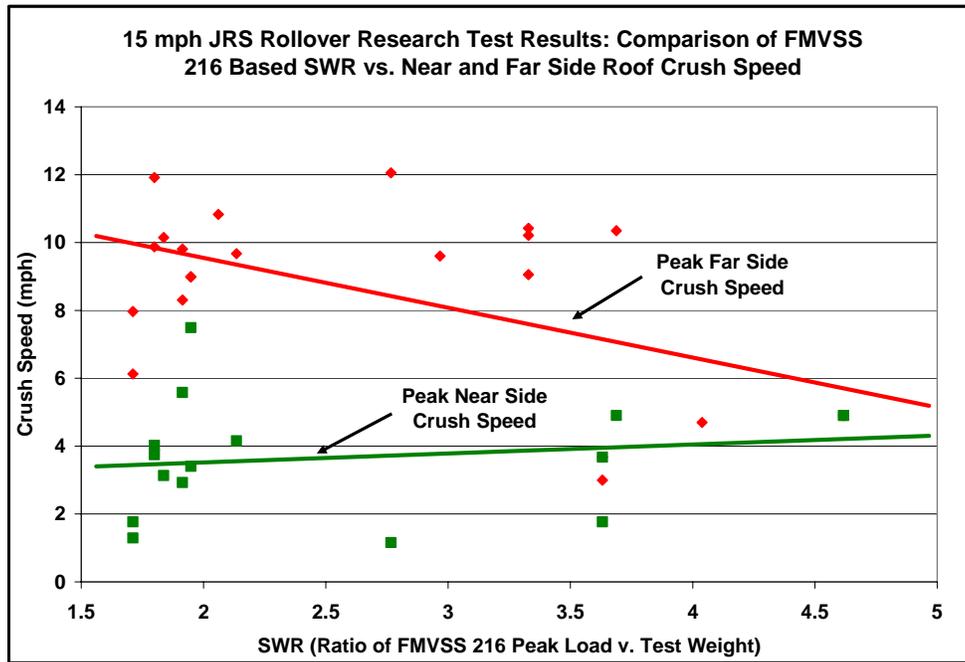


Figure 9. Peak roof crush speed of near and far side measurements vs. SWR at test weight.

There is some correlation between the SWR in FMVSS 216 testing and the results of JRS testing. Since the FMVSS 216 test does not initiate the buckles and collapse that are common in actual rollovers (and in JRS tests) it does not give results that correspond to the actual behavior of a roof in a rollover. However, if the roof were required to be strong enough to preclude buckling the correlation would be good.

The roof crush speed and roof crush indicated in Figure 9 and 10 is as measured in each impact and is not cumulative. From these tests it becomes very clear, that different roof structure designs have grossly different cumulative and residual crush characteristics, which are unknowable and misrepresented by post crash investigators without such JRS one roll at a time dynamic measurements.

As expected, the stronger the roof, as measured by the current FMVSS 216 test, the lower the far side roof crush speed as measured at the middle of the roof rail. For the near side as measured at the A-pillar the average crush speed is low and constant with SWR.

The near side roof crush at the 5 degree pitch impact angle was typically less than 4 inches, a level at which tempered glass resists fracturing and at which retained security (composite) glazing precludes portal creation (even when fractured by the side mirror).

Increasing the SWR, as demonstrated in either the FMVSS 216 or M216 test, does not necessarily ensure that the roof will not intrude to a dangerous degree in a rollover. A dynamic test (either the dolly rollover or the JRS test) will demonstrate whether a roof will buckle or collapse. The conclusion was reached that the failure mode (whether plastic or

elastic deformation) is more important than the actual SWR so long as the latter is above a threshold level.

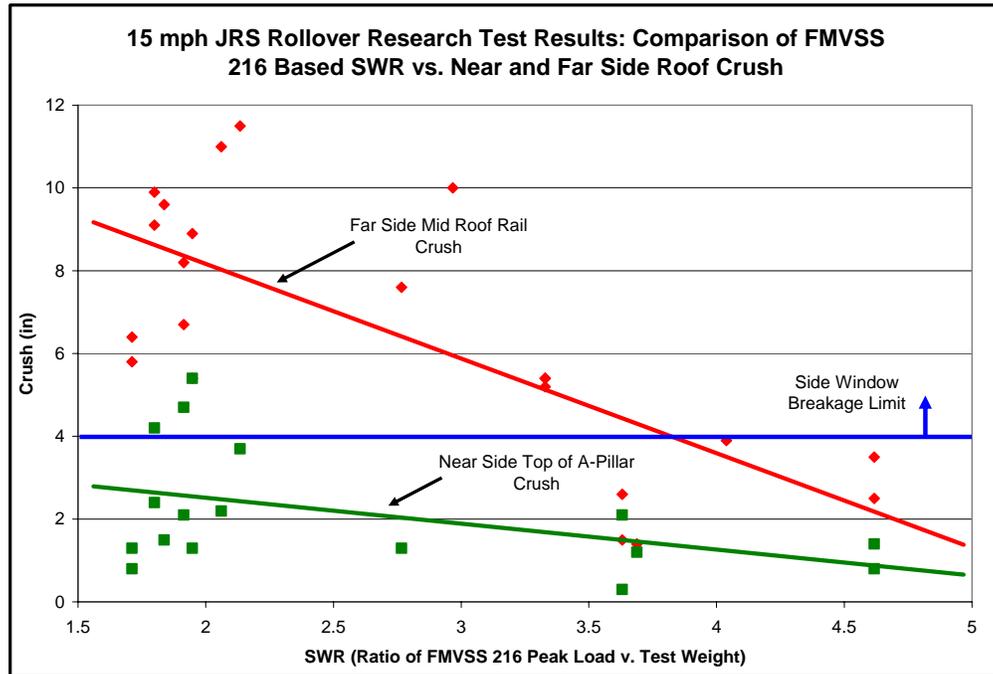


Figure 10. Comparison of Vehicle SWR and Far and Near Side Crush.

In the 5 degree pitch testing, it was found that the peak far side roof impact force in a JRS test in which roof crush is minimal, correlates with a SWR as measured in the FMVSS 216 test of at least 3.5, and a SWR as measured in the far side M216 test of at least 2.2.

The M216 near side peak roof strength is about three-quarters of that found in an FMVSS 216 test. The far side roof strength of a typical contemporary vehicle at 12.7 cm is roughly equal to its weight and about half the FMVSS 216 measured peak strength. For a production vehicle with a FMVSS 216 SWR of two, the near side strength may be adequate, but the far side strength is about one third of that needed to limit crush and crush speed.

SPECIFIC RESULTS FROM THE SECOND SERIES OF PRODUCTION JRS TESTING

A Production Vehicle Comparison

The test of the most popular SUV in the US (the 2000 Explorer) is compared to the Volvo XC90 claimed to be specifically designed to be reasonably safe in all accident modes. The XC90 in these tests shows that multiple roof impacts at 5 degrees pitch (a geometric rolling characteristic of the XC90 design) can be sustained by a well designed roof structure without compromising its ability to protect occupants.

The Explorer and the XC90 vehicles after two rolls are shown in Figure 11.

A comparison of the crush and crush speed between the two Ford production vehicles shows a dramatic difference between the rollover designed XC90 and the Explorer roof structures. In the XC90 there was a dramatic decrease in both of these crucial metrics; 82% in crush and 50% in crush speed. Figure 12 illustrates the reduction in crush speed and crush that is possible with a rollover designed vehicle (the XC90) as compared to a typical production roof vehicle (the Explorer).

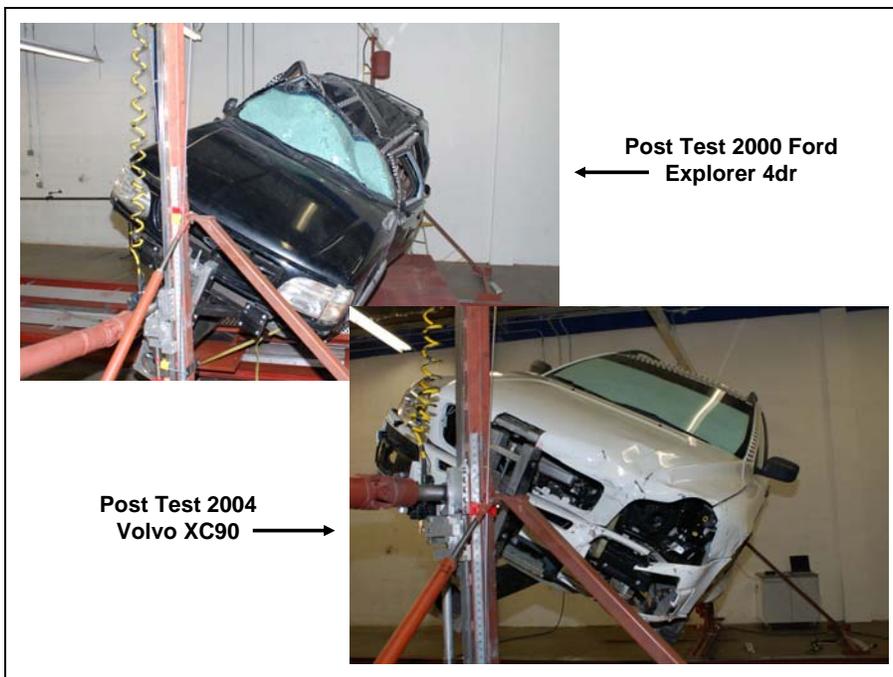


Figure 11. Post-Test Photographs of the Explorer and XC90.

2000 Ford Explorer 4dr Roll 1	Crush (in)		Peak Crush Speed (mph)
	Peak	End of Test	
A-Pillar	-8.7	-5.9	-6.3
Mid Point Between A and B Pillar	-9.1	-5.9	-6.7
B-Pillar	-6.7	-3.9	-5.5
Inboard of A-Pillar	-7.0	-4.9	-5.8
Inboard of Roof Rail Midpoint	-11.5	-8.5	-12.1
Inboard of B-Pillar	-8.7	-6.2	-9.1
Center of Roof	-8.2	-6.3	-7.6
Near Side A-Pillar	-4.2	-2.0	-3.8

2004 Volvo XC90 Roll 1	Crush (in)		Peak Crush Speed (mph)
	Peak	End of Test	
A-Pillar	-1.0	-0.1	-1.5
Mid Point Between A and B Pillar	-1.5	-0.3	-2.2
B Pillar	-1.2	-0.1	-1.9
Header Inboard of A-Pillar	-0.6	0.0	-1.2
Front of Sunroof	-1.1	-0.4	-1.8
Side of Sunroof	-1.5	-0.3	-2.3
Near Side A-Pillar	-2.1	-0.9	-3.3
Near Side B-Pillar	-3.2	-1.1	-3.7

2000 Ford Explorer 2 Roll JRS Tests
 Peak Dynamic Crush – 11.5 inches
 Peak Cumulative Crush – 14.5 inches
 Peak Crush Speed – 12.1 mph

2004 Volvo XC90 2 Roll JRS Tests
 Peak Dynamic Crush* – 2.6 inches
 Peak Cumulative Crush* – 1.1 inches
 Peak Crush Speed* – 3.0 mph

* Far side only

2000 Ford Explorer 4dr Roll 2	Crush (in)			Peak Crush Speed (mph)
	Peak	End of Test	Cumulative	
A-Pillar	-9.2	-6.4	-12.3	-9.6
Mid Point Between A and B Pillar	-9.9	-7.0	-12.9	-9.3
B-Pillar	-9.9	-6.7	-10.6	-8.8
Inboard of A-Pillar	-6.3	-4.2	-9.1	-7.0
Inboard of Roof Rail Midpoint	-9.5	-6.0	-14.5	-9.9
Inboard of B-Pillar	-8.9	-5.6	-11.8	-8.1
Center of Roof	-5.7	-3.1	-9.3	-8.5
Near Side A-Pillar	-2.4	1.0	-1.0	-4.1

2004 Volvo XC90 Roll 2	Crush (in)			Peak Crush Speed (mph)
	Peak	End of Test	Cumulative	
A-Pillar	-1.9	-0.5	-0.6	-2.0
Mid Point Between A and B Pillar	-2.6	-0.7	-1.0	-2.9
B Pillar	-2.6	-0.7	-0.9	-3.0
Header Inboard of A-Pillar	-1.2	-0.3	-0.3	-1.4
Front of Sunroof	-1.6	-0.5	-0.8	-2.1
Side of Sunroof	-2.5	-0.7	-1.1	-2.9
Near Side A-Pillar	-0.3	0.2	-0.7	-1.1
Near Side B-Pillar	-0.9	0.3	-0.8	-1.8

Figure 12 Comparison of XC90 and Explorer test results.

In the production and reinforced vehicle tests the maximum crush speed and corresponding crush values were selected from the six locations measured on the far side. Any of the points where roof crush was measured could have been used. However, the roof crush and crush speed is not uniform between vehicles and is affected by localized buckling and component failure, sometimes between measuring locations.

A Production Comparison by maximum crush speed

Given the Injury criteria previously described a sample rollover crashworthiness injury potential ranking system was developed as indicated in Figure

13. For this comparison we chose 10 tests conducted with equal severity on full production vehicles and the same initial conditions and test protocol. Since most of these tests were conducted on behalf of victims of rollover crashes the victim's injury under the deformed roof is indicated. For many of these vehicles such as the Explorer and Blazer the results are representative of dozens of cases the authors have investigated. The ranking basis was to assign labels of Unacceptable for a maximum crush speed of 10 or more mph, Poor for more than 8 and less than 10 mph, Good for less than 6 mph and Best for less than 6 mph and no created ejection portals.

JRS 15 mph Low Severity Dynamic Rolls Ordered by Max. Roof Crush Speed at any Point for Injury Potential Evaluation						
Model Years	Make/Models	216 SWR	Max Crush (Inches)	Maximum Speed (MPH)	Injury Probability	Case Injury
2002-2006	Volvo XC90 SUV	3.6	3.2	3.7	Best	NA
1999-2005	Hyundai Sonata Sedan	1.8	6.4	8.0	Fair	Quadriplegia
2003-2006	Kia Sorrento SUV	1.9	6.9	9.0	Poor	Quadriplegia
1995-1999	Nissan Sentra Sedan	3.2	9.1	9.6	Poor	Quadriplegia
1995-2001	GMC Jimmy SUV	2.4	6.7	9.8	Poor	Quadriplegia
1995-2005	Chevy Blazer SUV	2.4	9.6	10.1	Not Acceptable	Quadriplegia
1999-2001	Isuzu VehiCross SUV	NA	6.8	11.1	Not Acceptable	Brain Injury
2001-2006	C2500 HD Reg Cab Pickup	2.2	9.9	11.2	Not Acceptable	Fatal
1995-2001	Ford Explorer SUV	1.6	11.5	12.1	Not Acceptable	Quadriplegia
1994-1999	Mitsubishi Eclipse	2.5	7.6	12.1	Not Acceptable	Fatal

(Criteria: Best = < 6mph and no ejection portals; Good = < 6 mph; Fair = < 8 mph; Poor = < 10 mph; Not Acceptable = > 10mph)

Figure 13. Comparison of far side maximum crush and crush speed of production vehicles.

PRELIMINARY RESULTS FROM THE THIRD SERIES OF JRS REAL WORLD PROTOCOL TESTING

Having demonstrated the repeatability of the JRS in accurately duplicating initial impact conditions and the ability to distinguish between roofs with and

without acceptable injury potential crush speed, the next step is to develop a realistic real world protocol useful for regulatory compliance, New Car Assessment Program (NCAP) and crash victim injury severity investigations. The alternative protocols considered were:

A two roll test emulating a two roll crash encompassing 95% of serious to fatal Injuries is:

- 18mph, 240°/s Roll Rate, 10° pitch, 4” drop, 125° initial Roll angle. Stresses the leading side.
- 12mph, 180°/s Roll Rate, 10° pitch, 4” drop, 145° initial Roll angle. Stresses the trailing side.

A one roll test to emulating a one roll crash encompassing 65% of serious to fatal Injuries:

- 15mph, 200°/s Roll Rate, 10° pitch, 4” drop, 135° Roll Angle. Stresses both sides equally (similar road load).

Concerns about repeatability of injury measures, interest in matching or correlating the JRS and M216 performance for a minimum regulatory requirement, and a desire for simplicity, suggest the one roll test, possibly with a 145° roll angle. The study is ongoing with very preliminary results shown in Table 1, comparing the dynamic crush and crush speed results of 5 and 10 degree tests for two SUVs and a passenger car.

Injury potential repeatability may be inferred from the sequential results at 5 degrees of pitch with these high SWR roofed vehicles. A buckle in the Xterra roof accounts for the dangerous injury potential.

The study is now considering the correlation between FMVSS 216, M216, the JRS tests and with NASS residual crush. The main issue is the inability of a static test to induce buckling. Preliminarily, if the static 216 SWR criteria were high enough, say 3.5 in two inches of platen displacement, or the M216 SWR were 2.5, the likelihood of a buckle forming in a one roll real world JRS compliance test is unlikely unless induced by a roof rack or similar object.

WEIGHT AND COST OF ROOF STRENGTH IMPROVEMENT

Two generations of Toyota Corolla roof structures (1994 to 1997 and 1998 to 2002) were carefully inspected and compared. The FMVSS 216 and M216 test results are shown in Table 2.

The second generation roof structure was JRS tested with both 5 and 10 degree pitch protocols as shown in Table 2, although this front wheel drive vehicle is known to roll at 10 degrees of pitch. The roof structure inspection and comparison showed that the two roof structures were identical except that the inner surface of the 2002 roof rail had been reinforced on either side of the B-pillar to just before

the A and C pillars with a single stamped steel panel, probably of high strength steel, 41 inches long, 3 inches wide and 0.038 inches thick. The estimated weight for both sides is approximately 3 pounds. The 1994 FMVSS 216 test SWR was about 2.5 and the 2002 SWR was about 4.2. The 1994 M216 test results are a little low because of rear test damage, since the vehicles seem identical. The far side 1994 SWR was 1.2 and the 2002 M216 test SWR was 1.3. The JRS tests with the 5 degrees of pitch resulted in 4.1 and 5.1 mph crush speeds and confirmed the FMVSS 216 SWR improvement at the B-pillar. The JRS tests with the 10 degree protocol resulted in a 7 mph crush speed at the A-pillar (amplified by a buckle at the header and rain gutter which was not measured) that confirmed the M216 lack of improvement at the A-pillar. It was estimated that had the reinforcement been carried around the roof rail, A-pillar intersection and across the header, at an additional weight of 1.5 pounds and a cost of a few dollars, the crush speed of 4 mph could have been maintained when rolling with 10 degrees of pitch.

**Table 2
Toyota Corolla SWR results**

	1994-1997 Toyota Corolla SWR	1998-2002 Toyota Corolla SWR	Percent Increase
FMVSS 216 - Peak	2.5	4.2	68%
FMVSS 216 - 5”	2.3	2.95	28%
M215 1 st side - Peak	1.89	2.3	21%
M216 1 st side – 5”	1.43	1.8	25%
M216 2 nd side – Peak	1.24	1.33	9%
M216 2 nd side – 5”	1.13	1.25	10%

OTHER JRS TEST OBSERVATIONS

Approximately 50 JRS tests have been conducted with a wide variety of vehicles and under a wide range of test conditions. The focus and scope of this paper precludes detailed discussion of those observations but they include:

ROOF STRENGTH, GLAZING AND PORTAL CREATION AS IT EFFECTS PARTIAL AND COMPLETE EJECTION

M216 and JRS tests indicate that near and far side tempered glass windows break after about 4” of roof

crush. Near side crush in these tests seldom reached this level even in a vehicle with a SWR as low as 2.5 but windows often broke from side mirror impacts. Far side windows almost always break even in bucks simulating a 3.5 SWR. Vehicles reinforced or simulated at SWR of 4+ that we tested with tempered windows rarely broke except for side mirror impact. Side window breakage can be reduced by redesigning the window frame shape, size, location and strength and relocating the side mirrors.

OCCUPANT SIZE AND RESTRAINT EFFECTS

In spit tests using the JRS at rates to 220 degrees per sec with various size restrained humans and several different conventional belt systems, most 50th and 95th occupants reached the roof panel adjacent to the middle of the roof rail. Fifth percent females were able to reach the underside of the roof rail. When the sum of the excursion in the belts and the occupants seated height was greater than the head room the neck flexed such that it could not be effectively loaded axially.

PITCH EFFECTS ON ROOF LOADING AND CRUSH SPEED.

All tests have been conducted with 10 degrees of yaw. Variations in pitch from 10 degrees to zero resulted in similar far side crush and crush speed at the middle of the roof rail. Higher initial pitch angles resulted in more window breakage as well as roof panel and open section roof rail buckling over the far side occupant.

IMPACT ROLL ANGLE AND VEHICLE GEOMETRY AS THEY AFFECT ROAD LOAD AND CRUSH

The peak road load force and energy for far side roof crush varied as a function of roll angle. At 135 degrees the near and far sides were about equal, while at 155 degrees the far side load and duration (energy) was 2 to 4 times higher than the near side. Due to the web strength of the compartment rear closure panel and bonded rear window as well as the high aspect ratio of the corners of the roof in some pickups, only high initial near side roll angles will result in far side collapse.

CONCLUSION

A strong roof is critical both to prevent head impacts at a speed above 11.3 to 16.1 km/h (7 to 10 mph) that can cause head or neck injury. A strong roof will also protect side glazing so that it continues to provide a barrier to partial or complete ejection. Both the Malibu and JRS tests show that the basic conditions of a rollover are sufficiently benign that

even if there is some head contact with the roof under rollover conditions, it will not produce serious injury so long as the roof performs well. This will particularly be true if the vehicle has the head impact area padding now required by FMVSS 201.

The performance of the Volvo XC90 and the Toyota Corolla shows that there is no inherent problem in providing this level of protection in a light passenger vehicle. In fact, the use of advanced materials such as high strength steel and plastic inserts to control buckling of structural elements, could mean that adequate roof strength could be achieved with little or no net weight increase.

It is clear that we now have the testing tools and the vehicle technology to achieve a major reduction in rollover casualties even if rollover rates do not change significantly. In fact, the use of electronic stability controls will reduce the rate of rollovers in the future as well.

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