Observations from Repeatable Dynamic Rollover Tests

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Abstract – In an attempt to understand the relationship between quasi-static and dynamic test results, repeatable, dynamic rollover tests were conducted on production vehicles to determine intrusion and intrusion velocities using the Jordan Rollover System (JRS). These tests included complete production vehicles and body bucks at reduced weight, to vary the roof strength-to-weight ratio. Data from these tests are compared with the results of quasi-static roof strength tests measured at greater roll and pitch angles than are used in FMVSS 216. Biomechanical data indicates that serious head, face, neck or thoracic spine injury are a consequence of rapid impacts with significant amplitude. The test data suggests a correlation between quasi-static roof strength and dynamic roof intrusion velocity. Localized failures (buckling and collapse of structural elements that often translate into the roof panel) are a more critical aspect of roof performance than its strength as measured in FMVSS 216.

Introduction

One third of all light vehicle fatalities are in rollovers. In rollovers, partially or fully ejected occupants are the largest number of casualties, but a significant number of the most severe head and neck injuries result from roof intrusion. 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 dolly rollover test[1] (ejection) and proposed FMVSS 216 (roof crush).[2] The principles behind these standards for occupant crash protection were first articulated by Hugh DeHaven in 1952.[3]

SUVs have the highest rollover rate and rollover fatality rate. Belt use in all vehicles in rollovers where there is an AIS 3+ injury is below 50 percent.[4] Restraint use will not completely solve the rollover ejection problem in that partial ejections are about equally divided between restrained and unrestrained occupants and a small proportion of restrained occupants are fully ejected. Furthermore, increasing the proportion of occupants who are restrained will boost the number who are vulnerable to serious head, face, neck, and thoracic spinal injuries from intruding roof components in rollovers.

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 and neck injuries to occupants seated on the far side of the vehicle. Because of its effect on glazing, window openings and lateral roof displacement, roof crush can also promote both 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 and 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. The results of testing a vehicle with a typical contemporary roof structure and with a structure that has been reinforced to improve its crush resistance are also presented.

Head and Neck Injuries

Public data on rollover testing that measure the potential for occupant injury is limited. The most complete set is from a series of tests conducted in the 1980s by General Motors Corporation[5,6]. In this program, GM tested 16 1983 Chevrolet Malibu sedans. Half of them had roofs reinforced with a roll-cage structure. Half of each set of vehicles had unrestrained and half had restrained occupant dummies in the front outboard seating positions. An examination of this data has led to several insights about rollover conditions and occupant exposure.

The GM researchers selected a threshold of 2000 N, measured at the upper neck load cell, to illustrate neck loads that had the potential to injure occupants. This value was not based on any biomechanical data and was half of the very conservative value proposed earlier by their fellow GM researchers[8]. Under this criterion, the researchers identified 94 neck loads for examination, and selected ten cases with restrained occupants for further photoanalysis. This level of occupant neck injury-producing impacts, 5.8 per test is two orders of magnitude above the number that would be expected in actual rollover accidents. Nevertheless, this data gives insight into the motion of occupants in the vehicles during the roll sequence.

Separating neck load impacts in roll-caged and production vehicles, irrespective of restraint usage, allows an examination of the neck load environment seen by the occupant. For the roll-caged vehicles, the average impact load is approximately 3400 N. This neck load can be directly converted to an approximate head impact speed by using the composite data of Hybrid III axial neck loads as a function of measured head impact and buckle intrusion speeds and to a lesser extent drop height impact speeds. Using such a conversion, the average roll-caged occupant head impact velocity (where there was no significant roof crush) was about 1.4 m/sec (3.1 mph).

The neck loads and velocities measured in the roll-caged Malibu tests are due to the motion of the occupant within the vehicle in relation to the ground (in an inertial frame of reference). There is little difference between head impact velocities in rollcaged versus production Malibus in the absence of significant roof crush. The high neck loads seen in a few of the production Malibu tests are from intrusion of the crushing roof structure into the dummy's head. There are only minimal differences in the dummy's inertial motion as a function of roof crush even though the roll-caged vehicles had more severe *vehicle* accelerations from roof contact with the ground because of their stiffer roof structure. This is shown in Figure 1 for the rollcaged vehicles and Figure 2 for the production vehicles. The coding below these graphs detail the impacts as numbered in the Malibu studies.

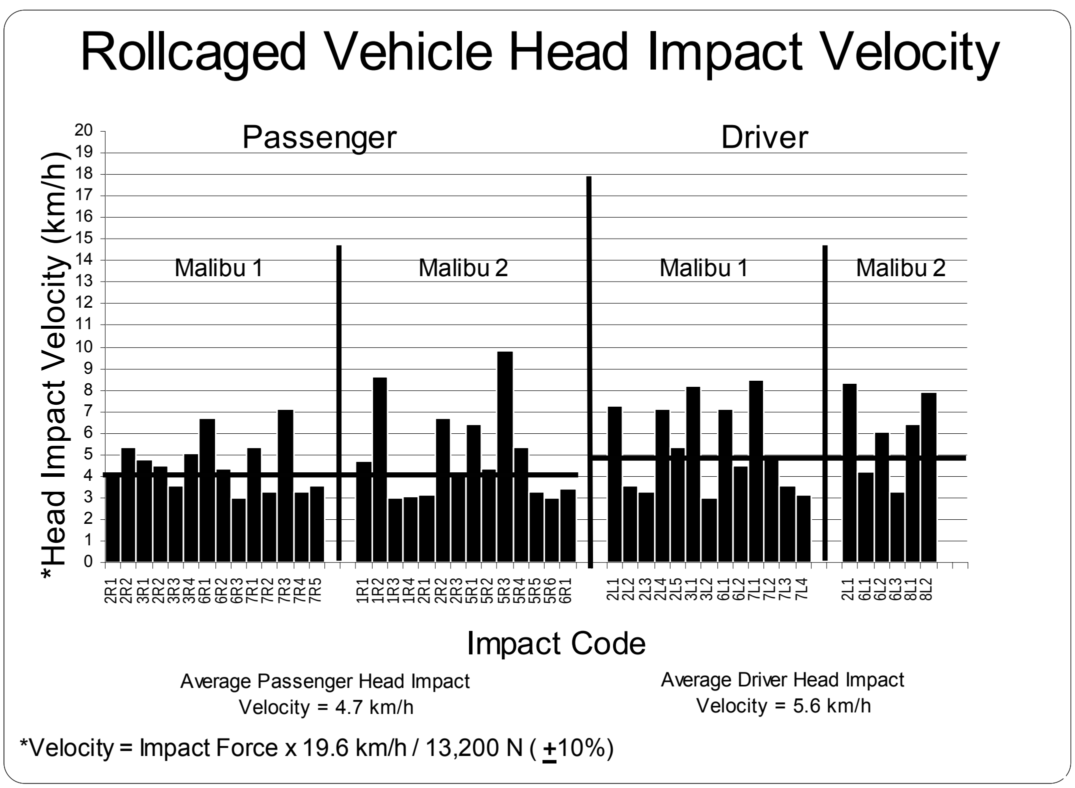


Figure 1. Head impacts in Chevrolet Malibus with roll cages reflect occupant falling velocities.

With a combination of inertial motion and roof intrusion, head impact velocities greater than 16.1 km/h were measured, but only in production roof Malibus. It should also be noted that the only head injury criteria (HICs) above 1000 were from an impact with an unpadded roll-bar in a production vehicle where roof intrusion caused major acceleration of an unrestrained dummy's head and where the dummy was laying on the roof of the vehicle.

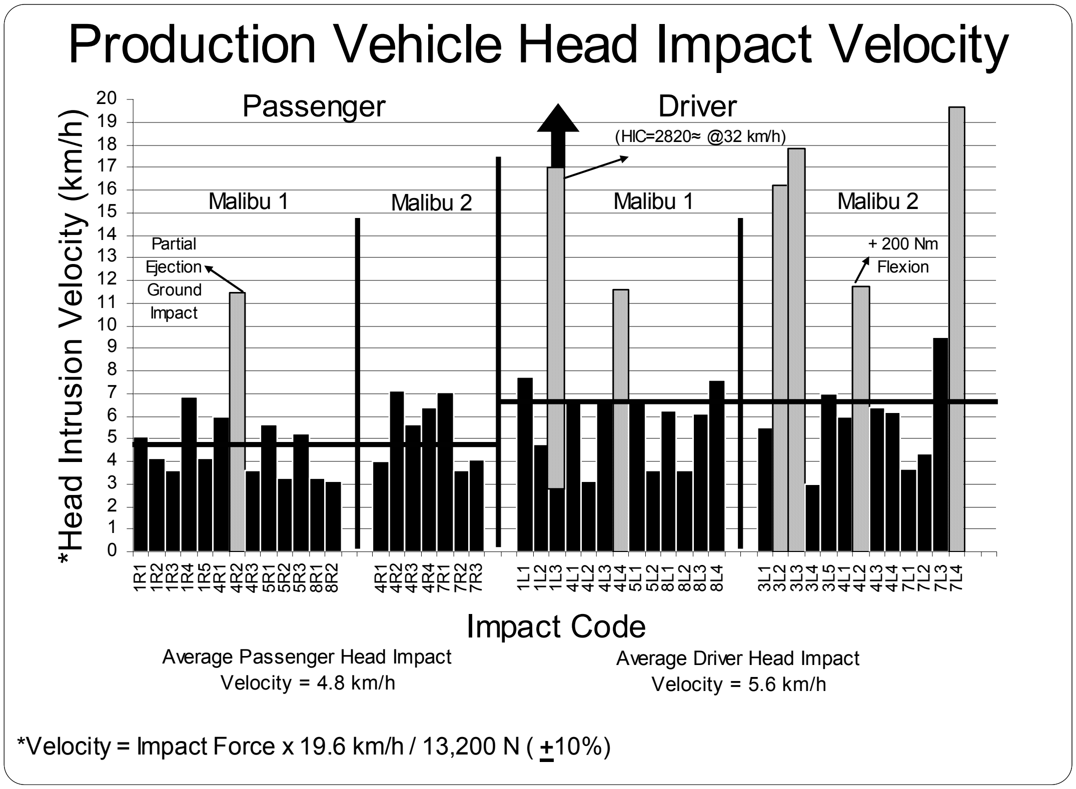


Figure 2. Head Impacts without significant roof crush or partial ejection in production Malibus also average about 1.3 m/sec (4.8 km/h).

Another interesting finding is that all of the higher head impact velocities and neck loads were recorded for far side occupants in production vehicles. This corresponds to what has been observed in actual rollovers from accident data[7].

The Malibu tests show that the danger of roof crush injuries to occupants who are not ejected are increased if the occupant is wearing a seat belt. This can be seen in Figures 1 and 2 where the highest neck loads and head impact velocities are recorded in Malibu II where the occupants were belted.

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. Mertz and Nyquist emulated the head impacts using helmeted Hybrid III dummies using the same model tackling block and recorded the neck loads. Their paper did not provide the dummies' head impact velocity.

A more recent study examined 27 National Football League player head impacts that were recreated in the laboratory using Hybrid III dummies.[9] The recreations were based on film from multiple cameras. The results were compared with medical records on the players. This study suggests that the serious neck injury criterion for young healthy adults should be above 7,000 N. This work also allows for the correlation between neck load and head impact velocity. A 7,000 N neck load in a Hybrid III corresponds to a head impact velocity of approximately 3.1 m/sec (7 mph).

These findings support research done by other investigators with cadavers (which are typically older or sick individuals who would be expected to be more vulnerable to neck fractures) and the Hybrid III dummy[10,11,12]. This body of research illustrates that the onset level for severe to fatal neck injury for these more vulnerable individuals is likely only in a head impact of at least 4.5 m/sec (10 mph).

Relating these findings to the Malibu studies and other rollover testing demonstrates that if the occupant is contained in an environment where his or her head cannot experience an impact in excess of 3.1 m/sec, serious neck injury is highly unlikely. The Malibu tests demonstrate such injury-producing impacts do not occur in vehicles with roofs that do not buckle or collapse. The tests also demonstrate that Hybrid III dummies, whether restrained or not, do not fall into the roof with sufficient velocity to cause serious neck (or head) injury. It is only in production roof vehicles that the dummies in the Malibu tests were subjected to high head impact velocities and neck loads from collapsing and intruding roofs that would produce serious and severe to fatal head and neck injuries.

With a serious neck load injury criteria level of at least 7,000 N (7 mph), and a severe to fatal level of 10,000 N (10 mph), the number of serious injuries and the number of fatalities in the 16 Malibu tests becomes more representative of that seen in actual accident data.

This analysis of the importance of roof crush agrees with a recent study by NHTSA[13]. It is clear that controlling the intrusion and intrusion velocity of roof crush is important in minimizing head and neck injuries in rollovers.

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 six different SUVs (among others) whose production FMVSS 216 Strength to Weight Ratio (SWR) ranged from 1.6 to 3.1. Each vehicle was first tested on the two-sided M216 static roof crush fixture and then on the JRS. Tests were conducted on two production and one physically reinforced 2 door Chevrolet Blazer/GMC Jimmy, a 4 door Chevrolet Blazer, a DaimlerChrysler Jeep Grand Cherokee, a Chevy Suburban, a Isuzu Rodeo, and a Nissan X-terra from the 1993 to 2001 model years.

The tested vehicles included vehicles with and without roof racks. Testing vehicle bucks at reduced weight simulated testing vehicles with higher SWRs. In one test series, a 1998 GMC Jimmy (Chevrolet Blazer) 2 door SUV (a vehicle that incidentally has one of the worst rollover fatality rates of all vehicles[14]) with a roof that was modified by invisibly adding 106 pounds of internal pillar structure and structural foam with all trim replaced such that the reinforcement is hidden was tested. These modifications simulate a well-designed production vehicle roof. This Blazer with a SWR of more than 4.5 (peak road load of 5.5) might be considered as the reference standard roof: one that performs well under known rollover conditions.

Description of 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 50° 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) and 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, see Figure 3[15,16]. Figure 4 compares the SWR of a midsize SUV in FMVSS 216 tests with those in the M216 tests.

Figure 3. Illustration of m216 test fixture with platen roll angles

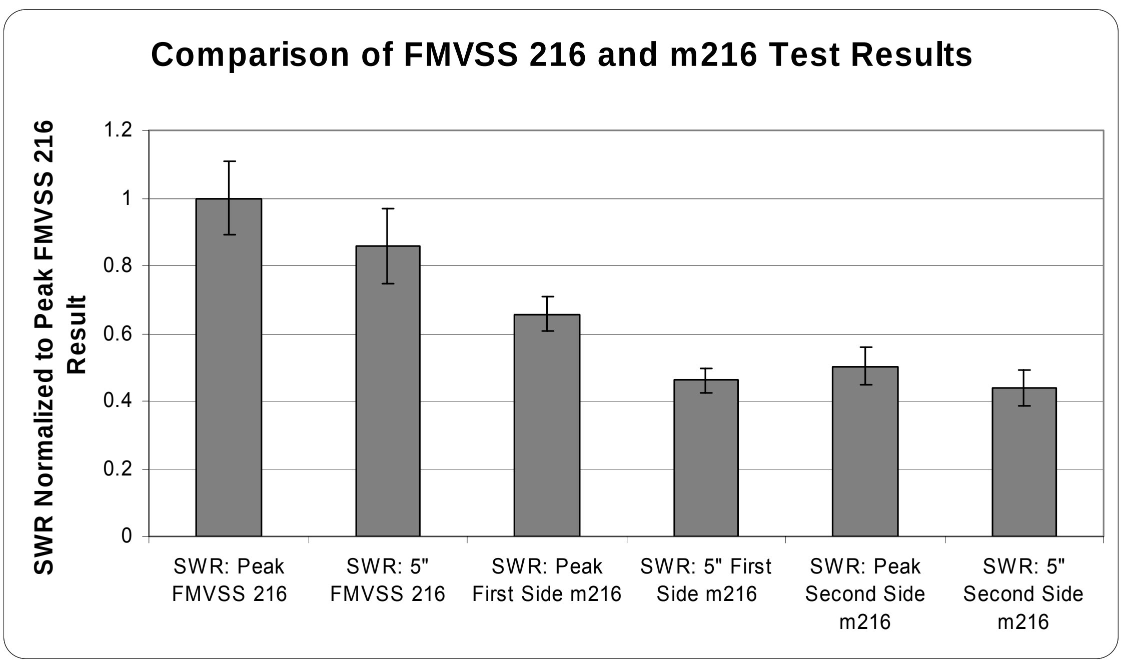


Figure 4. Comparison of FMVSS 216 and M216 tests at peak and 5” of displacement

The test conditions for the JRS test are derived from the conditions of a typical next-to-last and last roll of dolly rollover tests (which, according to the Malibu tests, are the most likely to produce serious head/neck injuries) as recorded from instruments and on film. 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 5 degrees of pitch and 10 degrees of yaw above a mobile roadbed segment that can move under the vehicle, see Figure 5. When the test is initiated, the vehicle is rotated at 190 degrees per second, freely falling 10 cm to contact the near side of the roof at a roll angle of 135 degrees on the roadbed moving at 24.1 km/h (15 mph) 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.[17] The roadbed is instrumented to record vertical and lateral impact loads. String potentiometers record roof displacement and velocity during roof impacts at 7 roof locations inside the vehicle. A number of high speed and real time cameras record the impact.

Figure 5. Jordan Rollover System dynamic rollover test fixture with a production vehicle prior to a test

These 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.

A few early rollover tests were conducted with dummies, but an occupant’s head position and the location of roof intrusion buckles are relatively unpredictable. The preferred protocol therefore was to study the over-the-seat potential injury environment with an array of string potentiometers measuring the intrusion of roof elements relative to the rotational axis of the vehicle.

Basic Results from JRS Testing

An examination of the test results gives insight into the rollover protection capabilities of several roof structures over a variety of test conditions. The data includes the intrusion and intrusion velocity 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 six vehicles a comparison can be made between roof intrusion velocity and roof strength. Figure 6 illustrates this analysis. As expected, the stronger the roof, as measured by the current FMVSS 216 test, the lower the far side roof intrusion velocity. For the near side, the average intrusion velocity is low, constant with SWR and approximately the same as was seen in the Malibu tests, see Figure 7.

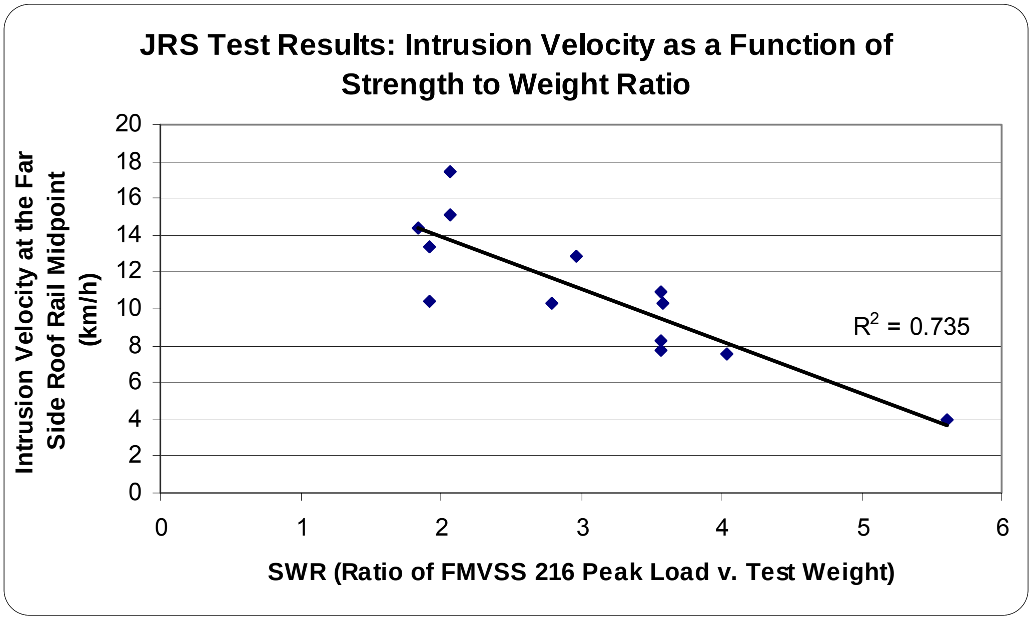


Figure 6. Comparison of Vehicle SWR and Far Side Intrusion Velocity

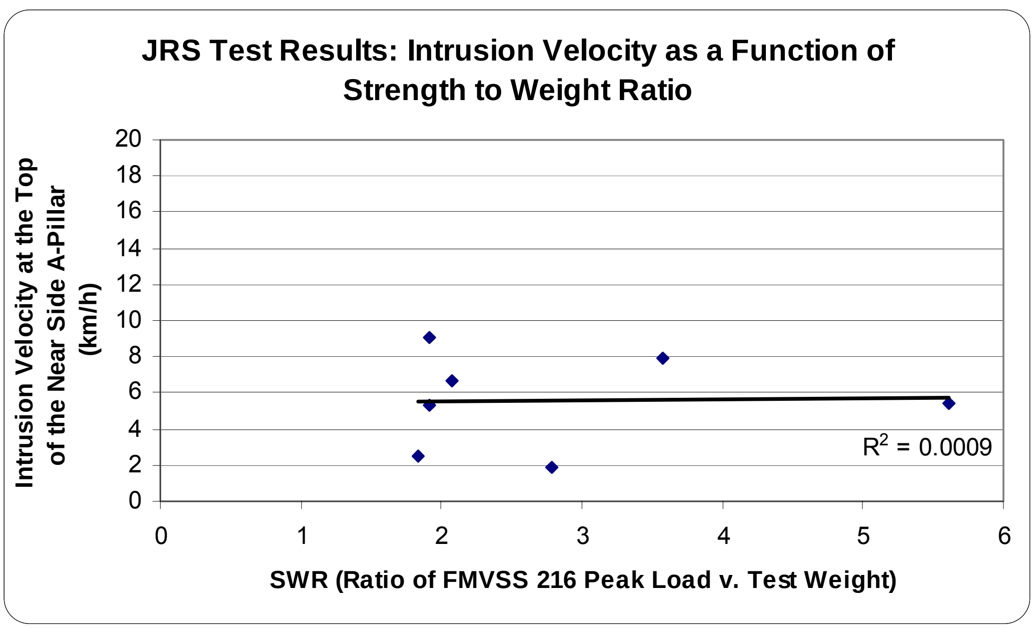


Figure 7. Comparison of Vehicle SWR and Near Side Intrusion Velocity

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 very stringent Volvo quasi-static test and criteria [18] may be sufficient to ensure good rollover performance. 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.

In the 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 M216 test of at least 2.5. 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 typically, 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 intrusion and intrusion velocity. Since vehicles are made symmetrical and either side can be the far side, a single sided static compliance test must have some yaw orientation, a SWR criteria of at least 3.5 at 5 cm of platen displacement, maintained to at least 12.7 cm, with no indication of incipient buckling, and without complete failure of the side windows that would provide an ejection portal. This is close to the Volvo requirement, and in effect, it requires that the deformation of the roof be essentially elastic rather than plastic.

Specific Results from JRS Testing

A Limiting Comparison

A set of tests was conducted on a late 1990's 2 door Blazer. Three vehicles were tested: two with production roofs and a third with a reinforced roof structure as described above. The first production vehicle was tested on the JRS twice to mimic a two roll accident. The second production vehicle was tested once on the JRS. The reinforced vehicle had previously been dropped from 30.5 cm onto the far side of the roof before the JRS test, but did not have significant structural damage to the roof. This shows that multiple roof impacts can be sustained by a well designed roof structure without compromising its ability to protect occupants. The vertical loads measured on the roof structures during each of these four JRS tests are presented in Figure 8.

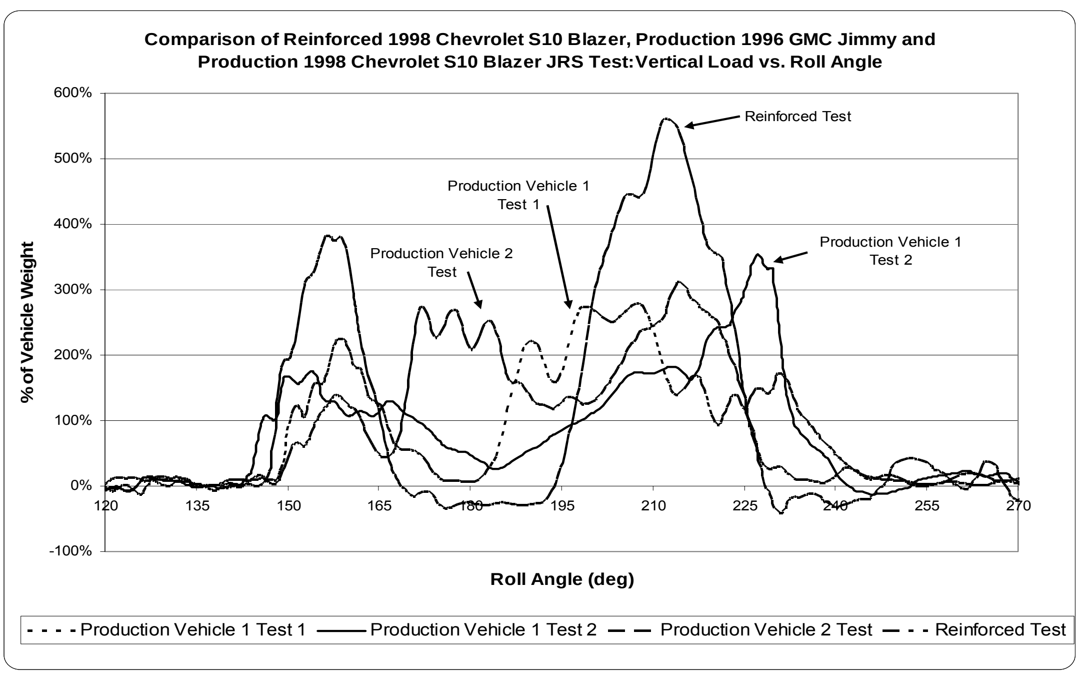


Figure 8. Vertical loads for four JRS tests.

The first production vehicle and the reinforced vehicle are shown in Figure 9.

Figure 9. Post-Test Photograph of the first production and reinforced blazer. (The torn windshield the passenger side of the production vehicle suggests damage, but here is very little on that side.)

A comparison of the intrusion and intrusion velocity shows a dramatic difference between the strengthened and production roof structures. With the reinforcement in this test, there was a dramatic decrease in both of these crucial metrics; 82% in deformation and 50% in intrusion velocity. Figure 10 illustrates the reduction in intrusion velocity and deformation that is possible with a strengthened roof. The results for the second production vehicle were very similar to the first production vehicle with a 79% reduction in deformation and a 52% reduction in intrusion velocity when the roof was strengthened.

In the production versus reinforced figures the values were taken above the driver's seat. This could have been done at any of the points where roof intrusion was measured. These are representative of the performance seen in these tests. However, the roof intrusion and intrusion velocity is not uniform and can be affected by localized buckling and component failure.

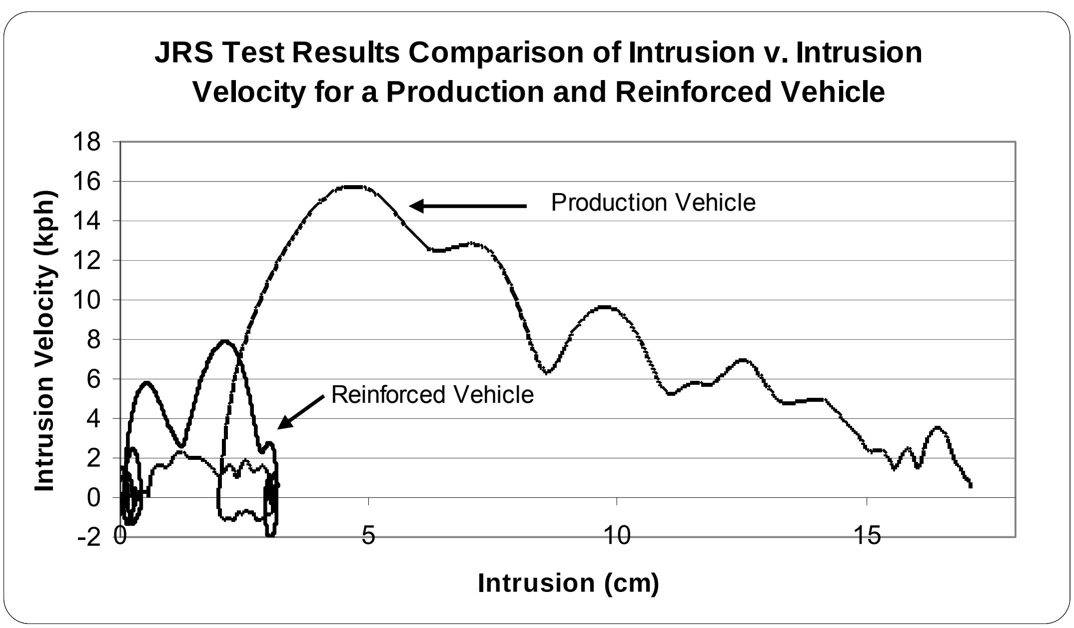


Figure 10. Comparison of Roof Intrusion vs. Intrusion Velocity for a Production and Reinforced Blazer.

The Possible Effect of a Roof Rack

The test vehicle that best illustrates the effect of a roof rack initiating and exacerbating intrusion and intrusion velocity is shown in Figure 11. There is an overlay on the vehicle showing the shape and location of the mid roof rail cross-section further described in Figure 12.

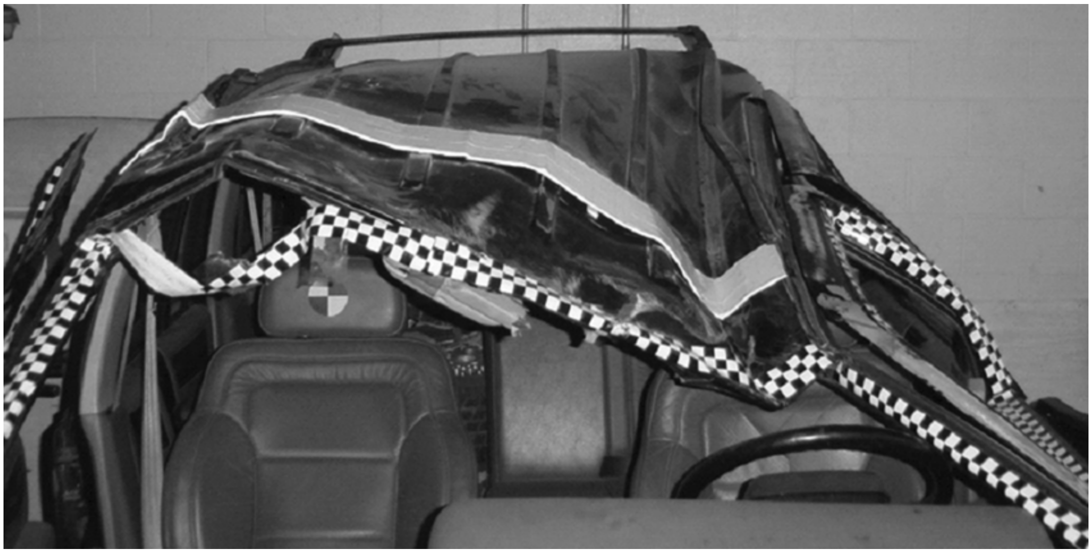
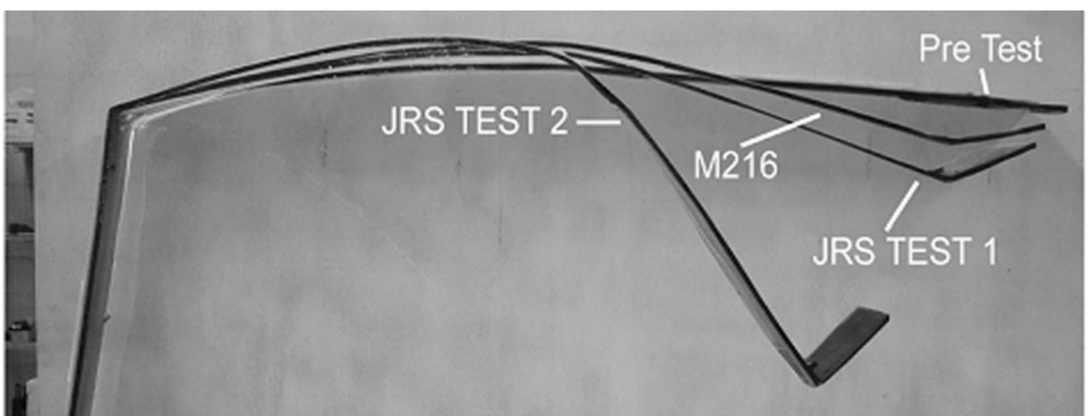


Figure 11. Roof Rack initiated buckle in test vehicle.

The intrusion and intrusion velocity as a result of the three tests on this vehicle is summarized in Figure 12. In this case the string pots were not located on the buckle such that the combined intrusion and buckle velocity is estimated from an analysis of the buckle dimensions. The point here is that the buckle adds to the mid roof rail intrusion velocity such that even a strong roof has a potential for injury unless it is designed to preclude buckling.



	SWR	Roof Rail Lateral Displacement (cm)	Roof Rail Vertical Displacement (cm)	Roof Rail Buckle Vertical Displacement (cm)	Cumulative Vertical Displacement (cm)	Roof Rail Intrusion Velocity (km/h)	Roof Rail plus Buckle Intrusion Velocity (km/h)
1. m216	1.6	3.3	5.1	3.8	5.1		
2. JRS Test 1	3.5	1.3	5.1	6.3	7.6	7.6	24.6
3. JRS Test 2	2.5	17.3	19.1	11.4	29.2	12.9	29.1

Figure 12. The sequence of tests and the mid-roof rail cross section intrusion and intrusion velocity

Measured Buckling Effects on Intrusion Velocity

In the previous example the velocity effect of the longitudinal buckle near the roof rail was estimated, because there was no string potentiometer near the peak of the buckle. This effect was measured in a JRS test of a 1991 Mitsubishi Eclipse passenger car (one of the many other JRS tests conducted to date). As the far side of that vehicle struck the ground, a buckle was formed above the driver's seat. There was a string potentiometer near the peak location of the buckle. Figure 13 is a comparison between the string potentiometer near the buckle above the driver's seat and at the adjacent midpoint of the roof rail. It shows a dramatic difference with an increase of ~170% due to the buckle. This illustrates the importance of preventing buckling and localized roof failures in order to provide effective rollover occupant protection.

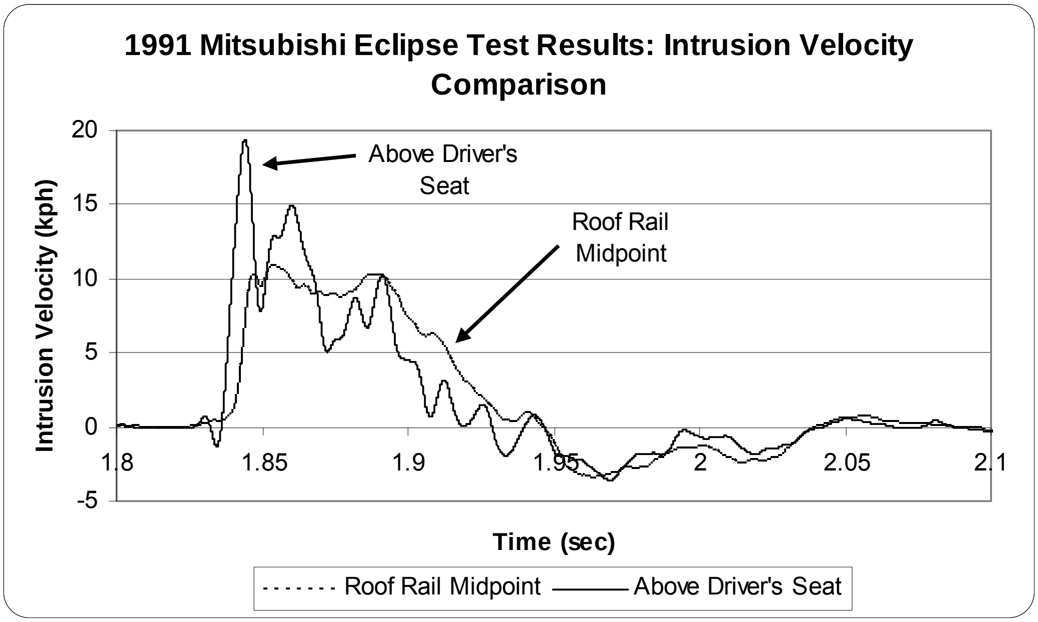


Figure 13. Effects of Buckling on Intrusion Velocity.

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 intrusion in these tests seldom reached this level even in a vehicle with a SWR as low as 2.5. 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 rarely broke. Side window breakage can be reduced by redesigning the window frame shape, size, location and strength.

- ***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 intrusion velocity.***
  All tests have been conducted with 10 degrees of yaw. Variations in pitch from 10 degrees to zero resulted in similar far side intrusion and intrusion velocity 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 intrusion.***
  The peak road load force and energy for far side roof intrusion 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 excellent performance of the Blazer with improved roof structure shows that there is no inherent problem in providing this level of protection in a light passenger vehicle. Although this vehicle had slightly more than 45 kg (99 lbs.) of added metal (2.5 percent of the vehicle's weight), the added weight for an adequately protective level of performance in an original design has been estimated at 11 to 23 kg (24 to 50 lbs). 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. The Volvo XC90, which we expect to subject to testing similar to that reported here, provides an example of a production vehicle designed with this philosophy.

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.

Acknowledgements

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