VEHICLE ROOF GEOMETRY AND ITS EFFECT ON ROLLOVER ROOF PERFORMANCE

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ABSTRACT

The Jordan Rollover System (JRS) provides a realistic, highly controlled, repeatable dynamic test of vehicle roof crush performance under typical rollover conditions [1],[2]. The principal use thus far has been in comparing vehicles' roof crush and injury potential performance in one and two roll events. Because the JRS directly measures the force between the roof and the ground during touchdown, it can be used to measure, assess and optimize occupant protection by adjusting roof geometry, roof structural design and material strength and elasticity, for the least cost and weight.

This study demonstrates that the peak force (load) between the initial leading side roof rail (near side) and the road is roughly four times the vehicle weight (the load-to-weight ratio or LWR) when a vehicle first touches down at around 150º of roll. The force then drops substantially as the vehicle continues to roll over the flat of the roof, in most instances dropping to zero because the vehicle is momentarily airborne. When the vehicle rolls beyond 180º and comes into contact with the side rail opposite to the leading side of roll (far side), the force rapidly rises again. The roof then either collapses or lifts the vehicle center of gravity (COG). The far side rail of a weak roof vehicle that cannot lift the COG may then halt the vehicle's downward fall, imposing even larger forces on the road segment when the vehicle's door and main body structure interact with the roadway. To deal with such forces, a long standing and natural presumption has been to substantially increase the roof strength to weight ratio (SWR), which can result in weight efficiency cost penalties. However, one production vehicle that was tested minimized roof crush without substantially increasing its SWR.

Analysis of the results has found that far side roof crush is strongly related to the difference between the major radius (the maximum distance from the principal axis of rotation to the roof rail) and minor radius (distance from that axis to the center of the roof). Three to four inches, as between cars and LTV's has a significant effect on injury potential. The typical difference in a light truck vehicle LTV is around 15 cm to 25 cm (6" to 10") while in an passenger car it is around 8 cm to 15 cm (3" to 6").

These observations were confirmed by physical tests of strong and weak roofed vehicles. These tests led to the conclusion that a geometry change in the roof to minimize the difference in radius across the roof would reduce the degree to which the far side of a less strong roof had to lift the vehicle as it rolled beyond 180º. A finite element analysis confirmed that for a vehicle of modest roof strength, a structurally strong, rounded roof panel will reduce the far side deformation and intrusion speed by about two-thirds without increasing underlying roof strength. These results were confirmed in JRS testing of current production passenger cars and SUV vehicles and with a "HALO" TM – High Attenuation Load Offset (U.S. and International Patent Pending Rollover Damage Minimization Device) retrofit kit for SUVs.

INTRODUCTION

In 1967, in an Advanced Notice of Proposed Rulemaking (ANPRM) [3] the National Highway Safety Bureau (NHSB) recognized intrusion as a major factor in occupant survival. Hugh DeHaven's 1952 SAE paper [4] suggested dynamic containment, leading to the FMVSS 208 dolly rollover test. With Franchini in 1969 [5], a general consensus limit of 5" of intrusion evolved. NHSB then initiated the ESV program, the performance specifications that limited roof intrusion in rollover tests to 5" to ensure the preservation of occupant survival space (OSS). When production vehicles of that time failed to meet that criterion in SAE Recommended Practice J996 drop tests at drop heights of 8 cm to 30 cm (3" to 12"), the dynamic intrusion test was abandoned by NHSB. A two-sided quasi static test using a small platen pitched at 10º and rolled at 25º at the A-pillar was proposed with a strength-to-weight ratio (SWR) criterion of 1.5 [6]. When almost all of the production vehicles failed that test, NHSB reduced the pitch angle to 5º and required that the test be conducted on only one side [7].

In 1989, a NHTSA evaluation showed that the static tests and criteria had no effect on roof strength or rollover casualties. Indeed, a recent paper by Young et al shows how US rollover fatalities continue to increase despite a number of rollover injury mitigation initiatives being introduced over the past two decades [8], [9]. In 1998, NHTSA studied the typical relationship between the FMVSS 216 static and dynamic drop tests with the same orientation. They found that the dynamic drop tests involve 1.6 times the force of the static tests for the same deformation, suggesting an increased SWR criterion of 1.5 times 1.6 or 2.5. Although it was obvious that drop tests ignore the rotational component of a roof-to ground impact (which accounts for substantially increased far-side crush), no alternative test protocol was available to directly measure and evaluate the roof SWR required to limit intrusion in a rollover.

In 2002, the Jordan Rollover System (JRS) was developed to provide a scientific basis for evaluating rollover occupant protection under dynamic conditions. Since that time, about 50 vehicles have been tested in one, two and three roll protocols, most recently with injury interpretation directly from dummy human surrogates. The results of those tests have been published in various conference proceedings [1],[2],[10],[11],[12]. Ratings of dynamic rollover structural performance have been based on NHTSA's 5" occupant survival space, post-crash negative headroom and a 11 km/hr (7 mph) onset of serious head and neck injury. As a body of data, the JRS tests establish relationships between measured parameters, such as crush and crush speed as a function of pitch, impact roll angle, peripheral and translational speed.

The JRS is the first rollover test device that can directly measure force-time histories between the roof and the ground during the roll as a function of roll angle. That force is also a function of the dynamic strength of the roof and, sometimes at high-roll angles, the body, the weight of the vehicle, and the dynamic extent of roof crush.

This paper presents plots of this load-to-weight ratio (LWR) and the interior intrusion measured on each side of the roof as a function of roll angle for 5 current model passenger cars and 5 current model LTVs. All of which were JRS tested with the same two roll protocol. Vehicle responses are compared and interpreted in the Discussion and Results sections.

A principal geometric conclusion was validated by designing an SUV retrofit kit to improve rollover occupant protection in weak-roofed vehicles. The kit was JRS tested to deal with the immediate concerns for rollover casualties in commercial, industrial and government off-road and rural undeveloped or poorly-maintained road operations.

METHODS

The JRS is versatile in that it can provide repeatable dynamic data under almost any realistic rollover protocol. A dynamic test is the best way to rate rollover crashworthiness performance. The fixture with a mounted vehicle is shown in Figure 1.

Figure 1. Jordan Rollover System (JRS) Test Rig.

Descriptions of how the test rig functions are described elsewhere [2], [13]. The vehicle is mounted to towers as on a spit through the COG and its axis of rotation. The vehicle is simultaneously rotated and released as a roadbed moves under it. The test is commenced from an almost vertically oriented position to the roadbed similar to that shown in Figure 1.

During the simultaneous rotation and fall, the vehicle strikes the moving roadbed below on the leading side of roll (near side) at the roof rail at the prescribed roadbed speed, vehicle angular rate, drop height and impact pitch angle. After striking the near side the vehicle continues to roll and strikes the side opposite to the leading side being the far side. The vehicle is then captured. The motions of the vehicle and roadway are coordinated so that the touchdown conditions can be controlled and thus repeated within a narrow range that was considered acceptable in other crash test protocols used by IIHS and NCAP [14],[15].

A 50^{th} percentile Hybrid III Anthropomorphic Test Dummy (ATD) is used to monitor head and neck loading in the driver seat position. String potentiometers are used to measure roof intrusion and intrusion rates, as well as the ATD's motion. High speed cameras also record vehicle and ATD motions. The ATD is setup by the FMVSS 208 protocol.

Measured parameters included: the roll angle and rate, the pitch angle and its variation, the dummy motion relative to the seat through a string pot to the dummy buttocks, the intrusion of both sides of the roof, and the forces between the vehicle roof, the roadbed and the towers.

In a rollover crashworthiness study of ten current production vehicles (5 passenger cars and 5 light trucks), the relationship of the forces between the ground and the roof and the deformation of the roof as a function of roll angle was investigated. The tests were conducted by the Center for Injury Research and funded by the Santos Family Foundation through the Center for Auto Safety. The vehicles were supplied by State Farm Insurance Company.

DISCUSSION

Generic SWR vs. Dynamic Injury Potential

A comparison of SWR ratings and dynamic ratings from a companion ratings paper [16] is shown in Figures 2 and 3. The slope of the lines represents a reduction in the injury risk rating comparable to the IIHS study. It is also worth noting that the risk of passenger and SUV vehicles at essentially the same SWR also varies greatly.

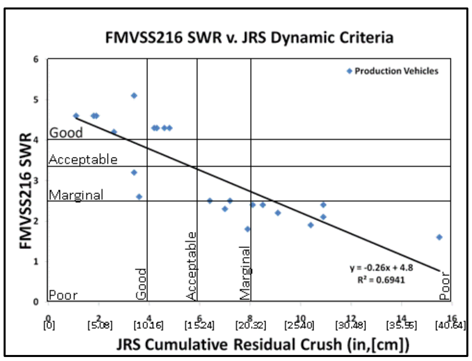


Figure 2. JRS Cumulative Residual Crush

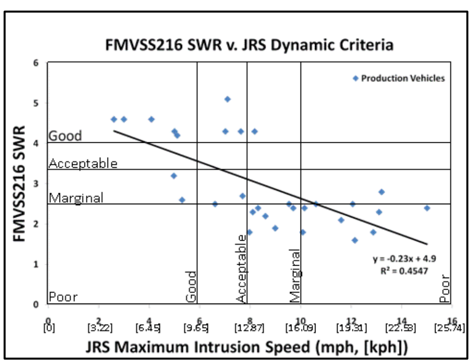


Figure 3. JRS Maximum Intrusion Speed

Since the JRS tests can be carried out with instrumented ATD's it is possible to individually measure the roof crush effects on various injury criteria of different vehicle roof geometric, structural and material designs. In other words a dynamic based rating system can resolve the disparities and reflect real world injury potential.

RESULTS

This section provides detail about the relationship between road load measurements as a function of roll angle and the resulting roof crush on the near (leading side of roll) and far (opposite to leading side of roll) sides. Figure 8 has an insert orienting the reader to the position of the vehicle at each peak load when seen from the ¾ view from the front. In this case the near side (passenger side for US vehicles, since all JRS tests are passenger side leading) peak road load is shown at ~155 degrees after first contacting at about 145 degrees as shown at the beginning of roof crush and road load. Similarly, the peak far side road load occurs at about 200 degrees and the loading affecting roof deformation ends when the peak roof crush occurs at about 210 degrees. After that point the road is recording the force that is loading the vehicle body in the area around the window sill to fender area. Notice in this case that the peaks are both about four times the vehicle weight.

The deformation of the roof is measured with string potentiometers and confirms the accuracy with video tracking software in the two interior camera recordings. As shown in Figure 4 and 5, the string potentiometers are placed at the center of the vehicle and are attached to the A-pillar on both the driver and passenger sides of the vehicle and to the B-Pillar on the driver's side. The reason for no additional string potentiometers is the Hybrid III dummy kinematics interfere with transducers. If additional data is required it can come from the video tracking software for any point on the interior. String potentiometers are reliable and have an accuracy of about one quarter of a centimeter (one tenth of an inch). However, the tracking software adds confirmation and the ability to resolve the radial displacement into rectilinear coordinates. Since the measurements of interest are in the order of 15 cm (6") of displacement, the error in measurement of the string potentiometer is at least an order of magnitude less.

Figure 4. Vehicle Interior String Potentiometers

Figure 5. String Potentiometers to A Pillar

The study focuses on the detail available from the five passenger cars and five LTVs shown in Figures 6 and 7. They are all shown in their post test conditions after JRS tests with identical two roll protocols, first at 5 degrees and the second at 10 degrees of pitch**.**

Characteristics affecting roof crush comparisons

Comparisons show dramatic differences in roof crush between vehicles of similar FMVSS 216 SWR class and between passenger cars and LTV classes. What factors in addition to SWR affect vehicle roof crush performance is not clear at this point in time.

As indicated in the last section of this paper, a geometry change to "roundness" produced spectacular results. Four factors have been identified which could affect the dynamic but not the static test results: 1) the geometry as described by the difference in ratio of the major and minor radius (the "roundness" of the roof) for a particular vehicle; 2) the geometry as described by the longitudinal rake of the windshield and roof as well as the front of the hood between different vehicles; 3) the structural section configurations and joint design; and 4) the construction material's elasticity. The specific effect of each, if any, on injury potential performance is a future effort.

Figure 6. JRS Post Test Two Roll 5 Passenger Vehicles.

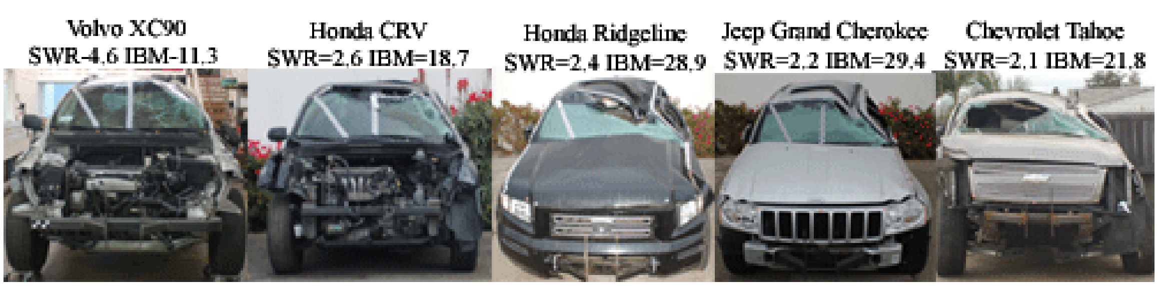


Figure 7. JRS Post Test Two Roll 5 LTV Vehicles.

Comparisons between similar SWR LTVs

Consider the roof crush performance of two LTV vehicles by the same manufacturer shown in Figures 9 and 10. The Honda CRV has a SWR of 2.6 and the Ridgeline SWR is 2.4. Notice that the roof crush in the CRV is half that of the Ridgeline in roll 1 at 5 degrees of pitch and in Roll 2 at 10 degrees of pitch. The peak roof intrusion speed is shown in Figures 11 and 12 where the chart starts at 175 degrees to highlight far side vehicle response. These plots show that when there is a significant force beyond the time of peak roof crush (about 210º of roll), it comes from the lower side of the upper vehicle structure contacting the road segment. To the extent that the force no longer crushes the roof laterally it is irrelevant to roof performance.

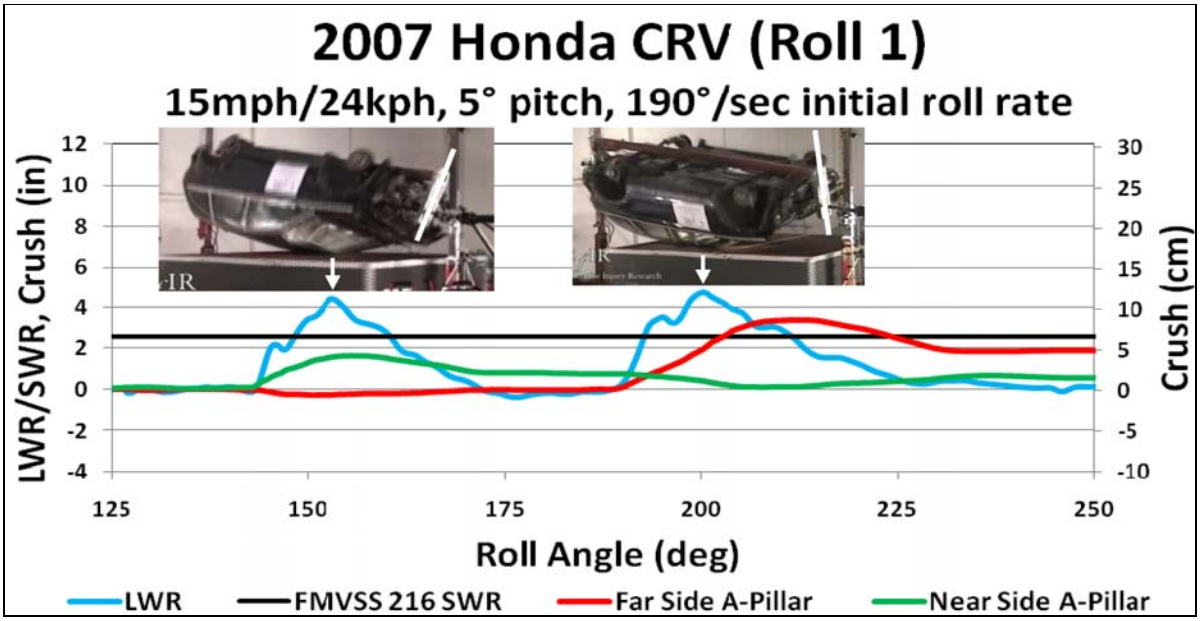


Figure 8. 2007 Honda CRV Test Results with Actual Vehicle Positions at Peaks.

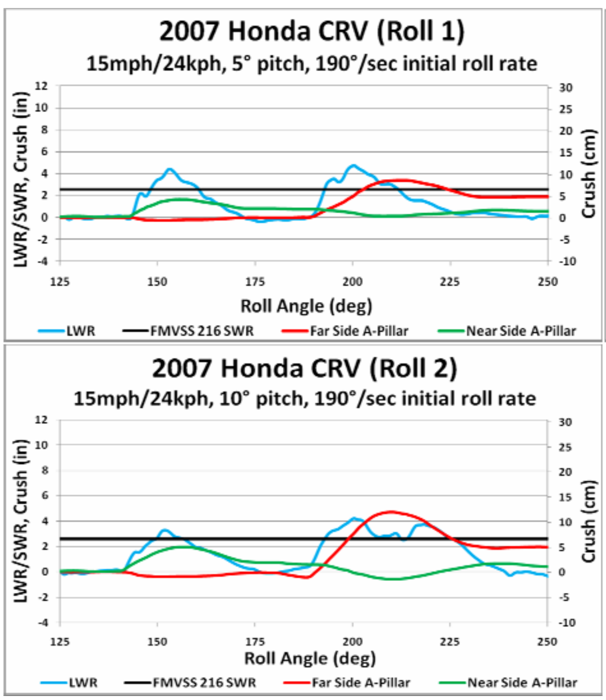


Figure 9. CRV Roof Crush vs. Roll Angle.

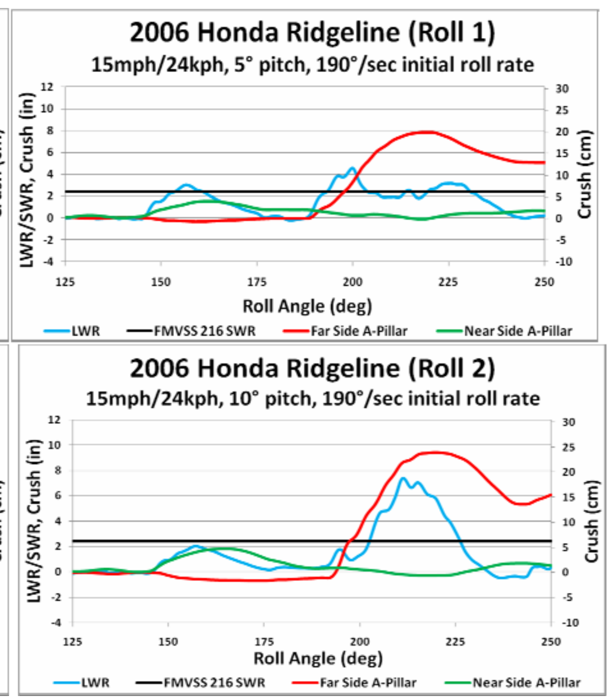


Figure 10. Ridgeline Roof Crush vs. Roll Angle.

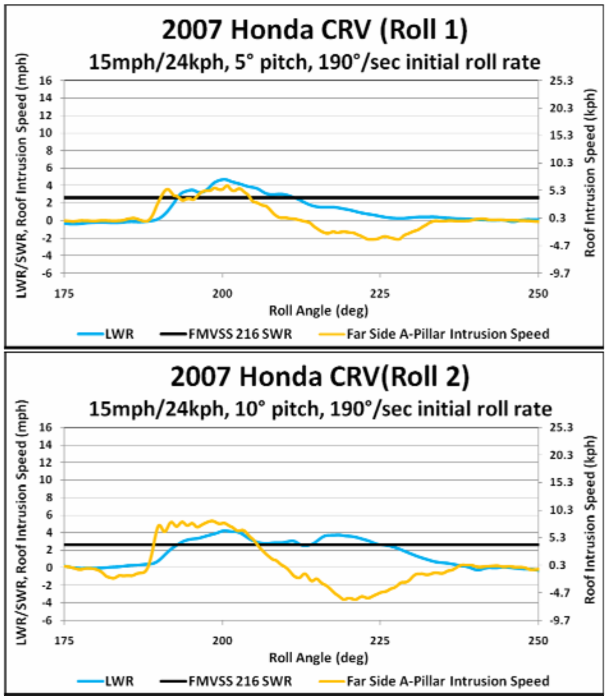


Figure 11. CRV Peak Roof Instrusion Speed.

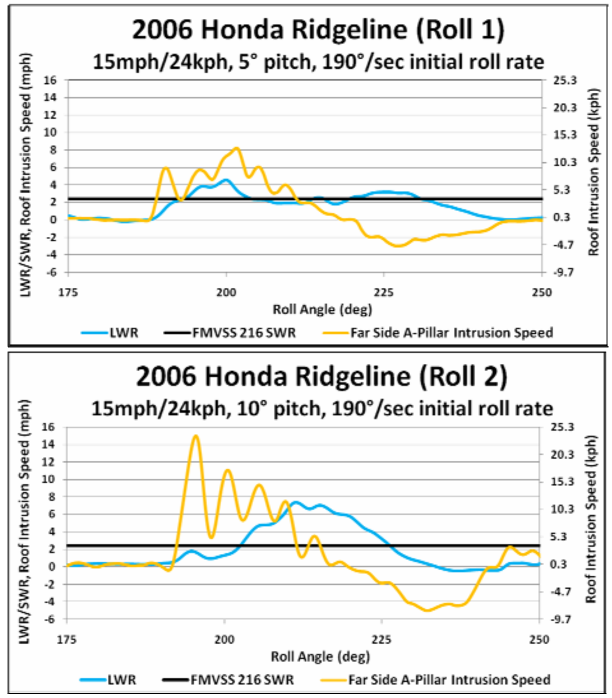


Figure 12. Ridgeline Peak Roof Instrusion Speed.

Comparisons Between Autos of Substantially Different SWR

The roof crush versus roll angle performance of two passenger cars, a VW Jetta with an SWR of 5.1 and a Pontiac G6 with an SWR of 2.3, is shown in Figures 13 and 14. Notice that the roof crush in the first 5 degree roll of the VW is one third of that of the G6 and the residual roof crush is 40% of peak value versus 75% of the peak value in the G6. In Roll 2 at 10 degrees of pitch the peak and the residual intrusion values are the same for both, but the cumulative residual for the Jetta is only about 9cm (3.5") compared to 18 cm (7") on the G6. The peak roof intrusion speed is shown in Figures 15 and 16, where the chart starts at 175 degrees to highlight far side vehicle response.

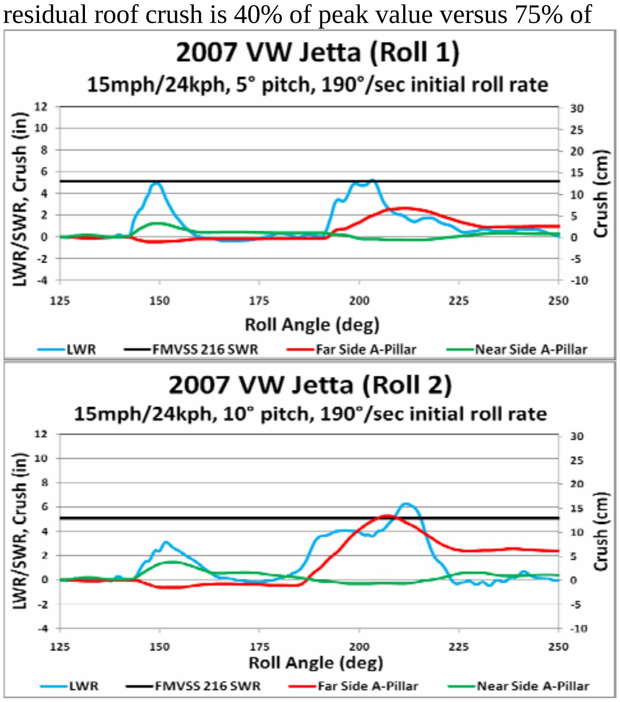


Figure 13. Jetta Roof Crush vs. Roll Angle.

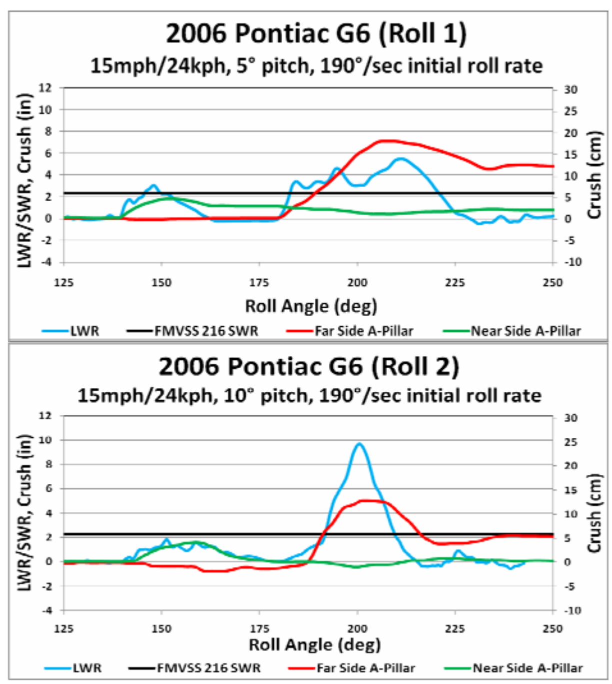


Figure 14. G6 Roof Crush vs. Roll Angle.

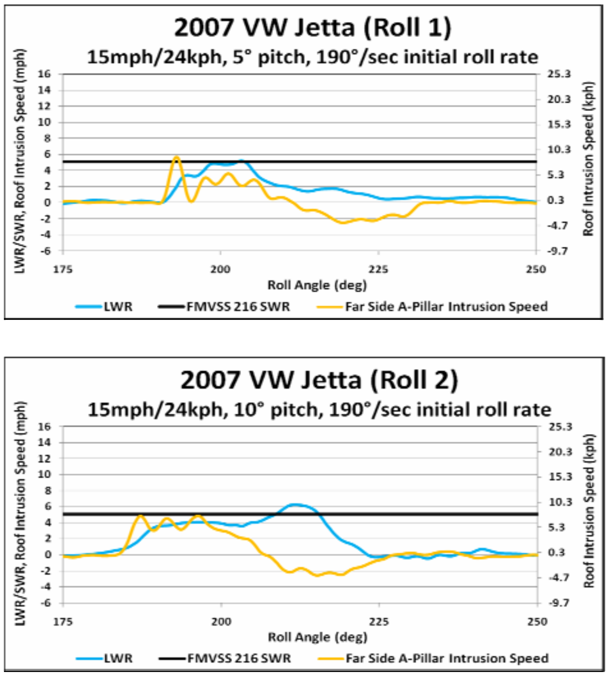


Figure 15. Jetta Peak Roof Instrusion Speed.

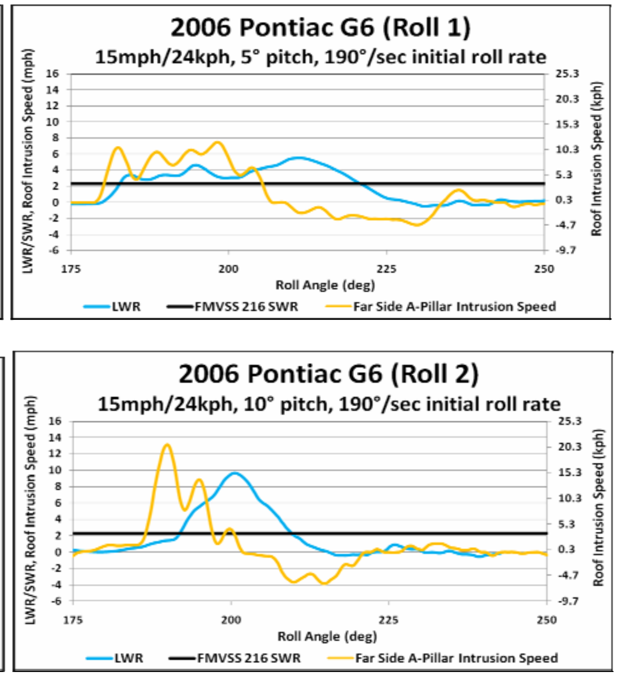
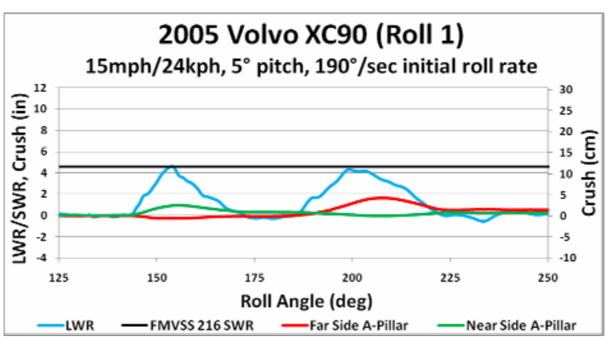
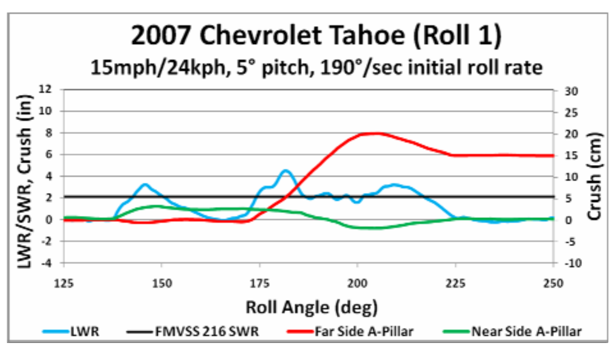


Figure 16. G6 Peak Roof Instrusion Speed.

Comparisons Between SUVs of Substantially Different SWR

The roof crush versus roll angle performance of two SUVs, an XC-90 with an SWR of 4.6 and a Chevrolet Tahoe with an SWR of 2.1, is shown in Figures 17 and 18. Notice that the roof crush in the first 5 degree roll of the XC-90 is one fourth of that of the Tahoe and the residual roof crush is 3 cm (1") versus 15 cm (6") in the Tahoe. In Roll 2 at 10 degrees of pitch the peak and the residual intrusion values are about 5 cm (2") compared to 15 cm (6") and the cumulative residual for the XC-90 is only about 5 cm (2") compared to 28 cm (11") on the Tahoe. Note that the near side damage in the second roll on the Tahoe first erected the far side to some degree before the rotational impact component collapsed it. The peak roof intrusion speed is shown in Figures 19 and 20, where the chart starts at 175 degrees to highlight far side vehicle response.





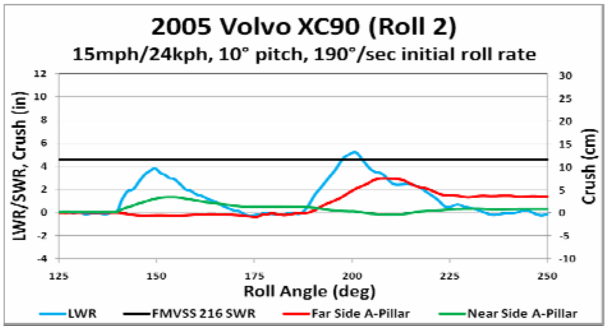


Figure 17. XC90 Roof Crush vs. Roll Angle.

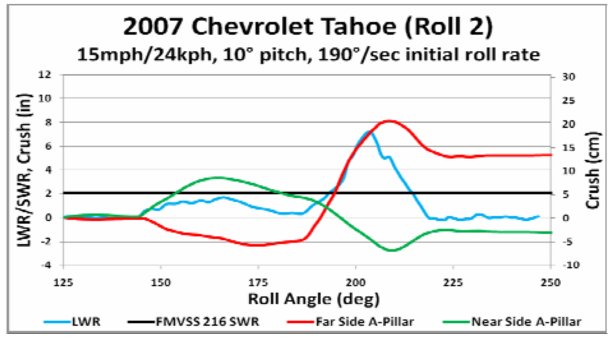


Figure 18. Tahoe Roof Crush vs. Roll Angle.

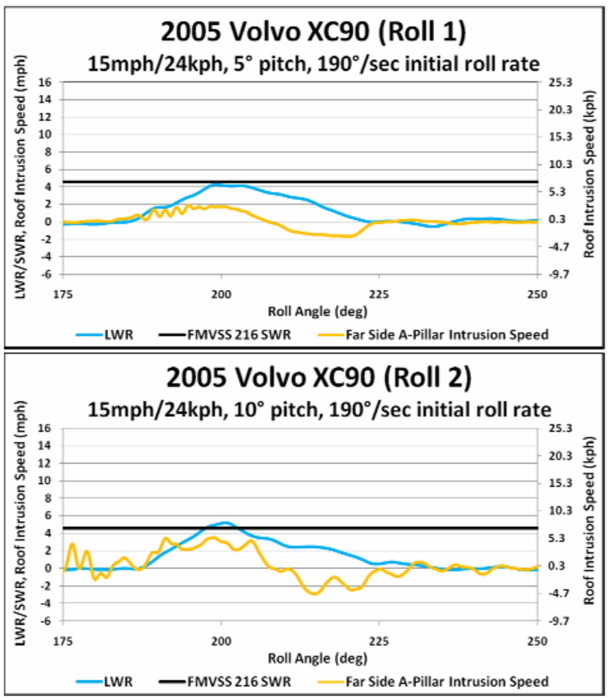


Figure 19. XC90 Peak Roof Instrusion Speed.

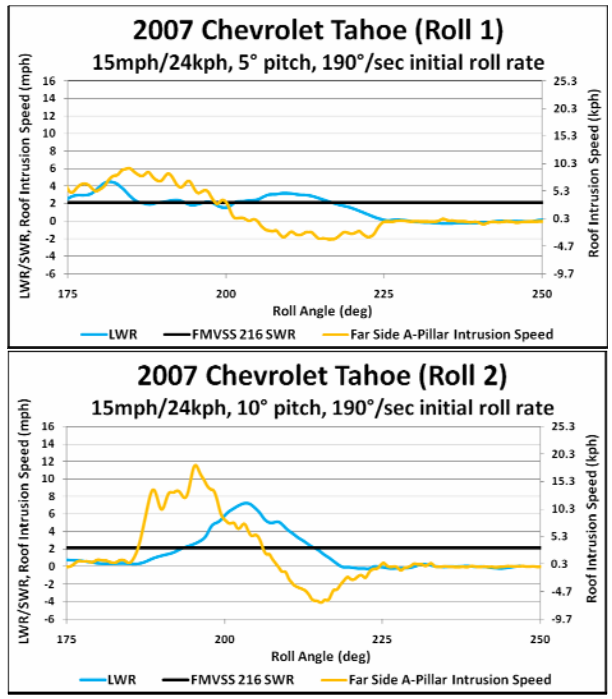
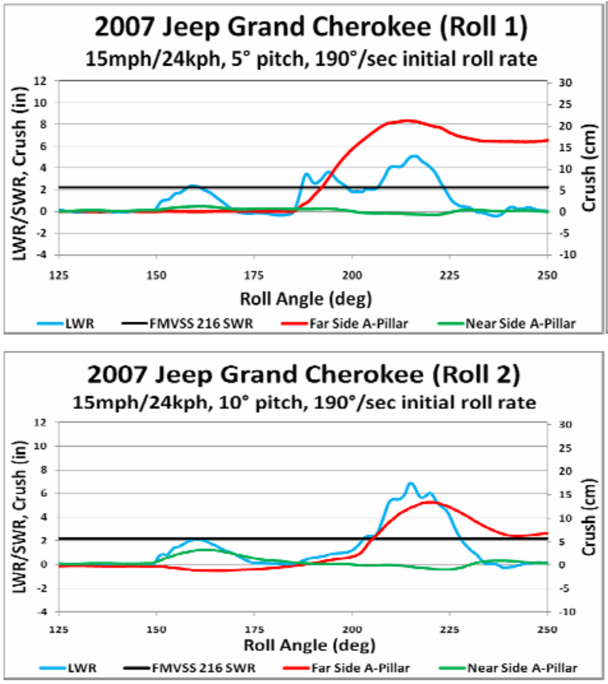


Figure 20. Tahoe Peak Roof Instrusion Speed.

Comparisons between a passenger car and an SUV of similar SWR

The roof crush versus roll angle performance of an SUV, the Jeep Grand Cherokee and a passenger car, the Chrysler 300 both with an SWR of about 2.5 but grossly different geometry, is shown in Figures 21 and 22. The peak and residual roof crush in the first 5 degree roll of both vehicles is about the same. In Roll 2 at 10 degrees of pitch the peak and the residual intrusion values are about 23 cm (9”) and 15 cm (6”) for the Cherokee compared to 13 cm (5”) and 5 cm (2”) for the 300. The cumulative residual for the Cherokee is about 28 cm (11”) compared to 18 cm (7”) on the 300. The peak roof intrusion speed is shown in Figures 23 and 24, where the chart starts at 175 degrees to highlight far side vehicle response.



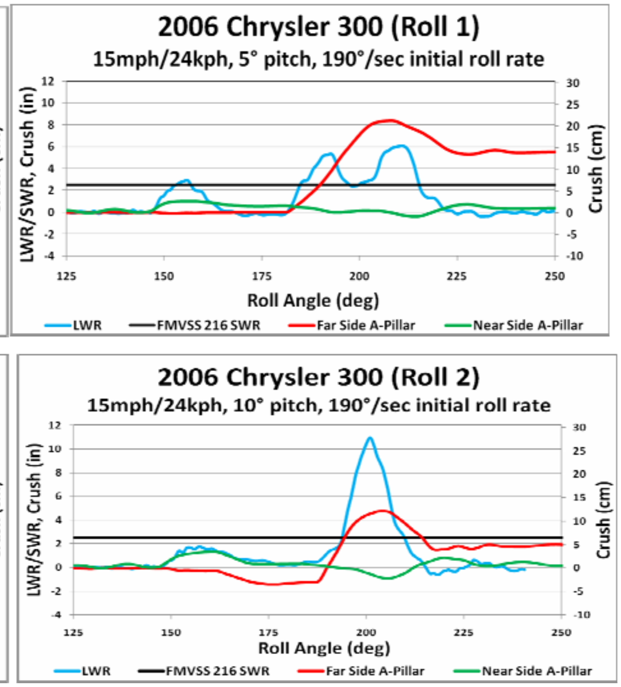
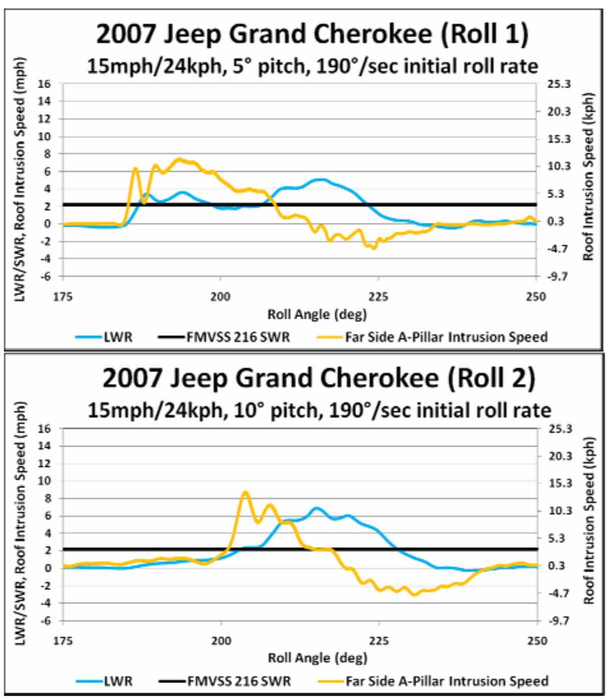


Figure 21. Cherokee Roof Crush vs. Roll Angle. **Figure 22. 300 Roof Crush vs. Roll Angle.**



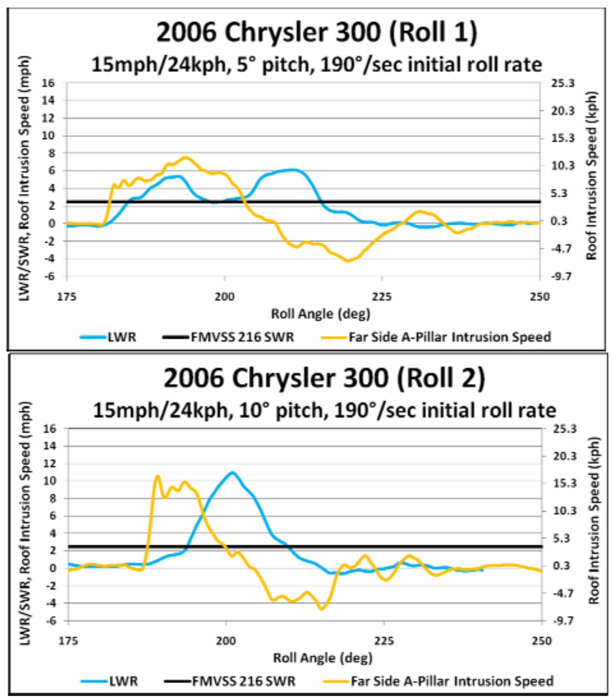


Figure 23. Grand Cherokee Peak Roof Instrusion Speed. **Figure 24. 300 Peak Roof Instrusion Speed.**

Geometric performance validation

Operations on unpaved road surfaces, such as U.S. Border Patrol operations, vehicle operations in theaters of war, energy and metals exploration and mining businesses, use production pick-up trucks, SUVs and buses for transportation. Consistent with the 10% fatality and serious injury performance of these vehicles in the mainly on-road private consumer usage, the frequency and injury risk of off road operation is also high. In consideration of their occupational health and safety requirements and liability for on-the-job injury, operators have established a voluntary rollover crashworthiness standard minimizing roof crush.

One solution for available production pick-up trucks is to design an external roll cage mounted in the pickup bed and extending over the cab [17]. Roll cages installed on the interior of SUV's interfere with the rollover activated window curtain airbags and are generally insufficiently padded, cumbersome and awkward for entry and exit, riding comfort and frontal safety as shown in Figure 25. The systems appear to employ the intrusion criteria formulated by Franchini in 1968 [5] and a blunt strategy of strengthening the roof well above what is accepted as industry best practice that has demonstrable good rollover crashworthiness, e.g. the Volvo XC-90. Because rollovers involve many impact orientations the accepted solutions are in some instances massive, unyieldingly rigid and cargo space consuming.

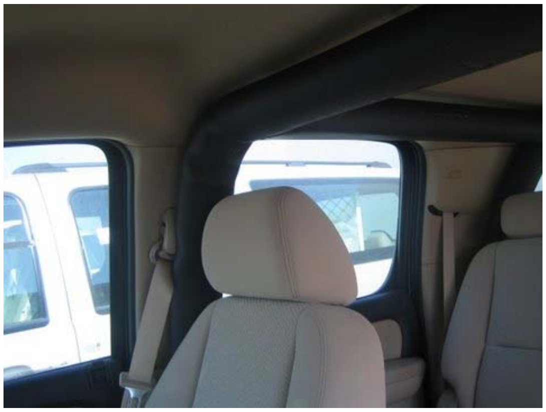


Figure 25. Internal Roll Cage.

The availability of the continuous time history of the forces between the vehicle roof and the roadbed spawned the development of a geometric roof design to evenly distribute the roof load during road contact, equate and minimize near and far side roof crush and thus reduce the risk of occupant injury at minimum cost and weight. The first application has been to develop an acceptably styled, universal retrofit kit for production vehicles to achieve state-of- the-art occupant protection at minimum production and installation cost. Most of the vehicles in use today have strength to weight ratio (SWR) roofs as measured by the U.S. FMVSS 216 test of 1.8 to 2.4. Figure 26 and 27 are pictures of a 1993 Jeep Grand Cherokee (JGC) (4400 lbs., SWR=2.3) before and after a one roll 10 degree JRS test.

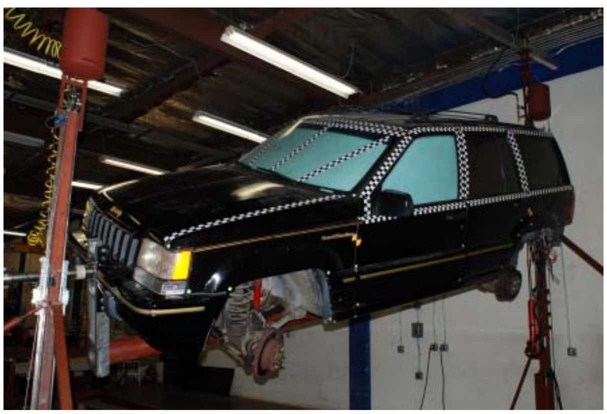


Figure 26. JRS Grand Cherokee (Before Test).

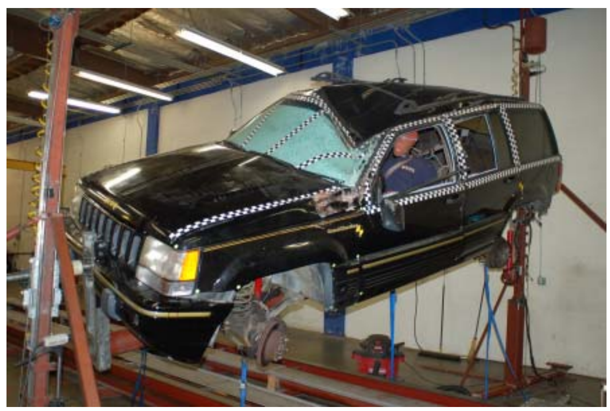


Figure 27. JRS Grand Cherokee (After 1 Roll).

The results of this one roll JRS test are shown in Figures 32 and 33. The far side A Pillar crush was close to 30 cm (12"). The far side A Pillar intrusion speed was over 16 km/p (10 mph).

The HALO ™ system, which was developed in early 2008, is shown in Figure 28. The structure was initially designed for the 1993 Jeep Grand Cherokee (JGC), which has one of the lowest "roof strength to vehicle weight ratios" and one of the worst rollover crash characteristics in terms of occupant injury potential as demonstrated on the JRS and shown in Figure 27.

Figure 28. HALO ™ Roof Damage Minimization Device

Several forms of evidence show how well HALO ™ works including physical crash testing, computer based finite element analysis (FEA), and photogrammetric 3D analysis. Two similar 1993 Jeep Grand Cherokees were tested on the JRS with the same protocol. The HALO ™ reduced dynamic roof intrusion at the A-Pillar by more than 27 cm and at the B Pillar by more than 16 cm. Roof intrusion speed was also reduced from 16 km/h to 1.6 km/h at the A-Pillar and from 12.4 km/h to 1.1 km/h at the B-Pillar. The interior camera view for each test at peak loading is shown in photos from the testing video in Figures 30 and 31. The Hybrid III dummy experienced axial neck loading of around 10 kN (1 ton) in the production vehicle versus only 1 kN (equivalent to standing on your head) in the Jeep with HALO ™.

A Finite Element analysis from Friedman Research Corporation of the first configuration indicated a reduction in far side intrusion at the A pillar from 30 cm (12") to 10 cm (4") with increased near side intrusion to 10 cm (4"). The initial design was tested on two different vehicles before the final design was achieved. Illustrations of this analysis are shown in Figure 32.

Figure 29. 1993 JGC's JRS Rollover Tested With and Without HALO ™ and the Corresponding Photogrammetric 3D Analysis.

Figure 30. Interior of a 1993 JGC Without HALO ™

Figure 31. Interior of a 1993 JGC With HALO ™

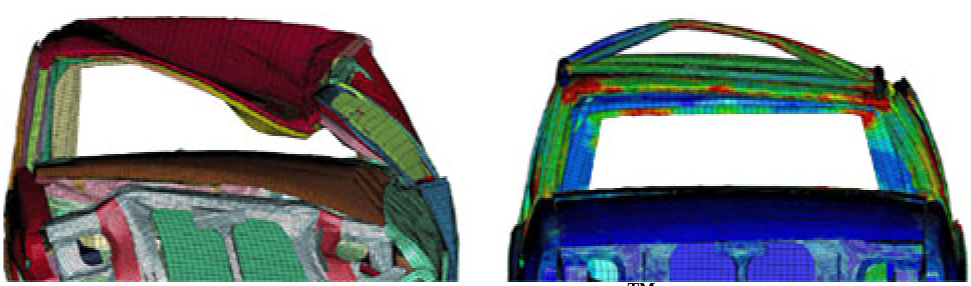


Figure 32. FEA – Finite Element Analysis with HALO ™ , Before and After One Roll.

Two derived versions of a retrofit kit have been developed. The primary difference in an SUV is an internal buttress' at the B-pillars for applications to vehicles with SWR's of less than 2.5. The system creates and supports a strong round roof a few inches forward of the B-pillar. This has two effects. The round roof (or attachment) causes the impact and rolling force load on the roof from the road, to be constant (distributed equally) from near to far side. Locating and supporting the strong round roof forward of the B-pillars transfers and relieves a portion of the load at the A-pillars (and distributes across the header), which are traditionally weak (because of the FMVSS 216 test conditions). Another 1993 Jeep was fitted with a HALO ™ and JRS tested again and the exterior views are shown in Figures 33 and 34. Very little change occurred in the structure, even after 2 test rolls. The data from the production JGC and the results for the three rolls with the final HALO ™ design are shown in Figures 35 through 42.

Figure 33. JGC with HALO ™ Before Testing.

Figure 34. JGC with HALO ™ After 2 Test Rolls.

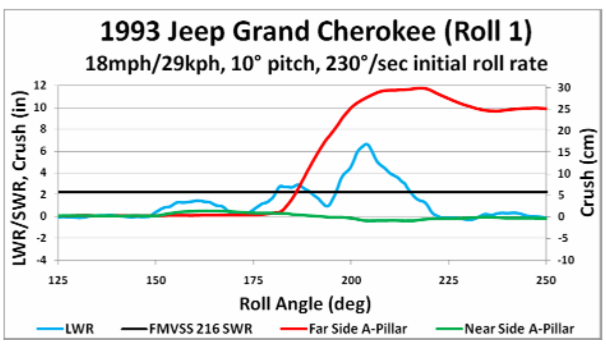


Figure 35. JGC Roof Crush vs. Roll Angle.

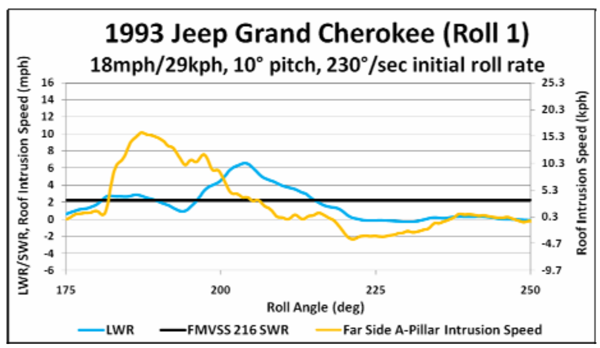


Figure 36. JCG Peak Roof Instrusion Speed.

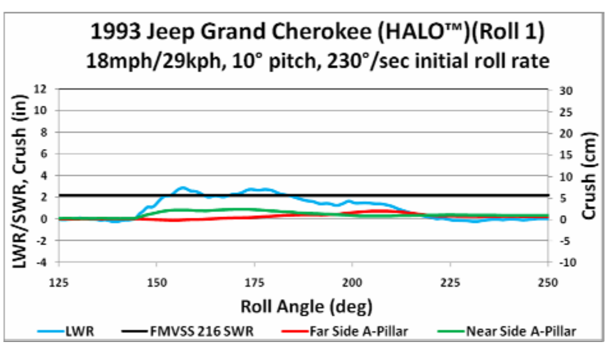


Figure 37. JGC w/HALO ™ Roll 1 Roof Crush

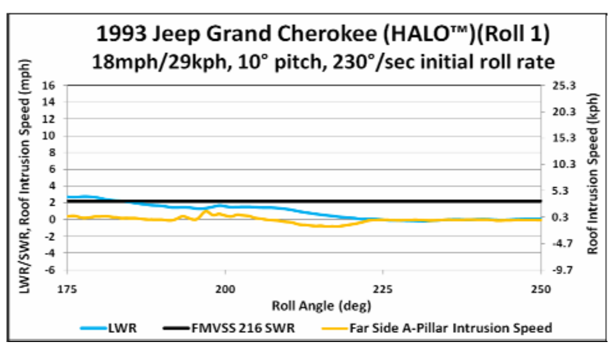


Figure 38. JGC w/HALO ™ Roll 1 Intrusion Speed

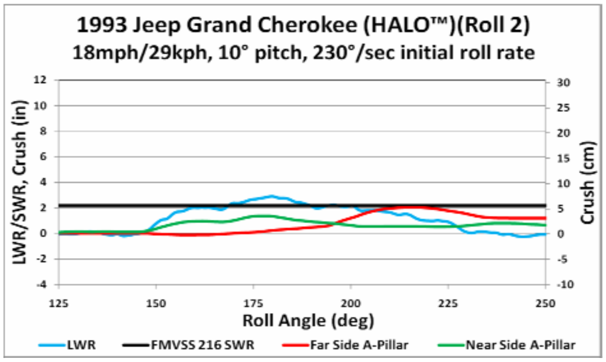


Figure 39. JGC w/HALO ™ Roll 2 Roof Crush

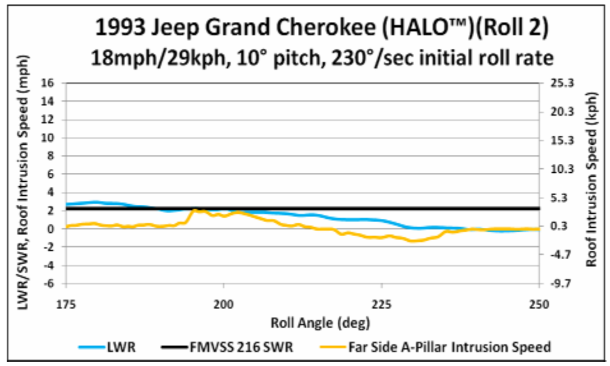


Figure 40. JGC w/HALO ™ Roll 2 Intrusion Speed

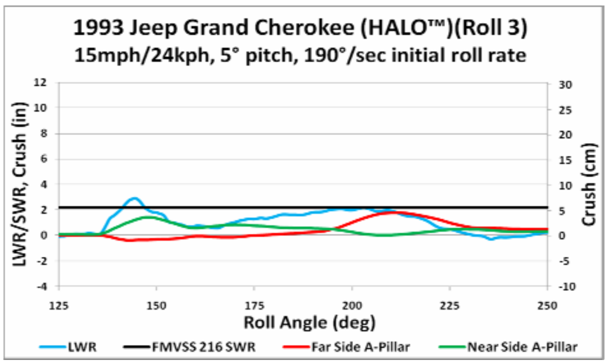


Figure 41. JGC w/HALO ™ Roll 3 Roof Crush

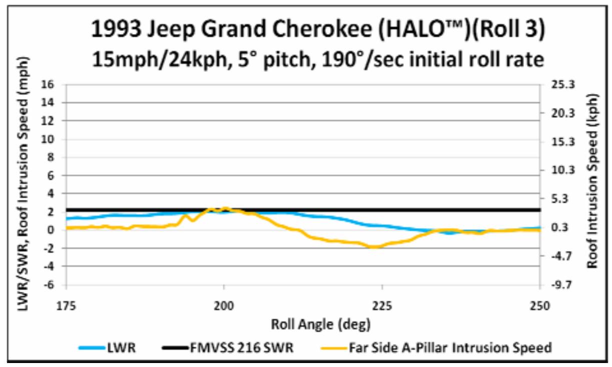


Figure 42. JGC with HALO ™ Roll 3 Intrusion Speed

CONCLUSIONS

- The geometry of a vehicle roof has a significant effect on the performance of that vehicle during a rollover and can be changed with little addition of weight.
- The geometry *alone* cannot compensate for fundamental weaknesses in the pillars
- Geometry alone can improve the performance of vehicles with relatively weak A-Pillar/Headers with reasonable B-Pillar strength.
- A vehicle's dynamic rollover characteristics largely determine the typical roof touchdown pitch orientation. Many vehicles with good FMVSS 216 SWR at 5 degrees of pitch are half as strong at 10 or more degrees of pitch. Therefore the touchdown pitch orientation of a FMVSS 216 compliant roof may or may not collapse unless its performance at 10 degrees of pitch has been assessed.
- A vehicle's roof contact pitch orientation strongly affects its injury potential performance in terms of roof crush and intrusion velocity.

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