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ROLLOVER PROTECTION – a Meaningful & Effective Solution

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Abstract

Rollover crashes remain over represented in land transportation around the world and in particular, the Oil and Gas industry, (OGP) when compared to other crash categories. The realities of this crash type is that within the USA alone it represents one in 33 car crashes each year, but it claims more than three of every ten lives lost on the nation's highways - 10,000 fatalities a year! As a crash type it is now responsible for more than a quarter of a million injuries, according to the National Highway Traffic Safety Administration (NHTSA) (NHTSA, 2009)

This alarming reality remains a very real exposure to land transportation safety within the OGP. In response, a variety of mitigation measures have been designed and installed worldwide. In the opinion of the authors, these traditional mitigation measures have become outdated and obsolete. Current research lends new insight into what causes injuries in rollovers and how to mitigate against those causes.

With the distinct lack of structural roof strength in most vehicles combined with the insubstantial crash performance criteria in vehicle roof design within the automotive industry, OEM’s are not compelled to ensure that the structure of their production vehicles are reinforced suitably to maintain occupant survival space in a rollover crash. Unfortunately this results in the vast majority of vehicles used within the industry today requiring some form of roof reinforcement to ensure that occupants are protected during a rollover crash.

Within the OGP today, a wide variety of Roll Over Protection Systems (ROPS) structures (both internal and external) are usually designed, purchased, manufactured, installed and maintained locally and with very little (if any) expert consultation. This has resulted in a wide variety of designs emerging with an alarming variance in the “assumed” effectiveness of each. Couple this alarming trend with the risk of rendering the existing intrinsic safety features ineffectual on modern vehicles, such as side air bag curtains and seat belt pre-tensioners, has resulted in vehicles with inadequate crash safety performance.

This paper describes how roof crush intrusion and intrusion speed into the occupant compartment can be minimized to an inconsequential amount using innovative design to externally retrofitted roof strengthening systems based on an understanding of road crash data, empirical evidence, and innovative state of the art testing and analysis to provide effective external ROPS structures for the OGP.

Introduction

For 35 years in the US, safety authorities, vehicle manufacturers, researcher and advocates have been carrying out comparative analytical and dynamic rollover tests investigating how to mitigate injury in rollover crashes. This has lead to comparative injury performance estimates of alternate roof designs that may not be effective. Recently, U.S. government and insurance industry statistical studies, backed up by comparative dynamic rollover tests have changed the rules and provided a means of resolving comparative performance claims.

The current real world occurrences involving rollover crashes have become a concern to mining and petroleum companies because of occupational health and safety requirements. Company vehicles are considered a workplace environment and hence, employees travelling in a company vehicle need to be protected in the event of a rollover crash. This is particularly so if the driver was travelling at the posted speed limit, all occupants were seat belted, and the vehicle has crashed through no fault of the driver.

As an example and case in point, there are no standards or consumer crashworthiness tests in Australia with regards to passive rollover crashworthiness of small and large vehicles such as passenger cars, four wheel drive (4WD) and sport utility vehicles (SUV) (Young, D.,2006). Moreover, no country or consumer group assesses “dynamically” the rollover crashworthiness of medium and small size passenger vehicles for the purposes of certification or crashworthiness ratings respectively. Nevertheless, the U.S. Insurance Institute for Highway Safety (IIHS) has introduced a roof strength rollover rating system for U.S. consumers based on the recent National Transport Highway Traffic Safety Administration’s (NHTSA) modified US FMVSS 216 quasi-static roof crush test protocol (NHTSA, 2009). As a beginning to the advancement of rollover safety, “quasi-static” testing allows for a general comparison of roof strength among different vehicles, however, this method of testing is not a full quantification of how the vehicle will protect the occupant in a rollover incident.

Typically, to mitigate the injuries observed in rollover crashes, a majority of mining and petroleum companies have installed rollover protection bars such as the examples shown in Figure 1 and Figure 2. Although such roof strengthening may at first appear to provide a survivable interior space to protect occupants against roof crush, these methods demonstrate a lack of the understanding of how vehicles deform and occupants are injured in rollover crashes. The design emphasis was based on static roof structure performance measurements. This approach has been proven to be somewhat unreliable. Results from dynamic performance tests compared to static performance can significantly differ, with both over- and under-estimates of a vehicle’s roof strength.

Figure 1. Examples of roof strengthening using internal rollover bars.

Figure 2. Vehicle reinforced with internal roll bar at B-pillar and external roll bar behind C-pillar. Note buckle of front windshield header rail intruding into occupant compartment.

It is Safety Engineering International's belief that static roll bar reinforcements based on a quasi-static test is limited without the understanding of the dynamic forces, occupant kinematics and restraint performance involved in a rollover incident. The latter part of this document will provide the theory and understanding of how rollover injury mechanisms can develop, and the effect roof crush has on an occupant during a rollover.

Definitions

- AIS: Abbreviated Injury Scale is a classification system for assessing the impact injury severity. It was developed and published by the Association for the Advancement of Automotive Medicine (AAAM)
- Far Side: This is the side of the vehicle roof that touches the ground second, after the near side has already touched down.
- FMVSS: United States Federal Motor Vehicle Safety Standard, as issued by NHTSA.
- Jordan Rollover System (JRS): Dynamic rollover testing system.
- MAIS: Maximum Abbreviated Injury Score
- Near side: The side of the vehicle roof that touches down first, once the vehicle is tripped.
- NHTSA: United States Department of Transportation agency called: National Highway Traffic Safety Administration
- RDMD: Rollover Damage Minimization Device, a roof retrofit system that reduces roof crush intrusion.
- Rollover: In this context, rollover refers to a laterally tripped vehicle roll scenario.
- Roof Crush (Intrusion): The case in which the dimension between the vehicle roof and occupant seating is decreased.
- Roof Crush Intrusion Speed: The speed, as measured, of the component roof part as it moves into the compartment.
- Rollover Occupant Protection System (ROPS): Although this traditionally speaks to roll cages and Roll Bars, the development of a better understanding of rollover incidents has given rise to designing a ROPS device that focuses on the 'system' that protects the occupants. Furthermore, the most advantageous design for a ROPS is an optimal combination of improvements to the vehicles structure and occupant restraints.
- Roll Bars (Conventional): Traditionally speaking, Roll Bars are welded steel tubes inserted inside the vehicle at the b-pillar or behind the c-pillar in SUV's and have been strictly used for static structural reinforcement and have minimal bearing on the dynamics of a vehicle rollover or occupant kinematics.
- Roof Strengthening: The result of the methods used to minimize Roof Crush Intrusion.
- Strength to Weight Ratio (SWR): A term derived from NHTSA's FMVSS-216 quasi-static roof crush test protocol where a metal platen is pushed against 1 side of a roof at a constant speed to determine the amount of force required

to deform the roof which is then divided by the weight of the vehicle to determine the SWR value. As an example, if a vehicle weighing 5000 lbs could withstand a force of 20,000lbs before reaching 5 inches of roof crush, it would have a strength-to-weight ratio (SWR) of 4.0.

- Trip Over: The most common mode of triggering a rollover.

Rollover Background and Statistics

Worldwide estimates in 1998 indicate there were 1 billion vehicles in operation, causing 1.1 million deaths and 38 million injuries every year. Figure 3 shows the distribution by Nations.

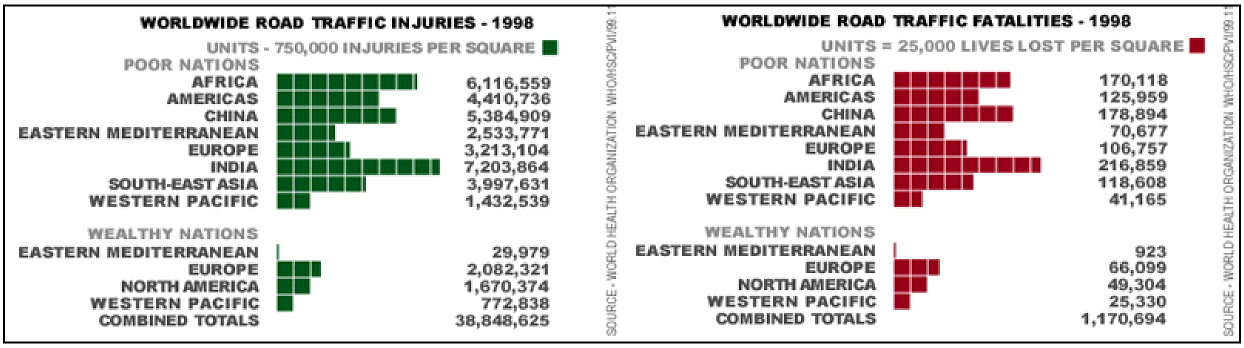


Figure 3. Worldwide cost of traffic accidents in deaths and injuries

In the United States, from data presented by NHTSA in 2007, there are about 306,000 rollover crashes each year representing only 3% of the incident pool. However, rollovers account for a full one third, or 33%, of all vehicle related fatalities (about 10,000) annually, as shown below in Figure 4. In addition, another study showed that rollovers have a fatality rate six times higher than frontal or side impact accidents as shown in Figure 5.

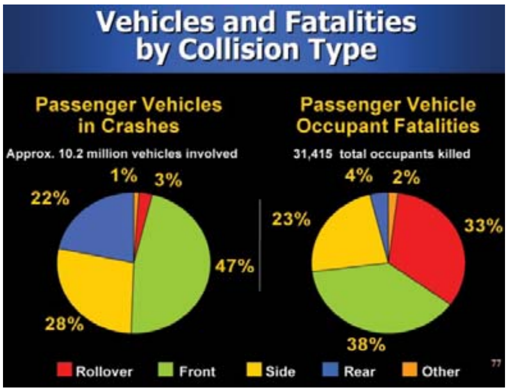


Figure 4. Vehicles and Fatalities by Collision Type

Crash Type	Total Occupants	Fatality Rate per Occupant
Rollover	418,371	0.02430
Frontal	2,921,864	0.00420
Side	1,359,538	0.00600
Rear	467,559	0.00220
Other	36,978	0.00620

Figure 5. Fatality Rate by Crash Type

In the past twenty years the US road fatality/population rate has declined from the best to 14th as compared European countries and Australia. Details of the rollover injury population are shown in Figure 6.

The US Rollover Injury Problem

306,000 Rollovers with 418,000 occupants and 40,000 (9.6%) are seriously injured or killed, 90% of which occur within two rolls.

Injury Type	Occupants	% of Total
Interior Fatalities	5400	1.3
Ejection Fatalities	4800	1.1
Severe and Critical Injury	12000	2.8
Serious Injury	18000	4.3
NOT Serously Injured	378000	90.5

Figure 6. Tabulation of Injury and Fatality distribution by severity and crash mode.

The data suggests that although the injury and fatality rates are extraordinarily high compared to frontal and side impacts, a surprising 90+% of occupants in the same vehicle rollover are virtually uninjured. Based on these detailed US statistics, it is estimated that about 3% of the worldwide injury road incidents are rollovers but they probably account for at least 350,000 annual deaths, a million serious and 400,000 permanently debilitating injuries. Worldwide and in the US, Motor Vehicle deaths are expected to be the third ranked cause of death and disease and first among 0-25 year old persons by 2020. At the rate new vehicles are produced and replaced, even if new designs were implemented soon and could prevent half of those deaths and injuries, the carnage would continue unabated to at least 2040. Installing retrofit vehicle systems and driver and occupant behavior aids appear to be the only possible way to reverse the trend in the near term.

Understanding Rollovers

Rollovers have been classified into several categories in the US based on typical rollover crash initiation scenarios. However, Eigen (Eigen, A.M., 2003) investigated a large number of these crashes that occurred between 1995 and 2001 using the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) and observed that 81% of all rollover crashes were single vehicle events, and 71% of these were initiated by the mechanism called the trip over.

From this investigation, Eigen concluded that the most common form of rollover crash in the US was a single vehicle event initiated by a tripping mechanism, which caused the vehicle to enter a lateral rollover. Young (Young, D., 2009) added to this by identifying, from all Australian rollover crashes in the years 2004 and 2005 where a fatality occurs, that the most common mechanisms initiating Australian rollovers where the occupant is contained within the vehicle during a rollover only crash event, is the trip over and turn over.

Moreover, Digges and Eigen (Digges, K.H.,2003) also identified that 8 quarter turns (i.e. two full rolls) or less accounted for more than 90% of all rollover crashes in Single Vehicle Rollovers for Non-Ejected Front Seat Belted Occupants Ages 12+ and Non-Ejected Front Seat Belted Occupants Ages 12+ with Maximum Abbreviated Injury Score (MAIS) 3+F Injuries. The AIS is a classification system for assessing the impact injury severity. It was developed and published by the Association for the Advancement of Automotive Medicine (AAAM). As a result of these observations and how vehicles deform during real world rollovers as shown in Figure 2, Figure 7, and Figure 11, the Jordan Rollover System (JRS) rollover crash test rig (Figure 9) was developed together with a rollover crash testing protocol. Detailed descriptions of how the test rig functions are described in the Jordan Rollover System section and in three conference papers. (Jordan, A., 2005) (Nash, C.E., 2007) (Bish, J., 2007).

Researchers have also identified that a relationship exists between serious and fatal injury and the location where a seat belted occupant sits in the vehicle. The studies of Parenteau et al (Parenteau, C.S., 2001) Digges et al (Digges, K.H., 2005), Friedman and Nash (Nash, C.E., 2005) and Nash and Paskin (Nash, C.E., 2005) all observed that occupants seated on the leading (near) side of roll are less likely to experience serious or fatal injuries than those on the side following (far side). In the case of a laterally tripped rollover incident, a leading “near side” and succeeding “far side” will always exist as a result of the directionality of the vehicle roll.

This explains part of the reason why 90% of rollover occupants are not injured. If the vehicle rolls toward the passenger side, the damage or crush occurs on the driver side and visa versa, example photos are shown in Figure 7. This results in non-injury such that about 50% of the uninjured occupants are seated where there is minimal damage. Furthermore, while on the road, in order to roll, the vehicle must rotate sideways moving the unbelted and belted driver out of the shoulder harness forward and towards the passenger side away from the crush. In a rollover accident the roof is mainly crushed and people are seriously injured on the FAR side, the side opposite to the direction of roll (called the NEAR side).

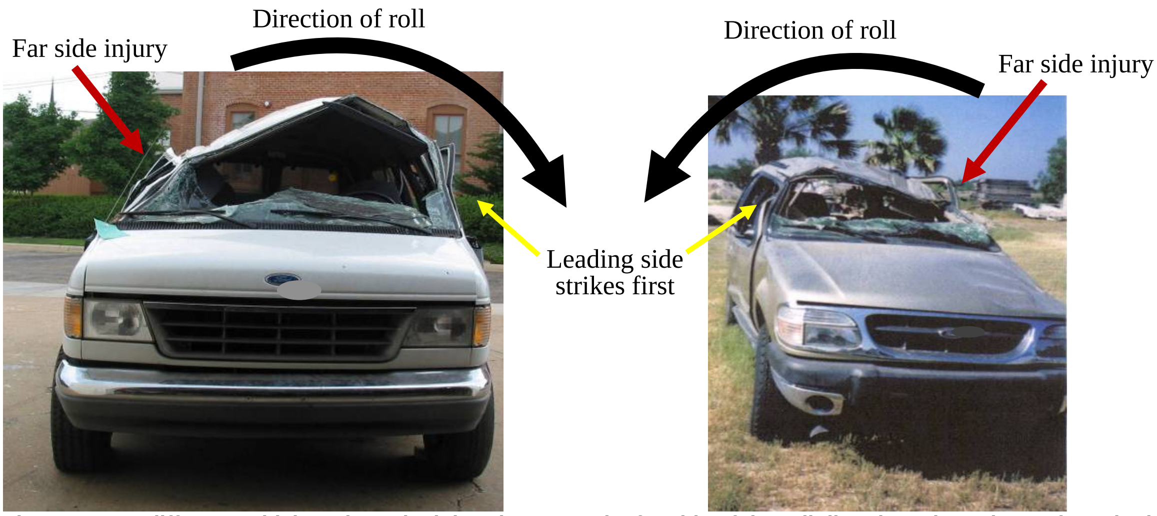


Figure 7. Two different vehicles where the injured were on the far side of the roll direction where the roof crushed.

Characterizing a Catastrophic Injury Rollover

When a rollover occurs, the roof first contacts the ground on the leading near side (left frame in Figure 8) the reaction load transmitted to the roof is in a direction that for the most part compresses the A-pillar. When the vehicle continues to roll it strikes the far side (right frame in Figure 8) more abruptly due to the square shape and weak structure of most vehicles. The reaction load is in a direction such that the A-pillar is loaded somewhat similar to a cantilever beam. Connectivity between the pillars and the roof are very weak, offering little or no moment transfer. Hence the A-pillar can be treated essentially as a cantilever beam with a weak pinned-end support that provides little to no resistance to the pillars bending about the base of the pillar. It is well known in structural mechanics that columns subjected to an axial load can tolerate much higher loading than the load required to bend the column like a cantilever. This is of course on the condition that the column is relatively stout (not slender).

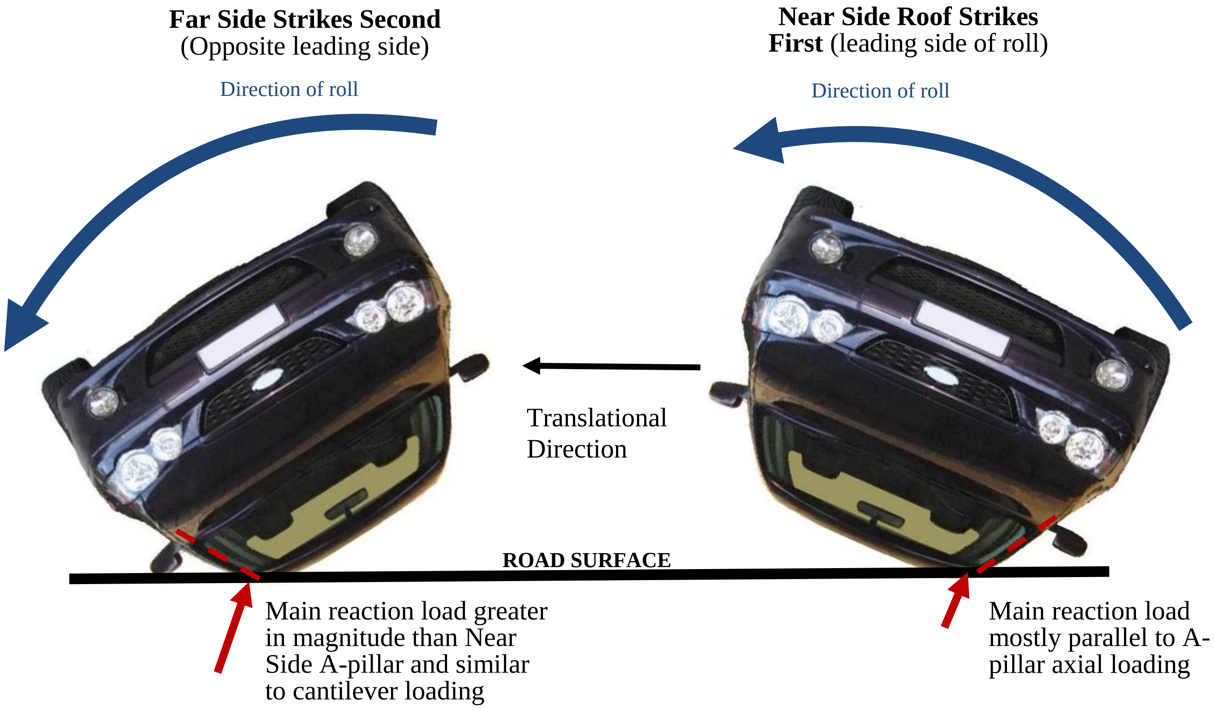


Figure 8. Loads applied to vehicle's roof during rollover.

Vehicle Structural Characteristics in Rollovers

The structural characteristics of the vehicle influence its performance in a rollover. Because the U.S. Government, since 1973, prescribed the minimum circumstances under which a vehicle roof must perform, most vehicles have common characteristics and deficiencies. The following list describes the deficiencies that exist in the current vehicle fleet and suggested remedies.

- A roof strength weight ratio (SWR) of about two in a 5° pitch test and one and a 10° pitch test.
  - Current studies indicate a need for an SWR of at least three but preferably 4 at any pitch.
- A geometry maximizing the strength under the mostly vertical test loading conditions, resulting in a kind of square frontal cross-section precluding the vehicle from rolling smoothly.
  - Current studies indicate that vehicle geometry must be considered for rollover performance.
- Stiffness allowing progressive intrusion to 5 inches before reaching the SWR criteria, thereby compromising the occupant's survival space.
  - Current studies indicate that reducing intrusion to less than 5 inches in any one roll, will keep the occupant survival space in tact.
- A lack of structural elasticity resulting in plastic deformation accumulating crush and reducing survival space for subsequent rolls.
  - Current studies show that after market high strength steel reinforcements or production structures like those in the Volvo XC90 can counter this effect.

The objective and purpose of a roof damage mitigation system must address and alter some or all of these fundamental safety deficient design characteristics. To achieve an optimum outcome, computer simulation and a rollover test fixture that allows for repeatable testing is needed.

The Jordan Rollover System

Comparative performance evaluations require a reliable, repeatable fixture which can accurately compare scientific, instrument measured performance. The Jordan Rollover System (JRS) is the first fully dynamic impact isolating fixture. It is now being assessed by some research organizations, Governments and industry as the test fixture offering the best possibility of development of a dynamic crashworthiness test protocol. It is shown in Figure 9 and described thereafter.

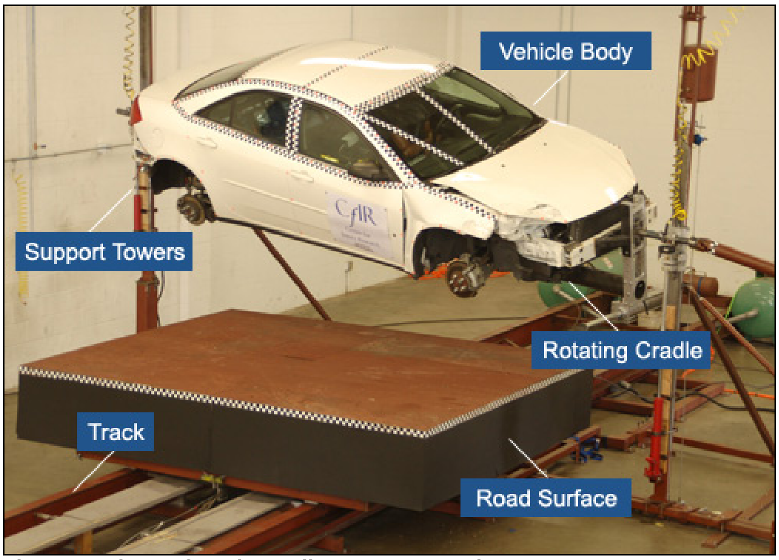


Figure 9. Photo of Jordan Rollover System Major Components

The Vehicle Body is mounted on the Rotating Cradle and then fitted into the Support Towers. The Road Surface is moved to the far end (not shown) of the Track. The Support Tower's release mechanism and the Road Surface trigger are synchronized to achieve the prescribed test parameters. All instrumentation and lighting are turned on and the Test Operator counts down and initiates the rollover. The Road Surface moves down the track at the prescribed speed and the Vehicle Body is rotated and released to meet the Road Surface at the prescribed angle and roll rate. Once contact is completed, the Vehicle Body and Rotating Cradle are arrested to isolate the individual impact for data and video analysis.

The test starts from an almost vertical orientation to the road bed position similar to that shown in the first frame in Figure 10. During the simultaneous rotation and fall, the vehicle strikes the moving roadbed below on the leading side of roll (near side – frame 3) at the side 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 (far side – frame 4). The motions of the vehicle and roadway are coordinated so that the touchdown conditions can be controlled and thus repeated within a narrow range.

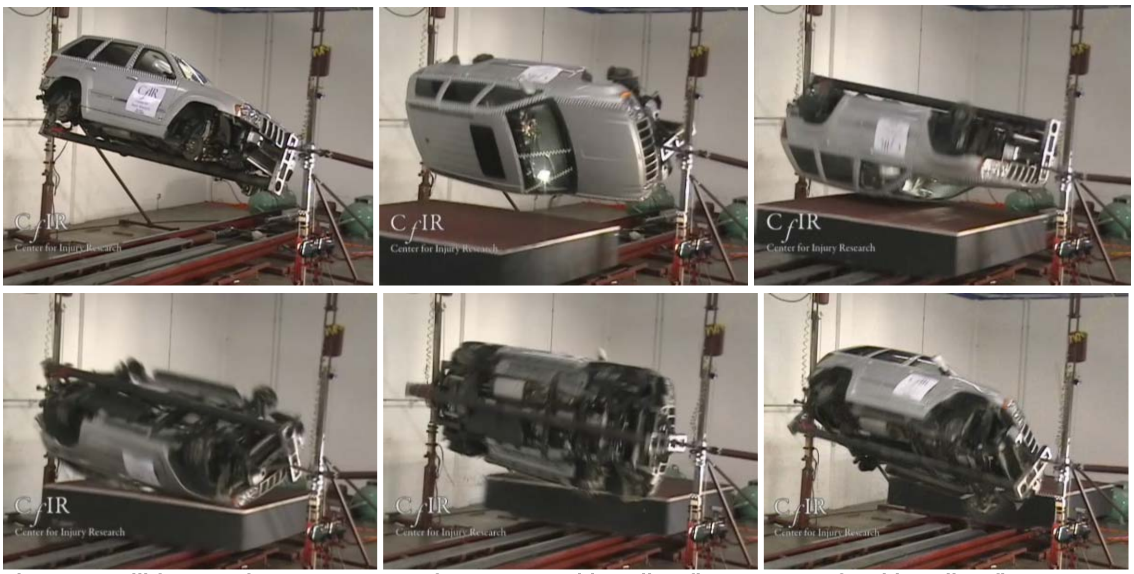


Figure 10. Still frames of a JRS test. Note: frame 3 near side strikes floor; Frame 4 far side strikes floor.

The JRS provides for a wide range of input parameters such as road speed, roll rate, pitch, initial impact angle, drop height, and other parameters, thereby characterizing rollover severity for the test. Since the vehicle is caught at the end of a completed passenger and driver roof impact sequence, to prevent further damage, a sequence of up to three rolls and the injury potential for each can be examined and identified. The JRS Road Surface is instrumented and measures the force of the vehicle roof contact during the test, thereby simulating the ground load, a measurement that has never before been available to researchers. Internal instrumentation collects data on the degree to which damage and intrusion occur and its injury effect on the Hybrid III Anthropomorphic Test Dummy (ATD).

Currently, there is not an Anthropomorphic Test Dummy (ATD) designed specifically for rollover occupant simulations. The Hybrid III ATD comes standard with a stiff neck and lumbar joint that is only marginally representative of the human equivalents. However, research shows that by placing a more biofidelic dummy neck and lumbar joint in the Hybrid III ATD, one can produce a more representative and realistic inertial reactive motion. The dummy mass centers can respond like humans (from comparison with human tests) with relative normal un-tensed musculature. (Friedman, D., 2008) (Paver, J., 2008)

In testing with the JRS fixture a 50th percentile Hybrid III Anthropomorphic Test Dummy (ATD) is used to monitor head and neck loads in the driver seat position. String potentiometers are mounted within the vehicle and are used to measure roof intrusion and intrusion velocities, as well as the ATD's motion. High speed cameras also record vehicle and ATD motions. The ATD is setup according to the FMVSS 208 protocol. Given that 8 quarter turns accounts for 90% of rollovers, in the first roll, the vehicle is set at 5º pitch angle whereas in the second roll the vehicle is set at 10º pitch angle. Roll rate at 190º per second, yaw at 10º and roadway speed at 24 km/h (6.7 m/s) are the same for each of the two rolls.

The test procedures provide a basis for comparing the safety performance with and without available or activated occupant protection systems on the same test vehicle with both a non-deforming and production roof (at variable road speeds, drop heights and rotation rates). With one test vehicle the JRS can quantify the injury measures of a long list of combined variables such as: two rotational speeds, two drop heights, two contact angles, two belt tensions, with and without air bags, in or out of position dummy and more. For example, using the same test procedure for two different rotational speeds it was discovered that the belted dummy head can go out the open side window at a high roll rate whereas it doesn't at a low rate.

As an example of the use of the JRS, in one particular study a series of JRS tests were conducted on 5 passenger cars and 5 sports utility vehicles (SUV) by the Center for Injury Research based in Goleta, California. The tests were funded by the Santos Family Foundation through the US Center for Auto Safety. The vehicles were supplied by the US State Farm Insurance Company. Descriptions of the tests and test results are provided elsewhere (Friedman, D., 2009). The relationship of the forces between the ground and the roof as well as the deformation of the roof as a function of roll angle were investigated and high speed films of the tests were recorded.

Rollover crash tests were carried out on a strong roof vehicle with a SWR of 4.6, a sample production vehicle with low roof strength to weight ratio (SWR) of 2.2 and similar make low roof strength vehicle with an external load attenuation device prototype attached. Figure 10, shows the low strength vehicle being tested in the JRS. Figure 11, shows exterior and interior views of the roof structure with and without the ATD after two rollover tests. It is clear from Figure 11 there is significant roof crush. The neck loading was significant at around 9.7 kN with a 60% probability of an AIS 3-4 neck injury. ATD neck injury measures are also provided in another paper elsewhere (Friedman, D., 2009).

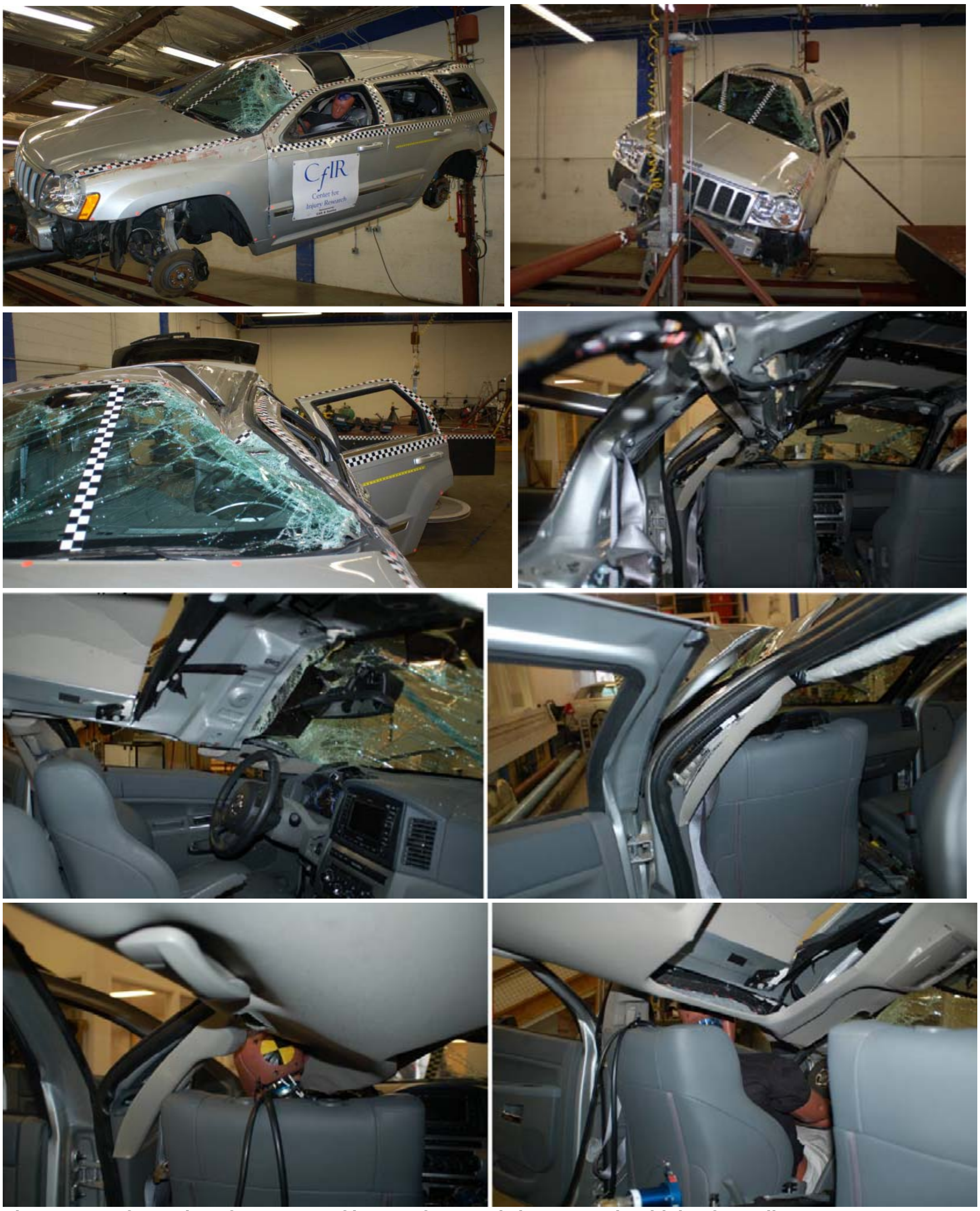


Figure 11. Deformed roof structure of low roof strength (SWR = 2.2) vehicle after roll 2 JRS test.

The test shown in Figure 10 and Figure 11 are of a 2007 production vehicle. For research purposes, an earlier model 1993 vehicle from the same manufacturer was used to fit an external load attenuation device and compare results to a JRS test of the 1993 production model (Figure 12). Details and discussion concerning this comparison is presented in an earlier paper (Grzebieta, R., 2009). The SWR for the 1993 model is 2.3 albeit the roof deformation appeared a little larger than the 2007 model and the neck load was close to 10 kN. An examination of the roof ground contact interaction and how an external load attenuation device can reduce the loads to the roof and the occupant are discussed next.

Figure 12. 1993 model of vehicle (SWR 2.3) shown in Figure 11.

Identifying Low Roof Strength Failures

Figure 13 shows a view from the high speed video from the floor inertial reference point. Frame 1 (t=1.712 sec) shows the vehicle during vertical release. Frame 2 (t=1.788) shows near side touch-down. Frame 3 (1.908 sec) shows that the middle of the roof touches down. This touchdown of the middle of the roof is important. It indicates that the vehicle's centre of gravity (CG) about which it rotates continues to move vertically downwards. The radius of rotation about the CG from the moment shown in frame 2 to the moment shown in frame 3 has now reduced by around 10 cm. In frame 4 (t=1.920 sec) the far side of the roof comes into contact. It is at this point in the roll the vehicle must raise the CG (increase its radius of rotation) to continue to rotate. In other words, the roof must be strong enough to lift the vehicle back up. Because the roof is weak, it collapses as shown in frames 5 to 9 (t=1.944 sec to 1.992 sec). The ATD's head being adjacent to the ground contact gets caught in the buckling roof and remains momentarily stationary (frames 4 to 7 – t=1.920 sec to t=1.960 sec). The ATD's torso continues to move forward and thus loads the ATD's neck. In frames 7 to 9 (t=1.960 sec to 1.992 sec) the roof buckles so much that the ATD's head is thrust upwards relative to the ground. The peak roof intrusion speed relative to the interior of the vehicle was around 12.6 km/hr (3.5 m/sec) (Grzebieta, R., 2009).

Identifying Strong Roof Strength Modes

In the case of a strong roof vehicle, the mechanism loading the ATD's neck is significantly different**.** Figure 14 shows the individual frames of the roof structure as it contacts the moving floor. What is interesting to note is that the ATD's head does not move relative to the front header rail line during the roll process. Frame 3 (t=1.900 sec) also shows the vehicle is airborne at that moment of the roll event. That is, the roof at the midpoint is not in contact with the floor. Hence when the far side of the vehicle comes into contact with the floor in Frames 4 (t=1.932 sec) and 5 (t=1.960 sec), the amount of lift of the vehicle's CG is not as great as in the case of the weak roof vehicle (Figure 13, Frame 4, t=1.920 sec). It should be noted that the axial neck load measured by the ATD was 3.6 KN in the second roll and the maximum roof intrusion velocity relative to the vehicle interior was 5.1 km/hr (1.41 m/sec).

Figure 13. ATD interaction with low roof strength vehicle's (SWR 2.2) roof and floor during near side and far side touches down.

Figure 14. ATD interaction with high roof strength vehicle's (SWR 4.6) roof and floor during near side and far side touchdown.

External Load Attenuation Device

It was this observation that led to the concept of fitting a hoop bar to the outside of the vehicle's roof that helped maintain the vehicle's roll radius. A proof of concept is shown in Figure 15. Obviously if the roundness of the roof about the vehicle's CG is maintained, the roll action will be smooth. Figure 16 shows the individual frames of the (1993) low strength roof structure fitted with an external load attenuation device, as it contacts the moving floor. The total assembly of the external load attenuation device also strengthened the roof. Internal flat plating was attached to the B-pillars to strengthen them as well. The ATD's head is visible in the frames. Note how the vehicle is supported by the round bar when the vehicle is rotated at 180° (T=1.652 sec). The frames show the ATD's head does not move towards the vehicles CG relative to the inside windshield header rail. Therefore, transition from the near side to the far side is smooth.

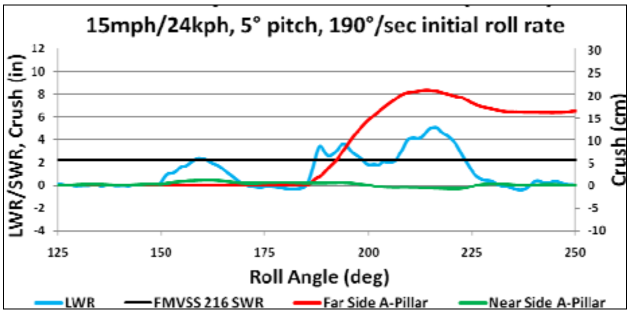
Figure 15. Prototype RDMD fitted to roof of low strength (1993) vehicle.

Figure 16. ATD interaction with (1993) low roof strength vehicle's (SWR 2.3) roof and floor during near side and far side touchdown. ATD's head is circled.

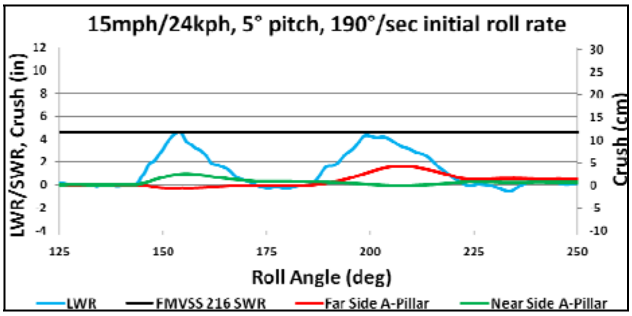
Importance of Measuring Roof Loads

Figure 17 shows the loads measured by the moving floor and roof crush versus roll angle. The dark black line in the plot indicates the vehicle's SWR capacity. The load to weight ratio (LWR – blue line) is a non-dimensional value of the load measured by the floor divided by the vehicle's total weight. The red and green lines indicate roof crush at the far and near side A-pillar/Roof Rail connection.

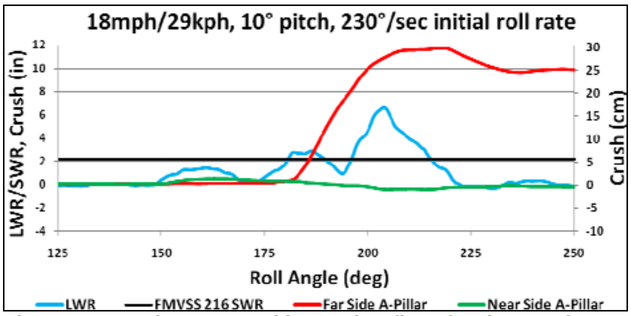
Low roof strength Jeep (2007) production vehicle



High roof strength Volvo XC90 (2004) production



Low roof strength Jeep (1993) production vehicle



Low roof strength Jeep (1993) production vehicle & HALO™

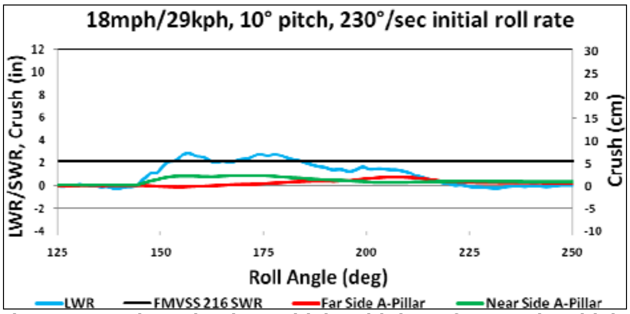


Figure 17. Loads measured in moving floor for: low roof strength (1993 & 2007) production vehicles; high roof strength vehicle; and low roof strength (1993) vehicle with RDMD.

Relating Roof Loads to Rollover Safety

Figure 17 shows that for both (1993 & 2007) low roof strength production vehicles the load demand exceeds the vehicle's A-pillar capacity to sustain the load. The high peak loads at 205° for the 2007 vehicle and 215° are likely interactions with the vehicle's dash board and side door as a result of complete roof collapse. The load demand for the high roof strength vehicle on the other hand is within the vehicle's pillar load capacity. Moreover, the load peaks for the high roof strength vehicle are uniform, indicating two evenly distributed peaks. On the other hand, the low strength roof vehicle displays uneven peaks when comparing the near side load interaction with the far side load interaction. The far side load interaction is also very large relative to the vehicles SWR as a result of the vehicle's interaction with its front door and dash board from complete roof collapse. Of particular note is the plot of the road loads for the (1993) low strength roof vehicle with the external load attenuation device fitted. It is clear that the roof load is distributed relatively evenly over the whole roll. Moreover, the magnitude of the load has been significantly reduced from a LWR of around 6 to around 2.5.

Figure 17 also shows that for both (1993 & 2007) low roof strength production vehicles, the maximum and residual roof crush is very large in comparison to the high strength vehicle and the vehicle with the external load attenuation device again because of its interaction with its front door and dash board as a result of complete roof collapse. Indeed the maximum roof crush is an order of magnitude less than the low strength vehicle's maximum roof crush and the residual roof crush for the high strength vehicle is barely discernable.

Occupant Kinematics

Figure 18 shows three frames in each row from the high speed video taken respectively for the high strength roof vehicle, the low strength (2007) roof vehicle, and the (1993) low strength roof vehicle with the external load attenuation device. The rotation angles were matched (vertically) in Figure 18. The yellow line is a reference line drawn relative to the vehicle's rear view mirror. The red circle shows the location of the ATD's head in each frame. The yellow line shows how the vehicle rotates about its CG and how the ATD's head moves relative to the line as well as relative to the moving floor. Figure 18 clearly shows that for the low strength roof vehicle (middle three frames) that the ATD's head moves towards the vehicle's seat base despite the rotation of the vehicle. This is the result of the vehicle's roof buckling and forcing the head inward towards the vehicle's seat base. Figure 18 also shows that the ATD's head is moving away from the floor for the low strength roof whereas in the case of the high strength roof, as well as for the external load attenuation device reinforced roof vehicle, the ATD's head moves closer to the floor and continues in a circular motion without any violent reverse direction motion relative to the vehicle's interior.

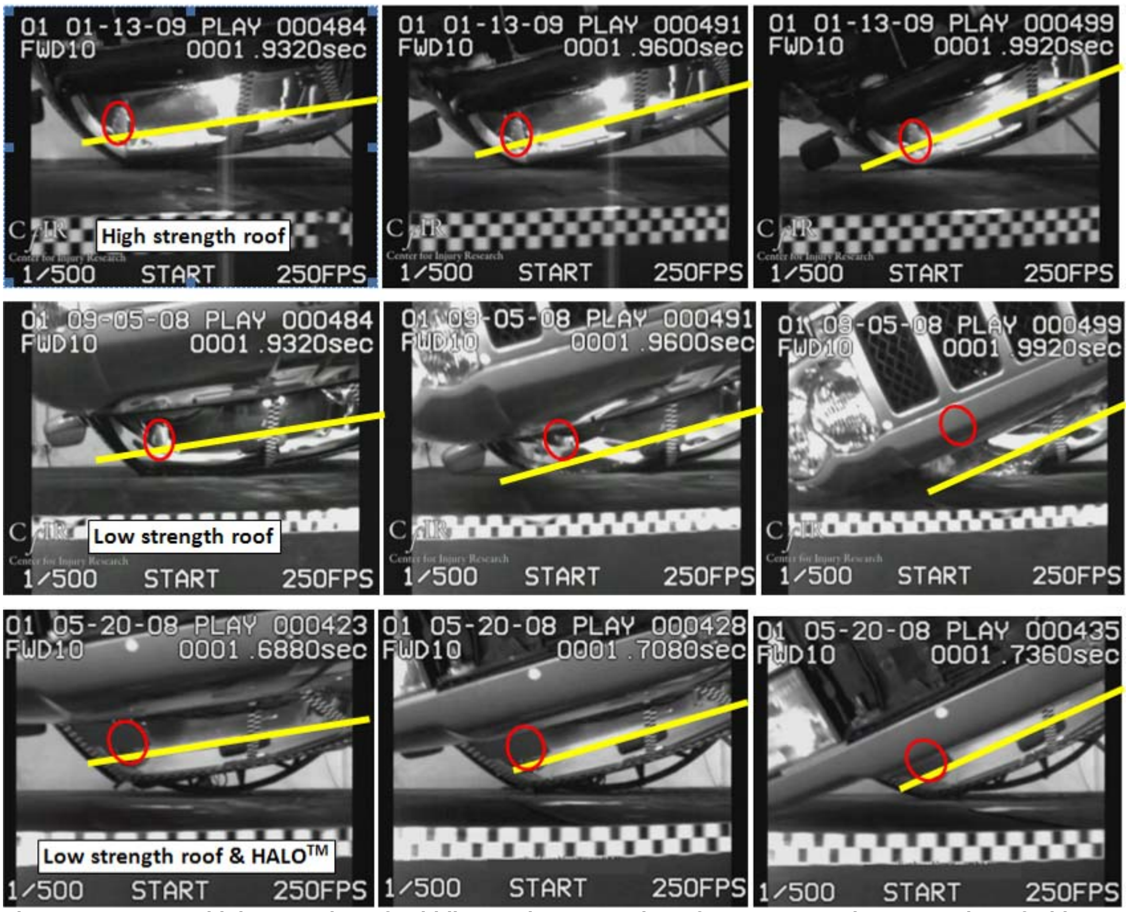


Figure 18. Top row: high strength roof; Middle row: low strength roof; Bottom row: low strength roof with RDMD.

In the case of the (1993) low strength roof vehicle fitted with the external load attenuation device, the ATD's axial neck load was 1 kN and the peak intrusion velocity was 1.6 km/hr (0.44 m/sec). Clearly when the roof of a vehicle is strengthened, the load imparted onto the occupant as a result of roof crush is significantly reduced. Moreover, the results presented in this paper also demonstrate that loads imparted to an occupant's head and neck when they are seated in the vicinity of where the roof crushes, is causally linked to roof crush.

RDMD Prototype Design Application and HALO™ Product Development

From the prototype development testing and analysis, a number of new prototypes were designed and tested to optimize the RDMD value to minimize roof crush intrusion and intrusion speed. The performance goals were to minimize roof crush intrusion and roof crush intrusion speed to non-injurious levels, have no internal visible components and no interference with internal production safety features.

With these parameters in mind, Safety Engineering International (SEI) designed and tested an RDMD that would prevent serious injuries in rollover crashes.

Part of the basis for the performance specifications of the RDMD were an analysis of thousands of typical on-road tripped rollovers investigated "in-depth" and entered into the U.S. National Accident Sampling System (NASS). It was found that a highway speed rollover of slightly more than 96 km/h (60 mph) rarely exceeds a trip speed of 70 km/h (44 mph) and usually not more than 2 rolls according to crash reconstruction cases investigated. The Insurance Institute for Highway Safety (IIHS) has established a real world relationship between Strength-to-Weight-Ratio (SWR) and incapacitating and fatal injury risk to belted, unbelted and ejected drivers in 42,000 rollover crashes. That relationship supports the National Highway Traffic Safety Administration's (NHTSA) statistical analysis and the Jordan Rollover System (JRS) dynamic rollover tests conducted by the Center for Injury Research (C*f*IR) as shown in Figure 11.

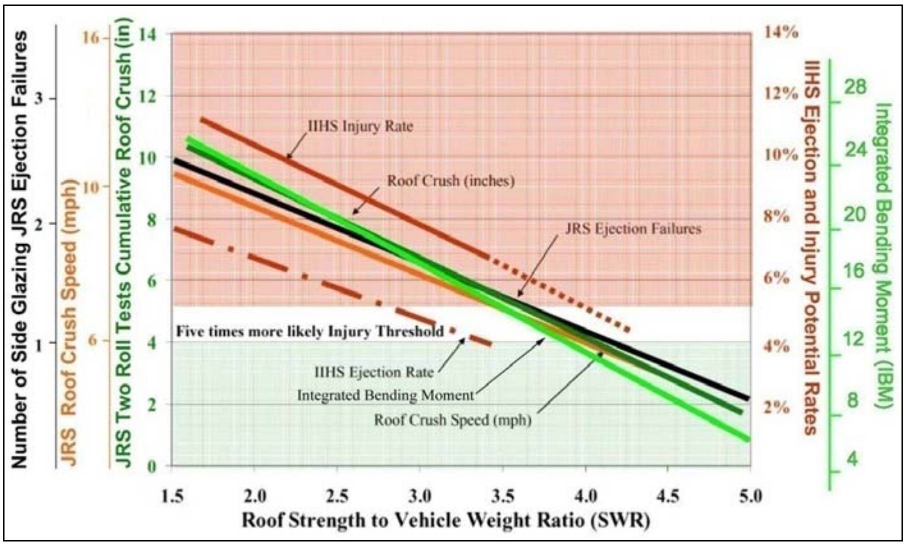


Figure 19. NHTSA, IIHS and CFIR/JRS injury potential correlation.

JRS dynamic testing also shows that SWR can incorrectly predict rollover performance, as was the case of the Honda CR-V (The CR-V is owned and trademarked by Honda Motor Co), which has a 2.6 SWR but performed almost as well as the Volvo XC90(The Volvo XC-90 is owned and trademarked by Ford Motor Co.) with a 4.6 SWR. The Volvo XC90 is considered the "gold standard" for rollover performance and was dolly rollover tested at a 70 km/h (44 mph) speed by Exponent with good results. The post test XC90 photos are shown in Figure 20.

Figure 20. 2004 Volvo XC90 post test photos – 70 km/h (44 mph) Dolly Rollover Test

While there is no objective consensus biomechanical criterion that has been developed for injury potential, a proposed criterion based on an injury potential threshold not to exceed more than 15 cm of crush and 9 km/h crush speed in any roll is shown in Figure 21. The chart depicts the threshold on the Abbreviated Injury Scale (AIS). The green area in the lower left, bordered in bold black, is the AIS 0-2 area where no, minor, or moderate injury potential occurs. Vehicle test results that fall outside this area will have greater probability of occupant injury.

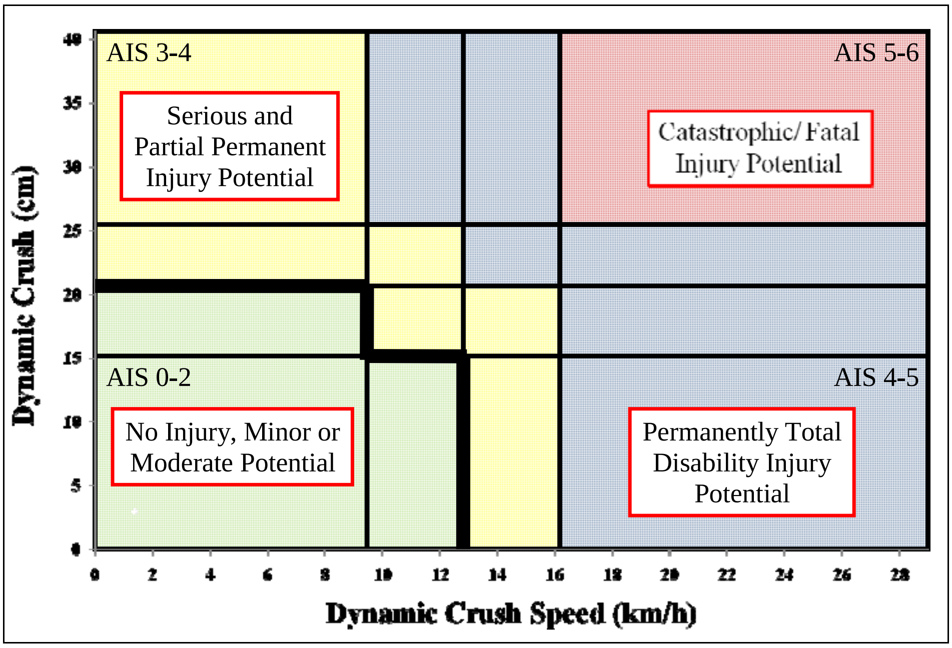


Figure 21. AIS Injury Scale for Motor Vehicle Accidents by Crush and Crush Speed

C*f*IR has tested over 50 vehicles on the JRS. Figure 22 shows the results and those from other SUV testing and defines the varying range of performance results that were seen in test vehicles in dynamic tests overlaid on the AIS Scale.

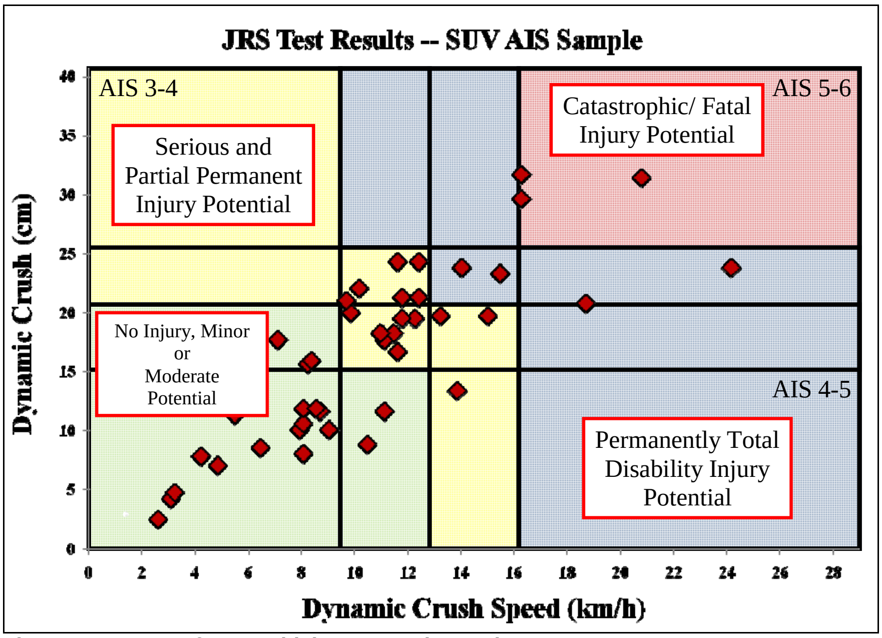


Figure 22. Range of SUV vehicle test results on the JRS.

The Prototype Testing- An Iterative Design Philosophy

Utilizing this body of research and information relative to how vehicles roll, the information on SWR and how it may be related to vehicle performance in rollovers, the analysis of the Volvo XC90 testing and the AIS injury scale, the second RDMD was developed and tested in a three roll sequence on another 1993 Jeep Grand Cherokee (Jeep Grand Cherokee is owned and trademarked by Chrysler), on the JRS to evaluate its rollover performance. The RDMD included a roof mounted structure and internal high strength steel b-pillar reinforcements and was named HALO™.

The test was successful, the RDMD held up and didn't allow the roof crush to exceed the limit of no more than 15 cm of crush and 9 km/h crush speed in any roll. However, more than moderate road loads were seen on the near-side touchdown of the prototype in the testing and so a redesign of the front section was undertaken to reduce initial side vehicle loading. A second prototype was made and attached to another 1993 Jeep Grand Cherokee and was again tested on the JRS. The redesign of the front section reduced the loads on the near-side touchdown by allowing the underlying vehicle structure to take some of the load. Prototype 1 and 2 are shown in Figure 23.

Figure 23. RDMD Prototype 1 & 2

With the results of the RDMD tests on the 1993 Jeep Grand Cherokees analyzed, a 1999 Toyota Land Cruiser (Land Cruiser is owned and trademarked by Toyota Motor Corporation) was fitted with the then current design. In order to evaluate the performance increase value of the internal high strength steel b-pillar reinforcements, the test was run without them and only included the roof mounted structure. The protocol was a three roll sequence at 10 degrees pitch and 15 mph on the first roll and 5 degrees pitch and 15 mph on the second and third rolls. The Land Cruiser with the RDMD performed moderately well with the results remaining in the AIS 0-2 range for all three rolls of the test as shown in Figure 24. The Far side measurements were higher than necessary and it was determined that the internal high strength steel b-pillar reinforcements were adding value.

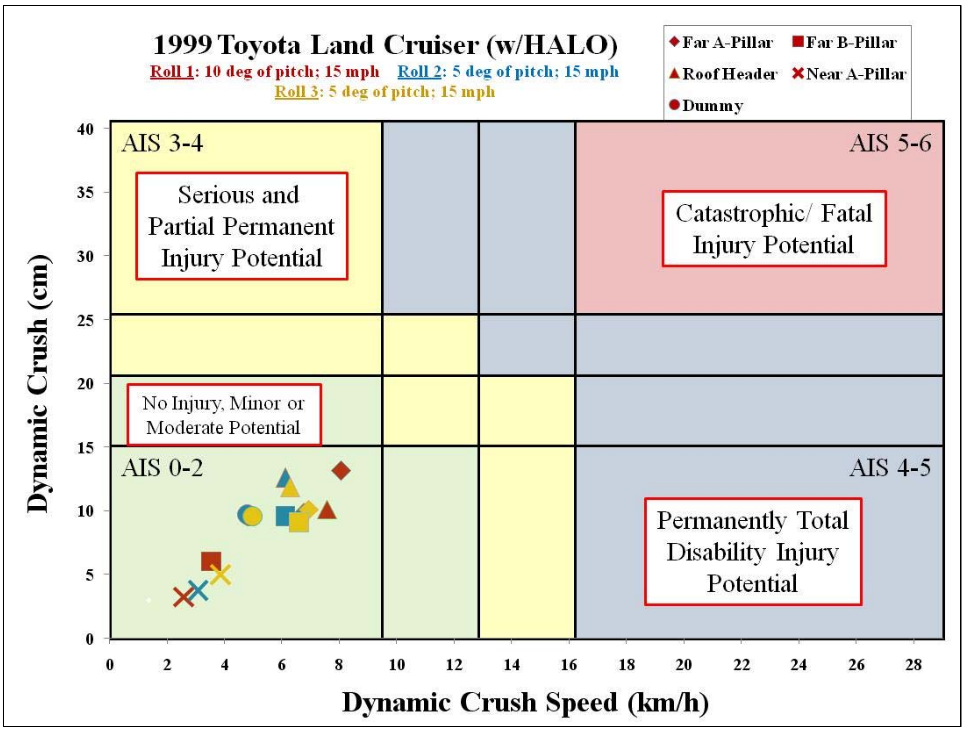


Figure 24. 1999 Toyota Land Cruiser Dynamic Test Results with RDMD attached.

Following this test, another RDMD was designed and built for another 1993 Jeep Grand Cherokee. For this prototype, the internal high strength steel b-pillar reinforcements were included but were only extended three quarters of the way up the pillar. A 15 year old, high mileage, somewhat rusted, used vehicle was retrofitted in accordance with installation and attachment instruction procedures. There was no occupant, fuel or ballast payload, so that a worst case pitch angle from the engine forward weight bias would result during the test. The vehicle was mounted on a dolly at a 23 degree inclination. The dolly was propelled to 67 k/ph (42 mph) and launched onto a macadam pad for the first roll and then into dirt as shown in the Figure 25.

The vehicle was instrumented with a high speed interior camera facing forward and with the ends of string potentiometers at the driver and passenger A and B pillars, between which is the typical mid seat position of the occupant's head. The origin (the reels) of the string potentiometers were near the CG of the vehicle such that the original measurements taken were radial displacements. The location of the ends and origin of the string potentiometers were documented photographically so as to be able to resolve the motion into vertical and horizontal coordinates. There was a high speed and several real time cameras recording the exterior vehicle kinematics. The timing between the string potentiometers and the external cameras was established by photoanalysis.

Figure 25. Sequence of photo's from 42 mph Dolly Rollover test of 1993 Jeep Grand Cherokee with RDMD HALO.

Video Analysis

The various videos were reviewed. From the photo-analysis, the vehicle came off the dolly with a low roll rate, reaching the driver's side at 89 degrees/sec such that it slid on the driver side before generating the roll momentum to result in the average roll rate in the first roll of 285°/sec. The average roll rate in the second roll was 335°/sec. The average roll rate in the last roll was 100°/sec.

Vertical Displacement, Velocity and Injury Analysis

The vehicle kinematics during the rollover were unusually severe involving on the second roll substantial lofting and pitch (the vehicle went about 2 feet in the air and pitched down about 10 degrees). Interior video and photographs indicate that the roof matchboxed. [Matchboxing is when the roof shifts from side to side rather than collapsing on one side.] This happened because the RDMD connected the two sides, and when the vehicle rolled, the sides shifted together laterally in the same direction due to the horizontal component. It distorted vertically in opposite directions (when the driver side was depressed the passenger side expanded). As a result, there was no significant possibility of loading the passenger that would result in an injury. The only circumstance during this three roll event where an injury could possibly occur is if an unbelted driver's head was at the A pillar on the driver side in the second roll.

The vertical displacement and velocity on the Driver's side at the mid A/B roof rail and B pillar are unlikely to be injurious. Also, all glass remained intact except the driver window limiting ejection possibilities to unbelted passengers. Photographs taken immediately after the vehicle came to rest show a flat roof interior somewhat lower on the driver's side and higher on the passenger side in Figure 26.

Figure 26. 1993 Jeep Grand Cherokee after 3 roll Dolly Rollover Test with RDMD attached.

Table 1 is a summary list of peak measured roof crush and roof crush speed of the Driver's side roof on each roll at the middle of the roof rail between the A and B pillars and directly at the B-pillar (where most head witness marks for restrained occupants are found). Also shown is the inferred medical probability of injury severity by the Abbreviated Injury Scale (AIS).

Drivers Side Vertical Position	Roll 1			Roll 2			Roll 3		
	Max Displacement (cm)	Max Velocity (km/h)	AIS Level	Max Displacement (cm)	Max Velocity (km/h)	AIS Level	Max Displacement (cm)	Max Velocity (km/h)	AIS Level
Mid A/B Rail	10.2	8	0-2	13.7	11.7	0-2	5.08	1.9	0-2
B-Pillar	10.7	10.4	0-2	11.7	10.9	0-2	4.57	3.2	0-2

Table 1. Peak Vertical Crush and Speed Measurements and the medical AIS injury probability.

The roof crush and roof crush speed for this test for the Driver's side mid-roof rail and b-pillar are plotted on the AIS injury scale in Figure 27. As a result of this test, the internal high strength steel b-pillar reinforcements will be extended to the top of the pillar to reduce buckling above the reinforcement.

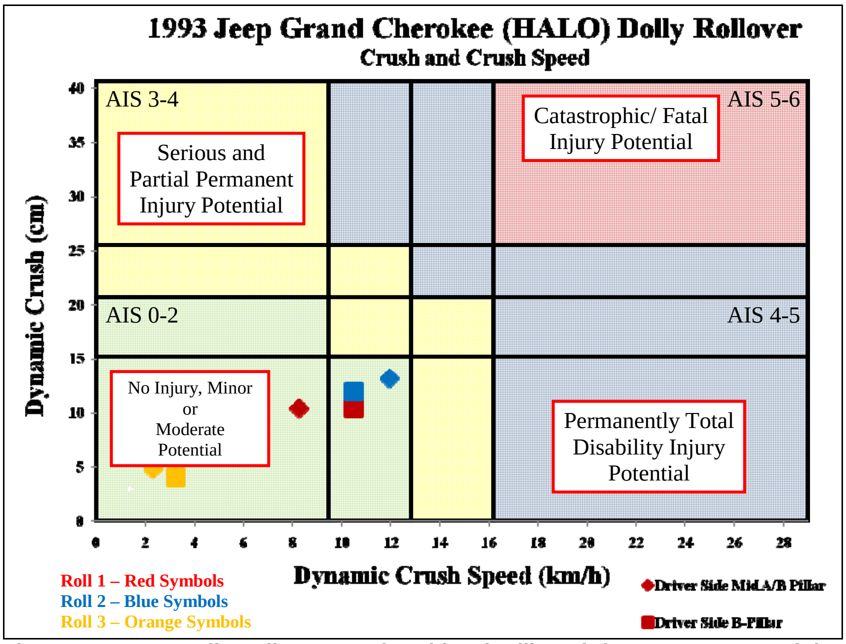


Figure 27. RDMD Dolly Rollover Results with ¾ b-pillar reinforcements on AIS injury chart.

The RDMD functioned as planned in this very severe rollover. However, the vehicle kinematics produced substantial driver side loading which the RDMD converted into matchboxing instead of roof intrusion. This test highlights the importance of the seatbelts maintaining the occupants head position as rearward toward the B pillar as possible. For vehicles with low A-pillar strength and questionable seatbelt retractor lock up and/or excessive belt excursion, a "belt clip" at the D ring or a retrofit of "all belts to seats" seats would be a wise precaution. These options are discussed further in the Structural Rollover Protection with Current Production Restraints

Final Design Product Specifications

The RDMD final design incorporates the research results learned throughout the testing and development phase. The final version was produced for another 1993 Jeep Grand Cherokee and another 3 roll series of tests was run on the JRS to confirm the design specification and performance criteria. This test series was run for the first two rolls at 10 degrees of pitch and 18 mph and the third roll at 5 degrees of pitch and 15 mph. The RDMD performed as expected and is compared to the Volvo XC90, which was tested slightly less severely, in Figure 28. All Injury measures remain in the AIS 0-2 range for all possible positions and rolls. Figure 29 is a blow up the AIS 0-2 region from the above graph to further illustrate the performance of the 1993 Jeep with the RDMD, regardless of head position. As can be seen, the RDMD fitted Jeep outperformed the Volvo XC90 and is estimated to be about 30% stronger in the rollover crash mode as measured by JRS tests.

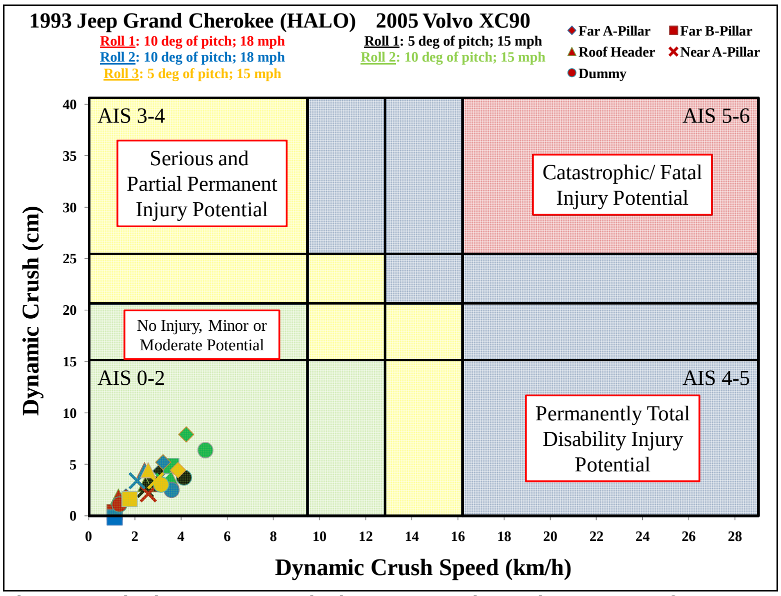


Figure 28. Final RDMD HALO design compared to Volvo XC90 Performance

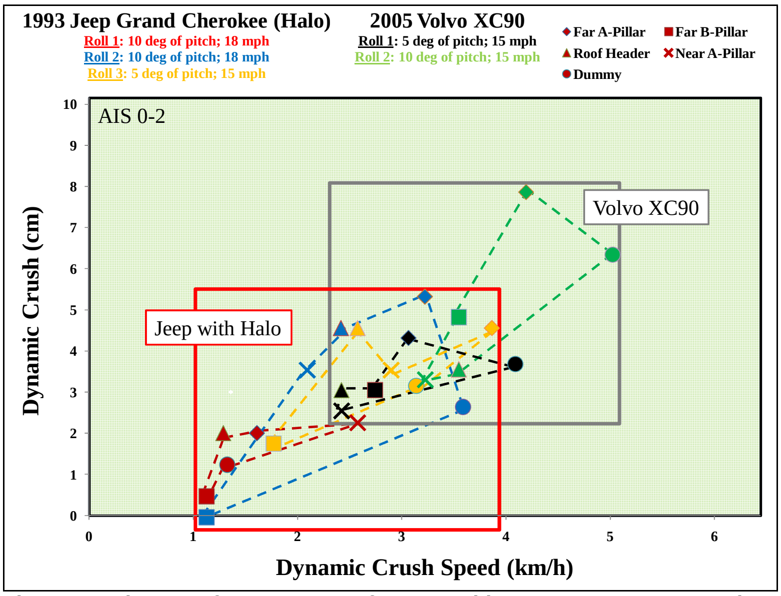


Figure 29. Blow up of AIS 0-2 range for Jeep with RDMD HALO compared to Volvo XC90

Structural Rollover Protection with Current Production Restraints

The comparative dynamic structural rollover effectiveness has been compiled into a database of 50 familiar vehicles and alternate structures with typical unmodified occupant protection systems. Figure 30 shows a safety factor performance chart of 10 SUVs taken from the database, in order of best performance to worst performance in a normalized one or two roll rollover test.

Comparative evaluations of occupant injury performance cannot take into account each and every aspect of the motion of a wobbling football. Instead the best available description of the most common rollover is embodied in the tests and applied uniformly to all vehicles. The evaluations of figure 30 are based on the characteristics of a one roll event by the green bar and by a red bar for a 2 roll event. The safety factor estimates the structural characteristic injury performance with standard belts. The third bar is for comparison with the strength of the roof alone as a criterion. The height of the bar corresponds to the probability of surviving without an incapacitating or fatal injury. The 10 vehicles shown here were selected from a database of 50 vehicles dynamically tested, to illustrate the difference in occupant protection performance of production and various structural retrofit modifications.

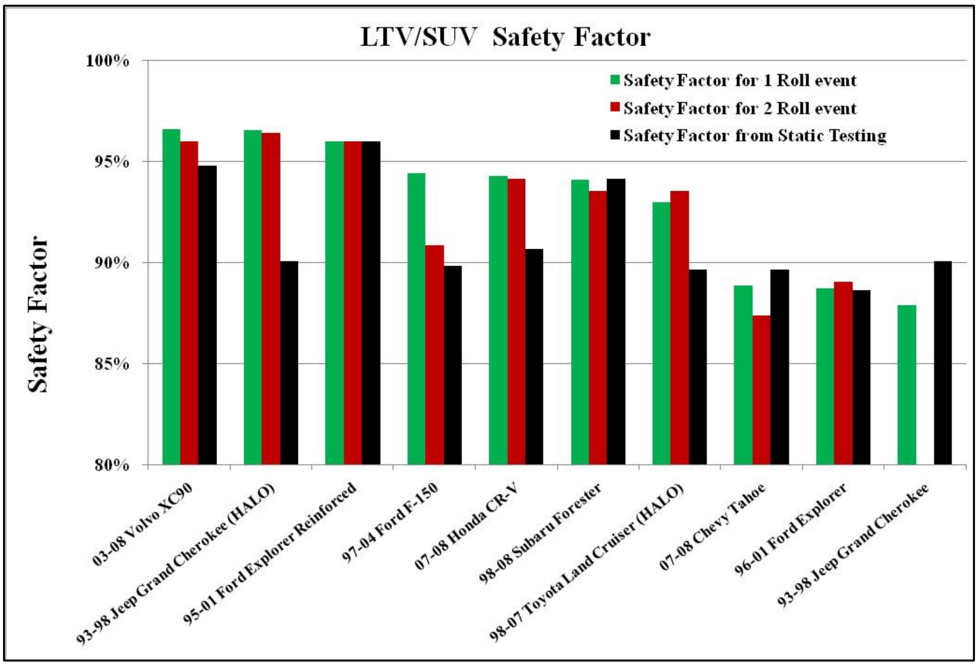


Figure 30. Tested production and modified SUV safety factor relationship for 10 vehicles

The Volvo XC 90 has been in production since the fall of 2002 and to date has not involved a rollover fatality but has only a 96% safety factor. The Ford Explorer and Jeep grand Cherokee at the other end of the chart have about the worst fatality records with an 88% Safety Factor. It should be noted that an occupant in a structurally reinforced vehicle has no better chance of surviving than the occupant of the Volvo XC 90. Also worth noting is that the Honda CR-V performs almost as well as the XC 90, but by static roof strength tests is only about 60% as strong.

The best example of the performance of a retrofit system is shown with the Jeep Grand Cherokee whose production performance is on the right end of the chart above, while its performance with the HALO retrofit (Figure 31) is the second from the left. The production Jeep Grand Cherokee roof crush in the first roll was so great that the dummy was trapped and made a second roll meaningless, hence there is no red bar. The Land Cruiser with the retrofit did not have a b-pillar retrofit.


Figure 31. RDMD HALO retrofit on a Jeep Grand Cherokee

The Explorer, on the left in Figure 30, was imperceptibly reinforced by adding steel inside the existing pillars, a very expensive modification. Notice however that the safety factor doesn't increase with additional roof strength. This is because roof crush is not the only cause of injury. Injury also results from ineffective belts, airbags, glazing and seat restraints. To achieve safety factors comparable to frontal and side impact performance, the effectiveness of current production restraints must be substantially improved.

Rollover Protection with Retrofit Restraints

Retrofit occupant protection systems can substantially alter the likelihood and severity of head and neck injury in a rollover. This is because human injury is the consequence of the position of the occupant's head, neck and torso relative to the location where the roof is intruding. For instance a simple belt clip can affect the occupant's position. Figure 32 shows the injury potential in a JRS test for the actual position of the dummy and if near the A-pillar and roof header or the B-pillar.

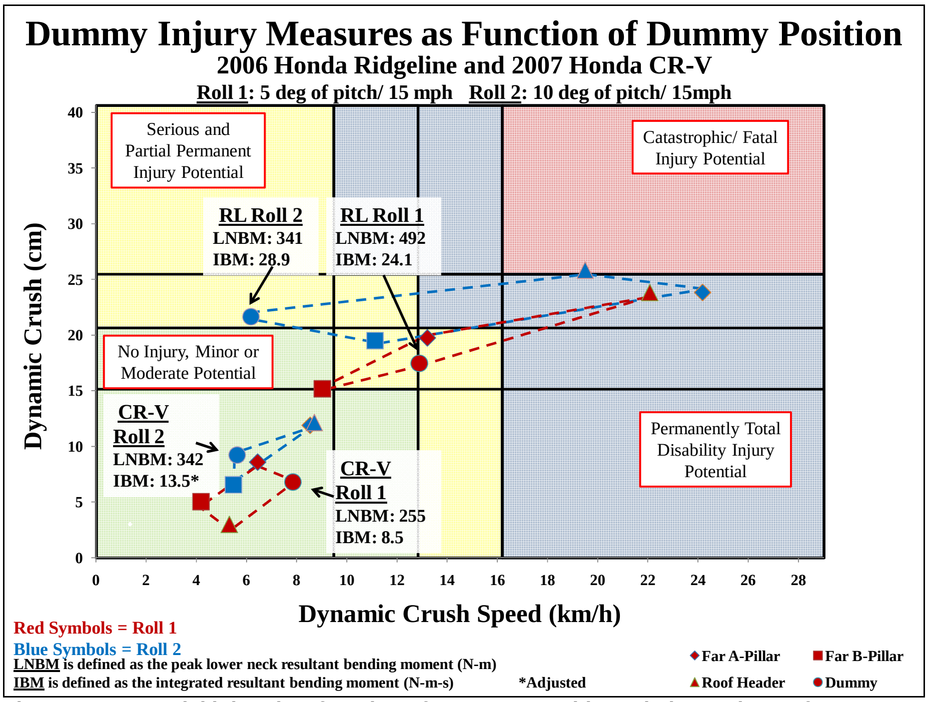


Figure 32. Potential injury is a function of occupant position relative to the roof components.

The difference in injury severity is significant from both vehicle to vehicle (Ridgeline to CRV) and roll 1 to roll 2. The triangles and diamonds represent the A Pillar and Roof Header and are clearly the areas that show the most potential for injury to occupants. If the vehicle does not have a pre-tensioner that triggers on rollover, it is possible that a simple seatbelt clip could keep the occupant out of harms way, rear at the B-pillar, instead of under a weak A-pillar/roof header vehicle or a poorly retrofitted one.

Another way to keep the occupant rearward at the b-pillar is to use a more sophisticated occupant restraint system. Such a system is in development with 'all-belts-to-seat' seat with built in and effective four point rollover restraint harness and a roll bar protected head rest shown in figure 33. This is a production seat, with modifications and features at any level of protective sophistication including airbags and pre-tensioners.

Figure 33. Prototype All-Belts-to-Seats Occupant Protection System.

Conclusions

Comparative dynamic rollover evaluations indicate that increased roof strength and/or better roof geometry can improve current fleet vehicle safety for serious to fatal injury by a factor of two or three times to a limit of about 96%.
Safety comparable to frontal and side impact protection requires improved restraints some of which may compromise consumer occupant comfort and convenience.

Retrofit structural and restraint systems for commercial vehicles are practical, effective and available.
The benefit/cost relationship of retrofit systems measured in deaths and injuries is good, but is currently limited by commercial requirements for small numbers of retrofits for a wide variety of vehicles in use worldwide.

The production RDMD named “HALO” has been designed to meet the latest NHTSA objective rollover injury criteria derived, validated by JRS tests and authenticated from the National Accident Sampling System (NASS) data base for post crash negative headroom for vehicle rollovers on level ground. It has also been designed and tested to minimize objective criteria for roof crush intrusion and roof crush intrusion speed in rollovers. Injury occurs in a rollover as the result of excessive crush and crush speed in any particular roll in the sequence of rolls in the vehicle’s trajectory to rest. Injury is not due to a sequence of non-injurious impacts.

Figure 34. Final RDMD HALO™ System base unit and with wind faring and lighting attached.

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