# An Analytic and Experimental Evaluation of the HALO™ Rollover Damage Minimization Device

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## Abstract

A new retrofit device that is designed to increase the rollover crashworthiness of light vehicles is described and evaluated. As has been recognized [e.g., NHTSA, 2003], rollovers are a disproportionately dangerous collision mode, causing life-altering injuries to occupants due to roof intrusion and ejection. The US-patented HALO™ device is an after-market cap that increases the roof strength of a vehicle, diminishing damage and preventing injuries. This new retrofit device is available, affordable, low-tech, and straightforward to install. The objective of this engineering analysis is to analyze the efficacy of the HALO™ based upon the destructive validation testing to which it has been subjected.

## Introduction

The U.S. Federal government has recently recognized the inadequacy of current National Highway Traffic Safety Administration (NHTSA) safety regulations regarding rollover protection. The new Federal Motor Vehicle Safety Standard (FMVSS) 216 "Roof Crush Resistance" requires that legal roofs will resist intrusion with at least twice as much strength as those produced under the previous standard [NHTSA, 2008]. A second, altogether new standard, FMVSS 226, "Ejection Mitigation" will govern window performance, either through requiring side curtain airbags or via laminated side glazing similar to the windshield, in order to diminish partial and full ejections [NHTSA, 2009].

The greatest need for rollover protection is associated with the occupants of light utility vehicles (SUVs, pickup trucks, vans). This is a simple reality due to the geometry of these vehicles. A higher center of gravity yields an increased rollover potential, and higher death and injury rates due to this accident mode, if countermeasures are not taken. Many companies are significant users of these vehicles both on and off road. When laden and off-road, the probability of turnover may further increase. Various industries, such as timber, petroleum, and mining, have either internal or federal requirements to provide an increased level of protection to their workers who are using these vehicles. A fully legal US vehicle that was involved in a rollover crash on flat, level ground is shown below:

Fig. 1: 2002 Toyota 4Runner post rollover accident, spinal injury incurred at position shown.

The mechanics of occupant protection of rollover are well understood, and conform to the occupant "packaging" principals put forward by De Haven in 1952 [De Haven, 1952]. De Haven survived an airplane crash, and realized that while the plane had been destroyed, he had been relatively unhurt because the cabin was largely intact. He viewed the cabin of any vehicle as a "survival space." By maintaining the interior volume, providing for exterior crush zones, fixating the occupant to the structure, and ensuring forgiving interior surfaces, occupant can be spared death and injury, even in relatively severe collisions.

Some vehicles today, particularly in the automotive racing industry, employ comprehensive rollover protections systems (ROPS). These systems combine a variety of technologies in order to address the various injury modes in rollover and implement De Haven's vision. These technologies include:

1. Strengthened, relatively undeformable roofs.
2. Safety belts, preferably with rollover-activated pretensioners.
3. Occupant-retention windows, either with airbags, laminated glazing, or netting.
4. Energy absorbing interior surfaces, ensuring that the occupant does not impact hard surfaces, sharp edges or corners.
5. Crashworthy latches that ensure doors remain closed.

The HALO™ addresses the first technological challenge of vehicle rollover listed above. Therefore, the HALO™ is a "Rollover Damage Minimization Device" (RDMD), rather than a comprehensive ROPS.

## Rollover Kinematics

Rollover occurs when the dynamic center of gravity of the yawing vehicle exceeds the contact patch of the tires. The yaw angle at 4-wheel lift has been directly observed to be very shallow for some SUV overturns [see Wilson, 2007], and can even exceed 90 degrees in some reconstructed accidents. The vehicle tends to rotate about its roll center of gravity, scrubbing and impacting to its point of rest. When compared to other accident modes such as frontal impacts and pole impacts, the dissipation rate of the kinetic energy of the vehicle is low; the lowest of any crash mode. Unless ejected, the occupants follow the kinematics of the vehicle, and simply "ride it out." Should the integrity of the vehicle be maintained, the low energy transfer rate nature of the collision benefits the occupants.

Two rollover impacts are disproportionately severe. Figure 2 shows a vehicle traveling from the right to the left. For this overturn, the driver's side (US Convention) or left side, is called "initially leading" as the vehicle yawed clockwise when viewed from above prior to overturn. This is a pure barrel roll. The roof rail on the left side of the vehicle should impact the ground first with a minor impact. As the vehicle continues to overturn, the center of gravity (CG) of the vehicle continues to accelerate downward. It is the second roof impact on the initially trailing, right hand side, of the vehicle that is severe and leads to significant occupant injury, particularly with belted occupants. This first major impact to the vehicle on the initially trailing side in a barrel rollover produces disproportionate damage if the roof is relatively weak and in fact serves as a roll direction indicator post collision. The second disproportionate impact occurs when a vehicle ends on its roof in conclusion of a multiple roll event. Damage that has accrued during previous roof impacts coupled with the high friction of rolling to a halt can induce a more damage than occurs during the previous higher velocity impacts. This may be counter-intuitive that lower velocity impacts cause increased damage, and yet it is well documented [e.g., Batzer, 2007].

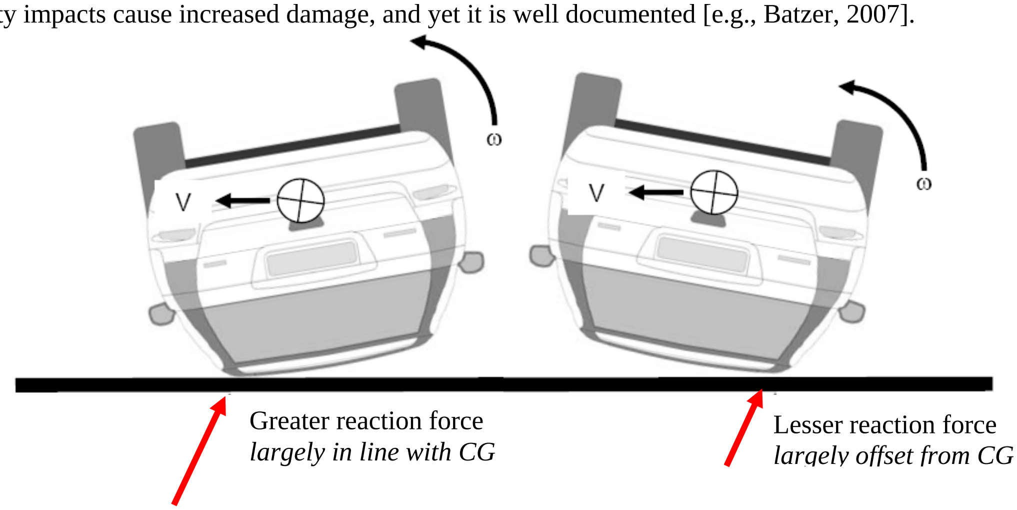



Fig. 2: Barrel rollover mechanics showing idealized ground interaction forces. Vehicle is moving right to left.

During rollovers it is this “breaking of contact” with the ground from the leading roof rail to the trailing roof rail that causes the severe impact. Note that when a tubular canister rolls along the ground, the periphery maintains contact and no abrupt changes in velocity occur. As the vehicle continues to rotate past contact of the leading side roof rail, the vehicle continues to move downward. As the trailing roof rail impacts, its geometry works to force a change in velocity of the center of gravity. If the roof is relatively weak, it will severely deform as did the roof in Figure 1.

Note that on the first strike of the vehicle shown at right, the force vector of ground loading, which is complex and includes both a normal and shear force, is relatively parallel to the driver’s side A-pillar. This brings about columnar loading for which the member is suited. The loading at the passenger’s side of the vehicle shown at left is not columnar, but cantilever loading. This large moment applied to the pillar can cause large deformation. The engaged columns are usually the A-pillars as vehicles tend to roll nose-down due to engine weight. Further, notice the direction of the applied reaction force vector to the center of gravity. The first impact, shown at right, obviously causes a moment couple as the force vector is significantly “off axis” from the center of gravity. This will cause the vehicle to increase its rotational motion. The second impact, shown at left, has the reaction force vector nearly coincident with the vehicle’s center of gravity. Thus the vehicle is less able to rotate out of the way of the applied force.


Fig. 3: Results of rollover showing disproportionate damage to initially trailing side. Note that 95% of rollovers are 2 revolutions or less [Hare, 2002].

### HALO$^{TM}$ Technical Approach

Stronger roofs are safer roofs. This is intuitively obvious and not controversial [e.g., Chirwa, 2006; Strashney, 2007; Brumbelow, 2008]. Baccouche [2000] indicated that, “The crush resistance of roof structures is critical to minimizing injuries and enhancing occupant survival during rollover crashes.” Saab, Mercedes-Benz, and Volvo have all touted their strong roofs as a definite safety plus for their customers. In fact, in the early 1970s the marketing arm of Volvo took seven flood damaged model 140 sedans and stacked them to show the roof strength of their vehicles. A review of available technical strategies for building strong, rollover crashworthy roofs was given by Herbst, et al. [Herbst, 1998]. Each of these techniques was for the production vehicle, and include high tensile strength steel, thick stampings, gussets at intersections, closed sections, and structural foam at points of maximum bending moment to prevent buckling. However, the FMVSS 216 standard that vehicles are currently required to meet is so inadequate that the Australian government was recommended to reject it as a national standard by independent engineers [Henderson, 1997]. While it is hoped that the newly upgraded FMVSS 216 will minimize roof crush to an acceptable level, there are many older and even currently produced vehicles that require roof strengthening in order to protect the occupants in rollover. Vehicles without strong roofs are notoriously difficult to retrofit. Two examples of external retrofits are shown in Figure 4, and are obviously sub-optimized systems.


Fig. 4: Two external rollover-protection roof retrofits; original roof structure is unaltered.

The HALO™ device uses a convex steel cap which is affixed to the top of the vehicle, similar to the luggage racks that act as decorative trim on many SUVs; it may be removed as required. The principal linear load bearing members are nominal 50 mm (2”) diameter high strength low alloy (HSLA) steel. This material combines good welding characteristics, high ductility/toughness, and strength above that of mild steel. The HALO™ is a single piece of contiguous welded tubing and plates, consisting of external roll bar hoops and longitudinal rails. There are attachment feet and internal B-Pillar reinforcement brackets. Two images of the HALO™ device are shown in Figure 5. Notice the convex shape of the front and rear hoops. This ensures that the major loading tends to be at the center of the hoops, supporting the vehicle’s center of gravity as the vehicle rotates. This diminishes impacts to the trailing (second) side of the roof. If the center of the fore and aft hoops receive loading toward the floor pan of the vehicle, this ensures that all eight pillars of a sport utility vehicle will be engaged. With engagement of more, rather than fewer, pillars, overall roof performance dramatically improves.

Fig. 5: HALO™ device unattached (L), and affixed to a Nissan Patrol vehicle (R). Note that this vehicle is equipped with a black engine snorkel on the left side.

RDMDs need to be easily mounted in the field without the need to take the vehicle to a specialty shop. Currently, some RDMDs use internal structures, interfering with the interior volume of the vehicle. This forces the companies to purchase vehicles without side curtain airbags or to disable the airbags which opens them up to legal liability because one aftermarket technology now interferes with or disables another. Figure 6 shows an example internal RDMD which does just that.

Fig. 6: Internal roll bar system designed to minimize roof crush. Notice size increase due to padding.

It is seen with relatively weak roofs that forces and damages are localized at the point of ground interaction. Shape integrity is not maintained. The roof intrudes rapidly into the occupant survival space as the roof supports the dynamic loading of the vehicle. The dynamic loads against the roof can range from one to three times the weight of the vehicle [Batzer, 2009]. Both high-velocity roof intrusion and excessive roof intrusion (greater than 5") are found to be particularly injurious to occupants. The center of gravity of an occupant in a rollover moves outward towards the crush, directly opposite the inward-directed intrusion. This difference of velocity can cause spinal injuries depending upon the orientation of the occupant. Ironically, those occupants who are restrained can face an *increased* risk of rollover spinal injury due to the orientation of their torsos [Weaver, 1968], penalizing them for wearing a restraint during this accident mode. In that seatbelts save lives, their use should (and is by the Engineering Institute) always be advocated. However, if the usage of a seatbelt diminishes occupant safety in some crash modes, then the mechanism of injury in that particular crash mode should be effectively addressed.

The HALO™ will distribute the loading across the roof structure, ensuring that more of the entire vehicle roof's load bearing (greenhouse) structure is engaged. This will produce several beneficial effects. The speed and total extent of roof intrusion diminishes. Side glazing (that is, the glass of the windows) will perform better [Orlowski, 1985], fracturing less on average, diminishing the risk of full or partial ejection.

## Validation of System Effectiveness

The HALO™ has been validated using a variety of techniques, including simulation, laboratory and dolly rollover. The principal validation has been using the Jordan Rollover System (JRS), see Figure 7. This device uses a balanced cradle to rotate the vehicle which then drops at a known velocity onto a moving "roadway" surface [see Jordan, 2005, Friedman, 2007a,b]. This laboratory fixture allows careful control over input parameters such as vertical impact velocity, pitch angle, and roll angle. The vehicle can be comprehensively instrumented to determine both the residual crush found at the end of the test, but also the peak dynamic crush that occurs while the roof is in contact with the roadway. As the vehicle revolves only once per test, damage can be comprehensively documented as the simulated accident is "frozen" between rolls. The intrusion velocity can also be measured, as opposed to being estimated. Further, by using an instrumented Hybrid-III Anthropomorphic Test Device (ATD), head and neck loads can be directly measured and compared within tests of this type and between tests of other types, such as dolly rollovers.

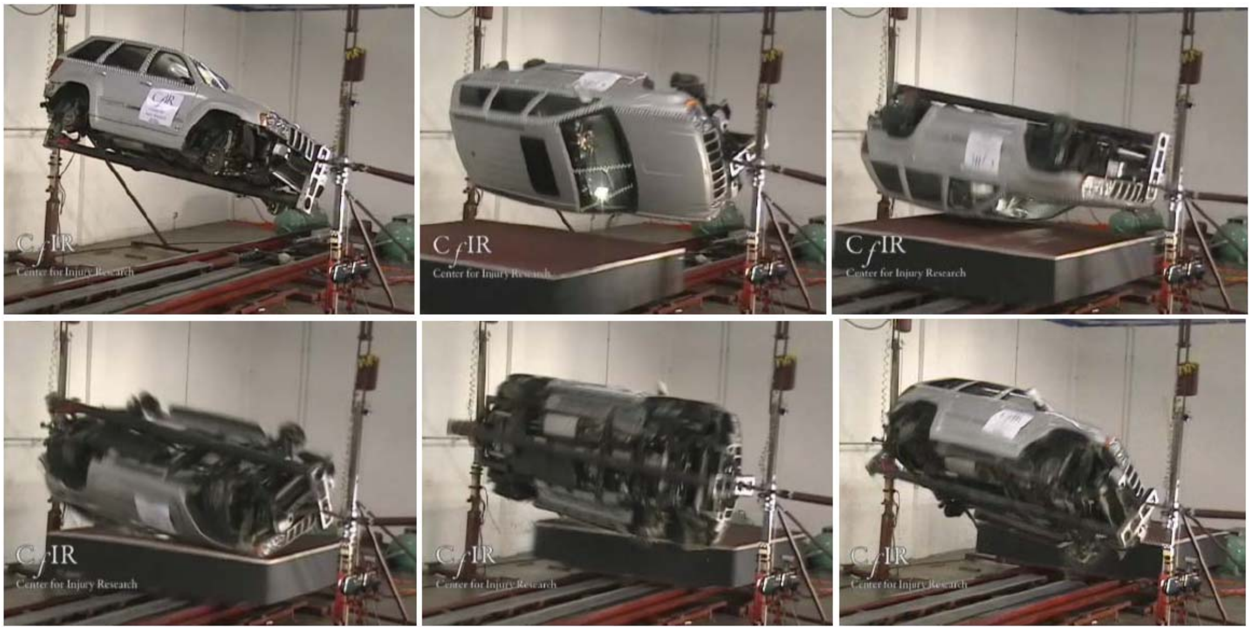


Fig. 7: JRS Test of a 2007 Jeep Grand Cherokee, Roll 1, showing kinematics of the test. Upper right frame shows the initially leading side impact, the lower left frame shows the initially trailing side roof rail impact.

The JRS dynamic rollover tests to validate the HALO™ were conducted by the Center for Injury Research (CFIR) on a 1993 Jeep Grand Cherokee with the HALO™, a production 1993 Jeep Grand Cherokee without the HALO™, and a 2005 Volvo XC90. The unmodified 1993 vehicle was used as a control to determine "stock" performance in a barrel rollover. The XC90 was used as a representative of a very strong production roof. Its strength-to-weight ratio (SWR) as measured by the FMVSS-216 protocol by NHTSA is 4.6 [NHTSA, 2008], and was the strongest production SUV roof at the time of its introduction in the 2003 model year.

Fig. 8: 2003 Volvo XC90 showing the desirable performance during rollover. The two belted first row occupants were uninjured in the 1.5 roll collision [Hinojosa, 2003]. Roof shows very modest upward tenting of header.

Output of the tests included total crush, dynamic crush, dynamic crush speed, and loading to the roadway. Their results show that the increased strength and improved geometry afforded by the HALO™ RDMD ensured that the retrofitted Jeep outperformed the Volvo XC90 and estimated to be about 30% stronger in the rollover crash mode. See Figure 9. It is common to focus on the total crush of a vehicle's roof crush as an indicator of injury potential (the "nutcracker" mode, trapping the occupant between roof and seat pan), but this is one of two relevant measures. For occupants whose heads are in contact with the roof, it is the intrusion speed which can produce injuries, regardless of total intrusion.

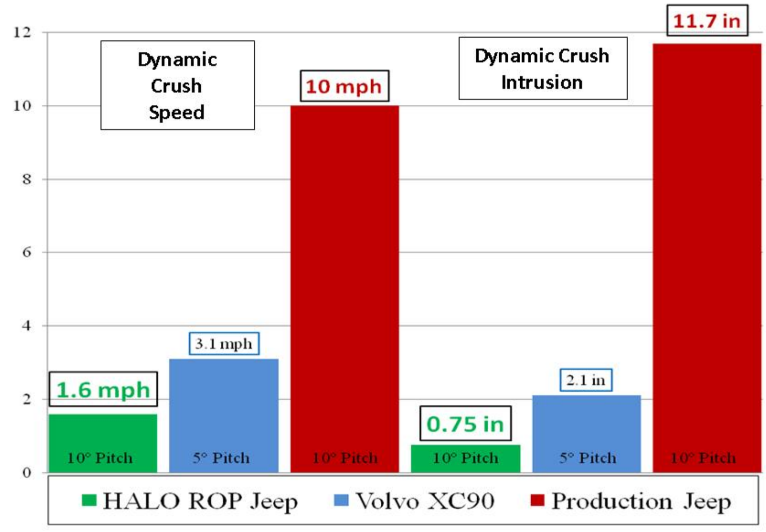
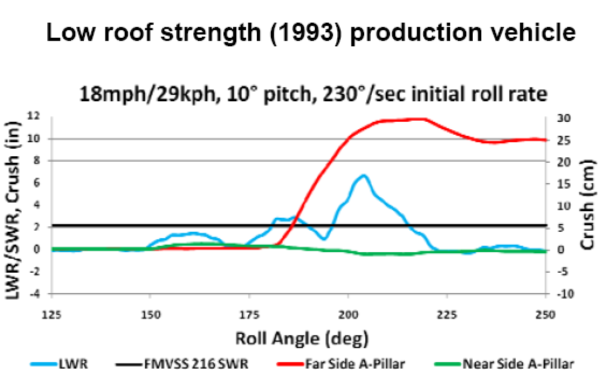



Fig. 9: Dynamic crush speed and intrusion comparison.

The instrumented roadway surface from the JRS mechanistically indicates why the device works, see Figure 10. As is known, a dropped object has a certain quantity of kinetic energy at impact, equal to the product of weight by drop height. This is a more or less fixed value. Vehicles must manage their own weights during collisions, and any difference in weight between the three tested vehicles is thus immaterial. However, if the energy can be managed uniformly, rather than piece-meal by corner impact, the peak magnitudes of interaction force can be diminished. The graph at left shows the results for the production vehicle. Notice that the peak intrusion, as shown by the red line, exceeded 10" which represents a high injury potential; typical static headroom is 5". The green line shows the near side A-pillar, which shows more-or-less no deformation. The blue line shows three spikes of increasing magnitude. The first spike, which starts at about 150 degrees of roll, is minor. It is the engagement of the initially leading side. The next two spikes are actually a single impact, the initially trailing side. Notice how the red line shows far-side A-pillar deformation rapidly, within 10 degrees of roll, with the impact of the trailing side. A peak measured load of approximately six times the vehicles weight is recorded.



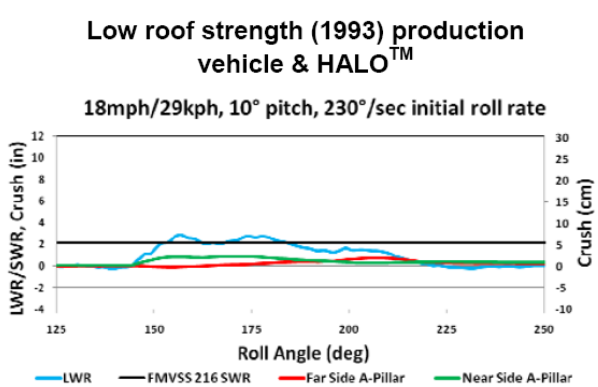




Fig. 10: JRS instrumented roadway surface plots. The dark line represents the vehicles FMVSS 216-measured strength to weight ratio. LWR is a ratio of the load measured by the floor divided by the weight of the vehicle. In that LWR, SWR and Crush in inches all have similar magnitudes, they share a common axis at the left of each graph.

The second graph at right is for the same vehicle modified with a HALO™ RDMD. The initially leading side engagement occurs at nearly the same time, but the measured load peaks are "smoothed out." Since the supporting hoops are centered on and in a constant radius with the vehicle’s center of gravity. The vehicle’s roof does not break contact with the roadway as it does with a squared segment. While inverted, the vehicle rolls like a paint cannister, rather than a brick. With a more-or-less constant loading of the roof without severe impact shock loading, the roof structure does not show strain localization and damage enhancement. The management of the loading along with the strengthening of the roof ensures that only cosmetic damage is done to the vehicle and the occupant survival space is not compromised.

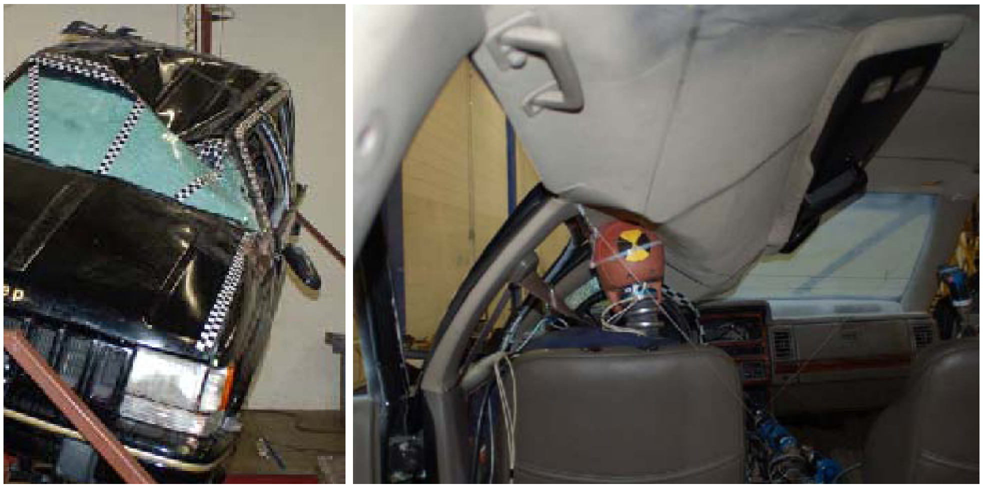


Fig. 11: JRS Test of production 1993 Jeep Grand Cherokee, post roll 1. The objectionable intrusion is obvious and would have caused a life-altering or ending injury. The identical vehicle model run with the HALO™, run twice, had no objectionable intrusion.

### Discussion

A flaw associated with the current US FMVSS-216 test is that it only produces a single damage mode, the inward intrusion of the top of one A-Pillar. As was illustrated by Friedewald [1994], numerous deformation modes are possible and in fact seen after real turnovers. Damage from one roll can act as a failure initiation point and can lead to gross distortion of the cabin.

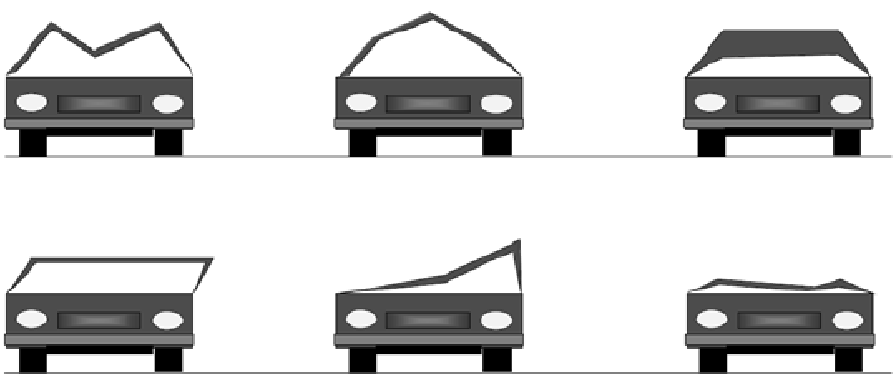


Fig. 12: Schema to describe actual roof deformation pattern as proposed by Friedewald [1994]

The “downward V” mode shown at top left of Figure 12 and the “upward tenting” mode as shown at top center are completely eliminated by the application of the HALO™. Further, the increased strength afforded by extra steel, improved geometry that ensures constant roof-to-ground engagement, and increased contiguity that ties the pillars together forcing them to deform in concert, rather than individually, is responsible for the dramatically improved roof performance. As is shown by destructive JRS testing, a roof that performs very poorly in rollover (Figure 11) can be improved with this retrofit device to exceed the performance of a vehicle that is touted as not requiring a roll cage to be safe in rollovers (Figure 8). Both total intrusion and intrusion speed are dropped to levels that, while non-zero, are also non-objectionable.

## Summary and Conclusions

It is common to see rollovers in off-road rally car racing, but rare to see objectionable roof intrusion or serious injuries. This is because each car is required to have significant roof reinforcement in the form of a roll cage. Design considerations for roll cages, as defined by the Sports Car Club of America (SCCA) [SCCA, 2006], "The basic purpose of the roll cage is to protect the driver if the car turns over, runs into an obstacle such as a guardrail or catch fence, or is struck by another car. It shall be designed to withstand compression forces from the weight of the car coming down on the rollover structure and to take fore/aft and lateral loads resulting from the car skidding on its rollover structure." Many if not most production light vehicles at this time are not designed with the intention of providing roof support in multiple revolution collisions.

The HALO™ rollover damage minimization device is a validated, effective low tech retrofit used to improve the roof strength of vehicles, particularly those used for commercial purposes. In the majority of rollovers in which the vehicle does not interact with a fixed object (e.g., tree) or oncoming vehicle, the HALO™ will diminish roof intrusion speed and total intrusion to non-injurious levels. This is accomplished in three ways. First, it improves the roof geometry by keeping the roof in contact with the roadway as the vehicle rolls from one side to the other, and diminishes the vertical velocity. Second, it prevents buckling of the header by adding additional steel to the roof. Third, it prevents the loading from being localized at the point of contact, distributing the loading across the greenhouse structure. This damage minimization also diminishes side glazing fracture, helping to ensure occupant containment. This device is straightforward to install, and requires no maintenance besides surveillance. As the device is lightweight and exterior to the cabin, it has an inconsequential effect on cargo capacity, fuel economy and rollover propensity.

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## Proviso

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