Commercial, Police, and Military Vehicle Rollover Protection and Evaluating the Effectiveness of Geometry and Retrofit Rollover Testing

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Abstract: Rollover crashes cause more than 10,000 fatalities and nearly 30,000 serious injuries per year in the U.S. alone. This is due to the fact that the vast majority of vehicles, including commercial, police, and military, lack the roof strength to preserve occupant survival space and protect their occupants in a rollover. Recent statistical and epidemiological studies have shown a significant relationship between roof crush and injury. This rollover occupant protection problem is well known to industries with large vehicle fleets; until now, this problem has eluded solution. Within these various industries a wide variety of rollover occupant protection systems (ROPS), both internal and external, have been designed, purchased, manufactured, installed, and maintained locally with little expert consultation. A wide variety of designs have emerged with an alarming variance in "assumed" crashworthiness. Couple this alarming trend with the risk of rendering the existing occupant protection features (e.g., airbags) ineffective, which has resulted in vehicles with inadequate crashworthiness. This paper describes how rollover damage to a vehicle with a weak roof and the resulting reduction of occupant headroom can be minimized to an inconsequential amount using an innovative externally retrofitted rollover load distribution device. This system was 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 commercial, police and military fleets.

Keywords: rollover protection, injury prevention, roof geometry, rollover testing, rollover load distribution device, HALO™.

INTRODUCTION

Each year in the United States (U.S.), approximately one in every three traffic-related deaths is the result of a rollover crash.[1] Australia has similar annual statistics; about one in every four occupant fatalities occurred in vehicles that rolled.[2,3,4] In Europe, around 15% of vehicle occupant fatalities involve some element of a rollover.[5]

The high incidence of rollover crashes have become a concern to global mining and petroleum companies, U.S. border patrol police and U.S. military personnel because of occupational health and safety requirements. The vehicle is considered a workplace environment. Hence, duty of care to provide a safe work environment extends to employees, police and military personnel travelling in either a company or government vehicle, including protection in a rollover crash. This is particularly true if the driver was travelling at the posted speed limit, all occupants were seat belted, and the crash was not due to driver or occupant error or negligence.

In terms of serious injuries, the National Highway Traffic Safety Administration (NHTSA) estimates around 24,000 serious injuries occur in approximately 273,000 rollover crashes.[6] Recent work by Mandell et al[7] investigated the Crash Injury Research Engineering Network (CIREN) database and the National Automotive Sampling System (NASS) CDS database for belted, adult (older than 15 years), outboard occupants in rollover crashes from 1993 to 2006. They used a logistic regression to establish a relationship between roof crush magnitude and severe-to-fatal (AIS≥3) injury. They found that the risk of mortality, traumatic brain injury, spine, and spinal cord injury increased with increasing roof crush. For spine injury, increased risk was observed when roof crush exceeded 3 inches (8 cm).

The relationship between roof deformation and serious injury in rollovers was also investigated by Rechnitzer and Lane[8] in 1994. Their study of Australian crashes concluded that roof crush was a significant factor in serious-to-fatal injury occurrence in rollovers. It is worth noting that rollover crashes are the leading cause (17%) of spinal cord injury in Australia.

Recent NHTSA studies have also shown "a statistically significant relationship existed between both vertical roof intrusion and post-crash headroom on the one hand and maximum injury severity of head, neck, or face injury from roof contact on the other hand. The relationship remained regardless of the statistical model used."[9] In 2001 NHTSA requested comments about upgrading the roof crush rule. In 2005 NHTSA issued a notice of proposed rulemaking (NPRM) suggesting an upgrade of the strength-to-weight ratio (SWR) criteria to either 2.5, 3.0 or 3.5. In January 2008 NHTSA issued a supplementary NPRM authenticating statistical research that post-crash negative headroom was 5 times more likely to be injurious (greater roof crush than original headroom). In May 2009 NHTSA issued a final rule setting a two-sided static SWR criteria of 3.0. Most significant was the fact that, at this time, NHTSA also issued a clear and unambiguous statement that "roof crush causes injury."[10]

A study was performed by the Insurance Institute for Highway Safety (IIHS) of 11 midsize sport utility vehicle (SUV) roof designs in single vehicle real-world rollover crashes.[11] Their study showed that, "In all cases, increased measures of roof strength resulted in significantly reduced rates of fatal or incapacitating driver injury after accounting for vehicle stability, driver age, and state differences." The IIHS found "A one-unit increase in peak SWR within 5 inches (mm) of plate displacement, the metric currently regulated under the Federal Motor Vehicle Safety Standard (FMVSS) 216, was estimated to reduce the risk of fatal or incapacitating injury by 28%."

A retrofitted structural system that distributes roof loads and can minimize roof crush during a rollover crash will best protect occupants. In order to distribute the roof loads the geometry of the roof structure must be changed. This paper extends the work of Grzebieta et al (2009)[12]. The hypothesis was that loads applied to the roof structure and hence roof crush and injury risk can be reduced by reinforcing the roof structure of a weak roof vehicle. The authors showed this using the 'proof of concept' device (HALO[TM] prototype 1), a hoop mounted to an external frame to hold the vehicle up as it rolls from one side of the roof to the other, thus changing the geometry. Results from the production vehicle and HALO[TM] Prototype 1 are presented in Grzebieta et al (2009)[12]. This paper provides further proof of this concept. The evolution of the HALO[TM] prototype 1 into the current HALO[TM] rollover load distribution device is described, including the design, construction, and JRS testing of 3 prototypes. A dolly rollover test of a HALO[TM] prototype is also presented here. The innovative HALO[TM] rollover load distribution device was designed for and is well suited for the Commercial, Police, and Military Vehicle fleets.

Government and Police Agency Vehicle Fleets

Several of the government and police agencies have vehicle fleets. For example, in 2008, the U.S. Border Patrol had over 33,000 vehicles.[13] In 2008, the non-profit "People Safe in Rollovers Foundation"[14], held a Rollover Summit in Washington D.C. to share ideas on how to keep people safe in rollovers. One of the speakers was Dr. David Garcia, a victim of roof crush in his Ford Escort. In his testimony at the Oversight Committee Hearing on Passenger Vehicle Roof Strength on June 4, 2008, he talked about two fellow Americans who were also victims of rollover crashes.

Case Studies – U.S. Border Patrol Vehicles

David Webb[15] was a 35 year-old Border Patrol agent out on a routine call when the right rear tire of his 1997 Chevrolet Tahoe blew out. This caused him to lose control and his SUV rolled over. He sustained a fractured skull and never regained consciousness. Figure 1 shows the vehicle with roof deformation at the driver-side A-pillar, after the crash. It is worth noting that the aftermarket roll cage in the rear for detainees was the section of the vehicle that did not crush.
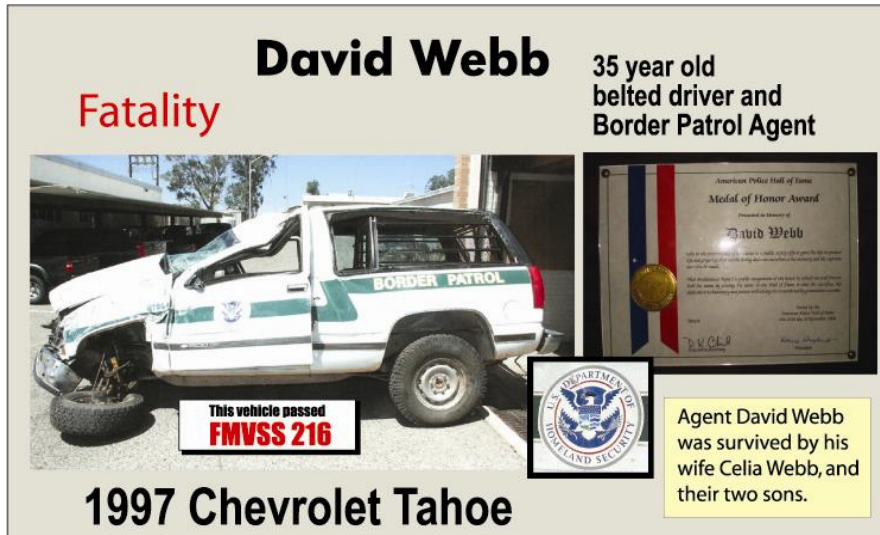
Figure 1. Government vehicle rollover victim (image from www.peoplesafeinrollovers.org)

The other victim was 30 year-old Border Patrol agent, Luis Pena, Jr.[16] Mr. Pena was amnesic to the event, but speculates that he may have tried to avoid hitting either a horse or cattle when his 2003 Ford F-250 XL rolled over. His injuries included vertebral dislocation with spinal cord injury, rendering him quadriplegic. Figure 2 shows the roof crush at the driver-side A and B-pillars.

Figure 2. Government vehicle rollover victim (image from www.peoplesafeinrollovers.org)

On June 6, 2008, Mr. Pena, presented his case to the current Chief and Assistant Chief of the Border Patrol. The Chief and Assistant Chief were shocked to know that the vehicles they provide for their agents were potentially unsafe. By law the Border Patrol is required to order only American-made vehicles. Mr. Pena was informed that he is the only Border Patrol Agent who has ever survived a rollover; there were 7 other Border Patrol Agents who had died in rollovers in the previous 1½ years.

Military Vehicle Fleets

The U.S. Military forces employ a fleet of 12 and 15 passenger vans to transport troops around the US. The current fleet size is unknown due to the unavailability of statistical information that shows the make-up of the current fleet of vehicles, likely for national security reasons. Nevertheless, evidence is found from accident information that the U.S. military forces do indeed employ these vehicles to move personnel.

Heavily-loaded 15-passenger vans are particularly susceptible to rollover crashes because of their high Center-of-Gravity (CG).[17] NHTSA research shows the rollover accident risk of 15-passenger vans increases dramatically as the number of occupants increases from fewer than five to more than 10. Vans with 10 or more occupants had a rollover rate nearly three times that of vans with fewer than five occupants.[18]

Case Study – U.S. Marine Transport Van

On June 10, 2001, a solo highway traffic collision involving a 1996 Ford 15 passenger Club Wagon owned by the U.S. Government resulted in fatal injuries to two of the U.S. Marine occupants and minor- to-major injuries to 12 others.

A volunteer driver departed Camp Wilson in route to Laughlin, Nevada, with 15 Marine Corp passengers. The Ford Club Wagon Van had a tire blow out, which caused a loss of control and vehicle rollover. This vehicle sustained multiple impacts to the roof, rear and both sides. There was a significant impact to the right roof and upper right side which caused significant intrusion into the right side of the passenger compartment. This major impact to the roof had a principal direction of force from top to bottom and right to left. Figure 3 shows the marine transport van after the crash; the exterior view is on the left and the interior view from the rear is on the right.

Figure 3. Military vehicle fleet - U.S. Marine transport van case study

Commercial Vehicle Fleets

Some of the largest commercial vehicle fleets are managed by the Oil, Gas and Mining industry (OGM). Some fleets have as many as 30,000 vehicles across the globe. The majority of the fleets are made up of light truck vehicles (i.e., SUV, pickup, van). These global companies provide vehicles, including fleets of 12 and 15 passenger vans, for use at and traveling to and from these sites.

These global companies recognize the need for occupant protection for their personnel as a result of their duty of care to provide a safe work environment. Most of the companies have some form of requirement for Rollover Occupant Protection Systems (ROPS) installed on their vehicles because of their concerns regarding roof crush. The types of ROPS structures used vary widely among the companies and to some degree is a function of location, availability, expertise and terrain at the site. For many years these systems have been primarily fitted internally to the vehicles. With the recent introduction of Side Curtain Airbags, these internal ROPS have become a problem. The OGM industry began looking for a solution that was external to the vehicle and would not interfere with the Side Curtain Airbags. In addition, any proposed ROPS design must maintain payload capacity and fuel economy.

DESIGNING AN EXTERNAL ROPS

The Concept

Grzebieta et al (2009)[12] demonstrated a 'proof of concept' how roof crush intrusion into the occupant compartment can be prevented using an innovative externally retrofitted rollover load distribution device. It was developed based on an understanding of how vehicles roll and roofs crush during rollover. It incorporates a roll "hoop" placed in line with the major radius of the vehicle changing and improving the vehicle geometry. Figure 4 demonstrates via sketches the concept of this process.

Grzebieta et al (2009)[12] presented rollover crash test results of a U.S. manufactured production SUV with a seat belted Hybrid III anthropomorphic test dummy (ATD) subjected to two rolls on the Jordan Rollover System (JRS). A second production SUV of the same make and model was fitted with the HALO™ Prototype 1 and was then subjected to the same dynamic rollover crash test using the JRS test rig. Injury measures from the ATD, crush and crush velocity from various locations in the retrofitted vehicle during testing were noted and compared to the measurements from the production vehicle. Roadway impact loads measured in both vehicles were compared to each other and to the Volvo XC90, the current best-performing rollover crashworthy production vehicle. Results showed that when both roof crush and vehicle's centre of gravity fall is prevented by the geometry change of the HALO™ Prototype 1 retrofit system, the ATD injury measures and road impact loads are significantly reduced.
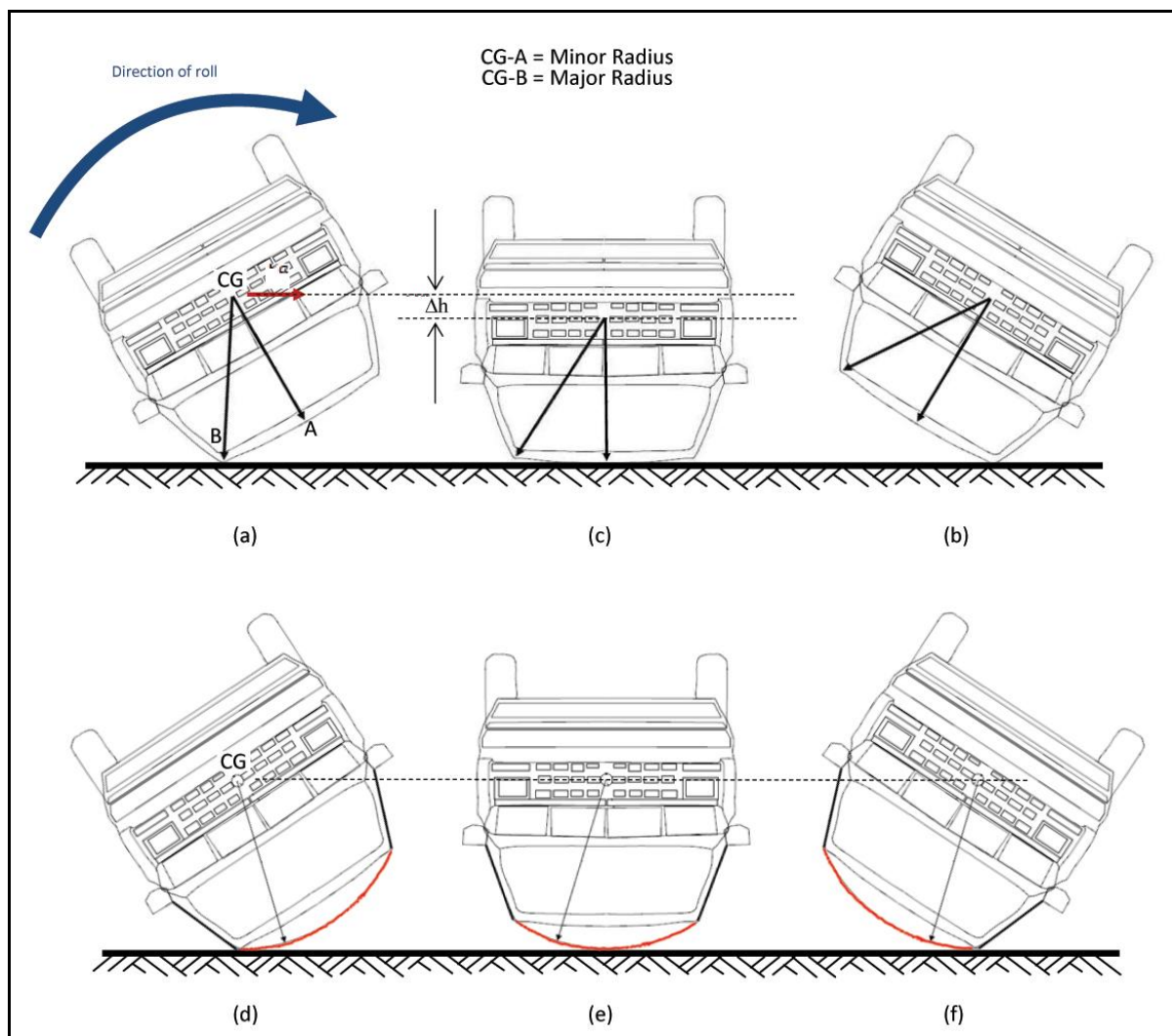

Figure 4.   Top row: Vehicle's CG drops during rollover and then rises again;
             Bottom row: Hoop maintains vehicle's CG at constant height, thus reducing roof load

Test Apparatus

The JRS

The JRS is shown in Figure 5. 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. 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, and arrested after each roll. Detailed descriptions of capabilities and operation of the JRS are published elsewhere.[19,20,21]
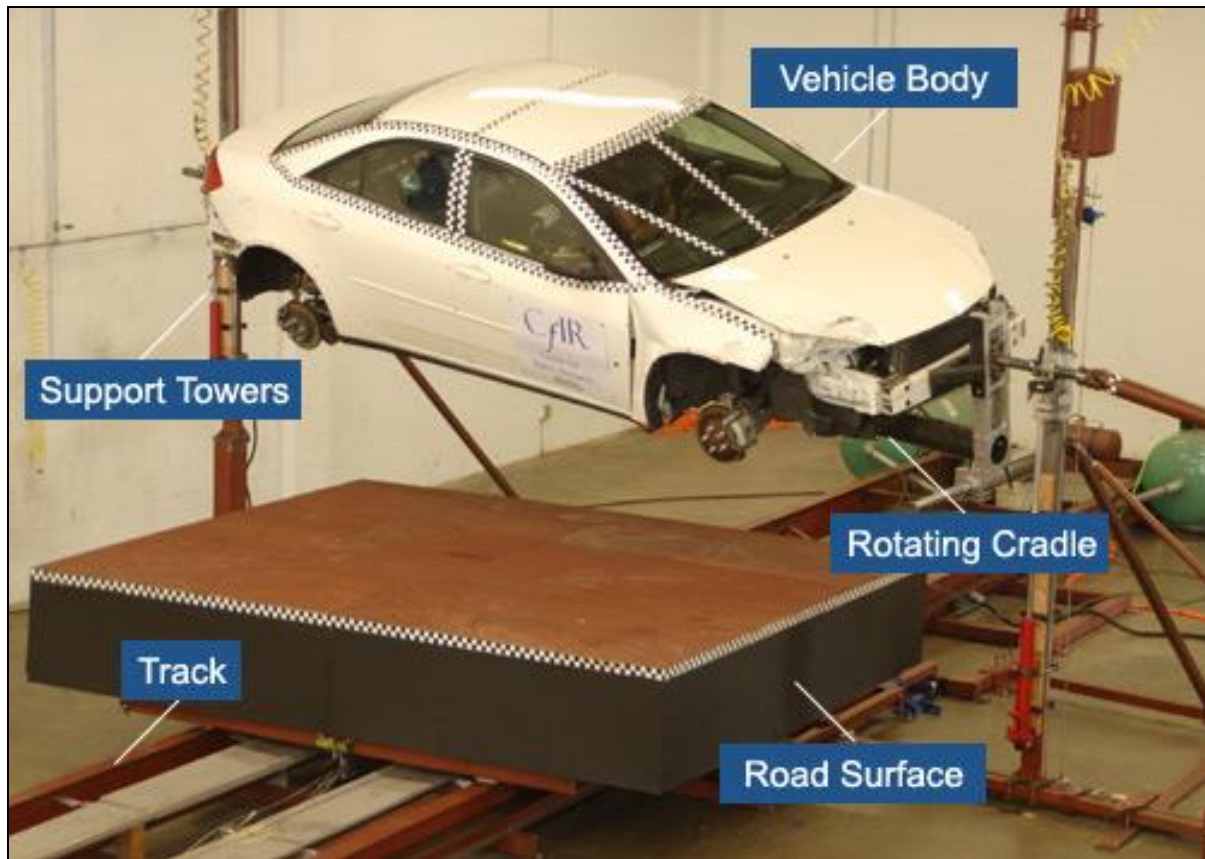

Figure 5. Photograph of the major components of the JRS

The protocol used to test the HALO™ prototypes was performed with at least 2 passenger side leading rolls at 18 mph (29 kph) roadbed speed, a 222 °/sec vehicle angular rate, a 4 inch (10.2 mm) drop height and a 10° impact pitch angle, most of these parameters are more severe than those recommended by Friedman and Grzebieta (2009).[12] If there was a third roll conducted, the road speed was 15 mph (24 kph) and the pitch angle was 5°, with the same drop height and equivalent angular rate. The vehicles were equipped with Hybrid III 50th percentile dummy belted in the driver's seat. For each roll, the dynamic peak roof crush was tabulated, the end of test residual roof crush, and dynamic peak roof crush speed at the pillars and roof header.

HALO™ Prototype 2 Development and Testing

The second prototype of the HALO™ was a much more intricate design with multiple attachment points, a fully integrated interior B-pillar to B-pillar reinforcement and a fully redesigned exterior front. This prototype worked very well in reducing roof crush as shown in Figure 6. The vehicle struck the ground at 147° on the near side and cleanly rolled over the far side with very little apparent damage. The dummy was only lightly loaded during the test. The test results for prototype 2 are shown in Table 1.

Figure 6. HALO™ Prototype 2; No noticeable deformation to the roof structure

Table 1. Test results for the HALO™ Prototype 2.

Prototype 1 ROLL 1	Peak Roof Crush (in)	Peak Roof Crush (mm)	End of Test Roof Crush (in)	End of Test Roof Crush (mm)	Peak Roof Crush Velocity (mph)	Peak Roof Crush Velocity (kph)
A-Pillar	-0.6	-15.2	-0.1	-2.5	1.0	1.6
B-Pillar	-0.3	-7.6	0.1	2.5	0.7	1.1
Roof Header	-1.2	-30.5	-0.4	-10.2	1.6	2.6
Near Side A-Pillar	-1.5	-38.1	-0.7	-17.8	2.5	4.0

HALO™ Prototype 3 Development and Testing

The third prototype of the HALO™ was a more simple design than the previous prototypes with a fully redesigned front. The HALO™ Prototype 3 on a different SUV was tested to check for differences in vehicle type performance and without the internal supports at the B-pillar. This prototype was not as successful in that the B-pillars had some buckling and the flat redesigned exterior front pushed in on the header more than considered acceptable as shown in Figure 8.

Figure 8. HALO™ Prototype 3 post-test photograph

HALO™ Prototype 4, The Current Design Configuration

For the fourth prototype test the original SUV type used for prototypes 1 and 2 was used again. The redesign included the B-pillar reinforcement plates, dual longitudinal rails and a redesign of the piece in front of the roll hoop. The same protocol for testing on the JRS was used. Photographs of this design before and after each roll of a 3 roll test series are shown in Figures 9a-d below.

Figure 9a: HALO™ Prototype 4 pre-test photograph

HALO™ prototype 4 performed very well in a three roll series of tests. The first roll was conducted with an 18 mph (30 kph) road speed, 10° of pitch and 145° roll contact angle. The resultant measurements of roof displacement are shown in Table 2. Figure 9b is the post-test photograph.

Table 2. HALO™ Prototype 4 – Roll 1 results.

Prototype 4 ROLL 1	Peak Roof Crush (in)	Peak Roof Crush (mm)	End of Test Roof Crush (in)	End of Test Roof Crush (mm)	Peak Roof Crush Velocity (mph)	Peak Roof Crush Velocity (kph)
A-Pillar	-0.8	-19.4	-0.2	-4.6	1.0	1.6
B-Pillar	-0.2	-5.6	0.2	4.7	0.7	1.2
Roof Header	-0.8	-21.4	-0.3	-7.9	1.5	1.3
Near Side A-Pillar	-0.9	-23.2	-0.3	-7.5	1.6	2.6

Figure 9b. HALO™ Prototype 4 Roll 1 post-test photograph

The second roll was conducted with an 18 mph (30 kph) road speed, 10° pitch and 145° roll contact angle. Table 3 lists resultant roof displacement measurements. Figure 9c is the post-test photograph.

Table 3. HALO™ Prototype 4 – Roll 2 results.

Prototype 4 ROLL 2	Peak Roof Crush (in)	Peak Roof Crush (mm)	End of Test Roof Crush (in)	End of Test Roof Crush (mm)	Peak Roof Crush Velocity (mph)	Peak Roof Crush Velocity (kph)
A-Pillar	-2.1	-52.1	-1.1	-27.0	2.0	3.2
B-Pillar	0.0	-0.5	0.5	11.5	0.7	1.2
Roof Header	-1.8	-46.6	-0.8	-19.8	1.5	2.4
Near Side A-Pillar	-1.4	-35.2	-0.5	-12.6	1.3	2.2

Figure 9c. HALO™ Prototype 4 Roll 2 post-test photograph

The third roll was conducted at a 15 mph (24 kph) road speed, 5° pitch and 135° roll contact angle. Table 4 lists resultant roof displacement measurements. The post-test photograph is Figure 9d.

Table 4. HALO™ Prototype 4 – Roll 3 results.

Prototype 4 ROLL 3	Peak Roof Crush (in)	Peak Roof Crush (mm)	End of Test Roof Crush (in)	End of Test Roof Crush (mm)	Peak Roof Crush Velocity (mph)	Peak Roof Crush Velocity (kph)
A-Pillar	-1.8	-45.0	-0.4	-10.7	2.4	3.9
B-Pillar	-0.7	-17.6	0.1	3.4	1.1	1.8
Roof Header	-1.8	-46.6	-0.5	-11.6	1.6	2.6
Near Side A-Pillar	-1.4	-36.2	-0.2	-6.3	1.8	2.9

Figure 9d. HALO™ Prototype 4 Roll 3 post-test photograph

Finally, a dolly rollover test was performed with HALO™ Prototype 4 on a 15 year-old, high-mileage, somewhat-rusted, used vehicle. The test was conducted at 42 mph (68 kph) off the dolly, which was more severe than FMVSS 208. A sequence of photographs from the test is shown in Figure 10.

Figure 10. HALO™ Prototype 4 during a FMVSS 208 dolly rollover test

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 °/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.

The vehicle kinematics during the rollover were unusually severe involving, on the second roll, substantial lofting and pitch (the vehicle elevated about 2 feet (61 cm) into the air and pitched down about 10°). 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 HALO™ connected the two sides, and when the vehicle rolled, the sides shifted together laterally in the same direction due to the horizontal loading 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 passengers that would result in an injury. The only foreseeable circumstance during this three roll event where an injury could 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 occupants. 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. A photograph of the exterior is shown in Figure 11.

Figure 11. Prototype 4 HALO™ after a 3 roll dolly rollover test

Table 5 is a summary list of peak measured driver-side roof crush and roof crush speed 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 injury marks for restrained occupants are found). Also shown is the inferred medical probability of injury severity by the Abbreviated Injury Scale (AIS) according to the correlation algorithms proposed by Friedman et al (2009).

Table 5. Prototype 4 HALO™ - Dolly Rollover Test results

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

From the dolly rollover test, it was clear that the HALO™ Prototype 4 B-pillar reinforcement plates needed to be extended to the roof rail. In addition, the front attachment plates were redesigned in an effort to spread the load over more of the contact surface and reduce the potential of point loading the A-pillar.

The final prototype was developed into the production HALO™ and was mounted on a 4WD vehicle for use in Australia as shown in Figure 12.

Figure 12. Final HALO™ mounted on 4WD for use in Australia

HALO™ Development for 12 to 15 Passenger Van

Once the SUV version of the HALO™ was completed, an interior retrofit strengthening system and external HALO™ was designed for a 12 to 15 passenger van, constructed, and installed. First, we performed a thorough examination of the production van structure. Weaknesses were identified. For example, there are no vertical load-bearing pillars between the B-pillars and the D-pillars and the distance between the load-bearing B-pillars and D-pillars is approximately 10 feet and excessive (Figure 13).

- On the driver's side, the vertical roof C-pillar is essentially a "false" non-structural pillar that provides only the minimum structure necessary to support the window sill (Figure 14).

Figure 13. Non-structural pillars

Figure 14. Driver-side "false" pillars

- On the passenger's side, the "C-pillar" has a relatively large overall profile, but is constructed of a single-layer 0.05-inch steel sheet and has open interior sections (Figures 15) that negate its strength, and necks down to a much smaller cross-section on its exterior and likely fails in buckling or local bending when subjected to the high stress concentrations in a rollover.

Figure 15. Passenger-side lower (left) and upper (right) C-pillar open sections

The production vehicle clearly required reinforcement to withstand the roof loads encountered in a typical rollover crash.

Next, a design was developed to compensate for the weak areas of the vehicle's structure, or lack of vertical structure, while retaining the interior. The proposed design includes the following changes.

Driver-side Structural reinforcement:

- Driver-Side B-Pillar Reinforcement within the interior plastic
- Four additional Driver-Side Structural Pillars were
    - attached to the floor, roof rail, window sill, and
    - gloved over the existing "false" pillars and then riveted to the pillar with plates added to the floor in the region of each newly added pillar
- Two additional short pillars were added to the Driver-Side stemming from the floor to window sill in order to provide better lateral support to the region.

Passenger-side Structural reinforcement:

- Passenger-Side B-Pillar reinforcement within the interior plastic.
- Passenger-Side C-Pillar reinforcement within the interior plastic.
- Two additional Passenger-Side Structural Pillars were
    - attached to the floor, roof rail, window sill, and
    - gloved over the existing "false" pillars and then riveted to the pillar with plates added to the floor in the region of each newly added pillar

To ensure compliance with FMVSS 201 (Occupant Protection in Interior Impact), interior padding and/or air gap padding was incorporated into the pillar designs above the window sill. The modified structure was tested to confirm compliance; the HIC of 660 met the HIC less than 1000 performance criterion. The dynamic rollover performance of the van retrofit will be discussed in a future paper.

Figure 16 shows the production vehicle. Figure 17 shows the modifications for the proposed internal retrofit strengthening system.

Figure 16. Production passenger van

Figure 17. Passenger van internal retrofit strengthening system

After finalizing the internal requirements for the retrofit, an external HALO™ was designed for the roof. Due to the length of this vehicle, the triple-hoop design shown in Figure 18 was developed for the van. With the proposed retrofit strengthening system, it is expected that the vehicle could withstand typical rollover roof loads.

Figure 18. 12 to 15 Passenger van with HALO™ rollover load distribution device.

CONCLUSION

An innovative HALO™ rollover load distribution retrofit device has been developed to protect commercial, police, and military fleet vehicle occupants in rollover crashes. The problem was defined by researching crash histories and identifying the fleet (primarily vans, pickups, and SUVs) and occupant population (primarily adults). The hypothesis was that reducing roof crush preserves the occupant survival space and, thereby, reduces the likelihood and severity of occupant injury and fatality. In this paper, the reduction of roof crush was achieved by placing an external roll "hoop" in line with the major radius of the vehicle, improving the roof geometry and distributing roof loading. The 4 prototypes and final external retrofit device designs were built and installed on intact vehicles. The final retrofit device, the HALO™ was tested dynamically in a three-roll test series on the JRS and in a dolly rollover test at a trip speed of 42 mph (68 kph), more severe than FMVSS 208. Rollover crash test results show that a weak-roofed vehicle fitted with the HALO™ markedly reduced far side loads, crush, and crush speed of the roof structure. Thus, these results confirm our hypothesis that vehicle roof loads, roof crush, and injury risk are reduced by reinforcing the roof structure with the HALO™ rollover load distribution device.

1. Digges K., Eigen A.M., 'Injuries in Rollovers by Crash Severity.' Proceedings 20th International Technical Conference on the Enhanced Safety of Vehicles, #07-0236, Lyon, France, 2007.

2. Fréchède B., McIntosh A., Grzebieta R.H., Bambach M., Young D., 'Compared Characteristics of 2000-2007 Single Vehicle Rollover Fatalities in three Australian States from the Australian National Coroners Information System (NCIS) Database.' Proceedings Road Safety Research, Policing and Education Conference, Sydney, Australia, 2009.

3. Grzebieta R.H., Young D., Bambach M., McIntosh A., 'Rollover Crashes: Diving Versus Roof Crush.' Proceedings 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France, 2007.

4. Young D., Grzebieta R.H., McIntosh A., Bambach A., Frechede B., 'Diving vs. Roof Intrusion: A Review of Rollover Injury Causation.' International Journal of Crashworthiness 12(6):609–628, December 2007.

5. Gugler J., Steffan H., 'Improvement of Rollover Safety for Passenger Vehicles, European Community.' R&TD - Project – 5th Framework - Programme "Growth", Contract #G3RD-CT-2002-00802, 2006.

6. National Highway Traffic Safety Administration, 'Notice of Proposed Rulemaking.' NHTSA-2005-22143-1, 2005.

7. Mandell S.P., Kaufman R., Mack C.D., Bulger W.M., 'Mortality and Injury Patterns Associated with Roof Crush in Rollover Crashes.' Accident Analysis and Prevention, Elsevier Ltd, doi:10.1016/j.aap.2010.02.013, February 2010.

8. Rechnitzer G., Lane J., 'Rollover Crash Study - Vehicle Design and Occupant Injuries.' Monash University Accident Research Centre, Melbourne, Report #65, 1994.

9. Strashny A., 'The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face during FMVSS 216 Rollovers: An Updated Analysis.' National Highway Traffic Safety Administration, DOT HS 810 847, 2007.

10. National Highway Traffic Safety Administration, Federal Register 74(90), Docket #NHTSA 2009-0093-1, 2009.

11. Brumbelow M.L., Teoh E.R., Zuby D.S., McCartt, A.T., 'Roof Strength and Injury Risk in Rollover Crashes.' Insurance Institute for Highway Safety, Arlington, Virginia, 2008.

12. Grzebieta R., Friedman D., Bozzini S., Shipp C., Jama H., 'Retrofitting For Rollover Crashworthiness Occupant Protection.' Proceedings Road Safety Research, Policing and Education Conference, Sydney, Australia, 2009.

13. David V. Aguilar, former U.S. Border Patrol Chief.

14. www.peoplesafeinrollovers.org

15. PR Newswire - US Newswire, Del Mar, CA, Photograph: http://www.newscom.com/cgi-bin/prnh/20080527/CLTU039, May 27, 2008.

16. PR Newswire - US Newswire, Philadelphia, PA, Photograph: http://www.newscom.com/cgi-bin/prnh/20080529/DC23606, May 29, 2008.

17. Bryant, K.L., Bojanowski C., Siervogel J., Wekezer J.W., Cichocki K., 'Crash and Safety Assessment Program for Paratransit Buses.' International Journal of Impact Engineering 36:235-242, 2009, SAE 2002-01-1604.

18. http://www.nhtsa.gov/cars/problems/studies/15passvans/index.htm.

19. Jordan A., Bish J., 'Repeatability Testing of a Dynamic Rollover Test Fixture.' Proceedings 19th International Conference on the Enhanced Safety of Vehicles, Washington, DC, #05-0362, 2005.

20. Friedman D., Nash C.E., Bish J., 'Observations from Repeatable Dynamic Rollover Tests.' International Journal of Crashworthiness 12(1):67-76, 2007.

21. Friedman D., Nash C.E., Caplinger J., 'Results from Two Sided Quasi-Static (M216) and Repeatable Dynamic Rollover Tests (JRS) Relative to FMVSS 216 Tests.' Proceedings 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France, #07-0361, 2007.