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A Study of Rollover Occupant Injury Mitigation Using Dynamic Testing To Evaluate Alternative Protection Systems

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Abstract

Since the onset of automotive safety awareness over 60 years ago the only rollover protection solution to be widely acknowledged and used in the E & P Industry has been the traditional internal roll cage. These traditional roll cages have become out-of-date and in recent testing are shown to be ineffective at the A-Pillar and windshield header.

An all-encompassing study of rollover accidents has shown that this old technology is not the best way to mitigate injury. Understanding “Real World” rollover crashes and how injuries occur is instrumental in pinpointing the key areas of the vehicle’s roof structure that require improvement. Our study included over 500 “Real World” rollover crash investigations and over 300 rollover crash tests performed with innovative dynamic testing using the Jordan Rollover System (JRS).

Over the past decade automobile manufacturers have improved roof strength and added computer controlled driver assistance measures to avoid crashes. Still, the need exists for a majority of the common SUV’s, Ute’s, Vans, and buses to use an aftermarket solution. This study illuminates the deficiencies in internal and other ROPS enabling HSE Managers to make more informed decisions when choosing a system. The goal of ROPS today should be to protect occupants without interfering with OEM safety systems.

Our investigation shows that rollovers producing serious to fatal injuries are characterized by a vehicle crash that includes rolling with forward pitch. In this circumstance, injury occurs when; vehicles roof strength is low, the geometry of the vehicle is poor including a large major radius, the structure of the roof is open section and/or the windshield header is weak. These crash characteristics show the importance of reinforcement at the A-Pillar and forward roof header. Traditional roll cages do not protect this area of the vehicle as shown in the new testing included in this paper.

The E & P Industry is spending millions of dollars annually on occupant protection systems that are not offering the best protection for their workforce. New technologies in current vehicles and research advances in the design and approach to protection systems can reduce overall costs without sacrificing protection.

Introduction

The research presented here has been collected while investigating the rollover fatality problem over the last 12 years. The United States Department of Transportation (DOT) and the automobile industry have been addressing the total fatality problem since DOT’s inception with the Traffic Safety Act of 1966. In 2004, DOT recognized the need to address the rollover fatality problem that had been escalating in the United States since the inception of the sports utility vehicles in the early 1980’s. The initial Federal Motor Vehicle Safety Standard 216 (FMVSS 216) for roof strength had been in place since 1973 [1]. It required vehicles, weighing less than 6000 lbs to have roof strength of one and one half times the gross vehicle weight when measured with a platen push test. The updated FMVSS 216 required vehicles to have roof strength of three times the gross vehicle weight with the same platen push test [2]. The platen used for the FMVSS 216 push test for testing roof strength is 70 inches long and spans most of the length of the roof and measures the combined strength of all the support pillars. Changing the standard has increased overall vehicle roof strength over the last several years in vehicles sold into the

US market, but it should be noted that FMVSS do not apply globally. If the vehicle is manufactured and sold outside the United States, the manufacturers are not required to comply.

The classic internal roll cages or rollover occupant protection system (ROPS) consists of two upsidedown horse shoe shaped metal bars with cross members connecting them longitudinally. These metal bars are usually attached to the vehicle just behind the front seats and just behind the second row seats, at what is refered to as the "B" and "C" pillars moving rearword in the vehicle. The area that is strengthened by this type of ROPS device is very similar to the area measured by the platen push test. Given the required increase in strength of this same area by the new FMVSS 216, these ROPS are no longer affording much, if any, additional protection to the occupants beyond what the manufactured vehicle structure is providing [3].

However, the rollover problem remains with thousands of catosprophic injuries and fatalites in the United States alone, each year. **Figure 1** illustrates the magnitude of theUnited States rollover tragedy. From the inception of the Fatal Accident Reporting System (FARS) in 1978 until 2008 [4], more than 1,350,000 occupants were killed in all of the vehicle crash modes, of which almost 318,000 lives, averaging 10,000 lives lost per year in rollover crashes alone.

Accident Year	Rollover Fatalities	Total Fatalities	Accident Year	Rollover Fatalities	Total Fatalities
1978	10,340	50,331	**1994**	9,472	40,716
1979	10,674	51,093	**1995**	9,991	41,817
1980	11,137	51,091	**1996**	10,096	42,065
1981	10,663	49,301	**1997**	10,068	42,013
1982	9,038	43,945	**1998**	10,334	41,501
1983	8,959	42,589	**1999**	10,701	41,717
1984	9,294	44,257	**2000**	10,530	41,945
1985	9,028	43,825	**2001**	10,684	42,196
1986	10,181	46,087	**2002**	11,309	43,005
1987	10,452	46,390	**2003**	11,050	42,884
1988	10,772	47,087	**2004**	11,210	42,836
1989	10,263	45,582	**2005**	11,505	43,510
1990	10,163	44,599	**2006**	11,417	42,708
1991	9,797	41,508	**2007**	10,938	41,259
1992	9,097	39,250	**2008**	9,628	37,261
1993	9,026	40,150	**Total**	**317,817**	**1,354,518**

Fig 1. Fatal Accident Reporting System, Fatalities from 1978-2008.

Discussion

Identifying the Problem – Type of Rollover mode that produces Catostrophic and Fatal Injuries

This research shows that the most serious injuries are occurring from forward pitch rollovers where the majority of the load is on the front or "A-pillars", those at the sides of the windshield. The roof strength at this specific point in the roof is not designed to take the full load of the vehicle and therefore collapses under the weight. Additionally, the windshield glass is bonded in place providing extra strength to the roof during the FMVSS 216 test. Often in a forward pitch rollover, the windshield breaks and as much as 30% of the roof strength [5] can be lost instantly. Additionally, an examination of the windshield header revels that without reinforcement, once the windshield breaks, the header structure loses its major support and collapses, inward and down or outward and up, depending on the forces and roll direction. The following section outlines our research on roof strength and dummy injury measures to coorelate laboratory testing to real world accident data.

Development of Rollover Injury Risk Based on Vehicle Structural Performance

In 2008, the Insurance Institute for Highway Safety (IIHS) published data on 22,000 SUV's involved in rollover crashes with incapacitating injuries [6]. Results indicated that the injury rate was reduced by 25% for each increment of vehicle strength-to-weight ratio (SWR) from SWR 2 to 3. The IIHS also derived a relationship between window breakage in rollovers, described in terms of ejection rate, and SWR. The IIHS reported that the ejection rate decreased with increasing vehicle SWR. At approximately the same time, the Center for Injury Research (CfIR), owner of an innovative dynamic rollover testing device called the Jordan Rollover System (JRS) compiled their dynamic testing, along with other dynamic rollover tests and confirmed the IIHS results.

CfIR defined the following momentum exchange dummy measures:

- a momentum exchange function, called the Integrated Bending Moment (IBM), and
- single and double integration product of head resultant acceleration (HRA).

Figure 2 is a composite plot of structural injury risk and momentum exchange injury measures showing rate reduction with increasing SWR. Results show that these parameters correlated with residual crush at an IBM value of 13.5 and a HRA exceeding a criteria of 48.

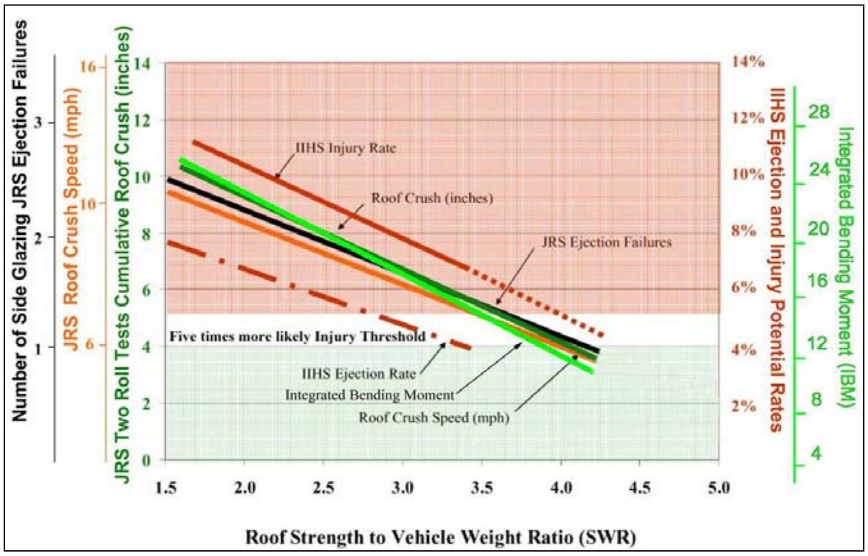

Fig 2. Composite plot of injury measures showing rate reduction with increasing vehicle SWR.

In 2008, NHTSA confirmed a National Accident Sampling System (NASS) statistical analysis indicating that, in rollover crashes, vehicles with post-crash negative headroom (more roof crush than original headroom) were 5 times more likely to be injurious (at any level of injury) than vehicles with post-crash positive headroom [7]. **Figure 3** is a plot of positive and negative post-crash headroom as a function of vehicle SWR in JRS rollover tests. This was a clear indication that roof crush leading to negative headroom, lead to increased injury probability.

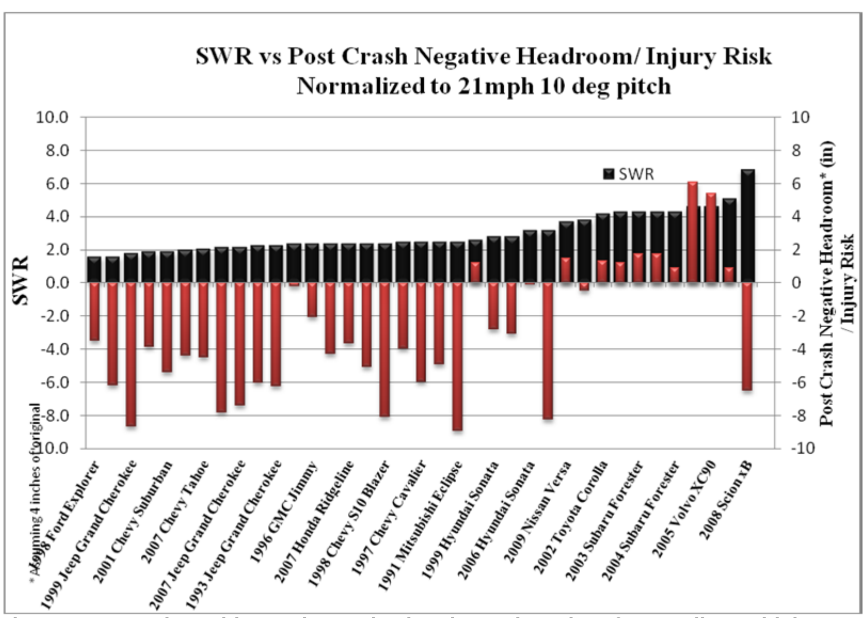

Fig 3. Post-crash positive and negative headroom in order of ascending vehicle SWR.

In 2009, a statistical analysis of NASS and Crash Injury Research and Network (CIREN) files [8] evaluated the probability and odds ratio of rollover fatalities and head, spine and spinal cord injury as a function of vehicle residual crush. For residual crush in bands of 0 to 3½, 3½ to 6, 6 to 12 and 12 inches and above, the corresponding ratings in order are "good," "acceptable" and "poor." The "acceptable" probability of injury is roughly 30% more likely than "good" and the probability of injury of a"poor" rating is 2.5 times greater than "acceptable." **Figure 4** is the fatality probability chart, showing increasing probability of fatality with increasing vehicle residual crush.

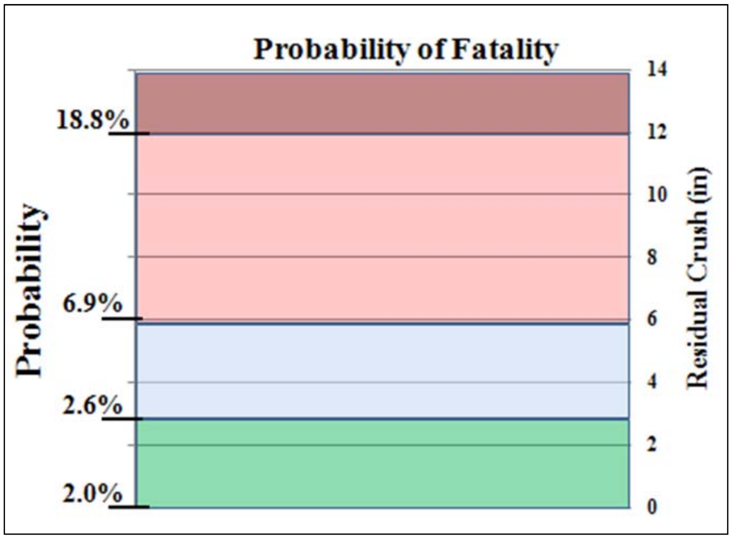

Fig 4. Fatal probability function vs. residual crush in inches.

Structural injury risk measures were identified in previously-published analyses of more than 50 JRS dynamic rollover tests and included the following as significant factors: SWR, major radius (MR) at the A-pillar, structural roof elasticity, impact angle, pitch angle and/or yaw angle [9]. These dynamic tests also identified vehicles with grossly underestimated injury potential based on FMVSS216 roof strength test alone. **Figure 5** shows residual crush from dynamic testing, normalized to a single test protocol, plotted on the fatality risk chart to 12 inches of residual crush of Figure 4. Note that the best performing vehicle (least likely to produce injury in a rollover) on the far left of Figure 5 is the Volvo XC90.

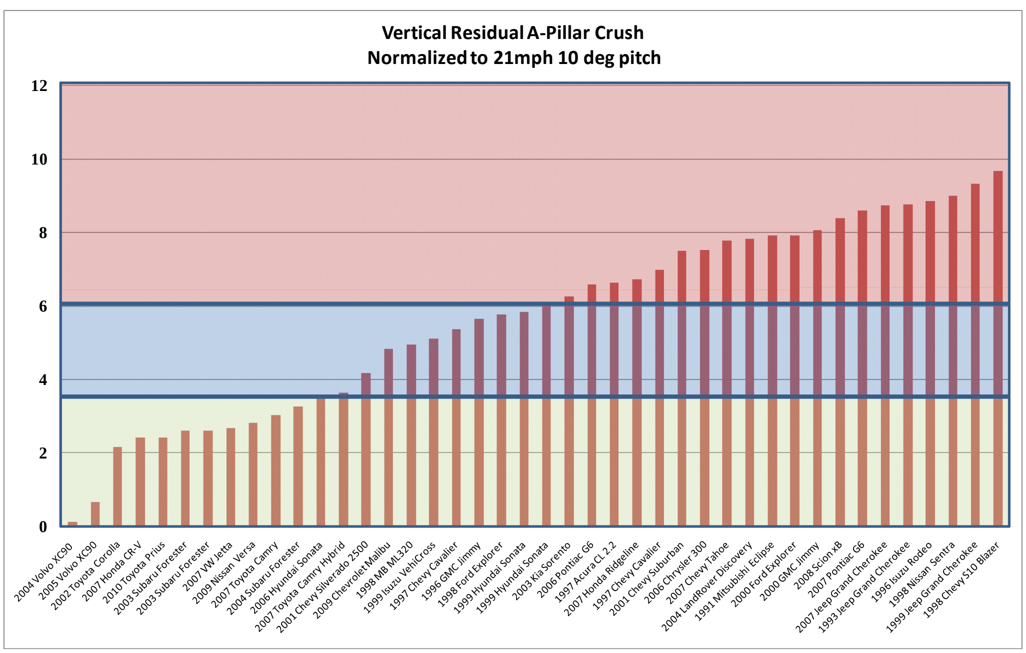

Fig 5. Residual crush normalized to 21 mph and 270° roll rate.

Development of Rollover Injury Risk Based on Vehicle Structural Performance using the AIS Injury Scale

CfIR conducted frontal impact testing on a Hybrid III dummy with a regular and less stiff modified dummy neck. The Injury Assessment Reference Value (IARV) injury criteria were recalibrated relative to the production neck. In tests with either neck, there was no correlation between injury risk, described by residual crush, and injury measures, described by IARV. The only consensus injury measures were roof crush and CfIR conducted rollover tests with a Hybrid III dummy and the

Injury Assessment Reference Value (IARV) criteria (for human injury) and found IARVunder estimated by half the structural injury risk described by residual crush, The only human consensus injury measures were head speed and displacement developed by McElhaney and mapped to the Abreviated Injury Scale (AIS)[10]. These dummy head integration injury measures correspond very well to Structural Injury risk. The level of injury sustained for each level of the AIS scale is shown in the red outlined text box in **Figure 6** plotted on the scale of dynamic head (or crush) speed and displacement. AIS 0-2, shown in the green area, at levels of displacement less than 6 inches and speeds of less than 8 mph produce little or no injury. Results in the AIS 0-2 range, in rollovers with forward pitch, are what vehicle manufacturers and ROPS designers alike, should strive to achieve.

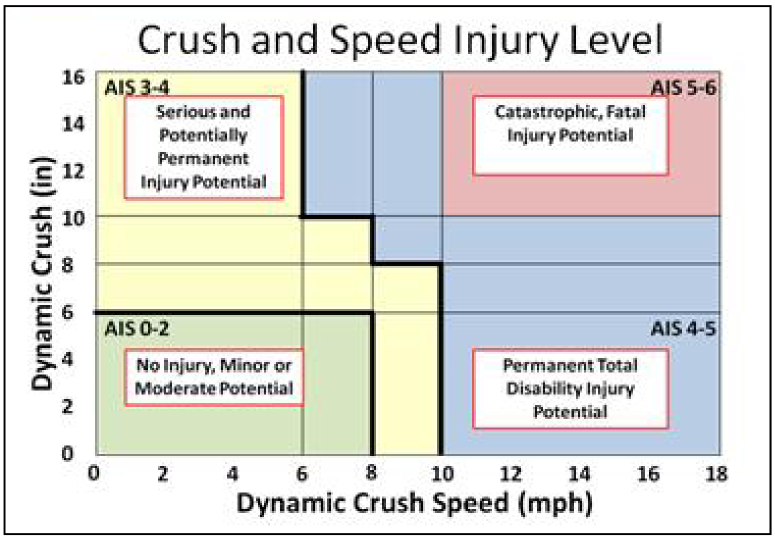

Fig 6. Consensus injury criteria map of dynamic crush and crush speed injury risk criteria.

Methods of Rollover Testing Reviewed

Rollovers are often thought of as chaotic events. Evaluating rollover protection by dynamic tests involves characterizing real world rollovers into types. There are primarily 4 different types of rollovers including as shown in **Figure 7** [11]:

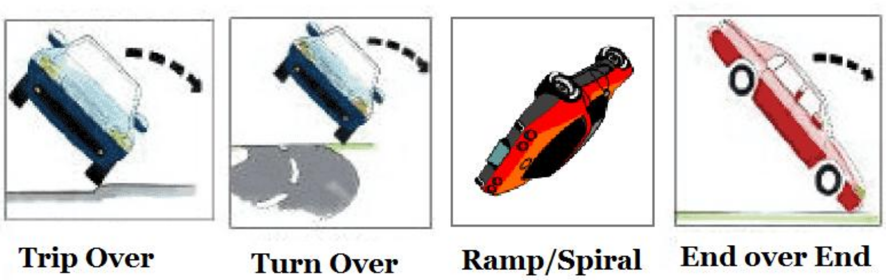

Fig 7. Types of rollovers.

1. Lateral rollovers (Trip-Over and Bounce-Over) account for about 60% of the total
2. Fall-Over and Turn-Over (Non-Trip) account for about 26%
3. Ramp or spiral rollovers (Flip-Over) account for about 8%
4. End over end rollovers are less than 1%

It's also necessary to understand the number of rollovers in each category may be misleading without considering the frequency of fatalities and the position in the vehicle at which the fatalities occurs. For instance in evaluating the NASS files for rollover characteristics, there was correlation with about five degrees of pitch. However when sorting the files into those with AIS three or greater injuries it was found that more than 80% of those vehicles correlated with more than 10° of pitch [12]. Furthermore almost all these AIS 3+ occupant injuries occurred to the front seat driver and passenger as a function of residual crush measured primarily at the A- pillar where the structure is weakest. **Figure 8** shows the number of AIS injuries per body part taken from the NASS database and weighted by Viano et al [11].

ROLLOVER	Injury	Head	Face	Neck	Thorax	Abdomen	Spine	UX	LX	total
Belted	AIS 1	269,700	451,629	33,296	197,340	52,953	336,576	796,258	494,586	2,674,230
	AIS 2	52,083	15,483	51	19,374	16,466	17,547	46,852	33,941	201,844
	AIS 3-6	28,545	1,026	85	27,873	3,884	8,741	13,983	6,154	90,913
	AIS 9	1,115	0	235	1,688	899	0	0	0	3,937
Subtotal		**351,443**	**468,138**	**33,667**	**246,275**	**74,202**	**362,864**	**857,093**	**534,681**	**2,970,924**
Not belted	AIS 1	106,209	289,260	7,420	63,206	38,864	74,118	228,014	185,380	1,020,473
	AIS 2	42,183	20,705	16	5,291	4,649	21,917	23,160	25,342	143,315
	AIS 3-6	26,418	2,186	338	17,844	5,072	6,902	4,891	13,708	77,780
	AIS 9	2,097	51	0	1,341	140	0	57	301	3,988
Subtotal		**176,907**	**312,203**	**7,774**	**87,682**	**48,726**	**102,937**	**256,122**	**224,731**	**1,245,556**
RISKS										
Belted		9.6%	0.2%	0.3%	12.4%	6.8%	2.5%	1.7%	1.2%	3.3%
Not belted		19.9%	0.8%	4.4%	22.0%	11.5%	8.5%	2.1%	6.9%	7.1%
% Diff		**-52.0%**	**-69.8%**	**-94.2%**	**-43.8%**	**-40.8%**	**-70.3%**	**-17.8%**	**-82.2%**	**-53.6%**

Fig 8. Weighted 1993-2000 NASS Injuries by Impact Type, Body Region, Severity and Belt Usage.

Ramp rollovers can be simulated using a ramp rollover test devise. Many testing facilities conduct these types of tests. This type of rollover test can be useful in determining roof strength for rollovers with less than one full revolution. Generally the vehicle being tested does not have the roll momentum to complete more than one revolution. Additionally, the launch off the ramp can produce different roll rates and drop profiles depending on the launch speed. A typical set up is shown in **Figure 9**.

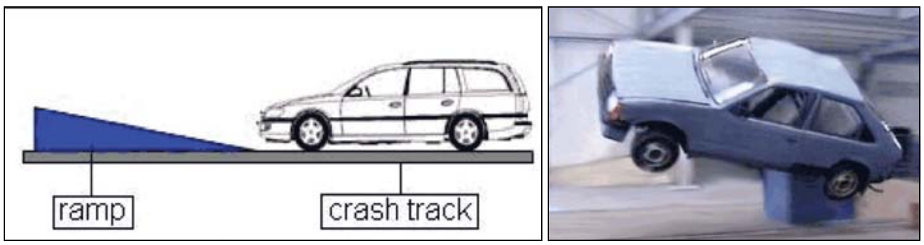

Fig 9. Ramp rollover basic test configuration.

In 2012, two ramp rollover tests were conducted on identical Toyota Hilux pick up trucks and one was fitted with an internal ROPS device [13]. The results showed that the internal ROPS did not protect at the A-Pillar and windshield header any better than the vehicle without the ROPS installed. This test represents only 8% of the real world rollovers as opposed to testing on a lateral fixture which represents more than half of all rollovers crashes. Unfortunately, the injury measures if taken were not reported, but visual inspection would suggest that there was at least 6 inches of dynamic crush and significant post crash negative head room over the front seat occupants meaning catostrophiic injury and fatality probability is high. Post test photos are shown in **Figure 10**.

Fig 10. Ramp Rollover testing with and without an internal 4 posted ROPS device.

A comparison of the internal post crash photo of the tested ROPS Hilux and a real world rollover shows that the deformation pattern is very similar, with most of the crush at the A-Pillar and windshield header as shown in **Figure 11**.

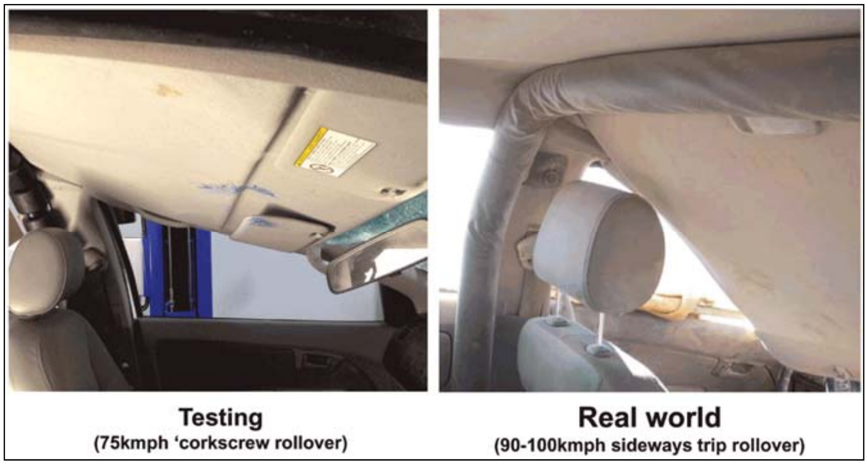

Fig 11. Comparison of the internal post crash photo of the tested ROPS Hilux and a real world rollover.

Flip over or lateral rollovers can be simulated using the dolly rollover system where a vehicle is mounted on a sled at 23 degrees, which is propelled down a test track at 48.3 kilometers per hour and then stopped abruptly to launch the vehicle off the dolly as shown in **Figure 12**. General Motors made significant use of this type of testing in the 1980's but moved to the ramp system due to the loss of control of the vehicle once launched off the dolly. There is not a way to isolate the impacts in this type of testing and therefore results can be muddled or difficult to determine at which point in the rollover what events occurred.

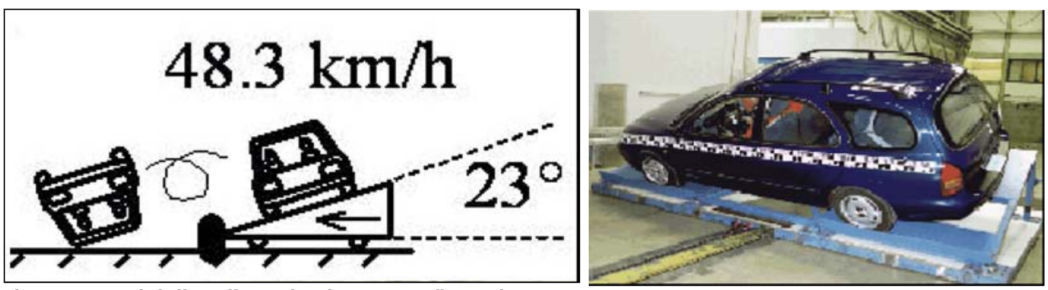

Fig 12. Lateral dolly rollover basic test configuration.

Flip over or lateral rollovers can be better simulated using the JRS at Crash Lab in Australia and the Center for Injury in California or the DROTS system (JRS based) that resides at the University of Virginia in the United States shown in **Figure 13**. Testing a vehicle on this type of device allows for multiple input parameters, including roll rate, pitch angle, and drop height to name a few. Additionally, the impact damage is isolated to one single impact that can be instrumented, reviewed and analyzed. Researchers using this type of device can fully examine the effects of forward pitch by raising or lowering the angle during the test. Additionally, side curtain airbags and seat belt pretentioners can be fired at different angles to examine deploy timing and duration of inflation and simultaneous firing of the pretentioners.

Fig 13. Lateral dynamic JRS rollover test devices in California, Austrailia and the Commonwealth of Virginia.

Types of Rollover Occupant Protection Systems Reviewed

There are a number of ROPS available in the marketplace today. There are internal ROPS which were described earlier in this paper and then there are the newer ROPS, mostly external to the vehicle, which have been developed in the last 10 years. One of the newer ROPS called the Swan was developed by DV Experts out of Australia. The Swan was designed to fit into the bed of a truck and reach out over the cabin to protect it in a rollover. The Swan was tested by being dropped off the back of an 18 wheel truck at speed and then examined to determine the amount of crush. The Swan did limit any deformation to the cabin of the truck as shown in **Figure 14**. This type of ROPS is designed to provide a rigid structure or barrier between the ground and the vehicle roof. The drawback to this design is that its ability to absorb the vehicle to ground forces is minimal given the rigid and square design.This type of ROPS is designed to avoid the vehicle to ground forces, never allowing the underlying vehicle roof to touch the ground. This is an effective way to minimize occupant injury. The down side to the Swan is two fold, first, it only fits on trucks and will not work for SUV's and its bulk and weight. It's quite heavy and significantly sized in both width and height, which may limit both payload capacity and fuel economy [14].

Fig 14. DV Experts Swan ROPS Testing.

A "skeletal" ROPS called Roll Over Protection Rack was developed by Safety Devices in the United Kingdom and is a metal web, if you will, surrounding the outside of the vehicle as shown in **Figure 15**. This type of ROPS is designed to protect at the A-Pillar with the front bars that are mounted through the hood of the vehicle. There is a roll bar internal component to this devise as well and reinforcement structures across the vehicle. However, this device was not tested on a test rig, but was certified based on Finite Element Analysis. A photo of a real world truck rollover with this device is shown in **Figure 16**. Although the occupant was ejected and not injuried, the A-Pillar and windshield header does sustain deformation [15].

Fig 15. Safety Device's Roll Over Protection Rack.


Fig 16. Real World rollover of vehicle with Safety Device ROPS.

The geometric ROPS called the HALO is designed to mount of the roof and prevent A-pillar and windsield header collapse. An additional B-Pillar reinforcement was designed to strengthen that pillar, as no internal roll bars are necessary. The HALO was designed to take advantage of the underlying vehicle strength and enhance it by distributing the rollover loading across more of the roof structure and not concentrated on the A-Pillar and windshield header in a forward pitch roll. The HALO was tested on the JRS rollover system at the protocol for the most injurious impact mode. A high degree of forward pitch at ten degrees, an 18 mph roadbed speed and 270 degrees per second roll rate. The performace of the HALO in these rollover tests was exemplary as shown in **Figure 17**. There was less than one inch of crush and no window breakage.

Fig 17. HALO JRS rollover testing, production vehicle on top and HALO equipped vehicle on bottom.

The performace was better than the Volvo XC90, the highest rated production vehicle the Center for Injury Research had ever tested on the JRS. Photos of the HALO can be seen in **Figure 18**. Results of the JRS testing in comparison to the Volvo XC90 are shown in **Figure 19**. The graph of the roof crush at the A-Pillar and road loads are shown in **Figure 20** and can be compared to the Volvo and Tahoe charts shown below in **Figure 22**. The HALO was also testing in a dolly rollover at 42 mph, launched on to asphalt and then into the dirt and grass. The results of this test showed that the roof was minimully deformed as shown in **Figure 21**. The geometry effects are illustrated in Figure 22 where the blue line is measuring the roof to ground forces in the JRS rollover test [16]. Good performance is a minimized major radius and strong A-Pillar and header which keep the blue line low and even, indicating a smooth roll from one A-Pillar, across the windshield header, and on to the opposite side A-Pillar.

Fig 18. Photos of HALO on Toyota Prado and Mitsubishi L200 truck.

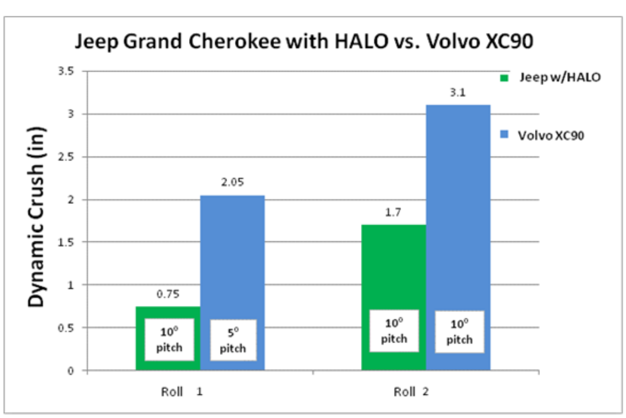

Fig 19. Jeep with HALO vs. Volvo XC90.

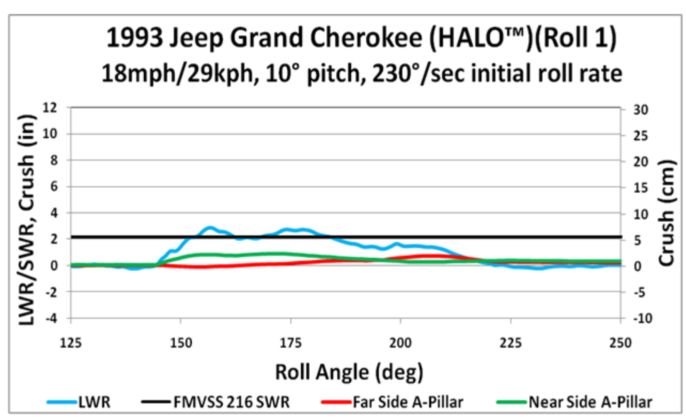

Fig 20. Road loads in blue and A-Pilllars in red and green.

Fig 21. HALO ROPS dolly Rollover testing.

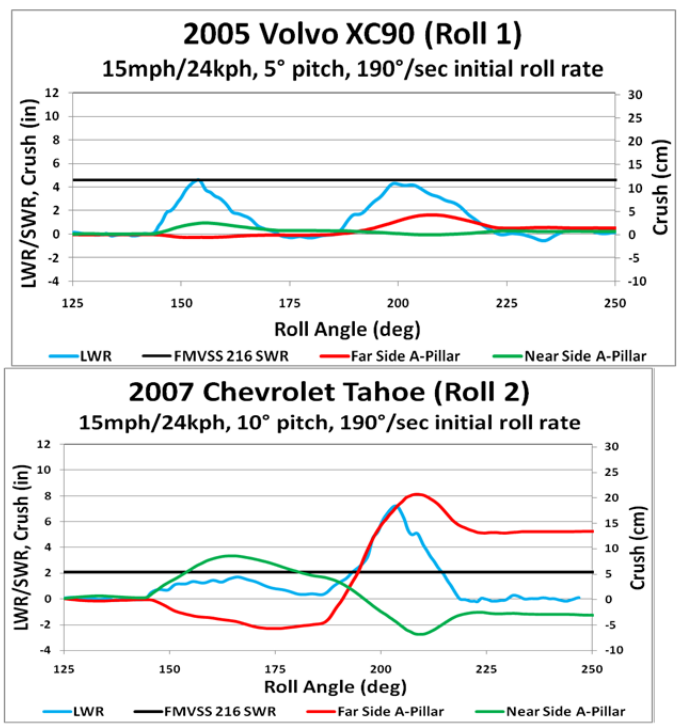

Fig 22. Comparison of Road Loads in JRS testing with a strong (Volvo XC90) and weak roof (Tahoe) vehcile.

Conclusion

Safety is only one consideration in the choice of a work truck and usually secondary to some combination of durability, cost, availability, reputation, service and other factors. However, safety should not be sacrificed to the level that the occupant is not being protected in a foreseeable rollover circumstance. There is a potential misunderstanding of the NCAP rollover rating which is a static stability factor and not an occupant protection rating in the five star rating systems. A Static Stability Factor tells you how likely the vehicle is to rollover, not what the structure will do upon impact. Relying on the five star rating or giving more considerations to the factors other than safety can potentially be a costly mistake. The point is a vehicle may have a 5 star rollover rating, but that doesn't mean it won't collapse in a rollover event.

The key to rollover protection for front seat occupants is for the vehicle to have strong A- pillars and front header which are intended to preclude structural failure. Also, good vehicle geometry, which minimizes the major radius (like the XC 90) is an important factor that can help choose between vehicle A or B. Finally, an attachment which limits or distributes ground contact loading of the A- pillar when rolling with forward pitch can significantly reduce the likelihood of catastrophic or fatal injury. Testing vehicles with dynamic test devices is far superior to any static test. Dynamic testing allows for test protocols with real world derived circumstances to best simulate how a vehicles structure will perform. Three dynamic test methods were discussed and each has different benefits for testing, but the JRS was found to be the most real world and versatile machine today. In addition to internal ROPS, three types of primarily external ROPS were discussed and each protects the front seat occupants by supporting the A-Pillar and windshield header in different ways.

Acknowledgements

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