Reliability and relevance of rollover occupant injury potential tests

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Abstract - From as early as 1965, US auto manufacturers have been researching means to reduce rollover injuries and fatalities. Dynamic rulemaking in 1970 was rejected by industry and in 1973 the Department of Transportation issued a static roof crush test rule proposed by the industry. That rule stood for 35 years until 2009 when the strength requirement was doubled and research was initiated into dynamic rollover means of testing. This paper reviews the literature, examines and compares the frequency and injury potential of rollover accident modes. Two modes are represented in test methodology by the lateral roll over (corresponding to trip-overs) and the ramp (or corkscrew) roll over (corresponding to flip-overs). The energy and impact orientation of the typical ramp rollover tests are dramatically more violent and not comparable to the results of lateral tests conducted with a real-world protocol representing 95% of serious injury rollovers.

Keywords: trip-over, flip-over, virtual testing, Jordan Rollover System, ramp rollover testing, dynamic rollover testing

INTRODUCTION

Since about 1980, researchers worldwide have been studying how to best assess occupant injury potential in the rollover crash mode. In the early 1980's, General Motors conducted the now famed "Malibu Dolly Rollover Tests" which was a significant study into injury potential with both belted and unbelted occupants as well as production and roll caged vehicles. In the next two decades a myriad of dynamic testing methods were used by Governments, OEM's and researchers. In the US, rollovers accounted for only 3% of the crash modes types, but generated 33% of the fatal occupant injuries. Due to this alarming statistic, many dynamic tests were investigated and compared to try to better predict occupant injury, including the J996 Inverted Vehicle Drop test, the Dolly Rollover test, the ramp rollover test, the Controlled Rollover Impact System test (CRIS) and the Jordan Rollover Test (JRS).

At the same time, in order to develop countermeasures to arrest the increasing injury rate, accident statistics in the U.S. and Germany were analyzed and identified more than eight rollover modes characterized by roll initiation such as trip-over, flip-over, end-over, etc [1-2]. The trip-over mode accounted for 60% and flip-over at 12% of the total rollovers included in the data.

The industry countermeasure of choice was the window curtain airbags which were incorporated voluntarily by manufacturers. The algorithms developed to sense the onset of a rollover do not readily accommodate the yaw motion of a pre-trip near side occupant towards the near side window. To demonstrate the effectiveness of the sensor algorithms and window curtain airbags, manufacturers have chosen the flip-over (ramp rollover) test which allows sensors time to activate pre-tensioners and airbags, even though flip-over represents only 12% of the vehicles in the real world rollover data.

A description and discussion of each of these tests is given in the methods section. That section also describes the real world structural injury risk criteria and the corresponding dummy injury criteria which should match. The effect of the test protocol's orientation, severity and loading are also discussed [3].

REAL WORLD ACCIDENT ANALYSIS

There are primarily 4 different types of rollovers including as shown in Figure 1 [4]:

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%

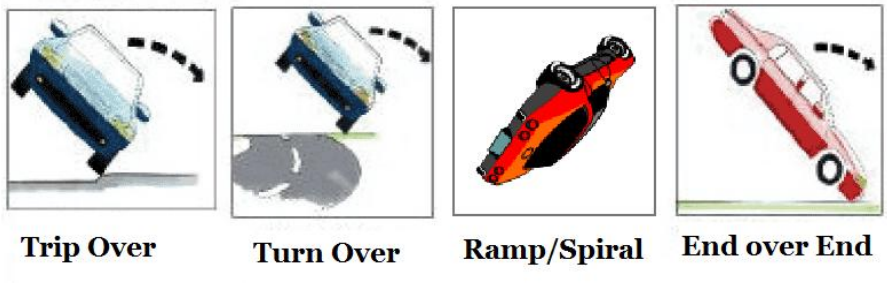

Figure 1. Types of rollovers.

The description and frequency of rollover types is shown in Figure 2 from reference 2 in order of frequency as follows:

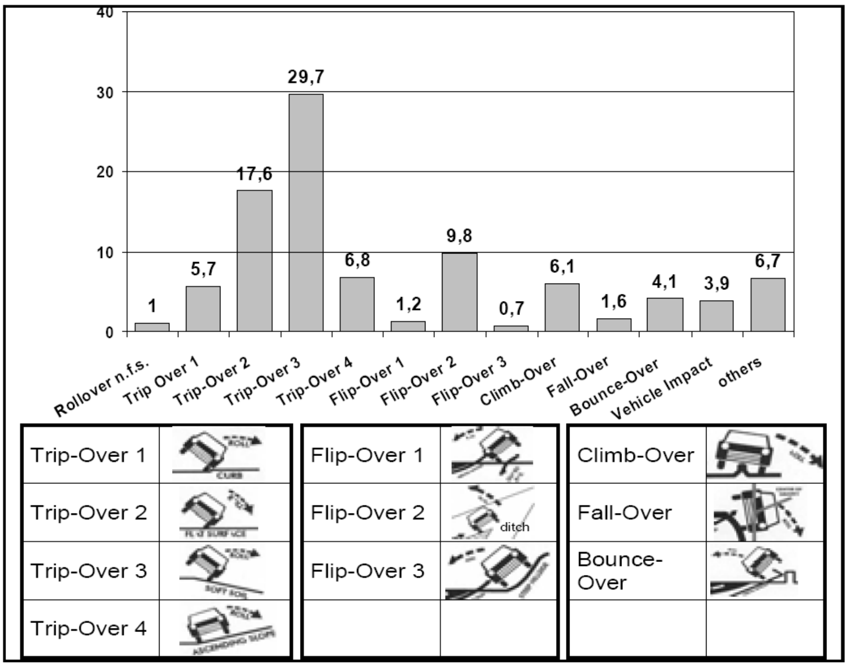

Figure 2. Frequencies of different rollover types

Table 1. Definitions of Trip-Overs

The four trip-overs constituting 59.8% of rollovers are characterized in tests as “lateral” rollovers such as dolly rollovers or JRS rollovers.	
Trip-Over 1:	Curb
Trip-Over 2:	The vehicle skids sideways on a flat surface and topples over.
Trip-Over 3:	This is a type of accident where the rollover occurs on a gradient with soft surface and a sideways tilting vehicle.
Trip-Over 4:	Ascending slope

Table 2. Definitions of Flip-Overs

These three flip-overs constituting 11.7% are characterized in tests as “ramp” rollovers.	
Flip-Over 1:	This is where a vehicle moves mainly along the longitudinal axis of the vehicle, reaches a mound, which causes it to rotate around its longitudinal axis, and topples over.
Flip-Over 2:	This is where a vehicle moves mainly along the longitudinal axis of the vehicle, reaches a ditch, which causes it to rotate around its longitudinal axis, and topples over.
Flip-Over 3:	This is where a vehicle falls sideways off the road onto a significantly lower terrain.

Table 3. Definitions of Other Types of Rollovers

Climb-Over:	When vehicle climbs up and over a fixed object (e.g. guardrail, barrier) that is high enough to lift the vehicle completely off the ground. The vehicle must roll on the opposite side from which it approached the object.
Fall-Over:	When the surface on which the vehicle is travelling slopes downward in the direction of movement of the vehicle such that the center of gravity (c.g.) becomes outboard of its wheels (the distinction between this code and turn-over is a negative slope).
Bounce-Over:	When a vehicle rebounds off a fixed object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected.
Vehicle Collision:	When an impact with another vehicle causes the rollover. The rollover must be the immediate result of an impact between the vehicles.
	Others of very low frequency

REAL WORLD INJURIES BY ROLLOVER MODE

Figure 3 describes the extent of injuries by rollover mode (from reference 2). The calculation of injury extent expressed as a percentage of the category is shown in Tables 4 to 6.

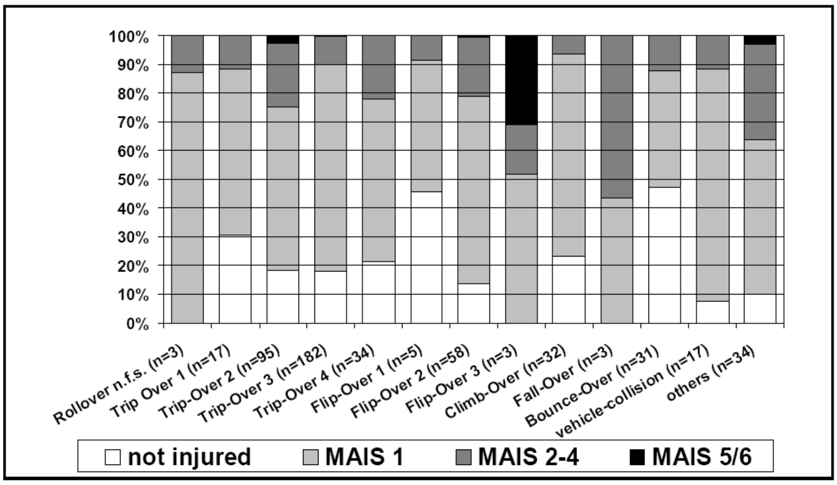

Figure 3. Injury severity grades of belted not ejected occupants for different kinds of rollover

Table 4. Trip-Over (Lateral Rollovers) Frequency/Injury

	Frequency	**Not Injured**	**MAIS 1**	**MAIS 2-4**	**MAIS 5/6**
Trip-Overs 1	5.7	30 / 1.7	58 / 3.3	12 / 0.68	0 / 0
Trip-Overs 2	17.6	19 / 3.3	56 / 9.8	22 / 3.8	3 / 0.53
Trip-Overs 3	29.7	18 / 5.3	72 / 21.4	9 / 2.7	1 / 0.29
Trip-Overs 4	6.8	20 / 1.36	58 / 3.9	22 / 1.5	0 /0
Total lateral rollovers*	59.8	11.66	38.4	8.68	0.82

* product of frequency and injury percentages

Table 5. Flip-Over (Ramp Rollovers) Frequency/Injury

	Frequency	**Not Injured**	**MAIS 1**	**MAIS 2-4**	**MAIS 5/6**
Flip-Overs 1	1.2	45 / 0.54	45 / 0.54	10 / 0.12	0 / 0
Flip-Overs 2	9.8	14 / 1.37	65 / 6.37	21 / 2.05	0 / 0
Flip-Overs 3	0.7	0 / 0	51 / 0.35	18 / 0.12	31 / 0.21
Total ramp rollovers*	11.7	1.91	9.17	2.29	0.21

* product of frequency and injury percentages

The calculation comparing trip-over (lateral) rollovers and flip-over (ramp) rollovers are shown in Table 6.

Table 6. Comparison of Trip-Over and Flip-Over Frequency/Injury

	Frequency	**Not Injured**	**MAIS 1**	**MAIS 2-4**	**MAIS 5/6**
Total Trip-Over Rollovers	59.8	11.66	38.4	8.68	0.82
Total Flip-Over Rollovers	11.7	1.91	9.17	2.29	0.21

The frequency and severity of injury for the two most significant modes relative to each other indicates injuries are approximately proportional to the frequency of occurrence.

We would then expect the results of the tests representing these two categories lateral and ramp to be of the same order, but they are grossly different.

TEST METHODS

Jordan Rollover System (JRS) Tests [Corresponding to Trip-Overs]

The test protocol which represents trip-over accidents is the “lateral” rollover and can be described by the JRS test fixture of Figure 4 [5].

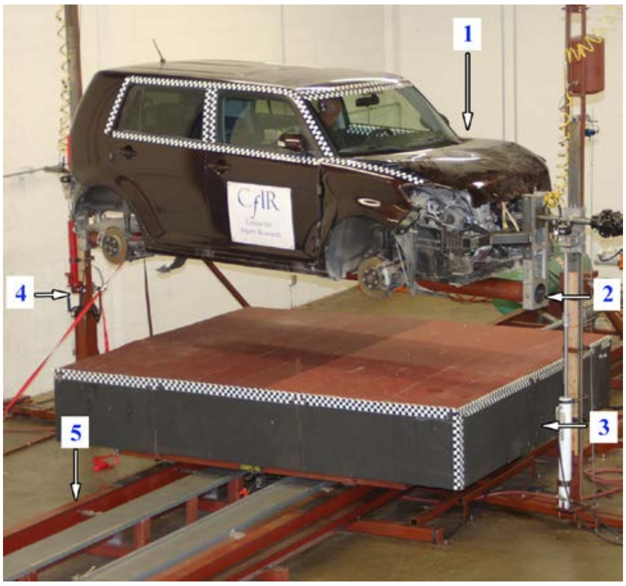

Figure 4. Key components of the JRS: (1) vehicle, (2) cradle/spit mount, (3) moving roadbed, (4) support towers, (5) coupled pneumatic -roadbed propulsion and roll drive

A protocol was developed to represent real world rollovers by considering studies which indicated that 95% of rollovers and 95% serious to fatal injuries occurred within two rolls at a launch velocity at 32mph. Further it was determined from the sequence of vehicle contacts with the ground that the most severe impact to the roof was to the far side of the first roll (of two) at 21 mph and 270 deg/sec as shown in Table 7.

Table 7. List of roll sequence segments and serious-to-fatal injury probability

Segments of the Roll Sequence	Potential for Serious to Fatal Injury
1. Vehicle loss of control	Non injurious
2. Yaw to trip orientation	Occupants move laterally out-of- position
3. Trip	Exacerbates lateral out-of-position
4. Roll rate	Potential for far side injury and ejection
5. Vehicle roof impacts with the road	Severely injurious to head/neck/spine
6. Wheel/underbody contacts	Potential for lower spine injuries
7. Suspension rebound and second roll lofting	Non Injurious
8. Near side roof impact, roll slowing ejection	Potentially injurious
9. Far side impact	Potentially injurious
10. Wheel contact to rest	Non injurious

The residual crush at the far side A-pillar for some 50 vehicles tested is shown in Figure 5. The background for this figure is the NASS/CIREN analysis of the probability of a fatality, head, spinal and spinal cord serious to fatal injury. From this data a vehicle's performance was rated by residual crush as "good" for residual crush of 3 1/2" or less, "acceptable" for residual crush up to 6", "poor" for residual crush up to 11" and "unacceptable" for more than 11".

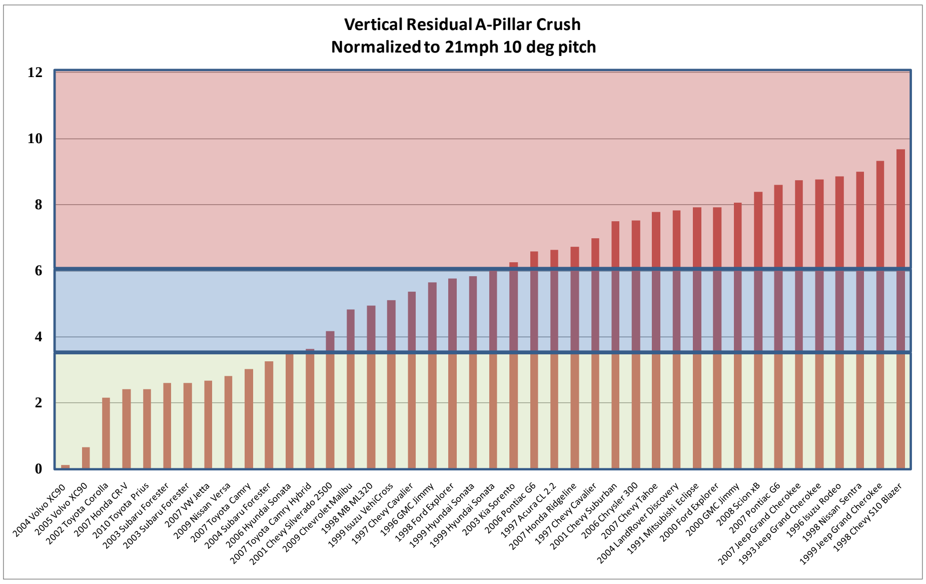

Figure 5. Normalized vertical residual A-pillar crush for various vehicles

Ramp Rollover Tests [Corresponding to Flip-Overs]

The test protocol which represents flip-over accidents is the “ramp” rollover and was described by GM as follows:

A ramp lifts the two right wheels of a speeding vehicle and flips the vehicle over on its top -- it then skids for several feet before being caught in a safety net. The test simulates a "corkscrew" or "ramp" rollover event, an accident that stems from an asymmetric upward force on one side of the vehicle (a "ditch" rollover directs one side of the vehicle downward instead of upward)[6]. See Figure 6.

Figure 6. Ramp Rollover

Manufacturers do not claim the ramp rollover is a structural injury risk or dummy injury measure severity test. The large number of such tests and the confidentiality of impact results have led to the presumption that they are a means of reducing roof crush injuries. A search of recent literature shows detailed physical and simulation ramp test data to the first roof contact with the ground.

The specific characteristics of the ramp (corkscrew) rollover test at 50 mph were studied in 2001 [7]. The ramp portion of an SUV to the near side ground contact were modeled to predict and describe the test in Figures 7 through 10. These inputs were compared to a weak roof SUV test vehicle with good agreement. The inputs were compiled into Table 1 as a sample input to a virtual test model of an SUV previously tested in a lateral rollover. When the inputs were adjusted to characterize the speed of the lateral test the residual roof crush of the far-side A-pillar of both vehicles were then comparable.

Figure 7 shows the roll and pitch velocities, while the pitch and roll angles are shown in Figure 8. Figure 9 shows the vehicle c.g. velocity, and the vehicle c.g. displacement is shown in Figure 10. The test speed in this case was 80 km/h.

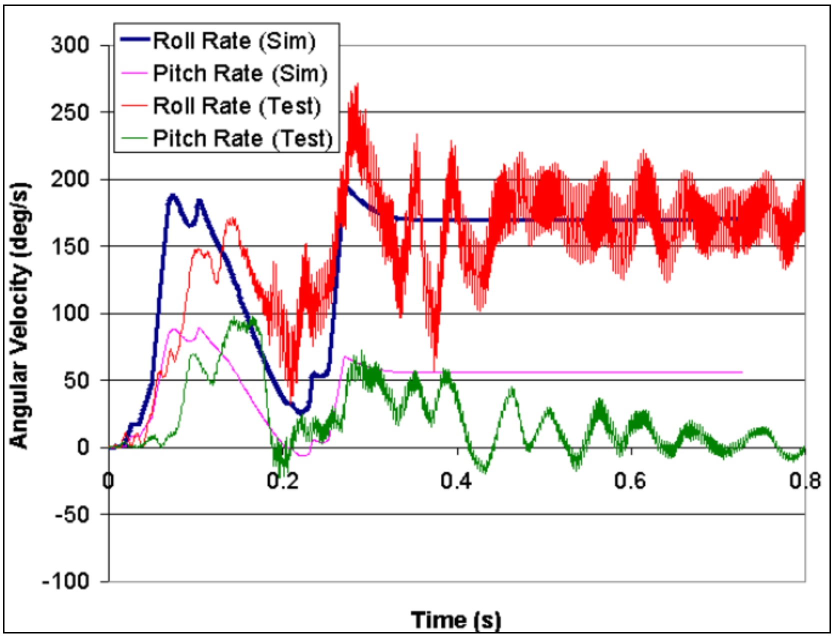

Figure 7. Spreadsheet and Test, Roll and Pitch Velocity - SUV

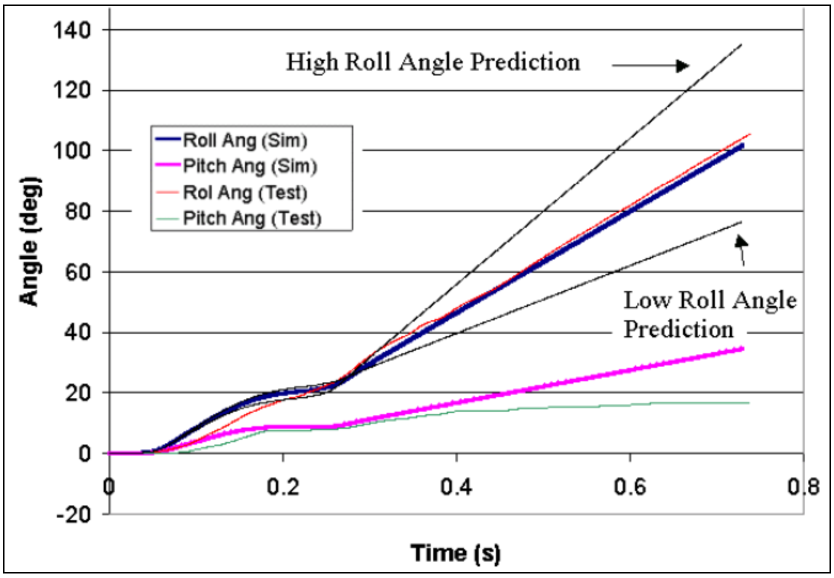

Figure 8. Spreadsheet and Test, Roll and Pitch Angles - SUV

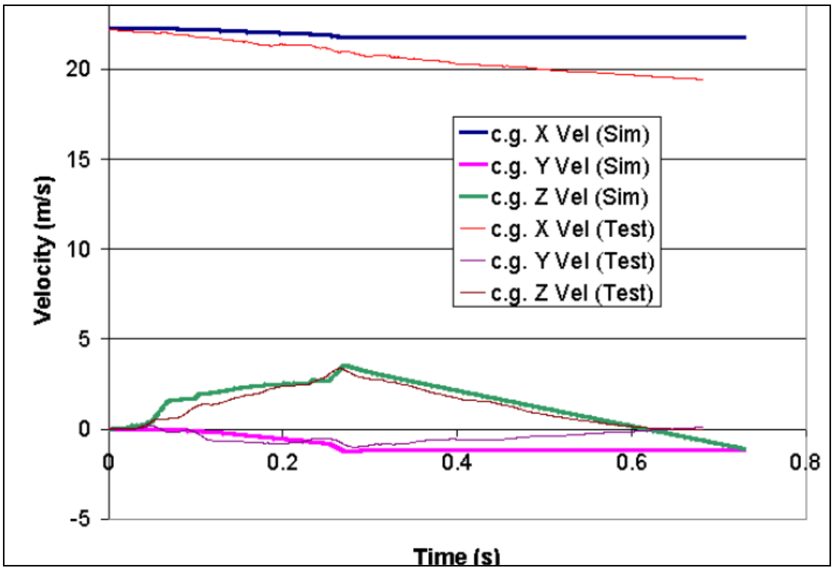

Figure 9. Spreadsheet and Test, Vehicle c.g. Velocity - SUV

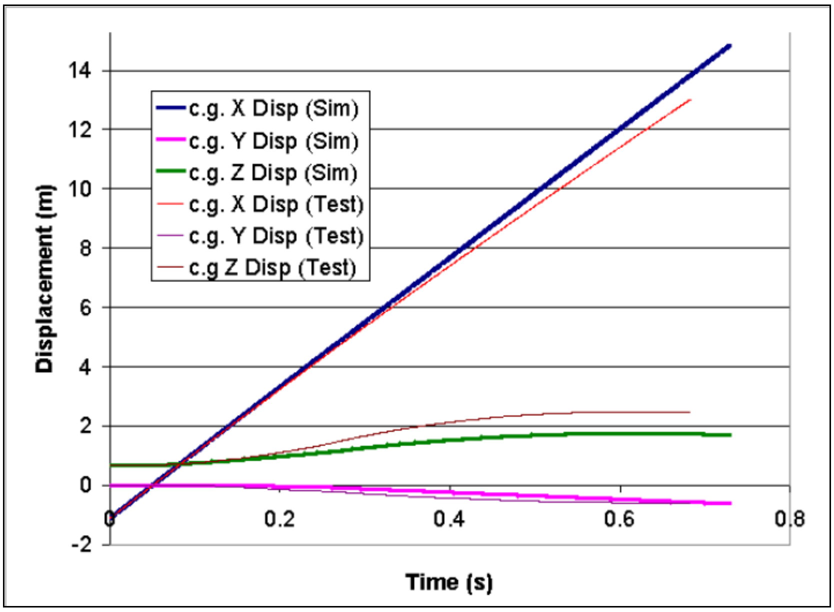

Figure 10. Spreadsheet and Test, Vehicle c.g. Displacement - SUV

Table 8. Composite ramp rollover impact parameters

Roll Rate (Test)	175 deg/sec at near side contact
Pitch Rate (Test)	15 deg/sec, oscillating from 0 front up
Roll Angle (Test)	105 degrees, a little more than 1/4 turn
Pitch Angle (Test)	18 degrees, front up
c.g. X velocity (Test)	19 m/s forward is 44 mph
c.g. Y velocity (Test)	0 m/s vehicle side on ground
c.g. Z velocity (Test)	0 m/s vehicle sliding on its side
c.g. X displacement (Test)	13 meters is 44 feet
c.g. Y displacement (Test)	-1.5 meters of side crush into ground
c.g. Z displacement (Test)	2.5 meters is 8.5 feet lateral displacement

That data for a sport utility vehicle was used to extend the roll angle to identify far side deformation and estimate the residual roof crush.

DISCUSSION

The roof crush severity of the two physical test methods are grossly different as are their typical ground contact orientation characteristics. Given that 8% of 12% of flip-overs are characterized as falling in a ditch is not reasonably represented by a 44 mile-per-hour ramp touchdown speed. The energy disparity in the 20 mph lateral and 44 mph ramp rollover tests is 2.5 times greater in the ramp test. The impact orientation in the ramp test results in mostly rearward deformation of the roof on the nearside while the lateral test deforms the far side roof vertically into the head of that occupant. Virtual testing at similar impact speeds and other modifications indicate about the same residual deformation of the lateral and ramp tests. An important observation is that while a ramp rollover test characterizes the form of a flip-over the speed and violence of the typical test is grossly dissimilar and does not characterize a flip-over accident. To suggest otherwise is misleading and intentionally deceptive.

The real world test protocol for a lateral rollover representing 95% of serious injury rollovers is characterized by a 30 mph launch speed with ground contact at 10 degrees of front down pitch. A typical ramp rollover is launched at 50 mph with ground contact at 15 degrees of front –up (rear down) pitch.

Manufacturers use the ramp rollover test as a method to reduce injury potential by deploying window curtain airbags and don't consider the disparate effect of the launch speed and impact pitch angle. The energy in a 50 mph ramp impact is 2 ½ times greater than in the 30 mph lateral test and the front seat occupants are less likely to be injured or killed by the ramp's front-up pitch roof crush.

Similarly, an internal roll cage at the B and C pillars is unlikely to have any affect on the ramp test's injury potential. Such a comparison when knowingly used to reject internal or any other ROPS at the expense of the injury and lives of employees to save the money is reprehensible [8].

Particularly so because an external or integrated patent based high attenuation load offset (HALO™) rollover occupant protection system (ROPS) has been demonstrated in lateral and dolly rollover tests to reduce the probability of a weak roof fatality from 14% to 4% (and so far completely protected two occupants from injury in a field rollover). Virtual test comparisons of production and HALO™ modified vehicles in ramp tests show similar to lateral results at the same speeds.

DESIGN CONSIDERATIONS FOR REDUCING INJURIES AND FATALITIES

The geometry of the roof has a substantial effect on the roof-to-ground loading [9] and therefore roof crush. Figure 11 shows the typical near- and far-side loading of a Jeep Grand Cherokee with almost 30 cm (12 inches) deformation of the roof. Figure 12 shows the loading and negligible deformation of an identical vehicle with a simple modification (i.e., rounding the roof geometry longitudinally). The vehicle was rolled two more times with no significant additional roof crush. This geometry change was achieved by installing an innovative aftermarket device, the HALO™, used by the Oil Gas and Mining Industry [10]. Further the 1993 Jeep Grand Cherokee and the patented external ROPS had no significant roof crush after a 40 mph, 3-roll rollover test [11,12,13].

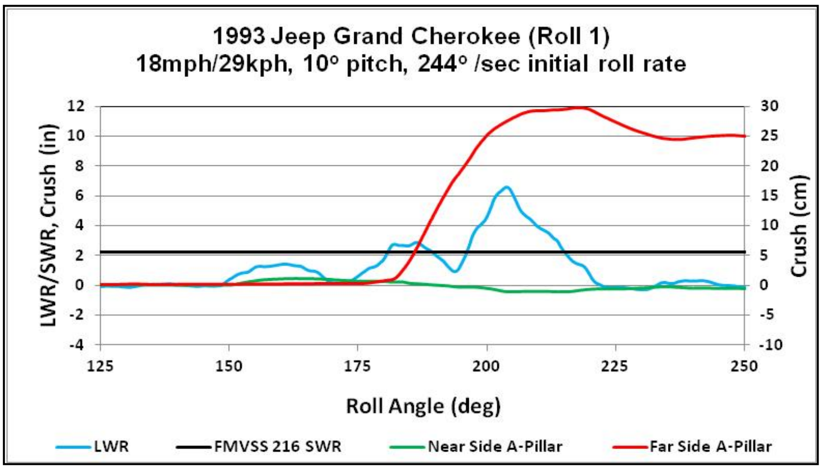

Figure 11. – Production SUV roof crush v. roll angle

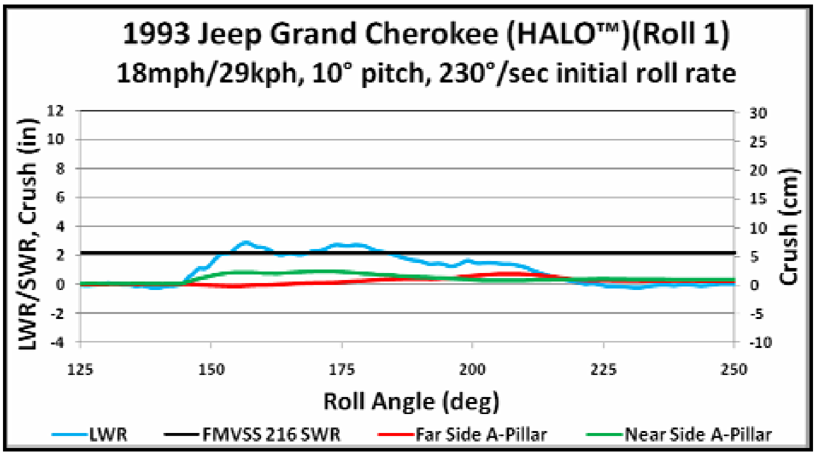

Figure 12. – SUV with HALO™ roof crush v. roll angle

CONCLUSIONS

Trip-over accidents represent 60% of rollovers and flip-overs represent 12%. Trip-overs are characterized by lateral rollover tests and flip-overs are characterized by ramp rollovers. Typical physical ramp rollover tests at 50 mph are 2 ½ times more energetic than 30 mph lateral tests and do not represent flip-over accidents.

Comparative virtual testing between ramp rollover and lateral rollover conditions using a typical SUV, suggest that ramp rollovers are typically more benign than lateral rolls. First roll roof crush was observed to be more significant under lateral roll test conditions compared with ramp rollover tests. Also the roof crush in ramp rollover conditions tends to be more significant on the leading impact side and the roll rates at contact with the trailing side are not as high as those observed with lateral roll test conditions. An aftermarket or OEM version of the HALO™ ROPS reduces the fatality rate of weak roofed SUVs from 14% to 4%.

ACKNOWLEDGEMENTS

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