PREDICTING A VEHICLE'S DYNAMIC ROLLOVER INJURY POTENTIAL FROM STATIC MEASUREMENTS

Donald Friedman
Josh A. Jimenez
Jacqueline Paver Ph.D.
Center *f*or Injury Research
United States
Paper Number 13-0107

ABSTRACT

The purpose of this research was to demonstrate a methodology for deriving a real world dynamic rollover injury potential rating system from static measurements. The methodology consists of an evaluation of vehicle strength to weight ratio (SWR), roof structure elasticity from static testing, major radius, minor radius, and major radius extension to predict residual roof crush. In addition to providing a hypothesis for evaluating the vehicles the major radius extension (MRE) will be looked at to provide insight for correcting existing anomalous static SWR measurements. These parameters are important because a 43 nation Global NCAP has been established to rate vehicles in all crash modes. Rollover performance is to be rated by SWR. Global NCAP will be responsible for reducing the 1,200,000 vehicle fatalities per year of which 25% can be rollovers when comparing rollover fatality proportionality to U.S vehicle fatality statistics.

Based on our rollover research of the past 12 years structural and occupant protection countermeasures can be used to significantly counter those fatalities. Disseminating the dynamic injury performance provides a world-wide opportunity to save many tens of thousands of lives annually. Jordan Rollover System (JRS) vehicle rollover dynamic testing apparatus has identified a significant number of vehicles which meet the most rigorous static roof strength criteria, but fail to provide occupant protection from injury risk.

Manufacturers can reduce the injury risk within size class by minimizing geometry effects and the likelihood of a high pitch rollover. While large, tall, heavy vehicles are protective in frontal and side impact accidents they are very high injury risk vehicles in rollovers for the very same reasons. This paper provides a prediction method for assessing dynamic injury probability from static test data and measurements.

INTRODUCTION

The establishment of a Global NCAP community provides an opportunity to help save tens of thousands of lives lost in rollovers worldwide by identifying dynamic rollover injury risk performance rather than statistically-derived static SWR measurements. The JRS research has identified geometric vehicle parameters, which significantly affect dynamic injury risk performance. Similarly consensus dummy injury criteria and measurements can correct the current grossly-understated dummy injury measures which mislead manufacturers as a result of dummy components that are not biofidelic. As a conclusion we are able to identify the significant number of vehicles which meet the most rigorous static roof strength criteria, but fail to protect human occupants. Figure 1 identifies the worldwide distribution of the 1.2 million people who die every year in vehicle accidents.
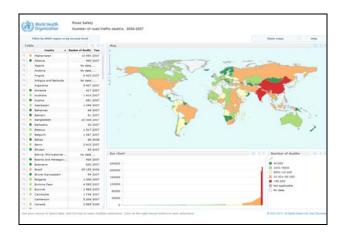

Figure 1. Distribution of Road Safety number of traffic deaths, 2006-2007.

Rollover fatalities and injuries have been a significant problem since identified in the hearings preceding the 1966 Traffic Safety Act. The problem was addressed in two regulatory efforts of the 1970 United States Federal Motor Vehicle Safety System (FMVSS) 208 and 216. FMVSS 208 addressed the ejection problem and FMVSS 216 addressed the roof crush problem. These regulatory efforts were rejected by the auto manufacturers because the production vehicles of the era could not meet the requirements. The auto manufacturers sued the US National Highway and Safety Board to squash FMVSS 208 (and lost in 1974) and offered a test variation for FMVSS 216 justified by geometric considerations which reduced the performance criteria by a factor of two, such that 1970 era vehicles could pass the test. The internal industry research

that thwarted the change in these standards for 39 years has been documented [1-11].

Then in 2005 through 2008 the JRS was developed shown in Figure 2. Results of JRS testing revealed the misconceptions as well as roof strength solutions that were available to avoid window breaking and ejection portal creation [12].
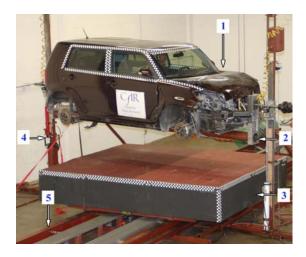

Figure 2. Key Components of the JRS: (1) Vehicle, (2) Cradle/Spit Mount, (3) Moving Roadbed, (4) Support Towers, (5) Coupled Pneumatic Roadbed Propulsion and Roll Drive.

Then in 2008 IIHS released a study which supported the JRS dynamic test results. IIHS found that incapacitating and fatal injury rates could be reduced by half if roof strength was doubled as shown in the composite IIHS and C*f*IR chart of Figure 3[13].
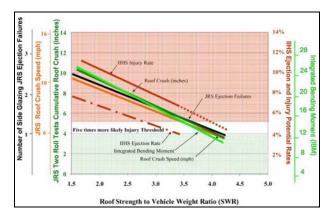

Figure 3 . CFIR and IIHS composite chart.

In 2009 NHTSA issued a final rule that required a two-sided static test with a minimum SWR requirement of 3 [14]. In 2010 IIHS established a three tiered static SWR level of good, acceptable and poor performance by SWR

(SWR=2.5 is poor, SWR =3.25 is acceptable, SWR= 4 is good [15]. CfIR attempted to validate IIHS criteria (using JRS dynamic test data) by an injury risk criteria and analysis. Data was collected with the JRS of Figure 3. The JRS found IIHS to be mostly valid with serious exceptions that produced large amounts of roof crush such as the 2008 Scion xB with an SWR of 6.7 and the 2010 Ford F150 Supercab with an SWR 4.7. The Scion xB had a residual roof crush of 11" and the Ford F150 Supercab had a residual crush of 4.6". These vehicles had severe dummy neck injury measures relative to consensus injury criteria. The only consensus injury measures were roof crush and roof crush speed based on criteria developed by McElhaney [16]. The map of the injury measures submitted to NHTSA in 2008 is shown in Figure 4.
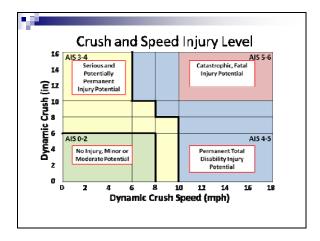

Figure 4 . Consensus injury criteria map of dynamic crush injury risk criteria

Published analyses of more than 50 comparable dynamic JRS rollover tests shown in Figure 5 has identified the major sources of increased injury and fatality risk in rollovers as measured by residual roof crush and correlated to consensus momentum exchange dummy injury measures [17]. In 2009, a statistical analysis of NASS and CIREN files evaluated to provide a probability of a rollover fatality by providing a rating of good, acceptable, and poor for 3 bands of roof crush as discussed in a companion paper [18]. This shows increasing probability of fatality with increasing vehicle residual crush. Figure 5 is a chart showing injury potential relative to roof crush. The chart is normalized to the 1st roll of a 2 Roll rollover representing 95% of all rollovers and AIS 3+ rollovers.
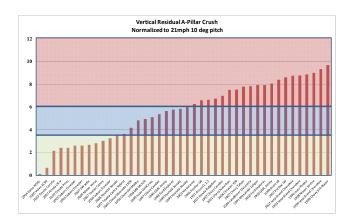
Figure 5. Residual crush on normalized test with named vehicles.

Figure 6 shows the 9 vehicles which were chosen for predicting dynamic performance. The Volvo XC90 is the best performing vehicle in a rollover and the Ford F150 is the worst performing vehicle when basing injury risk on residual roof crush.
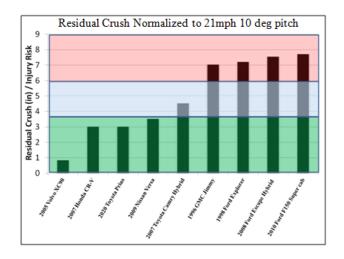

Figure 6. Nine vehicles shown on the normalized chart.

Above data (Figure 6) is taken after a 1 Roll using the first Roll in a 2 test protocol. The vehicles were normalized to extrapolate a 2 roll condition which is representative of real world crashes found in NASS, CIREN. Static measurements were taken before and after the first roll.

STATIC TEST METHODS

The basis for the predicted dynamic injury risk calculations should be with a common static test. The static test would measure the SWR as specified in the single sided FMVSS 216 test as shown in Figure 7. Roll 1 of the 2 Roll dynamic test protocol resembles the FMVSS 216B test the best.
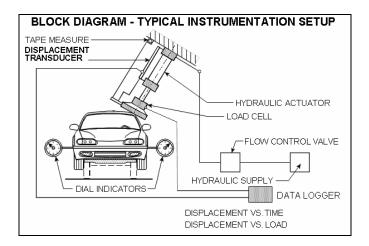

Figure 7. FMVSS 216 Quasi-Static Test Apparatus

Measuring SWR

The platens for the FMVSS 216 Machine should be at least 18 by 24 inches, set to 5 degrees of pitch and 25 degrees of roll. When measuring load and displacement the speed of the hydraulic ram in this quasi-static test is limited to 13 mm/sec until the displacement of the ram reaches 127 mm from initial contact with the roof. SWR is the maximum force in the system divided by vehicle curb weight for heaviest trim level within the model line.

Measuring Elasticity

A second measurement would be added to the existing FMVSS 216 test criteria by measuring load and displacement (using the 13mm/sec speed) as the ram reverses direction until the load reading approached some number close to zero. This displacement value would then represent the elasticity of the roof structure.

ELASTICITY

The injury risk of residual crush was based on NASS investigations of 1993 to 2006 vehicles such that residual crush and elasticity were characterized for a vehicle fleet population of the late 90's. The SWR of production vehicles improved after 2005 by the substitution or addition of high strength steel in the roof structure. Late model vehicles are deforming less and as a result the materials with the same characteristics are providing less residual crush as a result of increased column profiles.

Since injury risk is related to residual crush, an elasticity correction is necessary. The NASS-CIREN files (Mandel probability of injury charts) are based on fleet average vehicles of the 90's with SWR's of about two and an elasticity of about 30%. Post 2005 vehicles have SWR's greater than four and an elasticity of 60% as shown in Table

1. Elasticity is a function of roof structure elements being less deformed as a result of a stronger roof structure. This does not mean necessarily that materials are vastly

GEOMETRIC EVALUATION

There are 2 important geometric measurements – major radius and minor radius. From the two measurements major radius extension (MRE) can be calculated to predict residual roof crush.

Below is the list of vehicles used for evaluating the affect MRE can have on residual roof crush.

Table 1.
Major Radius Extension for Large Roof Widths

VEHICLE TYPE	SWR	MAJOR RADIUS	MAJOR RADIUS EXTENSION	ELASTICITY (%)	RESIDUAL
1998 Ford Explorer	1.6	45.3	5.03	38.6	4.3
2005 Volvo XC90	4.6	42.6	0.53	70.6	0.5
2010 Ford F150 Supercab	4.7	50.3	5.98	31.3	4.6
2007 Toyota Camry Hybrid	4.3	42.7	7.47	46.0	2.7
2008 Ford Escape Hybrid	2.6	44.3	2.83	44.4	4.5
2009 Nissan Versa	3.7	43.7	6.89	56.3	2.1
2010 Toyota Prius	4.2	39.9	3.7	59.1	1.8
1996 GMC Jimmy	1.6	43.3	3.63	33.3	4.2
2007 Honda CR-V	2.6	42.1	2.43	47.1	1.8

The major radius (MR) is the distance from the vehicle's longitudinal center of mass to the intersection of the header, roof rail and A- pillar. Minor radius is measured from the C.G height of the vehicle to the top of the roof.

The major radius is always larger than the minor radius and therefore the difference between the two radii is the major

radius extension (MRE). MRE is a characteristic that is typical of larger roof vehicles. While Major Radius Extension can be associated with large roof width as shown in Figure 8, MRE is not always associated with large vehicles.
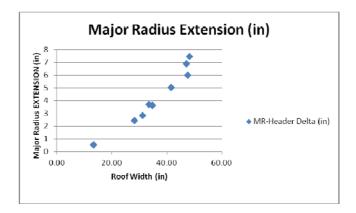

Figure 8. Major Radius Extension for Large Roof Widths.

The 2005 Volvo XC90 (lower left hand corner of the plot) is a large vehicle with a curb weight of 4,500 pounds (close to that of a same year Chevy Suburban) performs extremely well in a rollover and has the smallest Major Radius Extension in comparison to the other vehicles in this evaluation.

Loading force on the far side roof structure is proportional to MRE. MRE's that are large in relation to small MRE vehicles produce large forces on the roof as the vehicle rolls from the near side A-Pillar to the far side A-Pillar. This is caused by the roof structure having to lift the C.G up a distance Δh over the same time interval when comparing vehicles at same tangential velocities. Δh is equal to the Major Radius Extension. See Figure 9.
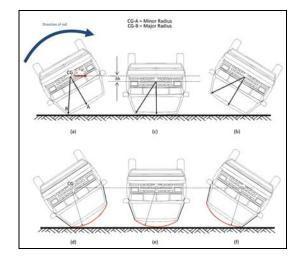

Figure 9 . Major Radius Extension relative to Minor Radius.

RESIDUAL ROOF CRUSH

This section provides a means for predicting residual roof crush in high SWR / high residual roof crush anomalous vehicles using both static test measurements and geometric considerations. The F-150 vehicle (upper right hand corner) in Figure 10 is an anomalous vehicle that has performed well in static testing, given their SWR values, but has performed poorly in a dynamic environment.

The paper that accompanies this is *Correlating Human and Flexible Dummy Head-Neck Injury Performances*. In this paper a 3 tier injury risk is developed for vehicle residual crush in bands (in inches) of 0 to 3½, 3½ to 6, and 6 and above. Correspondingly the rating in order would be good, acceptable and poor. The acceptable probability is roughly 30% greater than good and the probability of poor is 2.5 times greater than acceptable.

For vehicles that are anomalous like the 2010 Ford F150 Supercab that is shown in the upper right hand corner of Figure 10 a correlation value can be provided to account for high residual roof crush in a high SWR vehicle.
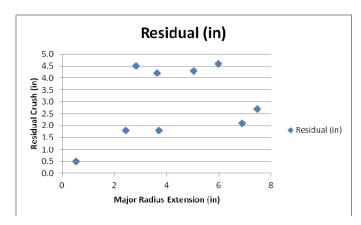

Figure 10. Residual Crush as a function of MRE.

The vehicles in Figure 10 that have a residual crush value of 4 inches or greater are either vehicles with small SWR values or vehicles with a large major radius extension.

ROLLOVER INJURY RISK

The benefit of reducing the Major Radius Extension, while maintaining the OEM Major Radius can be shown in the prototype of an alternate design as seen Figure 11.

Figure 11. Minimal Residual Crush with Zero Major Radius Extension.

The 2005 Volvo XC90, 2010 Ford F150 Supercab, and 1996 GMC Jimmy were used to develop 3 values that would correlate SWR, MRE, and Elasticity to acquire residual roof crush. The XC90 and F150 have large SWR (which corresponds to Good) values but different residual roof crush values. The 1996 GMC Jimmy has a Poor SWR value and Poor residual crush value. The equation

$$C_1 \, x(SWR) + C_2 \, x(MRE) + C_3 \, x(Elasticity) = Residual$$

was solved for the 3 correlation values. The value C_1 corresponds to the multiplier value of -0.65 in/lbs, C_2 equals 1.06 in, and C_3 equals 0.04 in/%.

RESULTS

Further investigation in the future could provide for an accurate correlation for all vehicles in the fleet using static testing and geometric measurements to identify vehicles with high SWR's that will perform poorly in a dynamic environment.

These values can be inserted into the equation to achieve residual crush values to within 2 decimal places for the 3 vehicles

Although the biomechanical community is fixed on its IARV criteria, our investigation indicates that the origin of those criteria was based on young military volunteers of the 1960's whose neck muscle strength in bending is 10 times that of the middle aged typical accident victim. JRS dynamic test results using IARV criteria and existing static testing injury risk criteria did not correlate very well. On the other hand there has been consensus on biomechanical head impact speed (which is independent of musculature and based on PMHS testing) that leads to neck and head injury [19-20]. Two injury measurements were derived.

The bending criteria, integrated bending moment (IBM) from lower neck My and Mx momentum exchange and the integration of the resultant head acceleration to measure head impact speed and displacement. Figure 12 illustrates the percent of criteria correlation of the injury risk parameters, IARV and head injury measurements of the 2010 Ford F-150 [21]. Clearly IARV underestimates the injury potential.
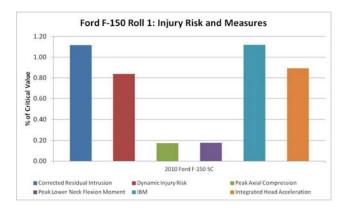

Figure 12. Injury Risk and Measures for Ford F-150.

The probability and odds ratio of a fatality, head, spinal and spinal cord injuries can be determined for each vehicle. Comparative ratings in a three tiered hierarchy provide consumers and manufacturers with quantified injury potential performance. Such predictions eliminate the unacceptable performance of many strong roof vehicles rated favorably by static SWR alone such as the F-150.

DISCUSSION AND LIMITATIONS

The original NASS / CIREN injury probability study was based on the fleet population of 1993 to 2006. The moving average vehicle model year is about 10 years older than the average study years. The correlation with residual crush was adjusted by the structural elasticity of new vehicles which has doubled in that time, and by the experimental results and criteria for injury based on dynamic roof crush and speed.

CONCLUSIONS

Accurate predictions of dynamic injury probability can be made from static test data and measurements. While large, tall, heavy vehicles are protective in frontal and side impact accidents they are very high injury risk vehicles in rollovers for the very same reasons. Manufacturers can reduce the injury risk within size class by minimizing the MR, the aspect ratio, other geometry effects and the likelihood of a high pitch rollover.

REFERENCES

[1] Federal Register, "Roof Intrusion Protection for Passenger Cars - Proposed Motor Vehicle Safety Standard 216" Docket No. 2-6; Notice 4, 1-6-1971
[2] Fisher Body Test Report, Body-Static Roof Intrusion Tests - 1970 and 1971 F, H, A, X, and B Styles, March 1971.
[3] GM, Chrysler, AMC and Ford Hearings before the Subcommittee on Executive Reorganization of the Committee on Government Operations United States Senate, 89th Congress, 1st Session, 1965.
[4] The National Archives – Conversation Among President Nixon, Lide Anthony Iacocca, Henry Ford II, and John D. Ehrlichman, April 1971.
[5] Orlowski, K.F., R T Bundorf and E.A. Moffatt, "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics," Society of Automotive Engineers, Paper No. 851734, 1985.
[6] Bahling, G.S., R.T. Bundorf, G.S. Kaspzyk, E.A. Moffatt, K. F. Orlowski and J.E. Stocke, "Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," Society of Automotive Engineers, Paper No. 902314, 1990.
[7] Moffatt, E.A. and J. Padmanaban, "The Relationship Between Roof Strength and Occupant Injury in Rollover Accident Data," Report No. FaAA-SF-R-95-05-37, May 1995.
[8] Moffat, E.A. et al., "Matched-Pair Rollover Impacts of Rollcaged and Production Roof Cars Using the Controlled Rollover Impact System (CRIS)," SAE, 2003.
[9] Nightingale, R.W., J.H. McElhaney, D.L. Camacho, M Kleinberger, B.A. Winkelstein and B.S. Myers, "The Dynamic Responses of the Cervical Spine: Buckling, End Conditions, and Tolerance in Compressive Impacts," Society of Automotive Engineers, Paper No. 973344, 1997.
[10] Paver , J. G. and D. Friedman, "Is BFD a Hyperflexion Injury or Compression with Localized Bending Injury or Both?" International Crashworthiness Conference 2012, Milano, Italy. 2012. Paper No. 2012-111.
[11] Allen, B. L., et al., "A Mechanistic Classification of Closed, Indirect Fractures, and Dislocations of the Lower Cervical Spine," Philadelphia, PA, 1982.
[12] Friedman, D., C.E. Nash, and J. Bish, "Observations From Repeatable Dynamic Rollover Tests", International Journal of Crashworthiness 2007, Vol. 12, No. 1, pp. 67-76.
[13] Brumbelow, M., E.R. Teoh, D.S. Zuby and A.T. McCart, "Roof Strength and Injury Risk in Rollover Crashes," Insurance Institute for Highway Safety, March 2008.
[14] Federal Register Final Rule FMVSS 216, Vol. 74, No. 90, 5-12-2009.
[15] Insurance Institute for Highway Safety, "First Time Institute Rates Small Pickups for Rollover Protection; Only One Model Rates Good in Test that Assures Strength of Roof," News Release, 2- 4-2010.

[16] McElhaney, J., R. Snyder, J. States, M.A. Gabrielsen, "Biomechanical Analysis of Swimming Pool Neck Injuries," Society of Automotive Engineers, Inc., 1979.
[17] Mattos,G., R.H. Bambach and A.S. McIntosh, "Validation of a Dynamic Rollover Test Device," International Crashworthiness Conference, Milano, Italy 2012.
[18] Paver, J., D. Friedman and J. Jimenez, "Correlating Human and Flexible Dummy Head-Neck Injury Performance," Enhanced Safety of Vehicles 2013, Paper No. 13-0282.
[19] McElhaney, J., R. Snyder, J. States, M.A. Gabrielsen, "Biomechanical Analysis of Swimming Pool Neck Injuries," Society of Automotive Engineers, Inc., 1979.
[20] Nash, C.E. and D. Friedman, "A Rollover Human/Dummy Head/Neck Injury Criteria," Enhanced Safety of Vehicles 2007, Paper No. 07-0357.
[21] Friedman, D., J. Paver and R. McGuan, "Design, Development and Validation of Rollover Dummy Injury Measures," International Crashworthiness Conference, Milano, Italy 2012.