THE DEVELOPMENT OF A DYNAMIC ROLLOVER RATING TEST

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ABSTRACT

The goal of this research is to develop a dynamic rollover test rating system similar to the star-rating system of frontal Federal Motor Vehicle Safety Standard (FMVSS) 208 and side FMVSS 214 compliance, New Car Assessment Program (NCAP) and Insurance Institute for Highway Safety (IIHS) tests. Until now, the requirement for vehicle and occupant crashworthiness in rollovers has been a structural measure only, the vehicle's strength-to-weight ratio (SWR), in a static roof crush test.

The short-term objective of this paper is to develop a quasi-dynamic rating system based on predictions derived from the Jordan Rollover System (JRS) dynamic rollover tests, IIHS static tests and finite element parameter sensitivity studies, verified by dynamic test sampling. The rating for the protocol is based on the National Accident Sampling System (NASS) and Crash Injury Research Engineering Network (CIREN) injury risk probability functions.

One method of predicting performance is to adjust the results of a dynamically-tested vehicle, similar to the vehicle whose performance is to be predicted, by the parameter sensitivity relationships correlated to a larger number of dynamically-tested vehicles. Another method is to formulate and then apply a multivariate equation based on the correlated parameters of a larger number of dynamically-tested vehicles.

This paper presents the prediction procedure based on a limited number of vehicles with a wide range of SWRs. The intent is to apply the procedure to vehicles compliant with 2009 FMVSS 216 and, as such, the illustrations herein are examples.
In this paper, the procedure is illustrated by a calculation of two parameters, SWR and major radius (MR). Normalization procedures have also been developed to estimate real-world dynamic test protocol performance, as well as the injury measures for 5th, 50th and 95th percentile dummies. This prediction procedure is an interim solution, not a substitute, for compliance or NCAP dynamic rollover testing.

A more detailed summary of the research basis for this effort is in a companion paper 11-0090 "Predicting and Verifying Dynamic Rollover Occupant Protection."

INTRODUCTION

The selection of parameters as possible test criteria independently or in combination was based upon results of dynamic tests by C*f*IR and other laboratories, case studies, and real-world crash databases.

The JRS test device was selected for this study. Since 2004, more than 50 dummy-occupied vehicles have been tested dynamically with the JRS. Up to 50 data channels were collected and examined as possible metrics. These included vehicle structural, dummy kinematics and injury measure data.

This study examined:

- vehicle structural measures and related injury risk, as well as
- dummy neck injury measures relative to criteria.

The degree of residual roof crush was selected as the vehicle structural measure with the corresponding probability and odds ratio of fatalities and AIS 3+ head, spinal, spinal cord injuries. These injury characteristics were based upon recent statistical analysis of NASS-CDS and CIREN data. The dummy injury measures and criteria were the Injury Assessment Reference Values (IARV) and Integrated Bending Moment (IBM) criteria.

Low-severity JRS test protocols included 1- and 2-roll dynamic tests of production and reinforced vehicles. The vehicles were compared by residual roof crush, injury risk and dummy injury measures. Disparities relative to SWR were identified and attributed to effects of other parameters that confounded the rating process. For example, dummy injury measures were also related to dynamic crush, crush speed and duration; headroom; belt excursion; and motion of the center of gravity (CG) in the ground reference plane. This study relies on the generic character of vehicles in the fleet and validating tests that can identify and factor in generic anomalies. It is not a substitute for full-scale testing, but may provide a market incentive for manufacturers to improve safety and reduce casualties.

The reliability and accuracy of the injury measures were compared to injury risk data. The structural probability of death and severe injury were correlated to the 10% probability of AIS = 3+ injury by IARV bending moments and IBM momentum exchange. In this study, the IBM was more accurate, less dependent on dummy position and more reliable than peak bending moment IARV and injury risk assessments. Dummy injury measures were related to residual roof crush. There was general correlation of dummy injury measures to one of three levels of injury risk probability.

Results of this study suggest that rollover test ratings should be a function of structural and dummy measures with vehicle-specific weightings of the most significant factors identified above. The complete formula for a rating system is:

$$\text{Rating} = f(\text{structural measures}) + f(\text{dummy injury measures}) \qquad (1).$$

The examples in this paper are focused on two parameters of the structural measures calculated from the weighted SWR and the distance between the roof rail and the roll axis or major radius (MR) as a function of residual crush. The results are roughly consistent with actual measured values.

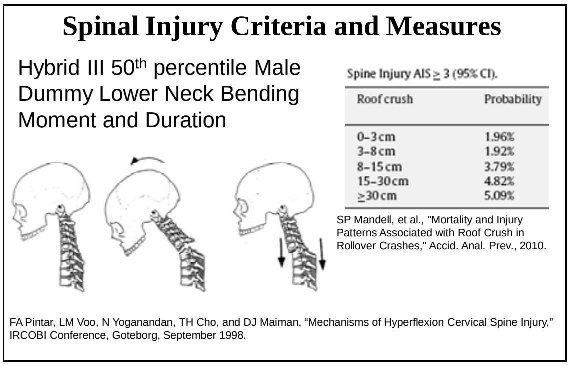
METHODS

There were seven main contributing developments, which will be discussed in sequence:

1. a Hybrid III dummy neck modified for rollover testing,
2. rollover injury measures, criteria and injury risk,
3. a real-world dynamic rollover test protocol,
4. vehicle structural parameter sensitivity,
5. structural injury risk and dummy injury measures,
6. a protocol normalization procedure, and
7. a ratings prediction procedure

1. A Hybrid III Dummy Neck Modified for Rollover Testing

The Hybrid III dummy neck used for frontal impact testing is representative of a 27-year-old soldier with tensed musculature, and is 10 times stiffer than a normal person's untensed musculature. Neck injury risk is assessed from data measured by its upper neck load cell, whereas rollover neck injuries typically occur in the lower neck. The Hybrid III neck is axially aligned and erect, whereas a human neck has lordosis. For these reasons, the production Hybrid III neck is not a good predictor of the real-world hyperflexion injury pattern and mechanism described by Pintar et al. [1] and shown below in Figure 1.



Spinal Injury Criteria and Measures

Hybrid III 50th percentile Male Dummy Lower Neck Bending Moment and Duration

Spine Injury AIS ≥ 3 (95% CI).

Roof crush	Probability
0–3 cm	1.96%
3–8 cm	1.92%
8–15 cm	3.79%
15–30 cm	4.82%
≥30 cm	5.09%

SP Mandell, et al., "Mortality and Injury Patterns Associated with Roof Crush in Rollover Crashes," Accid. Anal. Prev., 2010.

FA Pintar, LM Voo, N Yoganandan, TH Cho, and DJ Maiman, "Mechanisms of Hyperflexion Cervical Spine Injury," IRCOBI Conference, Goteborg, September 1998.

Figure 1. Spinal injury mechanism and criteria.

To compensate for these disparities, the production Hybrid III neck was modified using low-durometer butyl rubber discs with one-third the tensed soldier's musculature, a 30° inclined flexion lower neck bracket, and a lower neck load cell [2]. Tests with the modified neck reveal more realistic head-neck kinematics and injury prediction [3-5].

2. Rollover Injury Measures, Criteria and Injury Risk

Pendulum tests of the production and modified Hybrid III necks dispelled claims that short-duration peak loads are good predictors of lower neck bending injury [3-5]. Instead, a momentum exchange measure, called the Integrated Bending Moment (IBM), was developed by integrating the composite lower neck flexion moment My and the lateral moment Mx over the time duration above a minimum moment level [6]. Figure 2 illustrates the IBM as a dummy injury measure that distinguishes between production and reinforced roofs; the area under the production roof curve (more crush) is greater than the area under the reinforced roof curve (less crush).

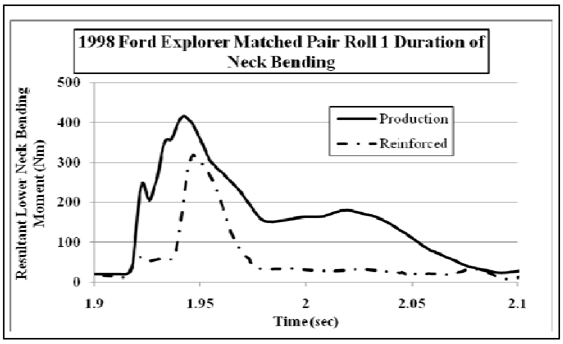


Figure 2. Illustration of IBM results.

We compared injury risk evaluations using the 2003 Mertz and Prasad IARV [7], the 1998 Pintar flexion bending moment criteria [8] and the IBM [8-9]. In more than a dozen JRS tests (see Figure 7), we found the IBM correlated well with residual crush (and injury) and was more independent of dummy head-neck position than the IARV [10].

3. A Real-World Dynamic Rollover Test Protocol

There are approximately 270,000 rollover crashes annually in the U.S., causing about 10,000 deaths and 26,000 serious injuries. A compliance test protocol is often an administrative decision about a political, technical compromise of the characteristics of the major types and severity of impacts, moderated by consideration for calculated benefits, cost and the capabilities of current production vehicles.

The objective of the 5-year multivariate NHTSA project is to define the global issue (i.e., to characterize a real-world rollover). C*f*IR seeks, more specifically, to identify the rollover segment with the greatest serious injury potential for FMVSS 216 compliant vehicles that would be consistent with a compliance or comparative evaluation dynamic rollover test. This process requires evaluating the injury potential sensitivity of each segment and its influence on the following segment. Since it has been shown that 95% of single vehicle rollovers and serious-to-fatal injuries occur within 8 quarter turns [11], we defined 10 segments of a 2-roll event and analyzed their consequences in Table 1 below. Segment 5, where the "vehicle roof impacts with the road" with the "potential for severe head/neck/ spine injuries," is the obvious choice for a test protocol.

Table 1.
Segments of the roll sequence and their potential for injury

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	Potential for severe head/neck/spine injury.
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

We performed a logical technical analysis of Malibu dolly rollover tests [12], over 400 rollover crash investigations [13], rollover crash statistics, the capabilities of the JRS rollover crash test machine [14], two-sided National Highway Safety Bureau's (NHSB) and M216 data, Hybrid III dummy and IARV, JRS rollover database and biomechanical epidemiology data and derived the proposed protocol described below in Table 2.

Table 2.
Proposed real-world rollover protocol

The Proposed Real-World Rollover Protocol

- Road speed 20 mph ± 5 mph
- Roll rate @ near-side impact 270 °/sec ± 20%
- Pitch 10° ± 5°
- Roll angle at impact 135° ± 10° and/or 185°
- Drop height 10 cm to 22 cm (4 to 9 inches)
- Yaw angle 15° ± 15°
- Dummy initially tethered @ 1 g and 60° toward the near side.

4. Vehicle Structural Parameter Sensitivity

Residual and cumulative vehicle roof crush has been found to be sensitive to several vehicle parameters (e.g., SWR, pitch, roof elasticity and road speed/roll rate).

Strength to weight ratio In 2008, JRS roof crush data plotted as a function of SWR had about the same slope as IIHS' analysis to an SWR of 4 and injury risk to about 4 or 5% [15]. That chart incorrectly projected the JRS data to an SWR of 5. Subsequent tests of vehicles with SWR above 4 show a substantially reduced effectiveness with increasing SWR. The example in this paper considers the performance of vehicles with SWRs from 2.1 to 6.8. This wide range is not representative of future vehicles, but results in the revised SWR versus cumulative residual crush in Figure 3 and demonstrates the effectiveness of the procedure. The highlighted point is a real test result of the limited number of vehicles plotted.

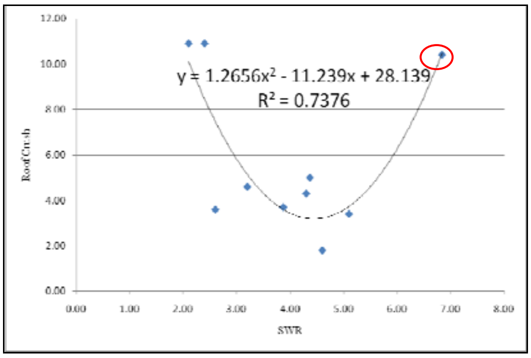


Figure 3. Residual roof crush vs. SWR.

Vehicle pitch A case-by-case study of 273 serious injury rollover crashes contained in NASS shows that more than 80% of the study vehicles had hood and top of fender damage that could only have occurred as a result of a roll with more than 10° pitch. The JRS test results in Figure 4 show the effect of pitch; there was greater residual crush at 10° of pitch compared to similar tests at 5° of pitch after roll 2.

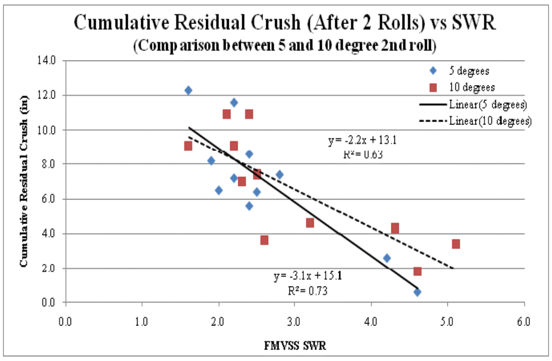


Figure 4. Comparison of residual crush vs. SWR after roll 2 at 5° vs. 10° pitch.

The diverging correlation lines show that, for vehicles with an SWR less than 3, there is little or no difference between the cumulative residual crush in second rolls at 5° and at 10° pitch. However, there is a large difference (60-175%) between the cumulative residual crush at 5° and 10° pitch for vehicles with SWRs greater than 3.

Major radius A vehicle's MR is the distance between the CG longitudinal (roll) axis and the roof rail at the A-pillar. The scatter plot of Figure 5 identifies the vehicles involved, their real-world and the cumulative residual crush at the A-pillar in a 2-roll event. The relationship is particularly striking for the slope, which indicates that each 1.2-inch change in MR affects the cumulative residual crush by 1 inch.

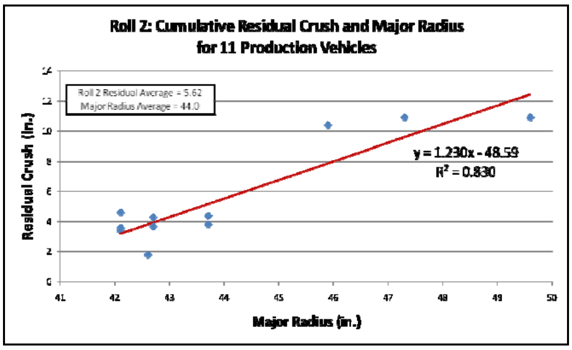


Figure 5. Cumulative Residual Crush vs. MR.

5. Structural Injury Risk vs. Dummy Injury Measures

Injury risk vs. residual roof crush Figure 6 is a plot of injury risk as a function of residual crush as defined by Mandell, et al. [16]. It shows from NASS and CIREN data that the probability of death and serious-to-fatal head, spine and spinal cord injury increases rapidly with cumulative residual crush over the occupant's seating position.

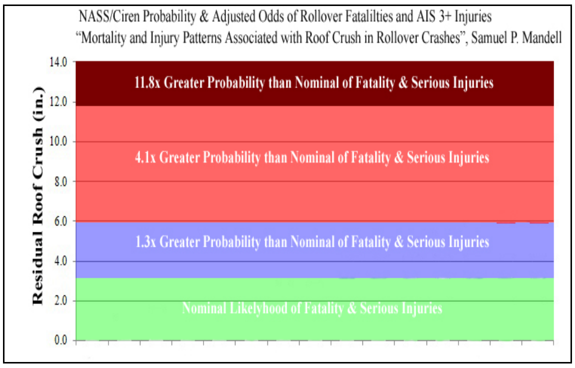


Figure 6. NASS/CIREN probability and adjusted odds.

Dummy injury measure vs. residual roof crush Figure 7 is a scatter plot of residual crush and the IBM for a 15 mph, 190°/sec, 5° pitch roll. The plot shows unacceptable neck injury severity for an IBM of 13.5 or more.

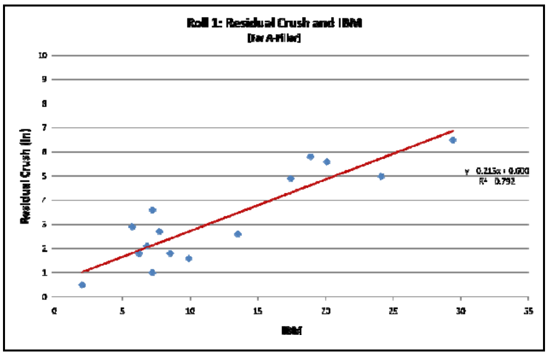


Figure 7. Residual crush vs. IBM.

Residual headroom vs. IBM The scatter plot of Figure 8 shows the effect of post-crash residual headroom and indicates that an IBM of 13.5 corresponds to1 inch of post-crash positive headroom. NHTSA has reported that post-crash negative headroom is 5 times more injurious than no or positive headroom.

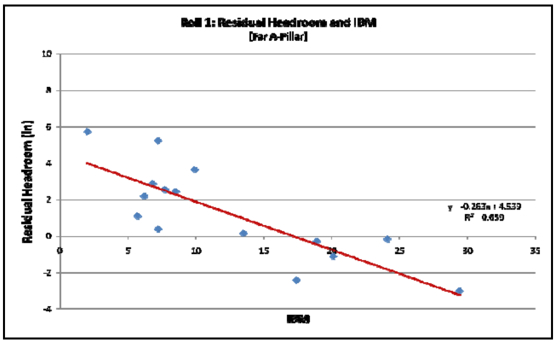


Figure 8. Residual headroom vs. IBM.

Roadbed speed and proportional roll rate Figure 9 shows that, when the residual crush is averaged for each roadbed speed with its proportional roll rate, the correlation is good. We found about 40% more residual crush at 21 mph than at 15 mph.

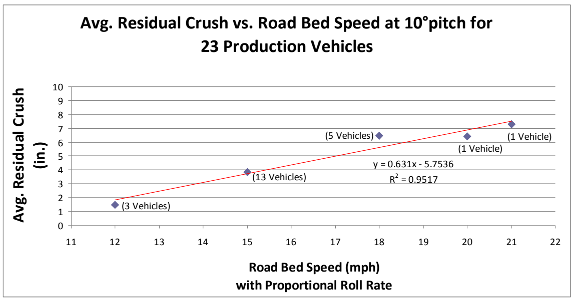


Figure 9. Residual crush vs. road bed speed.

Headroom and anthropometry The headroom for the 50th percentile Hybrid III dummy was measured preceding each test. In many cases, the motion off the seat was also measured during the test. The seated height of the 50ttj and 95th percentile males are 35.5 and 38.5 inches, respectively, while that of the 5th percentile female is approximately 32 inches. An estimated adjustment for headroom for the 5th and 95th relative to the tested 50th percentile male is plus and minus 3 inches, respectively.

Lap-and-shoulder belt A series of spit tests with 5th, 50th and 95th percentile volunteers at roll rates to 200 °/sec, the belted occupant's upward motion off the seat varied from 3 to 5 inches in a sequence of 3 to 5 rolls. When a representative seat belt pretensioner was fired, the occupant's motion was reduced by about 2 inches.

6. A Protocol Normalization Procedure

This procedure was developed to put all the data of the 50 JRS tests on a level rating system. It is also useful to relate the data to any protocol that National Highway Transportation Safety Administration (NHTSA) or University of Virginia (UVa) or George Washington University (GWU) derive as the "Real-World Rollover Test Protocol."

In order to compare the 1-roll performance of vehicles, we normalized the residual crush at the A-pillar (after 1 roll) for all vehicles to a 1-roll event at 10° pitch and 21 mph. This was done by increasing or decreasing the amount of residual crush by the ratio of the different test speeds in addition to increasing the amount of residual crush for a 5° pitch roll by 20% as determined empirically. For example, a vehicle tested at 5° pitch and 15 mph would have its residual crush increased by 60%; 40% (21/15 = 1.4) because of the difference in road speed and proportional roll rate and 20% for the pitch increase from 5° to 10°. In order to compare the 2-roll performance of vehicles tested at different protocols, we normalized the cumulative residual crush (after 2 rolls) for all vehicles to a roll sequence of 5°/15 mph roll 1 and 10°/15 mph roll 2. This was done by comparing the difference in cumulative residual crush between the 5° and 10° pitch roll 2 (at 15 mph), where roll 1 was conducted at 5° pitch and 15 mph as shown in Figure 4.

It should be noted that almost all JRS roof crush measurements were taken from string potentiometers from the roof rail to the roll axis and unless resolved by the tracking cameras should be considered as radial measurements at about 35 to 40º. Since the NASS/CIREN injury risk probability functions are based on vertical crush, for general comparison purposes, a rule of thumb is to reduce the radial value by 20%. The result is shown in Figure 10.

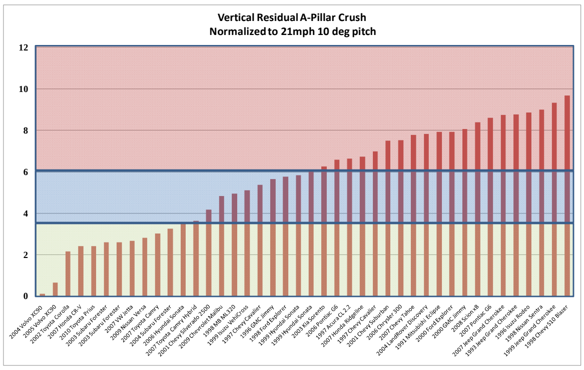


Figure 10. Vertical residual A-pillar crush.

Figure 10 confirms the Austin [17] and Strashny [18] statistical injury analysis and identifies the probability of injury to various body parts by Mandell [16] as a function of residual roof crush. This chart is normalized (from 5° pitch protocols for 10° pitch test data not previously considered in [19] to a 21 mph, 10°, 270 °/sec roll rate, 145° impact angle and 4-inch drop height. It is also corrected to vertical from radial JRS crush measurements.

The primary difference between these dynamic tests and FMVSS 216 static tests is the ability to grade vehicle compliance by injury risk and dummy injury measure (IBM) performance and to identify the effect of occupant protection features, as well as anomalies between the two. The horizontal lines delineate the injury probability levels of the Mandell chart of Figure 6.

The area below the first line at 3.5 inches represents "GOOD" performance. The area below the second line at 6 inches represents a 30%

increased probability of death and serious injury and would be "ACCEPTABLE". The area above the 6-inch line and below 12 inches represents 4.1 times the probability of death and injury and would be rated "POOR". Only vehicles of the 1980's and early 1990's should rate in the area above 12 inches, where the probability of death and injury is 11.8 times the nominally good performance.

Within this set of 40 JRS tests are 15 vehicles involved in 188 real-world rollover crashes investigated by the authors with catastrophic AIS 4 to 6 injuries which were the subject of extensively detailed investigation. Those 188 victims in every case validated this injury risk analysis. These normalized to the real-world protocol dynamic test results demonstrate the ability to comparatively rate vehicles by residual crush and injury risk.

7. A Ratings Prediction Procedure

Prediction of structural injury risk and dummy injury measure performance of new vehicles The analysis of parameter sensitivity to intrusion identified three significantly correlated factors: SWR, MR and Elasticity (recoverable deformation).

One method of predicting performance is to adjust the results of a dynamically-tested vehicle, similar to the vehicle whose performance is to be predicted, by the parameter sensitivity relationships that have been correlated to a representative sampling of dynamically-tested vehicles.

For a simple example, the cumulative intrusion of a 2004 Chevrolet Malibu with an SWR of 2.18 can be predicted from the already-tested 2009 Chevrolet Malibu with an SWR of 4.4. The body parameters, height, width, CG location and real-world are virtually the same as shown in Table 3. From Figure 3, the variation in SWR between 2.18 and 4.4 corresponds to a ratio of roof crush of 8.5/3.5 or 2.4. Since the crush in the 2009 vehicle was 5 inches, the crush in the 2004 vehicle under the same conditions would be 2.4 x 5 = 12 inches.

Table 3.
Predicting the 2004 Malibu cumulative crush from a 2009 Chevrolet Malibu

Vehicle	SWR	Cumulative Crush (in) Roll 2	Weight (lbs)	Height/ Width (in)	CG (in)	MR (in)
2004 Chevrolet Malibu	2.16	12	3262	58/70	22.8	40.1
2009 Chevrolet Malibu	4.37	5	3642	57/70	22.4	40.1

The second more accurate and sophisticated method is to formulate and use a multivariate analysis of all the parameter variations to optimize the prediction of new vehicles as tested to the real-world dynamic test protocol performance.

A multivariate analysis has not yet been conducted. However, Table 4 is a crude illustration, using two simple functions (instead of the multivariate functions) to weight the SWR relationship of Figure 3 and the MR of Figure 5.

In the illustration of Table 4, we calculated the residual crush for each vehicle for its SWR, from Figure 3. We also calculated the residual crush for its MR, from Figure 5. We then assumed that the crush contribution of SWR and MR represented the only factors contributing to the total and weighted them accordingly. We optimized the result by adjusting the weightings in 5% increments; a 55% SWR and 45% MR yielded the best fit.

Table 4.
Predicted crush vs. measured crush

Vehicle	Strength to Weight Ratio	Major Radius	Calculated Cumulative Radial Crush f(SWR) + f(MR)	Measured Radial Roof Crush
2007 Chevy Tahoe	2.10	49.6	10.82	10.90
2007 Honda Ridgeline	2.40	47.3	8.81	10.90
2007 Honda CR-V	2.60	42.1	5.82	3.60
2006 Hyundai Sonata	3.20	42.1	4.54	4.60
2007 Toyota Camry Hybrid	3.87	42.7	3.97	3.70
2007 Toyota Camry	4.30	42.7	3.76	4.30
2009 Malibu	4.37	40.1	2.53	5.00
2005 Volvo XC90	4.60	42.6	3.72	1.80
2007 VW Jetta	5.10	42.1	3.77	3.40
2008 Scion xB	6.84	45.9	9.27	10.40

Figure 11 compares the calculated/predicted results to actual measured intrusion. It shows that, in spite of the simple two-factor analysis and the broad range of SWRs, there is a reasonable semblance of comparable injury risk.

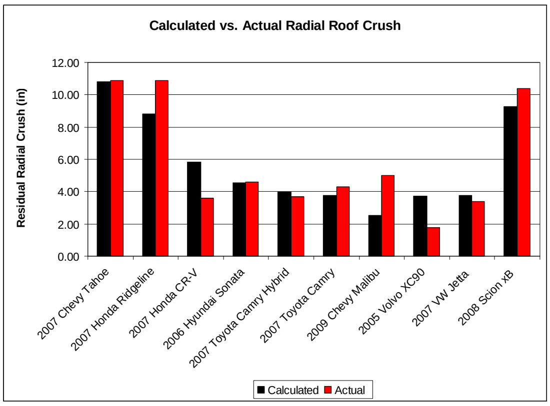


Figure 11. Calculated vs. actual roof crush.

The structural rating is the ratio of injury risk versus vertical residual crush in the NASS/CIREN statistical probability of fatality and head, spine and spinal cord serious injury data chart and consists of the SWR, MR and Elasticity terms in the following equation:

$$\text{Severity (S) x } \{f\text{(SWR)} + f\text{(MR)} + f\text{(Elasticity)}\} = \text{Structural/Injury Risk Rating} \qquad (2).$$

While the equation for the dummy injury measure rating for the probability of AIS ≥ 3 lower neck flexion bending injury is:

$$\text{Severity (S) x } \{f\text{(SWR)} + f\text{(MR)} + f\text{(Elasticity)} + f\text{(Headroom)} + f\text{(Belt Pretensioning}\} \text{ x } f\text{(IBM)} = \text{Dummy Injury Measure Rating} \qquad (3).$$

where:

Severity (S) is the percent increase in traveling speed and proportional roll rate protocol over the nominal 2-roll, 15 mph, 190 °/sec, 4-inch drop height, and 5° and then 10° pitch test.

To predict injury measures from the 50th for the 95th percentile male reduce HR by 3 inches and for a 5th percentile female increase HR by 3 inches. For persons 30% or more overweight in their size category reduce HR by 3 inches.

CONCLUSIONS

1. A real-world research protocol has been characterized and the segments have been analyzed for injury potential. For the compliance test, we identified the first roll ballistic segment as most likely to produce serious-to-fatal injury.
2. Dynamic JRS rollover tests of 40 vehicles with various protocols have been normalized to represent the first roll of a real-world protocol and matched to NASS/CIREN injury risk potential to various body parts.
3. Dynamic JRS tests provide detailed dummy injury measure potential assessments, not possible with static tests. JRS injury potential assessments are:
    - the rollover equivalent of frontal and side dynamic test injury potential,
    - comparative, instructive and relevant to a final real-world protocol,
    - determinate of individual vehicle injury risk and dummy injury measure ratings,
    - relative to statistically-derived criteria for injury risk and dummy injury measures,
    - inclusive of the dummy injury measure effects of occupant protection features,
    - likely to eliminate more casualties sooner than the regulatory comprehensive plan,
    - insightful for and supplemental to rollover injury research, and
    - useful in conjunction with consumer information as incentives to manufacturers.
4. NHTSA's 5-year research plan complements and will eventually validate this cooperative project to develop a real-world comparative evaluation and compliance test rating system.

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REFERENCES

[1] Pintar, F.A., L.M Voo, et al. 1998. "Mechanisms of Hyperflexion Cervical Spine Injury." IRCOBI Conference, Goteborg, September 1998.

[2] Paver J., Caplinger J., Friedman D., Mattos G. 2010. "An Improved Dummy Neck Assembly for Dynamic Rollover Testing." SBC Paper #2010-19656, ASME Summer Bioengineering Conference, Naples, Florida, 16-19 June 2010.

[3] Paver J.G., Carlin F., Bish, J., Caplinger J. 2008. "Development of Rollover Injury Assessment Instrumentation and Criteria." 36th International Workshop on Human Subjects for Biomechanical Research, NHTSA, San Antonio, Texas, November 2, 2008.

[4] Paver J.G., Friedman D., Caplinger J. 2008. "Rollover Roof Crush and Speed as Measures of Injury Potential vs. the Hybrid III Dummy." ICRASH Conference Proceedings, July 2008.

[5] Paver J., Caplinger J., Friedman D., Mattos G. 2010. "Testing of the Prototype Low-Durometer Hybrid III Neck for Improved Biofidelity." SBC Paper #2010-19688, ASME Summer Bioengineering Conference, Naples, Florida, 16-19 June 2010.

[6] Paver J.G., Friedman D., Carlin F., Bish J., Caplinger J., Rohde D. 2008. "Rollover Crash Neck Injury Replication and Injury Potential Assessment." IRCOBI Conference Proceedings, September 2008.

[7] Mertz, H.J, P. Prasad, et al. 2003. "Biomechanical and Scaling Bases for Frontal and Side Impact Injury Assessment Reference Values." Stapp Car Crash Journal, Vol. 47, 155-188.

[8] Friedman D., Paver J., Carlin F. 2010. "Hybrid III Correlation with Human Injury Potential in Rollovers." ASME Summer Bioengineering

Conference, Lake Tahoe, California, 17-21 June 2009.

[9] Paver J., Caplinger J., Mattos G., Friedman D. 2010. "The Development of IARV's for the Hybrid III Neck Modified for Dynamic Rollover Crash Testing," Washington D.C., International Crashworthiness Conference, 2010.

[10] Rico, D, "Parameter Analysis" JRS Dynamic Correlations for IARV = 0.456 and for IBM =0.708

[11] Digges, K. and A.M. Eigen. 2003. "Crash Attributes that Influence the Severity of Rollover Crashes." 18th Enhanced Safety of Vehicles, Nagoya, Japan, 2003.

[12] Orlowski, K.F., R.T. Bundorf and E.A. Moffatt. 1985. "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics." Society of Automotive Engineers, 1985.

[13] Tahan, F. 2010. "Jordan Rollover System Sensitivity Study for an Elastic Roof of a Ford Explorer FEA Model." National Crash Analysis Center, GWU, 2010.

[14] Friedman, D. and R. Grzebieta. 2009. "A Proposed Rollover and Comprehensive Rating System." 21st Enhanced Safety of Vehicles, Stuttgart, Germany, 2009.

[15] Paver J.G., Friedman D., Carlin F., Bish J., Caplinger J., Rohde D. 2008. "Rollover Crash Neck Injury Replication and Injury Potential Assessment." IRCOBI Conference Proceedings, September 2008.

[16] Mandell, S., R. Kaufman, C.D. Mack, E.M. Bulger. 2010. "Mortality and Injury Patterns Associated with Roof Crush in Rollover Crashes." Accident Analysis and Prevention, 2010, 10.1016/j.aap.2010.02.013.

[17] Austin, R., M. Hicks and S. Summers. 2005. "The Role of Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face During FMVSS No. 216 Rollovers." National Highway Traffic Safety Administration, 2005.

[18] Strashny, A. 2007. "The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face During FMVSS No. 216 Rollovers: An Updated Analysis." National Highway Traffic Safety Administration, 2007.

[19] Friedman, D. and G. Mattos. 2010. "The Effect of Static Roof Crush Tests Relative to Real-World Rollover Injury Potential." ASME International Mechanical Engineering Congress and Exposition, Vancouver, British Columbia, 2010.