Characterizing the Injury Potential of a Real World Rollover

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Abstract There are approximately 270,000 rollover crashes annually in the U.S., causing about 10,000 deaths and 30,000 serious injuries. The objective of a 5-year multivariate NHTSA project is to define the global issue: 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.

Ten segments of a 2-roll event were considered, because it has been shown that 95% of single vehicle rollovers and serious-to-fatal injuries occur within 8 quarter turns. A description of the preliminary segment-by-segment evaluation and the sensitivity to injury potential is characterized by analysis, experiments and illustrations. Parameters were derived and validated with JRS dynamic rollover tests. The test parameters were then applied and normalized to approximately 40 other JRS tests for a comparative pilot injury risk evaluation to the NHTSA post-crash negative headroom criteria.

Since many of the JRS tests included dummies, injury performance was also evaluated based on dummy injury measures from head and neck data collected during the tests. Tests were conducted with production and prototype Hybrid III necks and lumbar spines representing tensed and partially-relaxed human musculature. The results were also compared and correlated with Injury Assessment Reference Values (IARV), consensus impact speed injury criteria and dummy positioning. The results indicate that while the injury risk evaluation generally supports static compliance test criteria, dynamic tests identify vehicle geometry, structural design deficiencies and dummy injury measure results that roughly account for the substantial variation in injury rate identified by IIHS from the SWR static test norm. Examples of the data for some of these "anomalies" and failures are provided.

Keywords: dynamic rollover, protocol, injury measures, injury risk

INTRODUCTION

Although rollover is not the most frequently occurring crash mode, it is the most deadly. Ninety-five percent of single vehicle rollovers and serious-to-fatal injuries occur within 8 quarter turns [1]. A rollover event can be separated into 10 distinct segments and analyzed according to the injury potential of each segment as shown in Figure 1.

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

Figure 1 – Segments of the rollover sequence and their potential to inflict AIS ≥ 3+ injury

DATA SOURCES AND METHODS

This study considered single vehicle rollovers. Data was collected from 50 production and strengthened roof Jordan Rollover System (JRS) rollover tests, 15 directly corresponding to catastrophic injury investigations and most tested with a low severity two roll protocol. A real world event was characterized as a two roll rollover with initial and continuing test parameters derived from data of 400 in depth catastrophic crash investigations [2], previous studies [3], dolly rollover tests [4], these JRS [5] rollovers and specific experiments. Each segment of the rollover was analyzed for injury potential considering dummy kinematics and position at impacts with the ground. Those segments are: vehicle loss of control (the directional oscillations or fishtailing), yaw to trip, trip, accelerating roll rate, near and far side roof to ground impacts, wheel/underbody impact, second roll lofting, near side roof contact, far side roof contact, to rest.

There is virtually no injury potential when a vehicle fishtails. To explore the yaw to trip segment a test vehicle with belted human occupants was placed on a flatbed truck at a 60° angle of yaw. The truck, after reaching 50 mph was emergency braked to simulate a yaw for the test vehicle. The occupants came out of the shoulder belt and laid down on the console or seat without injury.

The Far Side Project [6] tested belted erect far side PMHS (Post Mortem Human Subjects) and the WorldSid dummy occupants with no serious injury at a near side lateral delta V of 8 mph and substantially higher lateral g's than would be experienced even in a curb trip.

Dolly rollovers [4] provide data to characterize the roll rate, vertical drop height and lateral speed at first near side roof contact in a two roll event. Although a two roll event was characterized, the injury potential on the first roll at 10 or more degrees of pitch has the greatest potential for injury, making the second roll superfluous.

Segment - by - Segment Description of a Real World Rollover

Of the 10 segments of the two rolls detailed in this study, upper and lower limb injuries could occur in any segment in which the vehicle and body kinematics cause the limbs to flail. Constraining the limbs inside the vehicle with padded packaging seems to be the only way to limit these injuries. Two segments, yaw to trip and trip appear to setup the potential for head or spine injury at the level of AIS ≥ 3+ by moving the far side occupant out of position and the roof impacts are determined to be the potentially injurious head and spine segments.

1. Vehicle loss of control

Vehicle loss of control (fishtailing) most commonly occurs due to a tire failure and an input by the driver (i.e. over correction). It can be exacerbated by poor road conditions, interaction between two or more cars (i.e. sideswipe that leads to over correcting) or by leaving the road. The loss of control begins when the vehicle does not respond appropriately to the combination of steering and acceleration input supplied by the driver, during a time from 1-5 seconds, < 400 feet. The loss of control is the segment of a rollover consisting of the vehicle traveling in a direction other than that which the front tires are pointing. This is exactly the situation for which the Electronic Stability Control (ESC) system was designed to assist the driver. This event in itself does not involve an impact with another object and is not injurious. The resulting positioning of the occupant due to the loss of control of the vehicle is very minimal. The occupant can be restrained adequately by the seatbelt.

2. Vehicle yaw

The yaw event occurs as a continuation in one direction of the driver's loss of control and is characterized by the vehicle moving with a component of its velocity in a direction perpendicular to the longitudinal axis of the vehicle leading to a rollover. Figure 2 shows a typical clockwise yaw sequence from a rollover accident reconstruction.

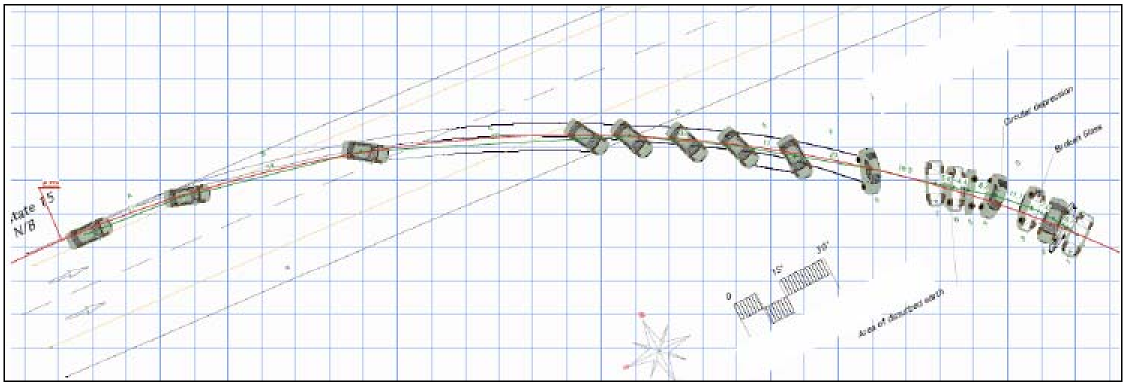

Figure 2. Typical rollover yaw trajectory by accident reconstruction

When the vehicle begins a clockwise yaw, the far side occupant (in this case the passenger) has an inertial acceleration in a direction that is out of the range of the restraining capability of the seatbelt. The seatbelt is designed to restrain an occupant traveling primarily in one direction; toward the front of the vehicle. As the vehicle continues to yaw the vehicle can experience an on road deceleration of 0.7 to 1 g due to the friction characteristics between the tires and the asphalt. Although this segment of the rollover is non-injurious, it does significantly affect the positioning of the occupant for the next segment of the rollover.

In a counter clockwise yaw, Figure 3 shows the far side driver will be forced toward the passenger side of the vehicle in the 100 ms pictogram (abstracted from the Far Side Study report) [6]. For an occupant positioned in the driver seat this force will try to bend the occupant over the center console (if there is one) and out of the shoulder belt.

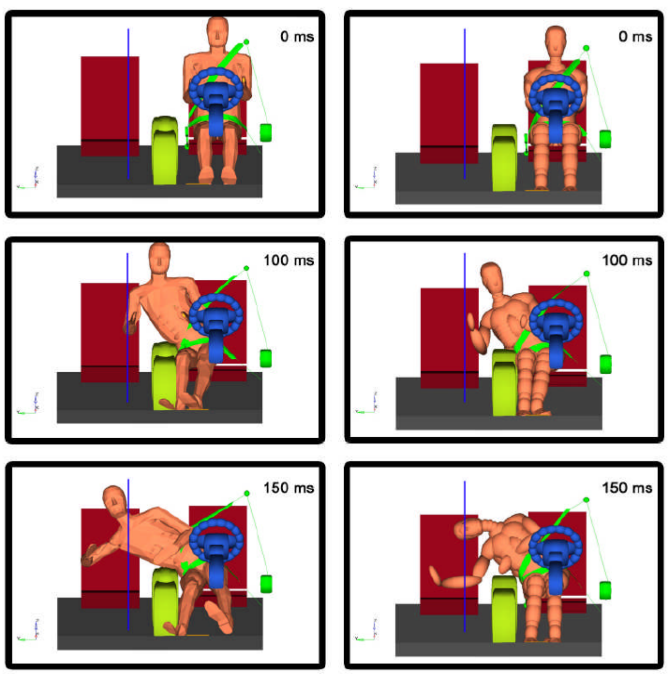

Figure 3. Illustration of the out-of-position extent of a far side dummy and human during yaw (100 ms) and trip (150 ms)

3. Trip

Compared to the yaw, the trip forces of a rollover may be much higher (2 to 4 g's), resulting in the excursion shown in the 150 ms pictogram of Figure 3. Curb trips are rare but similar to plowing or furrowed trips which take a little longer. It is possible that this could result in thoracic rib fractures if the out of position has not already occurred during yaw. However, even the trip segment of the rollover event alone is not likely to be AIS 3+ injurious as was demonstrated in an 8 mph delta V near side impact of the Far Side project [6]. For an occupant positioned in the passenger seat the force will move the occupant toward their door. For vehicles with rollover sensing airbags this could result in the occupant's head being in a position between the side curtain airbag and the door window.

More than half (51%) of all rollovers are initiated by a trip mechanism [7]. Experience suggests that the next 35% of tripping mechanisms involve similar occupant kinematics and no greater injury potential. The near side occupant is highly likely to be in the curtain deployment path when the trip is initiated. While this is a matter of concern for rollover activated curtains, until a predictive algorithm can be developed to initiate the near side bags during yaw and prior to the trip phase, our ballistic compliance tests will be initiated with both occupants tethered out of position and electronically released a few milliseconds after the initiation of roll. To avoid the obvious near side interaction we suggest leaving the near side dummy out of the test or deploying the far side bag first and deploying the near side bag after the far side impact when the near side dummy moves away from the window. To develop curtain deployment strategies see the companion paper at this conference entitled "Alternate Design Modifications of the Jordan Rollover System for Research, Development, and High Volume Testing".

4. Vehicle roll rate

The roll rate is potentially injurious because it erects the out-of-position occupant to contact the roof at a speed which contributes to the closing velocity of the head and roof intrusion speed, as well as the potential for partial ejection. Similarly, rapid changes in the vehicle roll rate effects the position and relative rotational speed of an uncoupled occupant whose kinematics contribute to injury potential. The roll rate also affects the severity of the far side roof impact with the ground. JRS tests indicate that near side roof contact friction increases the far side roll rate by about 20%. The roll rate also determines the peripheral velocity of the vehicle in comparison with the translational speed of the roadbed. For instance, a vehicle with a three foot radius from the CG to the corner of the roof, rotating at 360 deg/sec has a peripheral speed of 5.7 m/sec (12.9 mph). If it were moving down the road at that same speed, the vehicle would be rolling like a tire from corner to corner with no substantial impacts. On the other hand, if the road was moving by, at twice or half the peripheral speed, the corner impacts would be violent (more so at twice than at half because the momentum transfer is greater). Most JRS tests are run with a peripheral velocity about half of the road speed. In a real world two roll event the road speed is higher in the first roll which increases the roll rate, and lower in the second roll which decreases the roll rate.

5. Vehicle roof impacts

While it is obvious that roof crush and intrusion contributes to and causes injury, the way impact parameters and mechanisms affects roof crush is more subtle. The way the trip launches the vehicle determines the distance through which the vehicle falls to the ground and the yaw, roll and pitch angle at which the near side corner impacts the ground. JRS road load measurements indicate that shallower near side impact angles (~125 deg) take out more momentum via roof crush and round the roof such that the far side load is equalized. It seems that typical impact angles are more like 135-145 degrees. Patents have been issued on a device [8] to round the roof and distribute the crush energy more equally to both sides, reducing far side intrusion.

Most trips raise the CG by about a foot and the inverted roof A-pillar corner by less than half that amount. This determines the extent and direction of roof intrusion, because the roof structural strength varies with those parameters. A small percentage of trips, via the lift of tires and suspension, launch the vehicle at such a rate and height as to miss a near side contact and instead to contact the ground with the flat of the roof, a particularly severe and injurious impact. This has the effect of putting most of the rolling momentum into the far side roof. Even this contact can be controlled by a strong roof and a good restraint. On the other hand, roofs that meet the FMVSS 216 final rule fail in the far more frequent two sided roof contact because of vehicle geometry and the variability of roof strength as a function of impact orientation.

6. Wheel/underbody contacts

The end of far side roof contact precedes the far side wheel and or underbody contacts. The contacts reduce the roll rate and set the near side wheels and suspension to loft the vehicle at the reduced speed. In JRS tests underbody frame forces at 300 deg/sec exceeded 60 g's due to ground contact while seat frame forces 1.5 m from the point of impact exceed 10 g's, and could have an effect on lumbar loading [9][10], but the frequency of spinal injuries below T-10 is not significant.

7. Suspension rebound

The rotational loading of the far side suspension can and is often seen in dolly rollovers to cause lofting of the vehicle from curb trips, but at reduced velocity and roll rate. While there is injury potential from second rolls, the reduced severity relative to the first suggests that a first roll compliance test with initial test parameters of a two roll rollover would be sufficient to discriminate between reasonably safe and dangerously unsafe vehicles.

8. Near side roof impact

Although damage from the first roll may weaken the structure and allow substantial crush on the second roll, head and neck injury is associated with a severe impact force and duration and not a sequence of reduced severity events; head and neck injuries are not usually cumulative events.

9. Far side roof impact

The sequence of segments suggests that the second roll will be reduced in speed, roll rate, and severity relative to the first roll. A one roll compliance test with the speed, roll rate, drop height, and impact angles of the first roll of a two roll event with the highest severity parameters from either roll will suffice to differentiate levels of injury potential performance.

10. Wheel contact to rest

Although lower thoracic/lumbar injures are possible as in the segment Wheel/underbody impacts, the speeds and forces with seat cushions are frequently not sufficient to produce AIS 3+ injury.

RESULTS

Derived Real World Injury Risk Protocol

The derived and proposed protocol, with the possible range of parameters are:

- Road speed 33 kph ± 7 kph (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 tethered @ 1 g and 60° towards the near side.

JRS Tests

Contrary to popular thought, a compliance test protocol is usually 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 capability of current production vehicles. The dynamic JRS test fixture and derived protocol are in themselves not the answer to rollover casualties, but in conjunction with consumer information, will provide the framework and an industry incentive to develop solutions to dramatically reduce casualties.

Residual Crush of 40 JRS Tested Vehicles with NASS/Ciren Probability of AIS ≥ 3 Injury

Figure 4 and 5 confirm the Austin [11] and Strashny [12] statistical injury analysis and identifies the probability of injury to various body parts by Mandell [13] as a function of residual roof crush. The data is available, but not shown, for the percent and severity of injury by residual roof crush. This chart is normalized (from 5° pitch protocols and now corrected (identified by "x") for 10° pitch test data not previously considered in [14]) to a 21 mph, 10°, 270 deg/sec roll rate, 145° impact angle and 10 cm drop height. ***The primary difference between these dynamic tests and FMVSS 216 static tests is the ability to grade or rate vehicle compliance by injury risk performance and to identify anomalies between the two.*** 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.

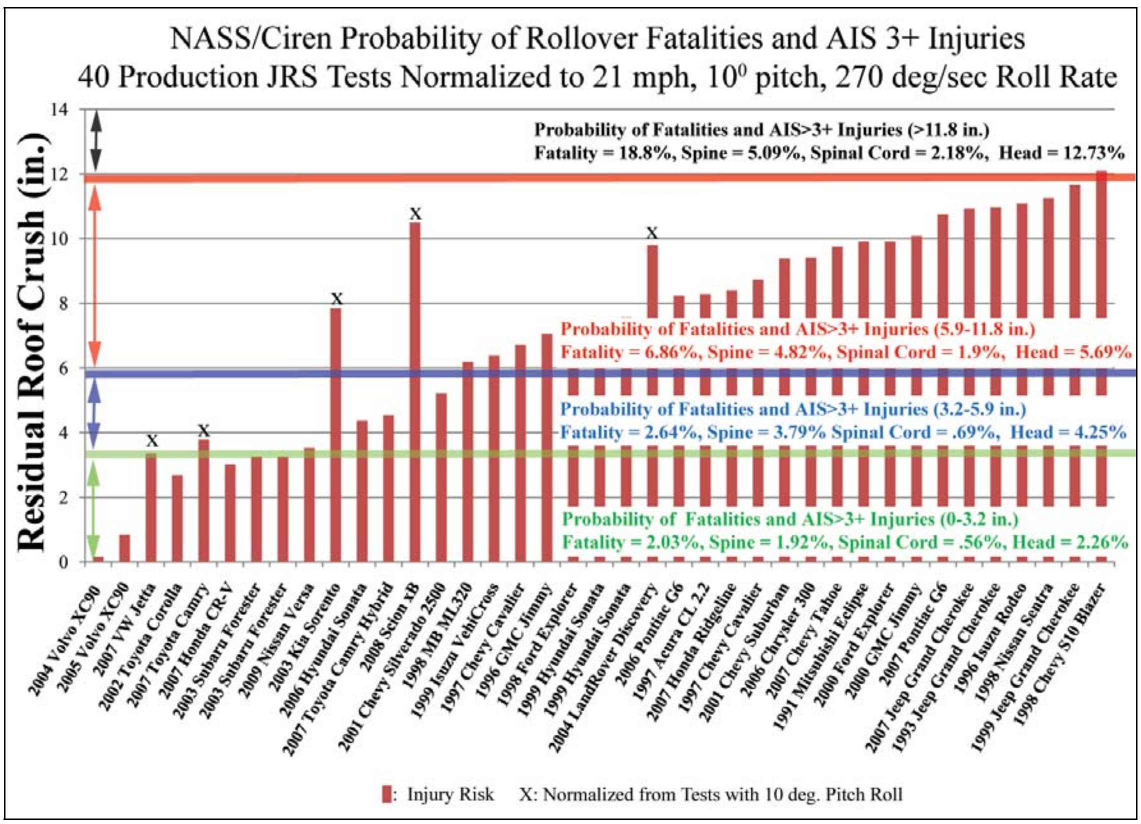

Figure 4. Residual crush of 40 normalized JRS tested production vehicles with NASS/Ciren probability of fatality and AIS ≥ 3 injury.

JRS Tests Illustrating Static SWR vs Dynamic Test Inconsistencies in 40 Vehicles

Figure 5 is the post crash negative and positive headroom (PCNH & PCPH) plot of the same data and in the same order as compared to roof strength expressed as SWR. The headroom by which the residual crush was reduced to derive PCNH and other data about these JRS tests are given in Annex A Figure 13. One striking result is that PCNH varies from about 5 cm to 20 cm (2" to 8") with average vehicle SWR of about 2.2. PCPH varies from nil to 15 cm (6") for average SWR of 4. The range of post crash headroom therefore is about 35 cm (14"). This most likely accounts for the variation in IIHS injury rate at the same SWR. A gross anomaly between SWR and roof crush is the Toyota Scion Xb. An anomaly would be when a vehicle exceeds the FMVSS 216 criteria and has post crash negative headroom (like the Scion) or when it has positive post crash headroom and doesn't comply with FMVSS 216 SWR criteria (like the Honda CRV). Figures 4 and 5 illustrate what the results of a compliance test series would be like, but these are normalizations.

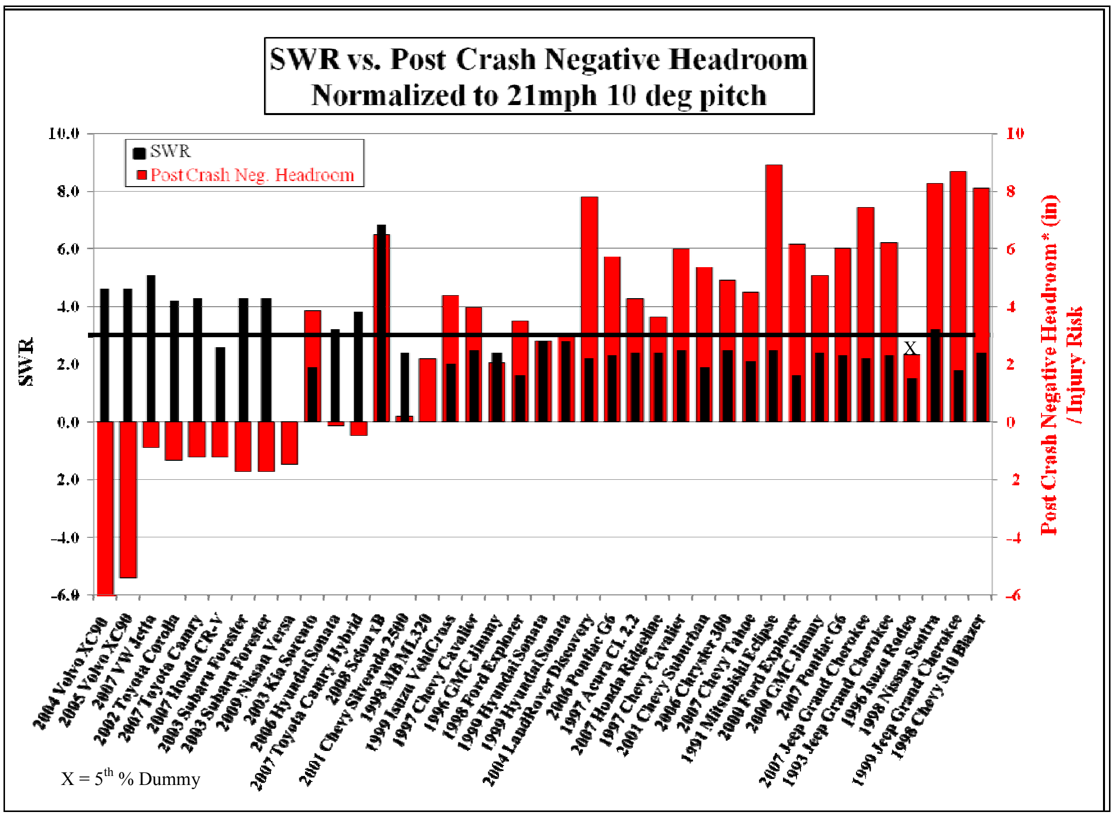

Figure 5. The relationship between post crash negative headroom and SWR

JRS Tests Illustrating Static SWR vs Dynamic Test Dummy Injury Measures in 16 Vehicles

The 16 vehicle subset of that data in the figures that follow are not normalized. That is, the tests were conducted to the same low severity 2 roll protocol with dummies and evaluated to published dummy injury criteria. Figure 6 like figure 5 compares the vehicle's SWR with the Integrated Bending Moment (IBM) [15], a neck injury bending criteria identifying a serious injury by the amount and the duration of bending (a momentum exchange). Here again an anomaly is when the SWR exceeds the FMVSS 216 criteria, but the IBM in either roll exceeds 13.5, as with the 2006 Sonata and the 2008 Scion on the second roll. It is also obvious in these low severity tests that all vehicles including the CRV which do not meet the SWR criteria substantially exceed the IBM injury criteria. Small increases in SWR to over 3 are not likely to bring the IBM to an acceptable range, particularly in a real world severity protocol.

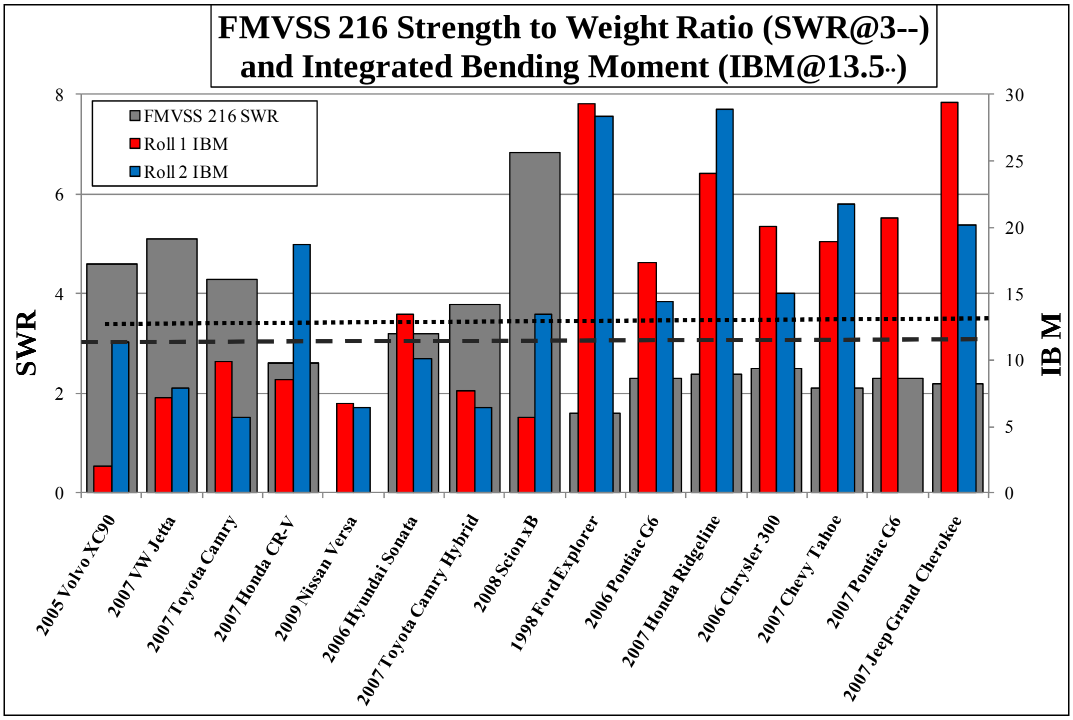

Figure 6. The relationship between the Integrated Bending Moment (IBM) and SWR

JRS Tests to the same Low Severity Protocol with Dummy Injury Measure Performance

Figure 7 compares dynamic crush to IBM. The dynamic crush correlates better with IBM because it is duration sensitive, while IARV are peak criteria measurements. Notice that the second roll of the CRV, an elastic structure, whose residual crush does not suggest injury, is contradicted by the IBM criteria. Also the Tahoe, which has major crush in each roll shows IBM injury in Figure 7 but no IARV bending injury in Figures 8, 9 or 10.

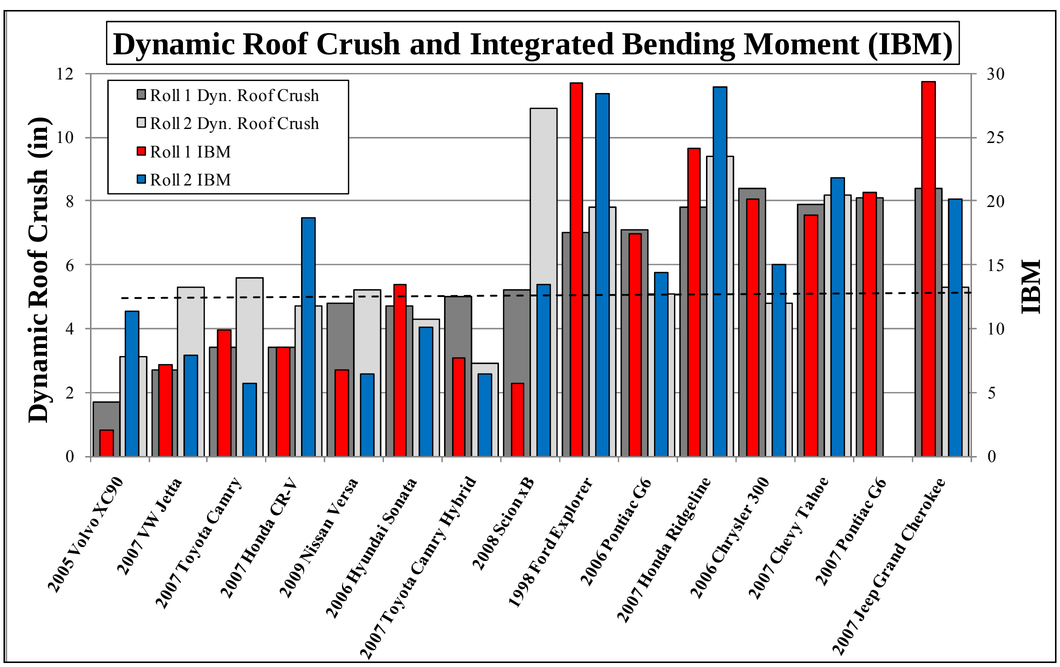

Figure 7. Dynamic Roof Crush and Integrated Bending Moment (IBM@13.5--)

JRS Tests Illustrating Dummy Injury Measures to IARV Criteria vs Residual Crush

Figure 12 in Annex A identifies the Injury Assessment Reference Value (IARV) relationship between a 10% probability of major human neck injury and dummy injury measures. These criteria have been applied to Figures 8, 9 and 10.

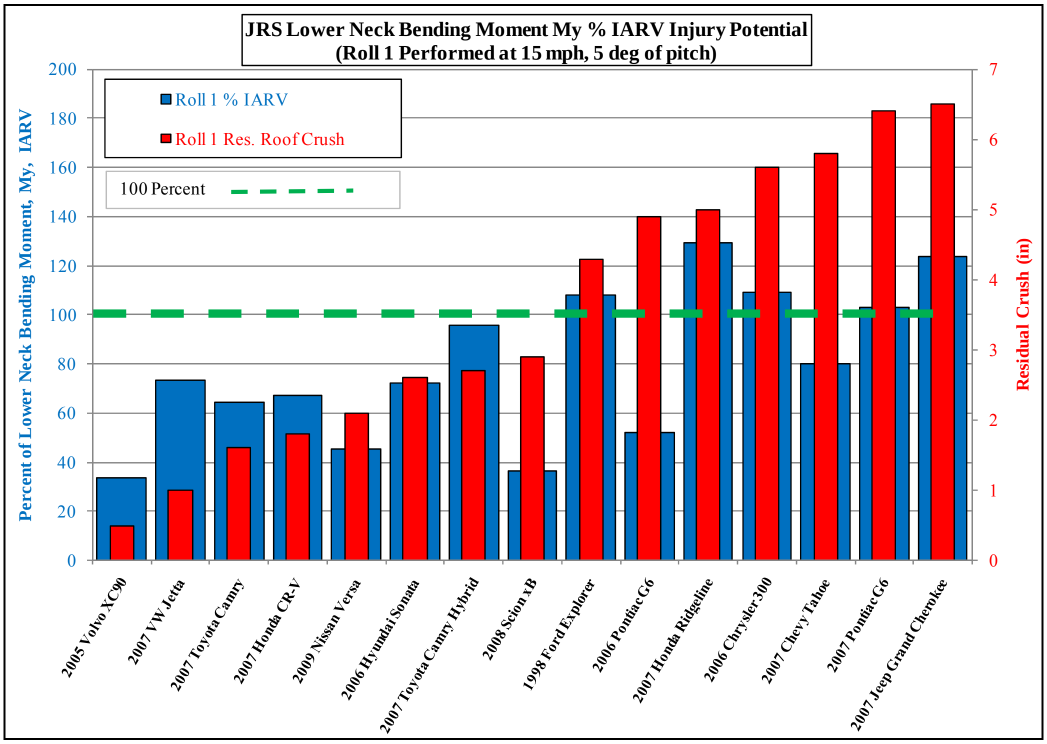

Figure 8. Residual crush in Roll 1 vs the percent of lower neck bending Moment to the IARV criteria

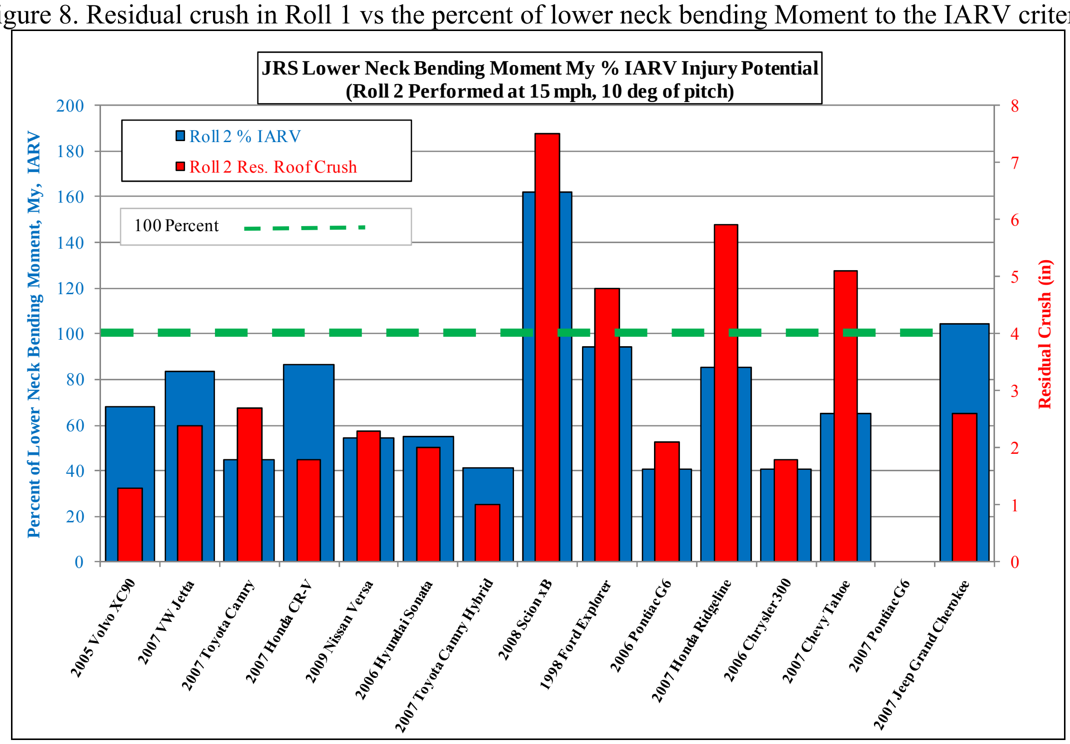

Figure 9. Residual crush in Roll 2 vs the percent of lower neck bending moment to the IARV criteria

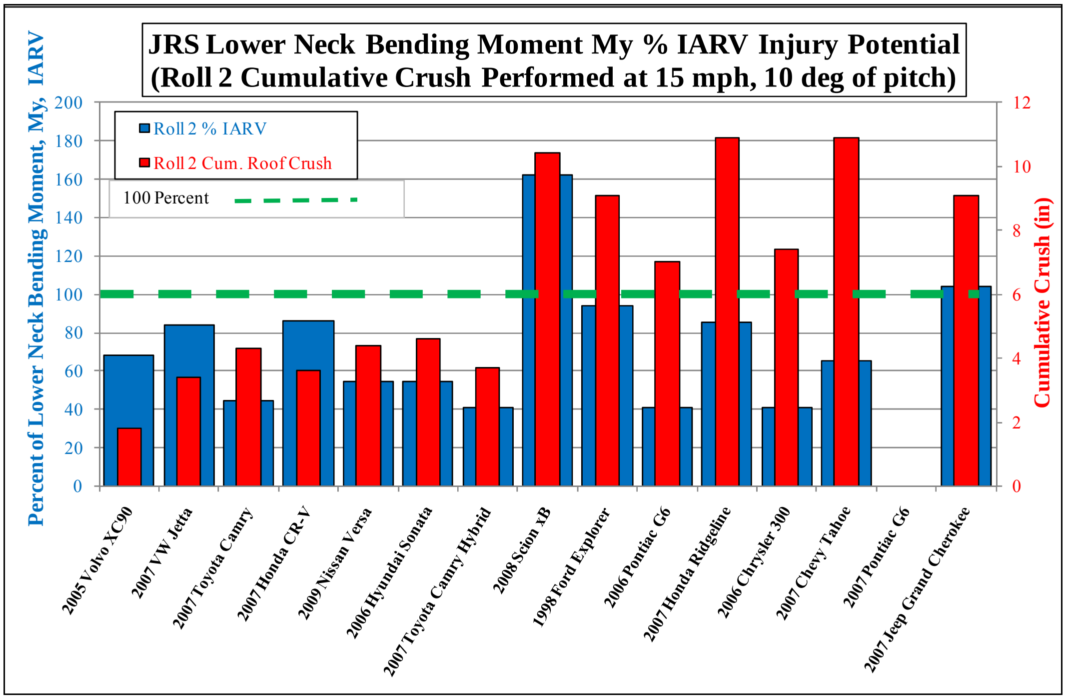

Figure 10. The relationship between cumulative residual crush in Roll 1 and 2 and the percent of lower neck bending moment relative to the IARV criteria

Figure 11 shows the relationship between the dummy neck compression loading and the applicable 4000 N IARV. Even if we assume a 6000 N IARV (corresponding to an IARV line at 150%), this peak value criteria is not a good measure of serious compression injury. Compression injuries have been shown to be about 10% of all serious neck injuries compared to 60% flexion and 30% extention injuries [16]. Considering the accepted consensus onset of injury impact speed of 3 to 4.4 m/sec (7 to 10 mph), it has been shown that these speeds correspond to 10,000 to 12,500 N [17].

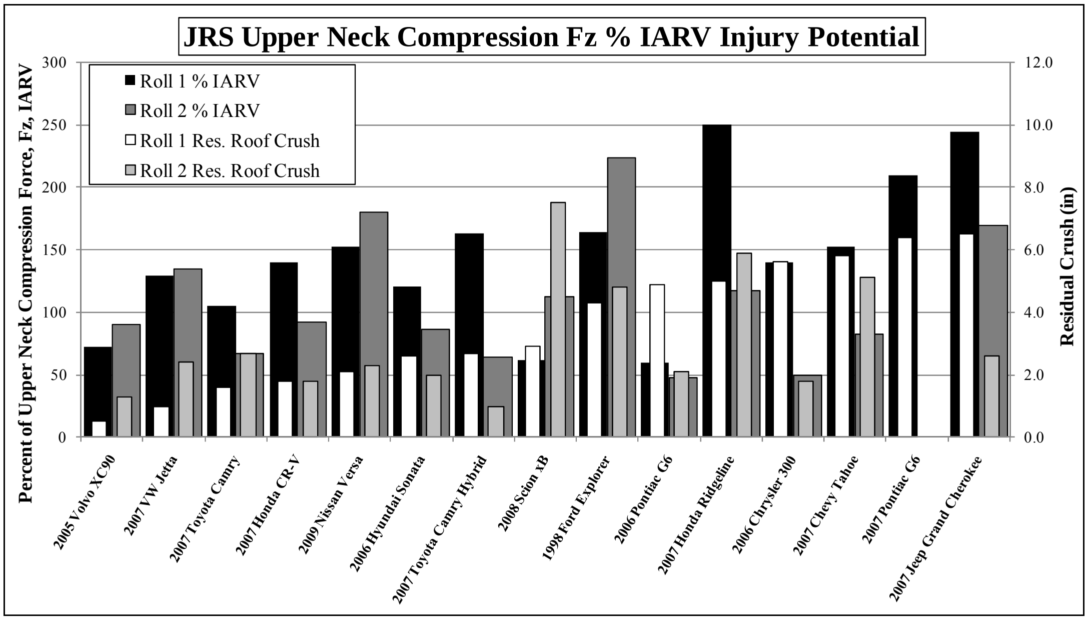

Figure 11. The relationship between upper neck compression force in each of two rolls expressed as a percent of the IARV criteria

JRS Tests Illustrating Geometric, Structural Construction and Impact Orientation Effects

A previous paper [18] has detailed the effects of vehicle roof geometry, construction and impact orientation. The variation in dynamic and residual roof crush and dummy injury measures at similar SWR are a direct consequence of these effects and they cannot be assessed by static tests. A prime example is the low severity JRS rolls of the 2008 Toyota Scion xB. This is a vehicle with an SWR of 6.8 and in a 10° of pitch JRS roll test, resulted in 25 cm (10”) of roof crush at 5.8 m/s (13 mph) with corresponding Injury measures. The data from that test is included in Annex A, Figure 14. Simply stated the vehicle’s roof is square with great headroom. When the near side impacted the roadbed at 145°, the rate of change of the major radius was so rapid as to limit the road load to about 13,200N (3000 lbs) which peaked at 157°. This caused most of the impact energy to be shifted to the far side at a peak of 40,040N (20,000 lbs.). Comparative data on the Honda CRV (Figure 15) and the Chevrolet Tahoe (Figure 16) are also included in Annex A.

CONCLUSIONS

1. A real world research protocol has been characterized and the segments have been analyzed for injury potential. In the context of a compliance test the first roll ballistic segment has been identified as most likely to produce serious to fatal injury.
2. Dynamic JRS rollover tests with various protocols of 40 vehicles have been roughly normalized to represent the first roll of a real world protocol and matched to NASS / CIREN injury risk potential to various body parts.
3. The static SWR of these vehicles were compared to NHTSA’s post crash headroom. Specific gross anomalies were identified as well as the geometry basis for IIHS’s injury rate disparities at similar SWRs.
4. Dynamic JRS tests provide detailed injury 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.
   - Useful in conjunction with consumer information as incentives to manufacturers.
   - As reliable as the injury criteria relating dummies to people.
   - Insightful for and supplemental to rollover injury research.
   - Likely to eliminate more casualties sooner than the regulatory comprehensive plan.
5. NHTSA's 5 year research plan complements and will eventually validate this cooperative project to develop a real world comparative evaluation and compliance test.

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REFERENCES

[1] K Digges and A M Eigen, 'Crash attributes that influence the severity of rollover crashes', 18th Enhanced Safety of Vehicles, Nagoya, Japan, 2003.
[2] F Tahan, 'Jordan rollover system sensitivity study for an elastic roof of a ford explorer FEA model', National Crash Analysis Center, GWU, 2010.
[3] Y Hu, C E Neal-Strugess, A Hassan and R Guo, 'Occupant kinematics in the rollover of a sports utility vehicle', ICrash, Birmingham Automotive Safety Centre, University of Birmingham 2006.
[4] K F Orlowski, R T Bundorf and E A Moffatt, 'Rollover crash tests – the influence of roof strength on injury mechanics', Society of Automotive Engineers, 1985.
[5] D Friedman and R Grzebieta, 'A proposed rollover and comprehensive rating system', 21st Enhanced Safety of Vehicle, Stuttgart, Germany, 2009.
[6] B Fildes and K Digges, 'Occupant protection in far-side crashes', National Crash Analysis Center, GWU, Monash University Accident Research Centre, 2009.
[7] K M Balavich, 'Dummy head kinematics in tripped rollover tests and a test method to evaluate the effect of curtain airbag deployment', Society of Automotive Engineers, Detroit, Michigan, 2002.
[8] S Bozzini, J Jimenez, R Grzebieta and D Friedman, 'Rollover protection – a meaningful & effective solution', Society of Petroleum Engineers International Conference, Rio de Janeiro, 2010.
[9] J Myklebust, A Sances, D Mainman, F Pintar, M Chilbert, W Rauschning, S Larson, J Cusick, C Ewing, D Thomas and B Saltzberg, 'Experimental spinal trauma studies in the human and monkey cadaver', Society of Automotive Engineers, 1983.
[10] C L Ewing, A I King and P Prasad, 'Structural considerations of the human vertebral column under +Gz impact acceleration', Naval Aerospace Medical Research Laboratory, Pensacola, Florida, 2001.
[11] R Austin, M Hicks and S Summers, '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.
[12] A Strashny, '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.
[13] S Mandell, R Kaufman, C D Mack, E M Bulger, 'Mortality and injury patterns associated with roof crush in rollover crashes', Accident Analysis and Prevention, 2010, 10.1016/j.aap.2010.02.013.
[14] D Friedman and G Mattos, 'The effect of static roof crush tests relative to real world rollover injury potential', ASME International Mechanical Engineering Congress and Exposition, Vancouver, BC, *In Press,* 2010.
[15] J Paver, "Rollover Crash Neck Injury Replication and Injury Potential Assessment", IRCOBI September 2008.
[16]B L Allen, R L Ferguson, T Lehmann and R P O'Brien, ' A mechanistic classification of closed, indirect fractures and dislocations of the lower cervical spine', Philadelphia, PA, 1982.
[17] C Ward, 'Repeatable rollover testing for injury analysis', American Academy of Forensic Sciences Annual Scientific Meeting, Washington, DC, 2008.
[18] D Friedman and R Grzebieta, 'Vehicle roof geometry and its effect on rollover roof performance', 21st Enhanced Safety of Vehicle, Stuttgart, Germany, 2009.

ANNEX A

Lower Neck IARV's for 10% Probability of an AIS ≥ 3 Injury

Neck Type	My (Nm) Flexion	My (Nm) Extension	Mx (Nm)	Axial Fz (N)
Production	380	−156	268	4000
Low Durometer	90-110	−38 - −46	59-90	1640-2000
Human/Cadaver	58			1500

Figure 12. Injury Measure Criteria

Vehicle	Headroom Measurement (inches)	Max. Lap Belt Load Roll 1 (lbs)	Max. Shoulder Belt Load Roll 1 (lbs)	Max. Lap Belt Load Roll 2 (lbs)	Max. Shoulder Belt Load Roll 2 (lbs)	Impact Angle, Roll Rate Roll 1	Impact Angle, Roll Rate Roll 2	Far Side Road Load Roll 1 (lbs)	Far Side Road Load Roll 2 (lbs)
2005 Volvo XC90	6.25	215	101	119	124	143º, 179º/sec	139º, 180º/sec	18,229	22.145
2007 VW Jetta	4.25	164	105	106	115	142º, 156/sec	143º, 172º/sec	17,362	20,798
2007 Toyota Camry	5	115	100	224	94	141º, 138º/sec	140º, 170º/sec	19,242	25,038
2007 Honda CR-V	4.25	123	102	126	119	143º, 196º/sec	141º, 209º/sec	16,115	14,264
2009 Nissan Versa	5	237	175	225	222	144º, 187º/sec	145º, 194º/sec	19,451	19,151
2006 Hyundai Sonata	4.5	127	93	200	190	143º, 133º/sec	145º, 166º/sec	17,711	31,380
2007 Toyota Camry (Hybrid)	5	177	136	154	123	143º, 180º/sec	136º, 185º/sec	20,024	28,919
2008 Scion xB	6.5	432	207	206	94	141º, 201º/sec	146º, 196º/sec	27,861	20,422
1998 Ford Explorer	3.75	104	69	62	7	146º, 183º/sec	143º, 186º/sec	15,964	25,624
2006 Pontiac G6	2.5	171	128	324	147	139º 172º/sec	140º, 175º/sec	19,062	33,406
2006 Honda Ridgeline	4.75	123	79	166	81	145º, 208º/sec	145º, 203º/sec	20,385	33,023
2006 Chrysler 300	4.5	137	101	539	127	146º, 161º/sec	147º, 156º/sec	24,001	43,085
2007 Chevrolet Tahoe	5.25	192	140	244	64	142º, 213º/sec	143º, 210º/sec	24,727	39,575
2007 Pontiac G6	4.75	87	92	N/A	N/A	142º, 172º/sec	N/A	19,185	N/A
2007 Jeep Grand Cherokee	3.5	125	91	30	10	147º, 197º/sec	149º, 190º/sec	23,908	32,293
2004 Volvo XC90 (White)	N/A	N/A	N/A	N/A	N/A	133º, 214º/sec	148º, 215º/sec	13,590	15,461
2004 Subaru Forester (Red)	N/A	N/A	N/A	N/A	N/A	147º, 223º/sec	150º, 139º/sec	14,723	15,756
2004 Land Rover Discovery II	N/A	122	102	74	38	136º, 212º/sec	145º, 207º/sec	13,608	10,240
2003 Subaru Forester (Tan)	N/A	N/A	N/A	125	114	147º, 212º/sec	151º, 173º/sec	15,283	13,151
2003 Subaru Forester (Green)	N/A	N/A	N/A	113	122	N/A	143º, 174º/sec	14,764	13,912
2002 Toyota Corolla	N/A	N/A	N/A	N/A	N/A	132º, 178º/sec	145º, 176º/sec	8,448	8,626
2001 Chevrolet Suburban	N/A	197	31	N/A	N/A	140º, 214º/sec	N/A	18,579	N/A
2000 GMC Jimmy	5	73	67	N/A	N/A	146º, 174º/sec	N/A	17,455	N/A
2000 Ford Explorer	N/A	N/A	N/A	N/A	N/A	134º, 200º/sec	144º, 188º/sec	9,263	14,251
1999 Oldsmobile Bravada	4.5	N/A	N/A	139	59	149º, 19º/sec	147º, 184º/sec	19,613	29,274
1999 Jeep Grand Cherokee	3	63	31	N/A	N/A	147º, 257º/sec	N/A	24,268	N/A
1999 Isuzu Vehicross	N/A	N/A	N/A	N/A	N/A	139º, 185º/sec	148º, 183º/sec	9,409	15,701
1999 Hyundai Sonata (Black-20.8mph)	4.5	68	29	N/A	N/A	145º, 275º/sec	N/A	20,232	N/A
1999 Hyundai Sonata	N/A	N/A	N/A	N/A	N/A	139º, 172º/sec	148º, 157º/sec	9,466	10,779
1998 MB ML320	4	N/A	97	N/A	N/A	144º, 231º/sec	N/A	17,143	N/A
1997 Chevrolet Cavalier	2.75	95	149	N/A	N/A	142º, 231º/sec	N/A	20,577	N/A
1997 Acura CL 2.2	4	136.6	76.3	N/A	N/A	144º, 205º/sec	N/A	15,351	N/A
1996 Isuzu Rodeo	8.75 X	74.3	78.7	N/A	N/A	148º, 239º/sec	N/A	18,946	N/A
1993 Jeep Grand Cherokee	4.75	160	N/A	N/A	N/A	148º, 244º/sec	N/A	25,068	N/A

Figure 13. Reference measurements for JRS Tests (x=5th % Dummy)

Figure 14. 2008 Scion xB

Roll 1 – 02/10/2010

Summary of Results

Instrument	Peak Value	Residual Intrusion (inches)	Peak Velocity (mph)
Sum of Vertical Load Cells (near side contact)	8,199 lbs		
Sum of Vertical Load Cells (far side contact)	27,861 lbs		
Sum of Lateral Load Cells (near side contact)	1,683 lbs		
Sum of Lateral Load Cells (far side contact)	3,253 lbs		
Driver's Side A-Pillar String Potentiometer	5.2 in	2.9	6.1
Driver's Side B-Pillar String Potentiometer	3.4 in	1.7	5.6
Roof Header String Potentiometer	3.7 in	1.8	6.1
Passenger's Side A-Pillar String Potentiometer	0.4 in	-0.3	1.7

Instrument	Maximum Value	Minimum Value
Lab Belt Load	432 lbs	0 lbs
Shoulder Belt Load	207 lbs	-5 lbs
Dummy Head Acceleration Ax	22 g	-5 g
Dummy Head Acceleration Ay	25 g	-2 g
Dummy Head Acceleration Az	14 g	-1 g
Lower Neck Load Cell Fx	566 N	-54 N
Lower Neck Load Cell Fy	289 N	-29 N
Lower Neck Load Cell Fz	700 N	-139 N
Lower Neck Load Cell Mx	14 N-m	-28 N-m
Lower Neck Load Cell My	6 N-m	-33 N-m
Upper Neck Load Cell Fz	483 N	-1,007 N

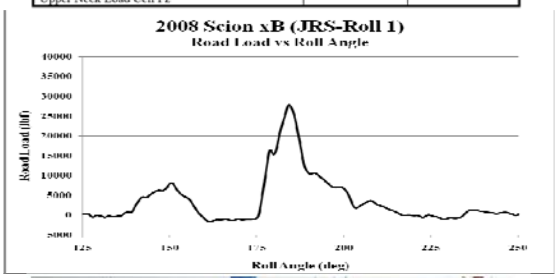


Figure 1: Vehicle Pre Roll 1

Figure 2: Vehicle Post Roll 1

of Roll 2 of the Toyota Scion xB with Low durometer Neck

Roll 2 – 02/12/2010

Summary of Results

Instrument	Peak Value	Residual Intrusion (inches)	Peak Velocity (mph)
Sum of Vertical Load Cells (near side contact)	3,283 lbs		
Sum of Vertical Load Cells (far side contact)	20,422 lbs		
Sum of Lateral Load Cells (near side contact)	664 lbs		
Sum of Lateral Load Cells (far side contact)	2,392 lbs		
Driver's Side A-Pillar String Potentiometer	10.9 in	7.5	13.0
Driver's Side B-Pillar String Potentiometer	4.6 in	2.7	5.8
Roof Header String Potentiometer*	13.5	10.0	13.7
Passenger's Side A-Pillar String Potentiometer	0.1 in	-0.2	1.4

*String Pot value measured by video analysis

Instrument	Maximum Value	Minimum Value
Lab Belt Load	206 lbs	-2 lbs
Shoulder Belt Load	94 lbs	-1 lbs
Dummy Head Acceleration Ax	44 g	-21 g
Dummy Head Acceleration Ay	28 g	-9 g
Dummy Head Acceleration Az	18 g	-5 g
Lower Neck Load Cell Fx	863 N	-302 N
Lower Neck Load Cell Fy	211 N	-542 N
Lower Neck Load Cell Fz	70 N	-937 N
Lower Neck Load Cell Mx	8 N-m	-29 N-m
Lower Neck Load Cell My	146 N-m	-18 N-m
Upper Neck Load Cell Fz	127 N	-1,842 N

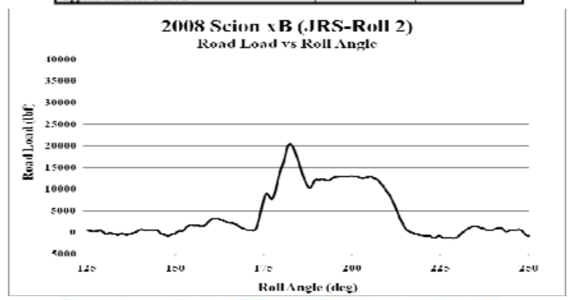


Figure 3: Vehicle Pre Roll 2

Figure 4: Vehicle Post Roll 2

Figure 15. 2007 Honda CRV

Roll 1 – 12/17/2008

Summary of Results

Instrument	Peak Value	Residual Intrusion (inches)	Peak Velocity (mph)
Sum of Vertical Load Cells (near side)	15,032 lbs		
Sum of Vertical Load Cells (far side)	16,115 lbs		
Sum of Lateral Load Cells (near side)	1,410 lbs		
Sum of Lateral Load Cells (far side)	1,328 lbs		
Driver's Side A-Pillar String Potentiometer	3.4 in	1.8	4.0
Driver's Side B-Pillar String Potentiometer	2.0 in	0.8	2.6
Roof Header String Potentiometer	1.2 in	-0.1	3.3
Passenger's Side A-Pillar String Potentiometer	1.7 in	0.6	3.3

Instrument	Maximum Value	Minimum Value
Lower Neck Load Cell, Fx	1,125 N	-87 N
Lower Neck Load Cell, Fy	192 N	-525 N
Lower Neck Load Cell, Fz	263 N	-4,873 N
Lower Neck Load Cell, Mx	67 N m	-38 N m
Lower Neck Load Cell, My	255 N m	-32 N m
Upper Neck Load Cell, Fz	178 N	-5,583 N
Upper Neck Load Cell, Mx	18 N m	-74 N m
Upper Neck Load Cell, My	49 N m	-9 N m
Upper Neck Injury Criteria*	1.02	0
Lower Neck Injury Criteria**	1.20	0
Belt Load Cell - lap	123 lbs	0 lbs
Belt Load Cell - torso	102 lbs	0 lbs

*Based on injury measures presented in Mertz, et. al., 2003.
**Based on injury measures presented by NHTSA.

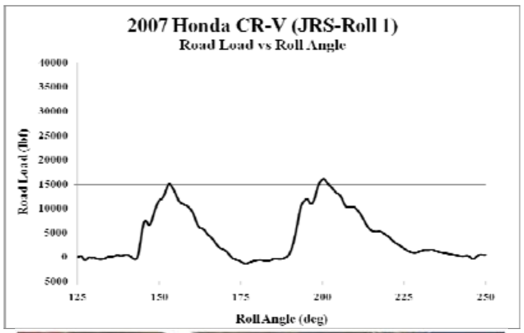


Figure 1: Vehicle Pre Roll 1

Figure 2: Vehicle Post Roll 1

of Roll 2 of the 2007 Honda CRV with Production Neck

Roll 2 – 12/18/2008

Summary of Results

Instrument	Peak Value	Residual Intrusion (inches)	Peak Velocity (mph)
Sum of Vertical Load Cells (near side)	11,128 lbs		
Sum of Vertical Load Cells (far side)	14,264 lbs		
Sum of Lateral Load Cells (near side)	879 lbs		
Sum of Lateral Load Cells (far side)	1,659 lbs		
Driver's Side A-Pillar String Potentiometer	4.7 in	1.8	5.3
Driver's Side B-Pillar String Potentiometer	2.6 in	0.6	3.4
Roof Header String Potentiometer	4.8 in	1.3	5.4
Passenger's Side A-Pillar String Potentiometer	2.0 in	0.6	2.4

Instrument	Maximum Value	Minimum Value
Lower Neck Load Cell, Fx	927 N	-170 N
Lower Neck Load Cell, Fy	26 N	-843 N
Lower Neck Load Cell, Fz	171 N	-3,496 N
Lower Neck Load Cell, Mx	8 N m	-107 N m
Lower Neck Load Cell, My	328 N m	-34 N m
Upper Neck Load Cell, Fz	133 N	-3,687 N
Upper Neck Load Cell, Mx	90 N m	-28 N m
Upper Neck Load Cell, My	18 N m	-103 N m
Upper Neck Injury Criteria*	1.30	0
Lower Neck Injury Criteria**	1.10	0
Belt Load Cell - lap	126 lbs	0 lbs
Belt Load Cell - torso	119 lbs	0 lbs

*Based on injury measures presented in Mertz, et. al., 2003.
**Based on injury measures presented by NHTSA.

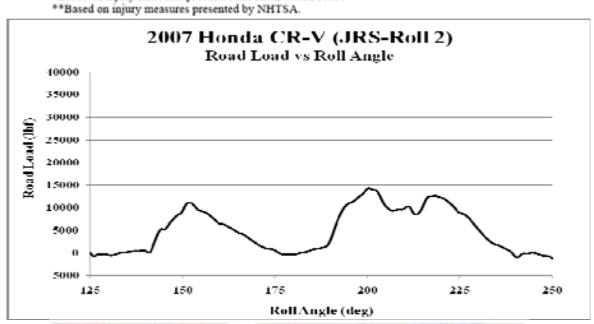


Figure 3: Vehicle Pre Roll 2

Figure 4: Vehicle Post Roll 2

2007 Chevrolet Tahoe

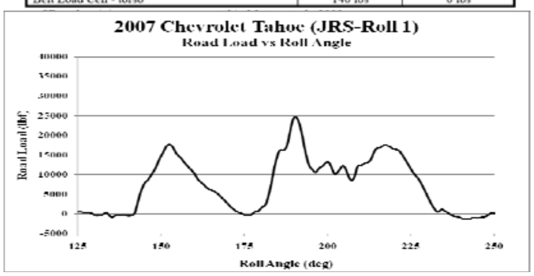
Roll 1 – 11/7/2008

Summary of Results

Instrument	Peak Value	Residual Intrusion (inches)	Peak Velocity (mph)
Sum of Vertical Load Cells (near side)	17,664 lbs		
Sum of Vertical Load Cells (far side)	24,727 lbs		
Sum of Lateral Load Cells (near side)	1,576 lbs		
Sum of Lateral Load Cells (far side)	1,377 lbs		
Driver's Side A-Pillar String Potentiometer	7.9 in	5.8	6.1
Driver's Side B-Pillar String Potentiometer	5.2 in	3.5	4.2
Roof Header String Potentiometer*	--	--	--
Passenger's Side A-Pillar String Potentiometer	1.2 in	0.1	1.9

*The roof header string potentiometer attachment moved slightly at the start of the roof crush.

Instrument	Maximum Value	Minimum Value
Lower Neck Load Cell, Fx	797 N	-161 N
Lower Neck Load Cell, Fy	77 N	-692 N
Lower Neck Load Cell, Fz	973 N	-4,726 N
Lower Neck Load Cell, Mx	56 N m	-86 N m
Lower Neck Load Cell, My	304 N m	-85 N m
Upper Neck Load Cell, Fz	1,024 N	-6,101 N
Upper Neck Load Cell, Mx	112 N m	-34 N m
Upper Neck Load Cell, My	41 N m	-37 N m
Upper Neck Injury Criteria*	1.09	0
Lower Neck Injury Criteria**	1.26	0
Belt Load Cell - lap	192 lbs	0 lbs
Belt Load Cell - torso	140 lbs	0 lbs



Roll 1 Comparison Photographs

Figure 1: Vehicle Pre Roll 1

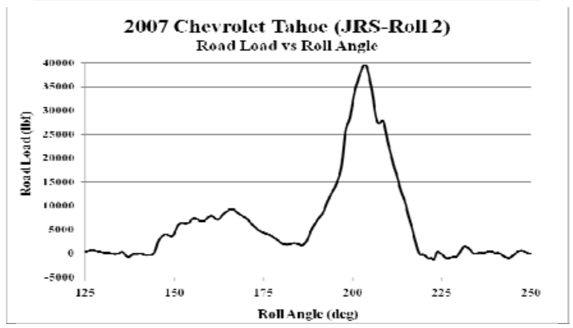
Figure 2: Vehicle Post Roll 1

Roll 2 – 11/9/2008

Summary of Results

Instrument	Peak Value	Residual Intrusion (inches)	Peak Velocity (mph)
Sum of Vertical Load Cells (near side)	9,295 lbs		
Sum of Vertical Load Cells (far side)	39,575 lbs		
Sum of Lateral Load Cells (near side)	1,173 lbs		
Sum of Lateral Load Cells (far side)	1,717 lbs		
Driver's Side A-Pillar String Potentiometer	8.2 in	5.1	11.6
Driver's Side B-Pillar String Potentiometer	6.3 in	3.4	7.0
Roof Header String Potentiometer	7.2 in	4.6	8.8
Passenger's Side A-Pillar String Potentiometer	3.3 in	-1.3	3.2

Instrument	Maximum Value	Minimum Value
Lower Neck Load Cell, Fx	1,676 N	-43 N
Lower Neck Load Cell, Fy	350 N	-481 N
Lower Neck Load Cell, Fz	149 N	-2,982 N
Lower Neck Load Cell, Mx	17 N m	-145 N m
Lower Neck Load Cell, My	247 N m	-21 N m
Upper Neck Load Cell, Fz	585 N	-3,318 N
Upper Neck Load Cell, Mx	81 N m	-49 N m
Upper Neck Load Cell, My	32 N m	-46 N m
Upper Neck Injury Criteria*	0.81	0
Lower Neck Injury Criteria**	0.87	0
Belt Load Cell - lap	244 lbs	0 lbs
Belt Load Cell - torso	64 lbs	0 lbs



Roll 2 Comparison Photographs

Figure 3: Vehicle Pre Roll 2

Figure 4: Vehicle Post Roll 2