Design, development and validation of rollover dummy injury measures

D Friedman, J Paver, Ph.D., R McGuan

Center for Injury Research, Goleta, California

Abstract - Existing and proposed U.S. rollover standards test only vehicle structural roof strength; there is no U.S. regulatory requirement based on dummy neck injury criteria for rollover occupant protection. The global New Car Assessment Program (NCAP) has adopted or is adopting a static roof strength test protocol similar to the U.S. Federal Motor Vehicle Safety Standard (FMVSS) 216 to certify and rate vehicles to strength-to-weight ratios (SWRs) varying from country to country between SWR= 2.5 to SWR=4.0. These vehicle tests and measurements were seemingly developed to predict the likelihood of inadequate dynamic neck injury protection performance. There now exists an extensive body of literature that lend credence to the claim that static roof strength tests are unreliable ways of ensuring safe vehicle designs. The vehicle and human structures in dynamic circumstances are nonlinear. Dummy neck injury measures best evaluate vehicle, geometry and occupant protection device effectiveness.

Keywords: Dummy, rollover, biomechanics, JRS, testing

INTRODUCTION AND HISTORY

There is no doubt that a dynamic rollover test, like those of frontal and side impact tests, is the best way to comparatively assess vehicle structural and occupant protection features. Four inter-related factors effect the choice of a dynamic compliance or NCAP test over that of a static roof strength test; 1.) an appropriately biofidelic dummy, 2.) dummy injury criteria, 3.) representative vehicle impact severity characteristics and 4.) a repeatable fixture for testing both, like the Jordan Rollover System (JRS). These factors are addressed in that order in this paper to report on current results.

The efforts of the Insurance Institute for Highway Safety (IIHS) have had a dramatic effect on new production vehicle structural roof strength which is now improving over a 10 year life cycle [1]. However, the fleet population takes a further 15 years to reflect the injury and fatality reduction. There is also a certain resistance to change or at least a requirement for overwhelming experimental proof of the need for change. That is probably why the dynamic tests for frontal and side impacts required in 1970 were finally implemented in 1995 and not yet fully effective [2,3]. This then leads to this opportunity to present our current research progress in improving rollover safety performance.

The magnitude of the U.S. rollover tragedy is shown in Figure 1. From the inception of the Fatal Accident Reporting System (FARS) in 1978 until 2008 [4], almost 318,000 lives have been lost in rollovers and three times more have been seriously injured [5].

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

Figure 1. Annual crash and rollover fatalities, 1978 to 2008

The regulatory problem in 1970 was, that although there were many crash investigations which related rollover roof crush to head and neck injury, there was no proof of a causal relationship. Then in 1985 and 1990 GM offered misleading interpretations of 16 dolly rollover tests as a massive proof that there was no causal relationship. The tests were conducted at 32 mph on 1983 rear wheel drive Malibu vehicles (with a strength to weight ratio (SWR) of 2.0) and a production Hybrid III dummy with an erect, axially-aligned neck. The 1985 paper [6] described eight of the vehicles (4 production and 4 roll caged) containing driver and passenger unbelted dummies seated erectly with upper neck instrumentation which resulted in potentially injurious injuries (Pii). The conclusion was that the average Pii of production vehicle dummies was 3,688 and roll caged was 3,318 so that roof strength had no significance.

The biomechanical community then initiated research on head/neck PMHS specimens with aligned vertebral bodies and a perpendicular impactor. They produced axial compression fractures and buckling of the cervical column which after the compression, were displaced relative to each other in much the same way the vertebral bodies were displaced in a compression flexion or hyperflexion bending injury. Because the impactor only had to move an inch or two, the experimental evidence supported the concept of severe neck compression or bending injury occurring before significant roof crush. Over the years some radiologists interpret almost all post injury CT scans as axial compression rather than bending (compression flexion) neck injuries. This is a complete reversal of a mechanistic study of lower neck injuries written by four neurosurgeons in a 1982 paper [7].

From 1996 thru 1998 new studies and experimentation led from a National Analysis Sampling System (NASS) analysis to the extent of roof crush in relation to injury shown in Figure 2 [8].

Restrained Occupant Injuries	Average Roof Crush		Average Impact Velocity	
	cm	in	kph	mph
None	4.67	1.84	3.0	1.9
No Head, Face, or Neck	6.12	2.41	3.5	2.2
Head, Face and Neck @ AIS 1-2	9.80	3.86	4.5	2.8
Neck @ AIS 2-6	18.38	7.24	6.5	4.0
Head and Face @ AIS 3-6	26.69	10.51	8.5	5.3

Figure 2. NASS data results for restrained rollover occupants

The studies were followed by a series of human rollover and drop test experiments with dummies and humans leading to the development of measuring equipment and the current results reported here. Investigation of vehicle rollover structural deformation characteristics began in 1999 and in 2001 NHTSA initiated a program to upgrade or revise FMVSS 216 [9].

An effort to develop a dynamic rollover test fixture began in 2002 and the Jordan Rollover System (JRS) became operational in Santa Barbara, California in 2004. Early tests investigated the relationship between roof crush and strength to weight ratio (SWR). By 2007 the Hybrid III dummy was incorporated into the vehicle test on the JRS fixture. Soon thereafter, it became obvious that the dummy neck was at least ten times stiffer in bending than that of an un-tensed or neutral human neck such that it could not be pre-flexed. A modification to the neck attachment plate was created to pre-flex the neck by 30°.

It was also determined that the production neck, even when pre-flexed, interfered with the motion of the head in contacting the roof and the roof rail. An identical neck of 30 durometer rubber (rather than 60 durometer) was fabricated and pendulum calibrated dynamically. The low durometer prototype neck represents about two-thirds the compression and one-third the bending stiffness of the production Hybrid III neck. While it was possible to measure the lower neck bending of the stiff production neck, the visual observations of bending in Figure 3 is clearer.

Figure 3. Scion xB bent and twisted neck

In the last four years rollover research has produced real world injury distribution data by body part confirming the predominance of spinal bending injuries, and thoracic and head injuries: 1.) 2008 NHTSA Stephen Ridella [10], 2.) 2010-2011 study by Kerrigen and Jeff Crandall [11,12], 3.) 2010 study by Kerrigen, Anna Marie Eigen, et al. [13]. 4.) UNSW study by Bambach, et al. [14].

Repeatable fixtures based on the JRS patent have been built and come into research use at University of Virginia (UVa) and University of New South Wales (UNSW) [15,16]. Parameter studies by finite element analysis with a MADYMO human facet dummy have been conducted at UVa and GWU [17].

The approach in this study has been to characterize, by experimentation, the four elements of the problem: the dummy occupant, dummy injury criteria, the vehicle and the fixture to conduct a typical injury accident scenario test. This paper will focus on the dummy and injury measure criteria; dealing with vehicles, fixtures and test protocols only to the extent necessary to provide context to their relationship and validate the results.

METHODS

A plethora of research has shown that static roof strength tests are an unreliable way of ensuring safe vehicle design due, in part, to the fact that the vehicle and human structures in dynamic circumstances are nonlinear. Dummy injury measures best evaluate vehicle, geometry and occupant protection device effectiveness.

A traditional iterative method has been used to: 1.) adjust and characterize the Hybrid III surrogate's body part orientation, musculature and flexibility starting with the neck, 2.) consider the available injury criteria and 3.) validate comparative performance by injury measure in JRS tests characterizing the typical rollover environment and its affect on dummy kinematics.

A dynamic rollover test is the most effective way to comparatively assess vehicle structural and occupant protection features. The following inter-related factors affect the choice of a dynamic compliance or NCAP test:

1) representative vehicle impact severity characteristics,
2) a repeatable test fixture, like the Jordan Rollover System (JRS),
3) an appropriately-biofidelic dummy, and
4) dummy neck injury criteria.

Characterizing the occupant

There were three relevant experimental studies preceding the Malibu tests.

1.) A 1982 mechanistic study that identified lower neck injury mechanisms to be 60% flexion, 30% extension and 10% axial compression [7].
2.) A 1983 PMHS drop test study which indicated that an axial compression neck injury requires an aligned neck which is perpendicular to the impact surface within 11 degrees [18].
3.) A 1978 diving study which developed a consensus for a seven mph onset of head and neck injury simulated by the 50^{th} percentile male Hybrid III dummy [19].

These human real world studies in combination make an axial compression neck injury extremely unlikely. Nevertheless the Hybrid III dummy in the Malibu tests were seated erectly such that the stiff aligned neck would be roughly perpendicular to the intruding roof and without lower neck instrumentation as shown in Figure 4.

Figure 4. Malibu II neck orientation

The 1990 Malibu paper [20] discussed eight identical tests conducted with belted Hybrid III dummies which resulted in the potentially injurious injuries (Pii) shown in Figure 5. The dummies were described as moving "up and out" towards and being in contact with the roof when it contacted the ground. The conclusion was that there was similar average Pii force of 3388 N for roll caged and 5168 for production vehicles. The Malibu II authors identified two of the four production vehicles which resulted in three axially aligned compression Pii's exceeding 10,000 Newtons (corresponding to a 7mph, 18 inch drop height). Only those three Piis of 94 in the 16 Malibu I and II rollovers were perpendicular to the dummy head/neck within the 11 degree misalignment tolerance. A second conclusion was that the 10,000 N "peak neck load (Pii force) occurred before significant roof crush" (2.5 to 5 cm, an inch or two). Subsequently some biomechanicists suggest that all "neck injury occurs before significant roof crush". No mention was made of the other 37 lower force Malibu II Piis that must have experienced at least an insignificant amount (2.5 to 5 cm, an inch or two) of roof crush. Those roofs must not have been perfectly aligned with the dummy neck. This is a new observation and refutes suggestions that axial compression is the principal cause of neck injury.

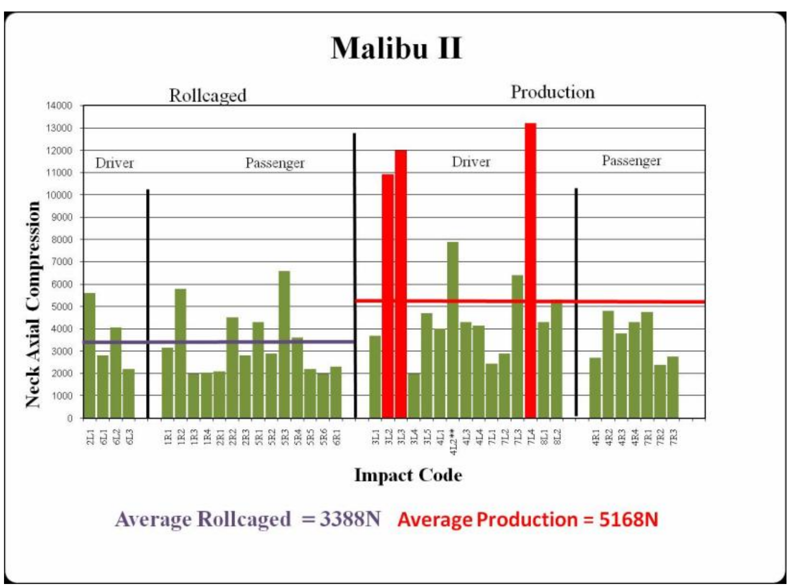


Figure 5. Malibu tests with belted III dummies

In 1996, the author statistically studied injury in rollovers and in 1998, concluded that injury severity was a function of the extent of roof crush [21]. At the same time it was decided to investigate the difference between human and dummy kinematics. The 1998 paper and a sequence of experiments indicated that head and neck injury would not occur to a belted occupant without significant roof crush. A fixture was built rigidizing a 1983 Malibu compartment, a dummy occupant and a human of equivalent size and weight, both restrained only by the production belts, were inverted and dropped from a height of 30 cm (one foot). By studying high-speed films it was determined that the human's interaction with the belt, in being inverted, resulted in the head and neck being pre-flexed by the time the vehicle roof hit the ground. Subsequent experiments at 50 cm and 90 cm drop heights confirmed the conclusion. Figure 6 includes frames from the drop test [Courtesy of Friedman Research] never before released, which identify the time history and motion amplitude of the pre-flexing head/neck.

Figure 6. (Left) Dummy and human in drop test fixture.
(Right) High speed video frames of 30-cm drop test

The inertial reaction to the release of the compartment causes the human body to experience free-fall and resets neutral muscular tension. The top frame shows the head target coming into view of the high-speed camera at 72 ms. In the 30 cm (12 inches) drop test, the roof contacts the ground at 250 ms. The middle frame shows the occupants after the vehicle contacts the ground at 272 ms and the head is flexing chin-to-chest. The target is about 7.6 cm (3 inches) from the roof (measured from the roof rail). In the bottom frame at 360 ms the human volunteer exhibits about 40° of inertial-induced flexion of the head, neck and thoracic spine limited by his lap-and-shoulder belt. At this point, the head target is approximately 12.7 cm (5 inches) off the roof (measured from the roof rail) and 8.9 cm (3.5 inches) forward of its initial position. In the test the human volunteer barely contacted the roof and neck loading was minimal, whereas the dummy head-roof contact was more forceful and resulted in an axial neck force of 4,255 N (967 pounds).

Figure 7 is a similar example of pre-flexion and shows an un-validated finite element vehicle rollover analysis where the inversion of a 50th percentile Madymo human facet neck/spine dummy without muscle restraints flexes to the joint limits [22].

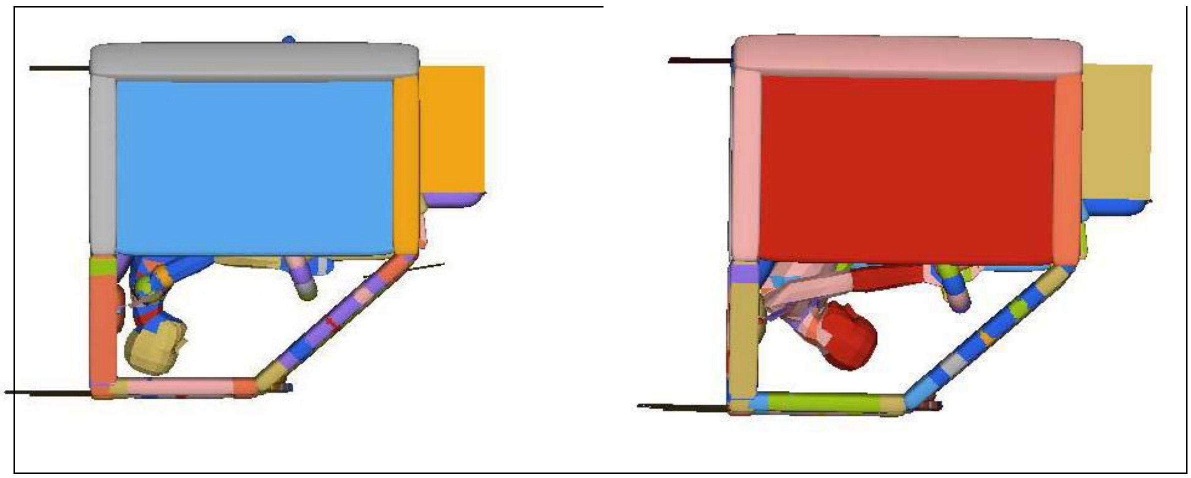


Figure 7. Side view of human facet model rollover simulation with active muscle restraints (left) and without active muscle restraints (right)

Biomechanical consensus on the predominant human neck injury has been thwarted by the Malibu tests with the Hybrid III dummy and the aforementioned aligned axial compression experiments with PMHS head/neck specimens. The issue is that some post injury radiology (CT Scans) can be interpreted either as buckling of an axial compression injury or as a traditional lower neck bending injury. The injury mechanism difference is that the former occurs almost instantaneously and before 5 cm (2 in) of roof crush, while the latter occurs over a duration of 60 to 140 ms and 15 cm (6 in) or more of roof crush.

In the stiff neck Hybrid III dummy surrogate world, the difference between axial compression and compression flexion is easily discerned by the misaligned lower amplitude of force before significant roof crush and the subsequent bending moment of the lower neck. To resolve these issues the dummy neck and spine combination has to be reasonably representative of the human skeleton and musculature. Thus far the pre-flexed orientation and bending musculature has been replicated to 3 times neutral or un-tensed strength, but compression stiffness is still six times greater than neutral. Current efforts to improve the biofidelity of the Hybrid III component body parts are described later in this paper.

Neck injury risk criteria

There are three injury risk or injury probability criteria:

- SWR vs. Injury rate derived by IIHS statistical analysis of incapacitating and fatal injuries
- Residual crush derived from NASS / CIREN statistical data and
- A proposed AIS injury map of composite dynamic impact crush and speed.

There are also 5 neck bending injury criteria proposed for use with the modified Hybrid III dummy neck:

1.) Pintar's hyperflexion Fz and
2.) Pintar's hyperflexion My [23],
3.) The production lower neck bending IARV,
4.) The product of dummy head speed and motion,
5.) Lower neck Integrated Bending Moment (IBM) [24].

In order to compare the possible dummy injury measures and the probability of injury (injury risk) for a particular test result, each measure will be resolved into a normalized value which is a percent of its criteria, i.e. a bending moment of 190 Nm relative to an IARV criteria of 380 Nm would have a normalized value of 50%.

IIHS injury rate reduction

The 2008 IIHS analysis of incapacitating and fatal driver injuries of 1990-1995 SUVs indicated a reduction of 28% for each increment of SWR [25]. Their injury rate reduction and the associated effects on ejection, etc. are plotted in Figure 8 with the results of 21 JRS tests.

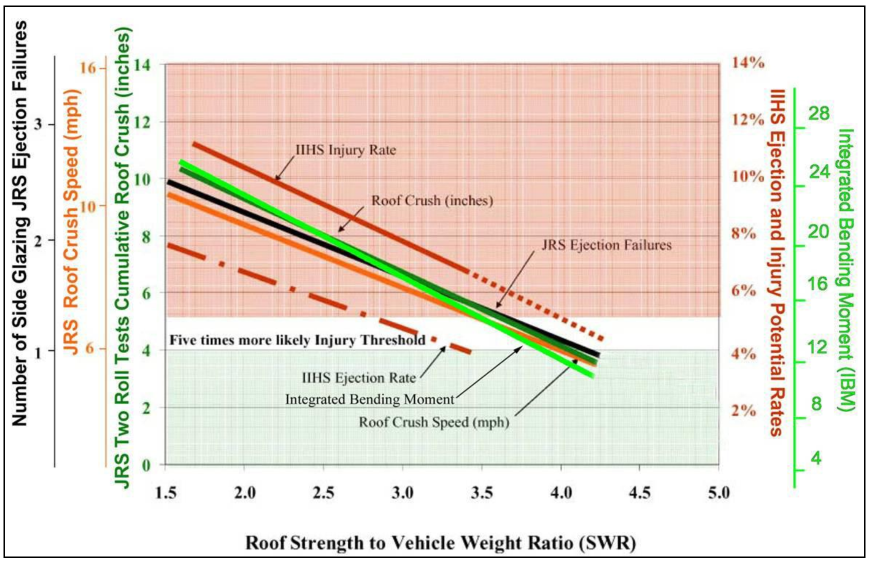


Figure 8. Neck injury risk criteria

NASS/CIREN statistical injury risk

Neck injury risk analysis results, based on residual crush of the U.S. fleet and the NASS/CIREN files, are shown in Figure 9 [26]. The probability of fatality or spinal, spinal cord and/or head-brain injuries can be predicted as a function of residual crush.

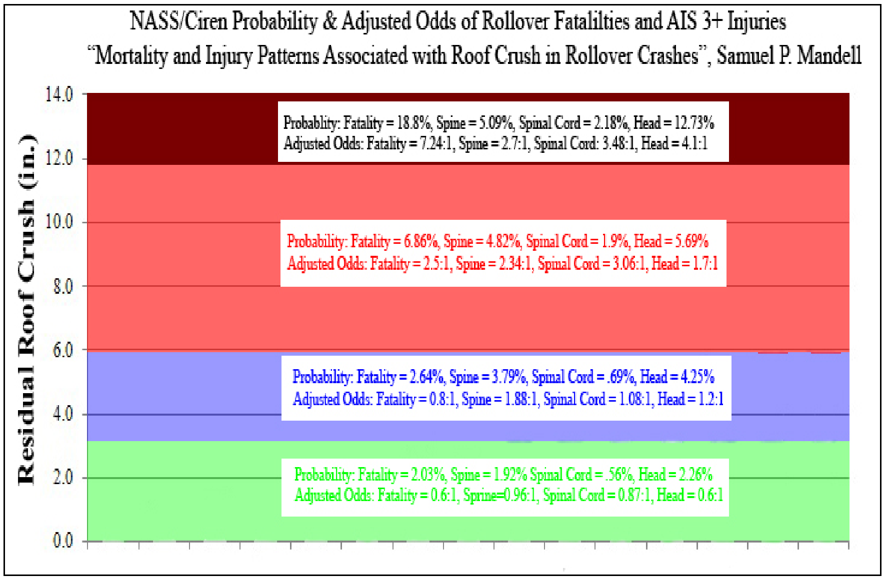


Figure 9. The residual crush injury risk criteria

It is important to note that this neck injury probability analysis was conducted for vehicle crash data from 1993 to 2006. The vehicles in the fleet during the study period were of significantly older vintage and had an estimated SWR of 2+ and elasticity {(dynamic – residual) / dynamic} of about 30%. Current new vehicle roof strength and elasticity is now typically at an SWR of 4+ and elasticity of 60% as shown in Figure 10.

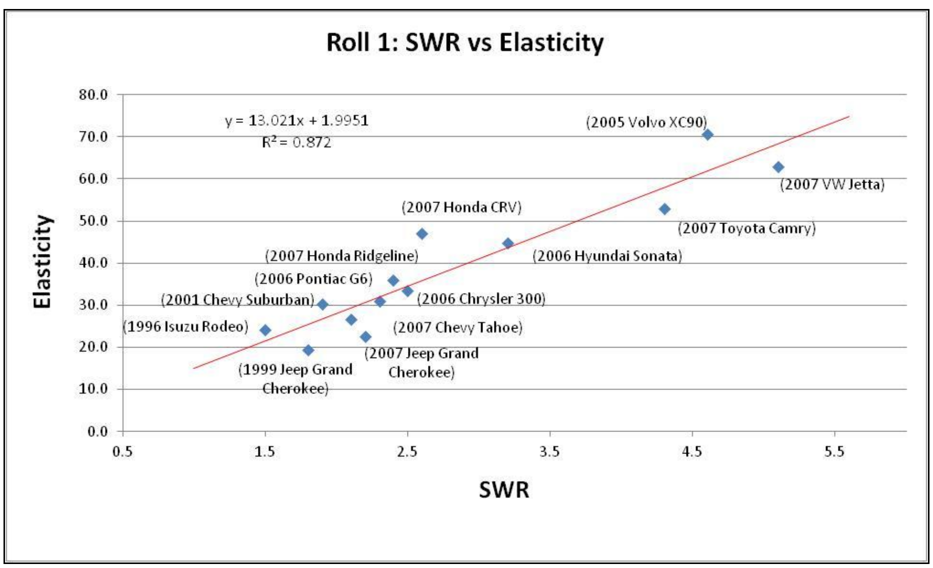


Figure 10. SWR and elasticity

The detailed probability of injury for fatalities, spinal, spinal cord and head/brain AIS = 3+ are shown in Figure 11 [27].

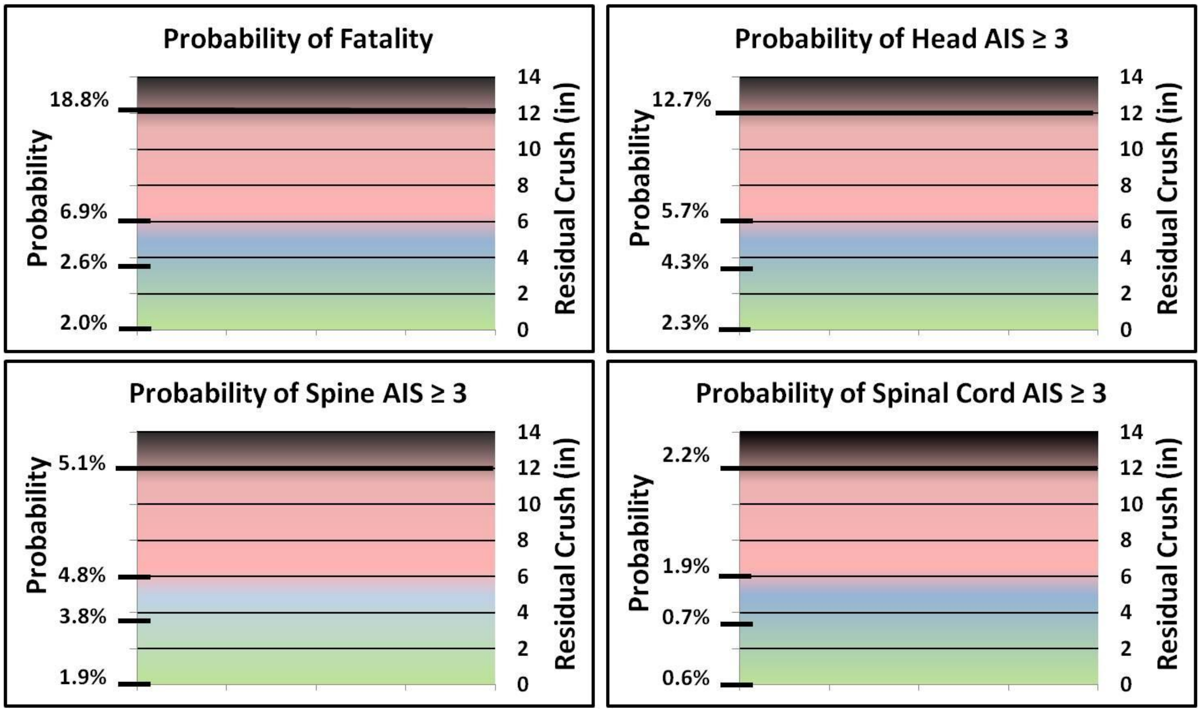


Figure 11. Probabilities of fatality, head, spine and spinal cord injuries

Since JRS tests identify the residual/dynamic ratio it provides a basis for adjusting measured residual crush relative to the fleet average values and therefore the probability of injury. The difference is illustrated in Figure 12.

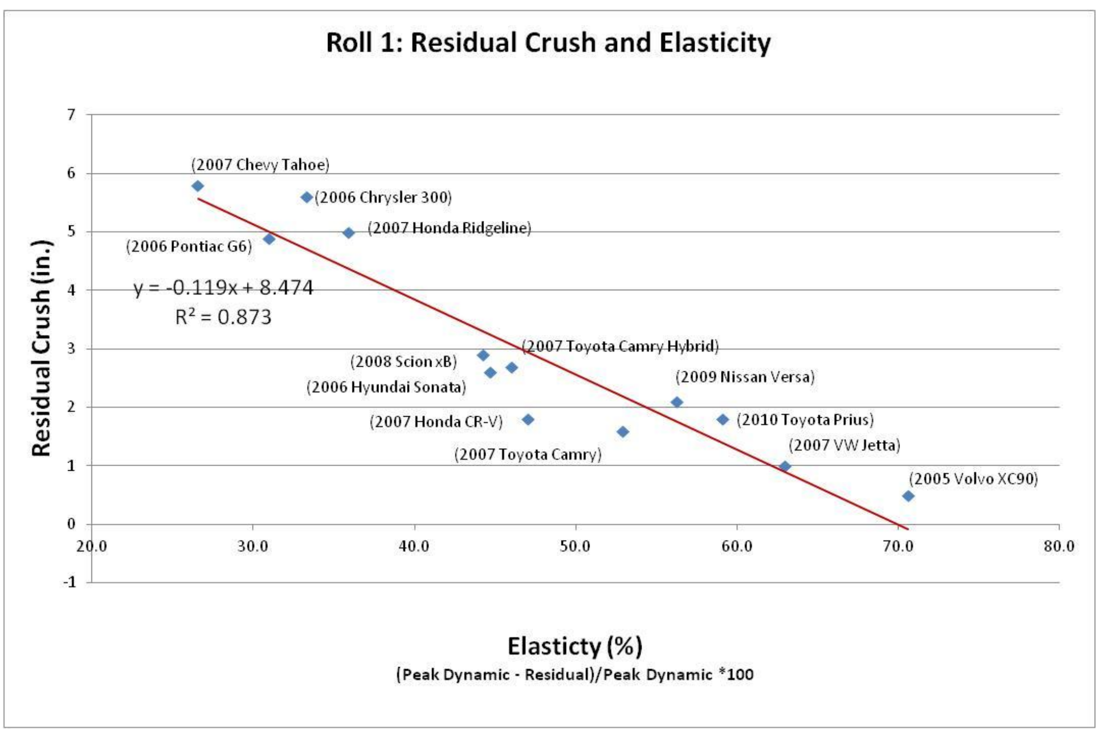


Figure 12. Residual roof crush v. elasticity for various vehicles

To evaluate current model vehicles relative to injury probability it is then necessary on average to double the measured residual crush or more specifically to multiply by the dynamic to residual elasticity ratio compared to 30%. To compare to dummy injury measures, the criteria for normalization of 3.5 inches of residual crush applies the concept of acceptable performance to account for inexplicable injury.

Dynamic injury risk criteria

The dynamic injury risk criteria of six inches of crush and 8 mph of crush speed were taken from the AIS map of injury shown in Figure 13. A dummy injury measure could be derived from the product of the integration and double integration of resultant head acceleration that exceeds a criteria of 48.

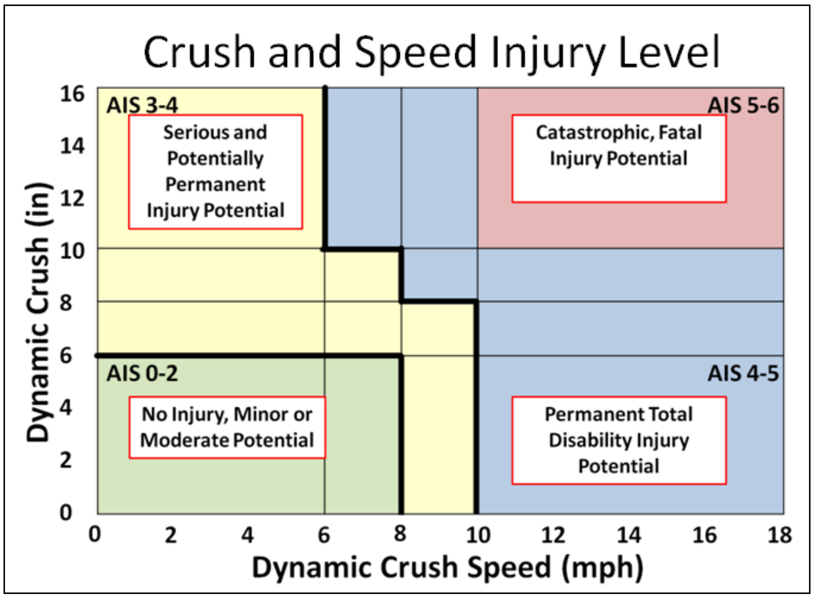


Figure 13. The dynamic crush injury risk criteria

Dummy lower neck injury criteria

1. and 2.) In 1998 an experimental study of compression flexion and hyperflexion was published which provided human force and bending moment criteria for the probability of severe lower neck injury as shown in Figure 14 [23].

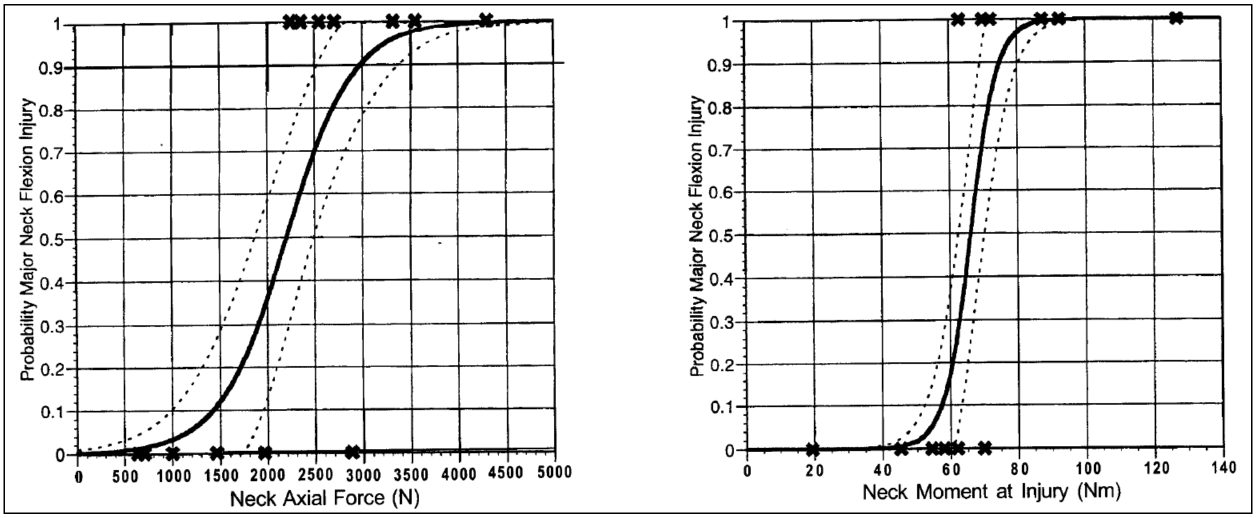


Figure 14. Human force and bending moment criteria

The criteria for normalization were selected as the 10% probability of major flexion injury.

3. The production neck {Fy peak Lower neck, 380 Nm Injury Assessment Reference Value (IARV)} or the 30% calibration of the low durometer criteria,
4. The product of dummy head velocity and displacement relative to a criteria of 48.
5. The momentum exchange Integrated Bending Moment (IBM) of 13.5 was derived from its relationship to residual roof crush injury risk as shown in Figure 15.

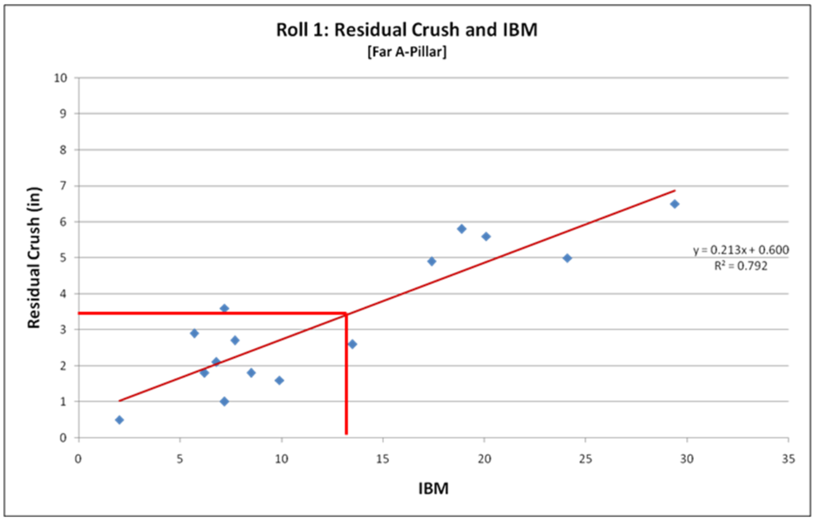


Figure 15. Residual crush vs. IBM

Though we have not calibrated compression stiffness, the difference between the production neck force Fz for a critical speed (10,000 N) and the maximum hyperflexion force (3000 N) is about 3 to 1, the criteria for the prototype neck would be about 3,000 N [27]. All of these are summarized in Table I.

Table I. Summary Hybrid III developed bending and compression criteria

Neck Type	My (Nm) Flexion	My (Nm) Extension	Mx (Nm)	Axial Fz (N)	IBM	Intrusion Speed (mph)
Production Upper	190	-78	134	10,000	13.5	7
Production Lower	380	-156	268	8,000	13.5	7
Low Durometer Upper	50*	-22*	37*	6,300*	13.5	7
Low Durometer Lower	126	-52	89	3,300	13.5	7
Human/Cadaver**	58			1,500	13.5	7

*Values estimated by scaling lower neck

**Estimated high probability criteria of a lower neck Major Hyperflexion bending injury from regression curves of experiments in Reference Figure 3 of "Mechanisms of Hyperflexion Cervical Spine Injury" by Pintar and Yogananda 1998

Real-world protocol

The author's investigation of over 400 serious injury vehicle rollovers provided unequivocal evidence that vehicle structures crushed non-linearly and with greater extent on the far side front A-pillar. This was interpreted to suggest that injury accidents involved rolling with significant pitch and with increased far side severity. A NASS case-by-case investigation of 274 serious injury rollovers confirmed that more than 80% rolled with 10° of pitch [28]. Static tests with a two-sided M216 fixture also confirmed that at 10° of pitch, the roof strength on the far side was about half what was measured in the FMVSS 216, 5° platen test. This led to the conclusion that a test to protect the occupant should be conducted with 10° of pitch and the occupant on the far side of the vehicle.

In 1991, with the publication of the Malibu II study, it became clear that rollover injuries were a consequence of the occupant's interaction with the vehicle structure, particularly the roof as it impacted the ground. While the sequence of contacts might be more like a wobbling football, it was basically rolling lateral to its direction of travel. In order to study the issue it was necessary to define a device which would physically simulate the rolling motion of the vehicle and its impacts with the ground, in a laboratory environment. In 2001, the laboratory fixture, now called the Jordan Rollover System (JRS), was conceived (Figure 16). It was designed, developed and became a reality in 2004. By 2006, we had published the observations from rolling six different vehicles at different roof strengths.

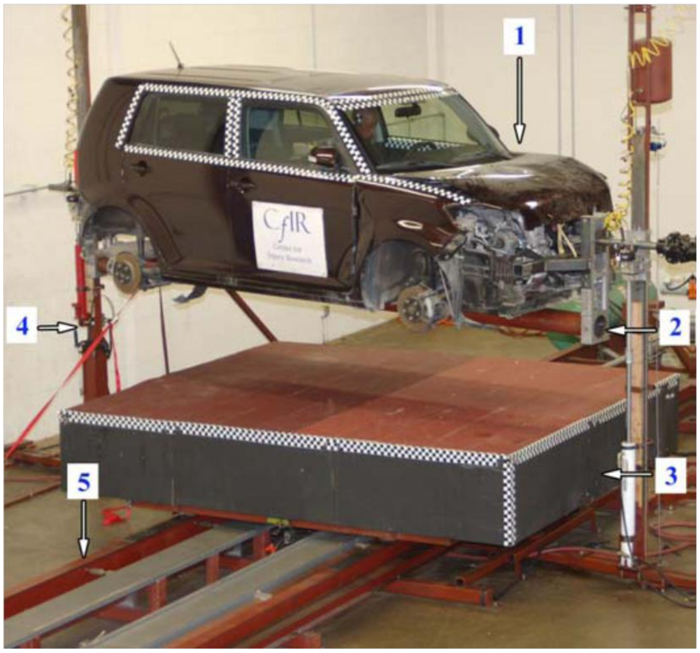


Figure 16. 1) Vehicle, 2) cradle/spit mount, 3) moving roadbed, 4) support towers, 5) coupled pneumatic roadbed population and roll drive

In the interval from 2006 to 2012, more than 300 rolls have been conducted on about 60 different full sized vehicles. The thought was that the likelihood of injury would occur in the most violent ballistic phase of rolling when the vehicle impacted the ground.

Data was also available to indicate that more than 95% of the serious injury rollovers occurred within 8 quarter-turns, or two rolls. From the Malibu II data, it was determined that a 30 mph dolly rollover would result in a first roof contact at about 21 mph taking into account the transfer of linear to rotational momentum. If a vehicle were to stop rolling and be at rest within two rolls, the first roll would have to end and the second roll begins at about 12 to 15 mph.

To illustrate the effect of roof strength and test protocol on two, one roll 15 mph tests and the first 21 mph roll of a two roll real world protocol on injury, three identical 1999 Hyundai Sonata (SWR=2.9) vehicles were JRS tested. Two were production models and one was reinforced to an SWR=5+. One was tested with two low severity rolls at (15 mph, 5° pitch). One production and the reinforced vehicles were tested at 20.8 mph, 10° pitch. The alternate protocols are described in Figure 17.

Number of Rolls	1	2
Road Speed (mph)	20.8	15
Roll Rate (deg/sec)	270	190
Pitch (deg)	10	5
Yaw (deg/sec)	10	10
Drop Height (in)	4	4
Impact Angle (deg)	145	145

Figure 17. Alternate protocols

The purpose of the two 15 mph, 5 deg pitch rolls is to compare the roof crush severity with the 20.8 mph, 10 deg pitch roll. The results indicate that the two roll protocol is comparable to the one roll protocol from the point of view of cumulative momentum exchange and residual crush. See Figure 18.

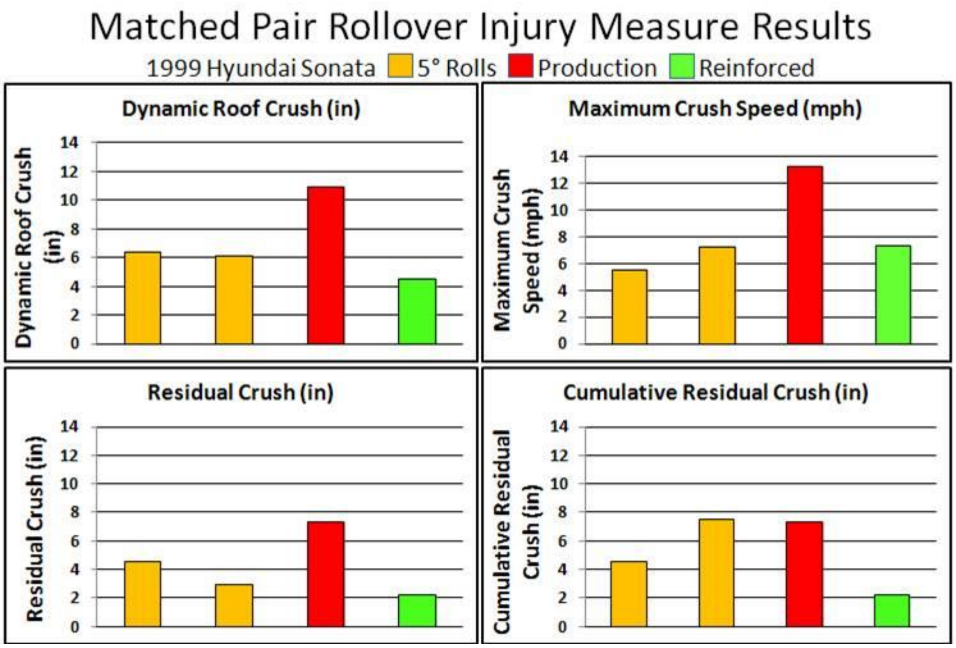


Figure 18. Matched pair rollover injury measure results

However, the residual crush in each of the 15 mph, 5 deg pitch rolls is about half of the 20.8 mph residual crush. From a dummy injury measure point of view dynamic crush and speed in each roll is what is relevant as seen in the upper charts of Figure 18. Injury probability as defined from the Mandell chart is shown in Figure 19. Each roll of the two roll protocol is about half the probability of specific body part injury or death compared to the single roll at 20.8 mph. Furthermore, the reinforced vehicle is 1/3 to 1/4 the injury probability of the production vehicle.

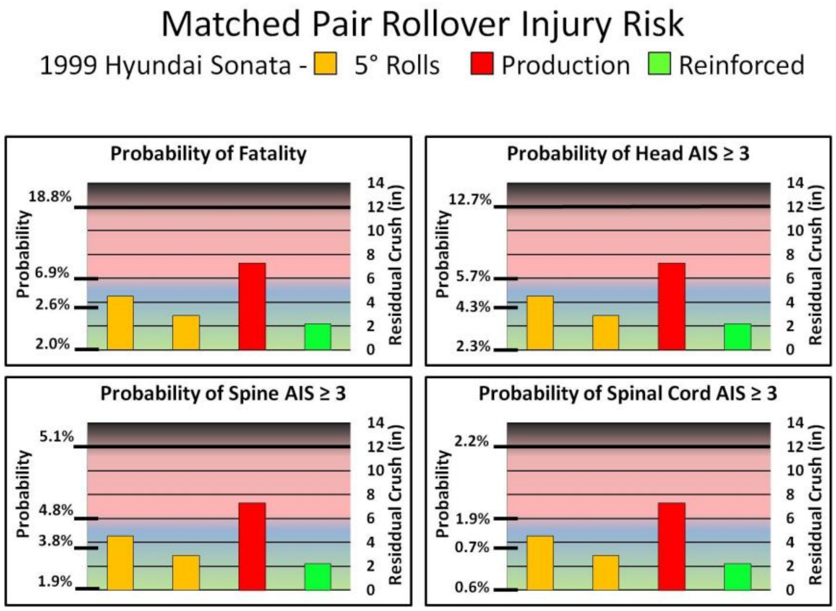


Figure 19. Matched pair rollover injury risk

Figure 20 plots the previous vehicle results on the criteria map of Figure 13. The AIS dummy injury measures of both vehicles in the two roll sequence correspond to the AIS 3-4, while the reinforced vehicle is in the AIS 0-2 area. The real-world protocol production vehicle dummy injury measure is in the AIS 5-6 range.

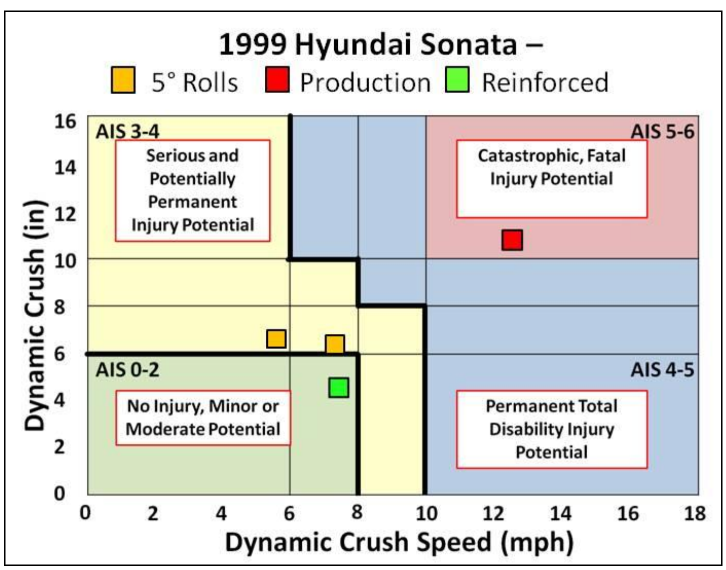


Figure 20. 1999 Hyundai Sonata dynamic crush v. speed

RESULTS

To compare these alternate injury risk and dummy injury measure criteria each was normalized to its AIS ≥ 3 reference value. For each JRS test the percentage of injury risk and dummy measure criteria was determined and compared. See Figure 21. These include: 1.) the injury risk performance of the elastically corrected residual crush and the product of crush and crush speed, and 2.) the low durometer adjusted IARV and Pintar Fz and My, the IBM and the integrated and double integrated product of resultant head acceleration dummy injury measures.

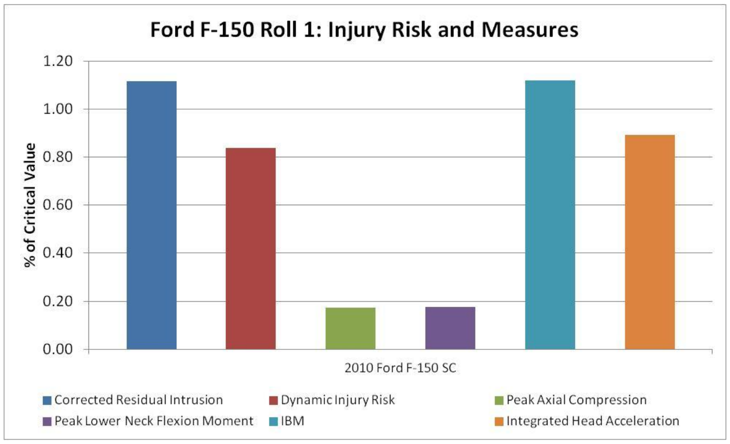


Figure 21. Ford F-150 roll 1: injury risk and measures

The peak IARV values are substantially low. The normalized percentage of injury risk and the last two dummy injury measures are consistent with each other to the extent that could be expected. The disparities between those two injury risk and the two injury measures can be accounted for by considering original headroom, pre-tensioning, Mx in IBM, and roof crush versus head contact motion.

Using these criteria for the JRS tests with identical low energy (15 mph) protocols we can compare the normalize percent of critical injury risk and dummy injury measures to each other as shown in Figure 22.

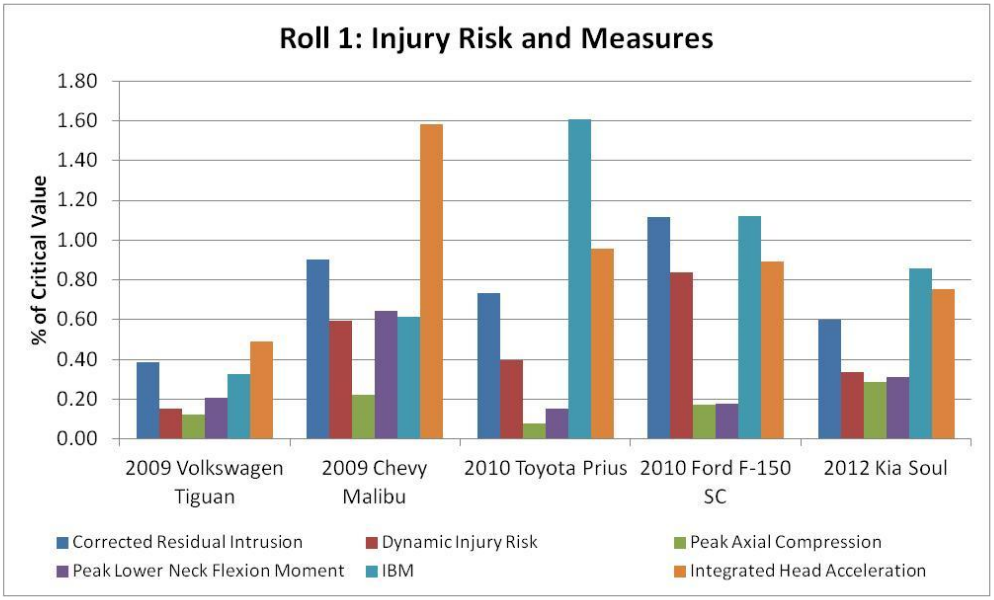


Figure 22. Roll 1: injury risk and measures

Most of these vehicles perform well in a one roll low severity crashes but as data is available from a real world energy protocol (21 mph) the injury performance will be degraded and the difference between vehicles will be more obvious.

DISCUSSION AND ANALYSIS OF RESULTS

The problem in rating rollover safety performance by injury risk is that injury risk is a statistical relationship with residual crush, only one of several factors affecting structural intrusion (like geometry and elasticity), whereas a rating system should be compared by dummy injury measures relative to human/dummy criteria. To create a dummy injury measure rating system, it's necessary to recognize that residual crush is probably not as related to thorax or brain injury as cervical spine injury. Having developed the IBM for cervical spine injury, the task is now to rate the same vehicle severity protocol to thorax and brain injury. The development and incorporation of occupant protection devices such as rollover activated window curtain airbags and seat belt pre-tensioners strongly affect and mitigate structurally incurred intrusion. On the other hand the pre-roll yaw puts the occupant out of the shoulder belt when the pre-tensioner fires, keeping the occupant's shoulder out of the belt and leaning forward. Combination side impact and window curtain airbags may solve that problem. The test criteria for side impact thoracic injury currently involves, triaxial chest accelerometers or instrumented circumferential chest belts, for neither of which is there a specific criteria. The work in progress to study these issues are discussed in Appendix 1.

CONCLUSIONS

An injury risk rating system has been developed and characterizes the statistical probability of a fatality and spinal, spinal cord and brain damage injuries.

A dummy injury measure rating system has been developed and characterizes severity of injury to the lower cervical spinal cord but there is no consensus among biomechanicists as to what specific dummy injury measures constitute a good or acceptable or poor human-related safe design.

Worldwide NCAP is adopting a static test protocol to certify and rate vehicles to strength-to-weight ratios (SWRs) varying from country to country between SWR = 2.5 to 4.0.

Static roof strength tests are an unreliable way of ensuring a safe design since structures in dynamic circumstances are non-linear and dummy injury measures are the only way to identify vehicle, geometry and occupant protection device effectiveness.

Vehicle tests and measurements have been developed to predict the likelihood of inadequate dynamic injury protection performance. A multivariate analysis is needed to combine and predict the effect of vehicle structural strength, aspect ratio or major radius, elasticity, and the effectiveness of occupant protection features.

APPENDIX 1

WORK IN PROGRESS ON DUMMY INJURY MEASURES

The proposed lower neck dummy injury bending measures are consistent with each other and injury risk performance to within about ± 30%. This is within the acceptable variation in frontal and side impact dummy injury measures used for regulatory and NCAP ratings.

However, NASS and CIREN data have been analyzed in rollover accidents of the last ten years and indicate, in order of frequency of occurrence, spinal, thoracic and head AIS ≥ 3 injuries [10]. See Figure 23. Further analysis was completed by UNSW in 2011[14] and NHTSA/UVa in 2012 [29].

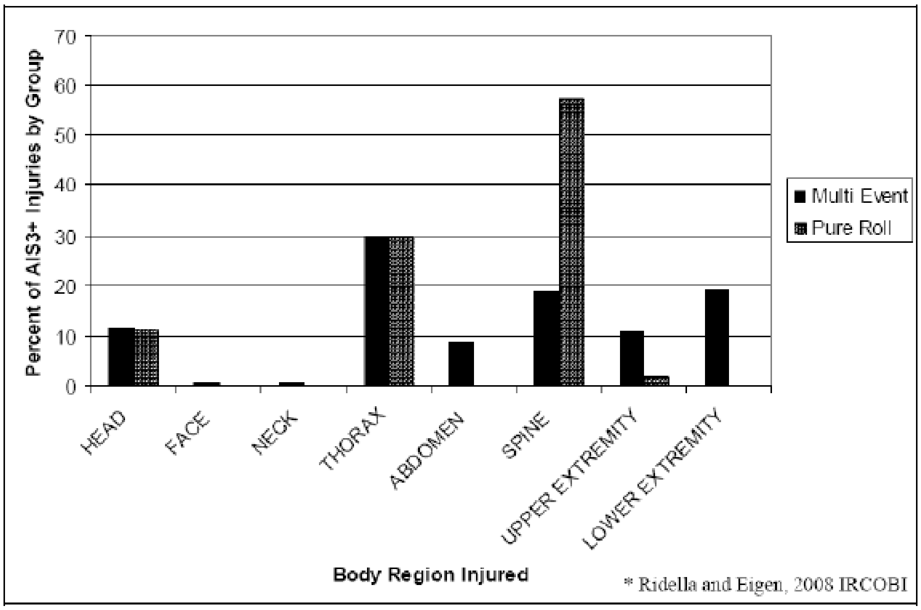
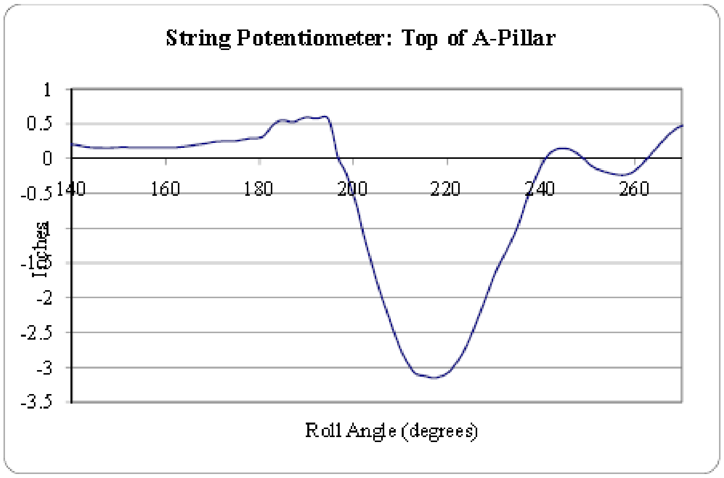


Figure 23. Body region distribution of AIS 3+ injuries

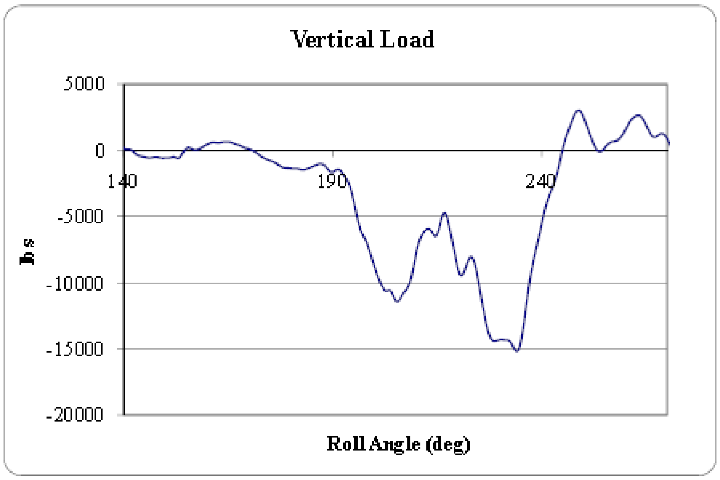
Efforts are currently underway to identify the mechanism of thoracic and head injury. Current experimental observations indicate that thoracic injuries may occur from roof-to-shoulder loading of a hyper-flexed spine, or due to thoracic impact with the adjacent door and window sill [14]. Head injury may occur from head contact, with the ground through an open side window portal or from roof intrusion, when the roof is in contact with the roadbed at impact angles greater than 215° (the current end of contact with the roadbed).

To facilitate this research the test protocol is being adjusted to initiate roadbed contact later and maintain it longer. The description of a real world protocol successfully identified the relationship between lower neck cervical injury and roof crush in terms of injury risk and dummy injury measures. However, the protocol and the fixture's roadbed were designed to interact over a seventy degree segment from 145 to 215 degrees. This precludes head to roof rail or ground impact at higher angles of roll as well as thoracic interaction with the window sill and door when the side or wheels of the vehicle at 225 to 270 degrees impacts the roadbed. Although the roadbed could be made longer, it was simpler to shift the initial impact angle from 145 to 185 degrees which with available roadbed length margin, allowed violent contact with the roof to 240 degrees and the side of this high strength vehicle to be over the roadbed at 270 degrees of roll (Figure 24 and Figure 25).



Roll 4 A-pillar roof crush as a function of roll angle

Figure 24. Measurement at top of A-pillar



Roll 4 Roadbed load as a function of roll angle

Figure 25. Vertical load

In this test the head went out the window as shown in Figure 26.


Figure 26. Dummy head out window in Kia Soul

Results from the extended protocol in an F-150 produce a road load of 35,000 lbs at 240 degrees and resultant side impact chest accelerations of 25 Gs. Wheel contact with the roadbed at about 255 degrees is expected to produce 60 G's of vehicle angular acceleration.

The developmental experience with the stiffness of the neck and the Finite Element Analysis of rolling vehicles with restrained MADYMO human facet dummies suggest that the rigidity of the Hybrid III thorax and spinal column between the neck and the lumbar region need to be significantly more flexible [22]. Humanetics has developed for NHTSA a prototype dummy with this type of flexibility. The characteristics include: contoured shoulder flesh, ball joint for shoulder, heavy flesh outside ribs, heavy arm flesh over plastic bone, Neoprene suit and z-pivot above elbow. Working with them we hope to have incremental modifications of the Hybrid III dummy integrating the low durometer neck, a flexible spine and attached more sensitive thorax which will facilitate measuring injuries.

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