Methodology Developed for Dynamic Rollover Regulation and Ratings

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Abstract - At present, most governments require vehicle compliance to a quasi-static Roof Crush Resistance test similar to the Federal Motor Vehicle Safety Standard (FMVSS) 216. In this paper Center for Injury Research (C*f*IR) proposes a global full-scale dynamic rollover compliance test and rollover rating system. Compliance in these tests is a function of both vehicle structural and dummy responses. The methods include: 1) design and build a rollover test fixture, 2) apply structural injury risk statistics, 3) evaluate the relative structural injury risk performance of production vehicles 4) modify the Hybrid III dummy to be more humanlike, 5) develop momentum exchange dummy head, neck and spine injury measures and criteria, 6) demonstrate the match between structural injury risk relative to criteria and dummy injury measures relative to criteria, 7) identify a real-world test protocol, 8) demonstrate the real-world injury risk rating system and 9) summarize the proposed rollover compliance test regulation.

Keywords: methods, rollover tests, Jordan Rollover System (JRS), regulatory, ratings

INTRODUCTION

Historically, rollover regulations have been less rigorous than frontal and side crashworthiness regulations. Rollover injury potential and manufacturers' efforts to reduce casualties were first highlighted by congressional testimony in 1965 and incorporated into the Safety Act of 1966 [1]. An advanced notice of proposed rulemaking (NPRM) in 1968 identified roof crush as a major contributor to injury in rollovers [2]. The 1970 NPRM of FMVSS 208 incorporated an unrestrained occupant containment provision in a 48.3 kph (30 mph) dolly rollover test, but the test dummies were not instrumented [3]. Since the technology to conduct experimental tests with instrumented dummies was not available until the late 1970's, the NPRM of FMVSS 216 proposed in 1971 a 2-sided quasi-static platen test at 10° of pitch requiring a strength-to-weight ratio (SWR) of 1.5 before 12.7 cm (5 inches) of platen displacement [4]. However, the two-sided test was not implemented due to objections to the platen size and pitch angle; the one-sided quasi-static test at 5° of pitch and 25° of roll was temporarily authorized in 1973 (and reauthorized annually) as FMVSS 216 until 2009 [5].

The National Highway Traffic Safety Administration (NHTSA), in 1990, required light truck vehicles (i.e., pickups, utility vehicles and vans) to comply with FMVSS 216. In 1995 FMVSS 201 required upper interior padding to prevent head injury. Statistical studies in 1995 and 2005 suggested that there was no relationship between vehicle SWR and incapacitating and fatal injury [6-7]. In 1996 a statistical study of the National Accident Sampling System (NASS) files indicated that the amount of roof crush was directly related to head and neck injury in restrained occupants [8]. In 1998 the specific relationship was detailed with the publication of a series of head-at-the-roof, belted human volunteer drop tests onto a non-deforming roof from 30, 50 and 90 cm (12, 19.7 and 36 inches) [9]. In 2001 NHTSA reported on alternate means of mitigating ejections [10]. Ford in 2002 funded the development of the dynamic Controlled Rollover Impact System (CRIS) by Failure Analysis Associates [11]. By unrealistically setting the initial test conditions (e.g., removing the headliner, incorporating slack in the seatbelt, raising the seat to its highest position, and deliberately locating the head of the dummy on the roof panel at roof touchdown), production and roll-caged vehicles demonstrated no difference in dummy injury measures.

In spite of these research efforts, rollovers from 1978 to 2008 accounted for 317,000 fatalities [12]. In 2009 the NHTSA initiated a series of component rollover regulations, a dynamic regulatory rollover research program at UVa and issues a NPRM updating FMVSS 216. The update was from a single-sided SWR of 1.5 to greater than 3 before contacting a head form at the occupant seating position in sequence on both sides of a vehicle's roof.

After 28 years of inaction the NHTSA in 2001 requested comments regarding roof crush regulations [13]. The C*f*IR responded over the next 8 years with 34 submissions to NHTSA dockets including almost 100,000 pages of text, experimental test data, video and recommendations. The C*f*IR data included more than 200 rolls of more than 25 vehicles tested dynamically with the JRS at C*f*IR using 1- and 2-roll test protocols. Up to 50 fixture, vehicle and dummy data channels were collected for each test and examined as possible rollover test performance parameters.

In 2009 the NHTSA initiated a series of component rollover regulations, a dynamic regulatory rollover research program at University at Virginia (UVa), and issued a NPRM updating FMVSS 216 from a single-sided SWR of 1.5 to greater than 3 in sequence on both sides of a vehicle's roof.

In the public interest, C*f*IR and the University of New South Wales (UNSW) undertook privately-funded efforts to achieve the 2009 NHTSA objectives. C*f*IR took a pragmatic research approach. Rollover structural injury risk test performance was evaluated from vertical residual roof crush and crush speed, and criteria were selected from results of dynamic tests, case studies, real-world crash structural injury risk data from the NASS-CDS, the Crash Injury Research and Engineering Network (CIREN) databases and biomechanical research. Comparisons were made of the structural performance of a variety of production vehicles in terms of the residual roof crush and major radius (MR), which is the distance between the vehicle center-of-gravity (CG) and the intersection of the windshield header, roof rail, and the A-Pillar. Dummy injury measures included the Integrated Bending Moment (IBM), defined as the integration of the resultant Mx, My values between minimum limits, and the Integrated Head Acceleration (IHA), defined as the first integration of the resultant head acceleration for velocity and the second integration for head displacement. More than 25 additional dummy-occupied vehicle JRS tests were conducted.

The C*f*IR program methods have been documented in more than 15 conference papers published in the last five years and are summarized here. The intent is to provide a basis for the proposed controlled dynamic full-scale, real-world rollover compliance test with instrumented anthropomorphic dummies similar to the FMVSS 208 frontal and FMVSS 214 lateral occupant protection tests, where "structural injury risk" correlates with dummy injury measures. Results of this study demonstrate that regulatory and NCAP rollover test performance in the specified single-roll test protocol can be measured by a numerical match of:

- structural injury risk in terms of residual vertical roof crush and crush speed at the A-pillar relative to criteria, and
- the momentum exchange dummy injury measures relative to criteria.

Presently, full-scale dynamic rollover crash testing and data analysis using the JRS has been concluded at C*f*IR, having achieved all of its objectives. Methodologies were developed to characterize a dynamic regulatory compliance test and minimal acceptable performance criteria using a modified Hybrid III dummy. Results allow the comparative evaluation, rating, prediction and optimization of vehicle and occupant responses in rollovers. The primary benefit of the JRS dynamic tests compared to FMVSS 216 quasi-static tests is the ability to grade vehicle performance with matching structural injury risk and dummy head, neck and spine injury measures. The secondary benefit is that the results identify anomalies between quasi-static and dynamic test methodologies. The tertiary benefit of the JRS dynamic tests is its capacity to evaluate the effects of occupant protection features.

SUMMARY OF C*f*IR PROGRAM

A summary of the objectives and accomplishments of the C*f*IR effort is provided below; the supporting research is detailed in the body of this paper.

1. **Design and build a rollover test fixture,** a reliable, repeatable, adjustable, mechanical rollover laboratory test fixture. The JRS-1 fixture was designed, constructed and utilized in government sresearch programs. The test fixture performed reliably with excellent repeatability and flexibility in more than 300 rolls and more than 50 vehicles. There are currently three JRS dynamic test fixtures in the world (i.e., the 1st-generation JRS-1 fixture at C*f*IR and the 2nd-generation JRS-2 at University of Virginia (UVa)/NHTSA in the U.S. and University of New South Wales (UNSW)/Crashlab in Australia) with almost identical specifications and performance.
2. **Apply structural injury risk statistics;** apply a NASS/CIREN statistically-derived "structural injury risk" criteria. A NASS/CIREN statistical analysis of more than 20,000 vehicles from model years 1993 to 2007 related the probability of injury to the maximum residual crash at the seated location in the occupant compartment at four levels; "good", "acceptable", "poor" and "unacceptable".
3. **Evaluate the relative structural injury risk performance of production vehicles;** more than 50 vehicles' residual crush has been measured and compared using four different speed protocols. Recorded data parameters have identified relationships between vehicle structural parameters and residual crush.
4. **Modify the Hybrid III dummy to be more humanlike;** to better emulate typical pre-trip human head, neck, and torso orientation and lessen the spine stiffness to better predict typical head, spine and torso injuries precluded by the excessively-stiff production Hybrid III spines. Since matching the aligned human neck requires about 30° dummy neck flexion, Humanetics fabricated prototype rollover neck incorporating a neck bracket for the 30° inclination and a low-durometer neck with about 30% of the stiffness of the production neck.
5. **Develop momentum exchange dummy head, neck and spine injury measures and criteria**.
   - IBM, an injury measure representing the momentum exchange between roof contact and neck flexion, was defined as the integral of the resultant lower neck bending moments; an IBM criteria of 13.5 was correlated with residual crush.
   - IHA, the product of the head velocity (i.e., single integral of the resultant head acceleration) and head displacement; an IHA criteria of 48 corresponded to AIS 3+ injury (i.e., double integral of the resultant head acceleration).
6. **Demonstrate the match between structural injury risk relative to criteria and dummy injury measures relative to criteria**, with a standard protocol: There were five vehicles tested; test results demonstrated that the structural injury risk relative to criteria was matched by the dummy injury measures relative to criteria (with variations associated with measured seatbelt loadings and other factors).
7. **Identify a real-world test protocol;** the most severe phase of a test protocol reflecting 95% of real-world rollovers and serious AIS 3+ injuries. The ballistic trajectory phase (trip to far side contact) of the first roll of a two-roll rollover representing 95% of rollovers and AIS 3+ injuries has been characterized with a 21 mph roof contact velocity at 10° pitch, 145° contact angle and 250 °/s roll rate.
8. **Demonstrate the real-world injury risk rating system;** since many of the tests were conducted with different protocols, a previously published normalization procedure converted the measured residual crush to the residual crush which would have occurred had all of the tests been conducted with the real-world protocol. Those values were ordered by amplitude and overlaid on the four rating levels Section 2.
9. **Summary of the proposed dynamic rollover compliance test regulation;** a regulatory standard is paraphrased from NHTSA published regulations FMVSS 208 and 216. It describes the salient paragraphs of the fixture, test, vehicle, dummy, injury measures, instrumentation and criteria.

BODY OF RESEARCH

1. **Design and build a rollover test fixture;** a mechanical rollover laboratory test fixture that is reliable, repeatable, and adjustable. The 1st-generation JRS-1, shown in Figure 1, was designed, built, installed and operational at C*f*IR by 2004. The test fixture performed reliably with excellent repeatability and flexibility in more than 300 rolls and more than 50 vehicles. There are currently three JRS dynamic test fixtures in the world (i.e., the 1st-generation JRS-1 fixture at C*f*IR and the 2nd-generation JRS-2 at University of Virginia (UVa)/NHTSA in the U.S. and University of New South Wales (UNSW)/Crashlab in Australia) with almost identical specifications and performance. Figure 2 shows the gantry-based 2nd-generation research JRS-2 fixture at UNSW/CrashLab. Each test laboratory performed independent research with its own unique methodology and evaluation criteria. Presently, full-scale dynamic rollover crash testing using the JRS has been concluded at C*f*IR having achieved all its objectives.

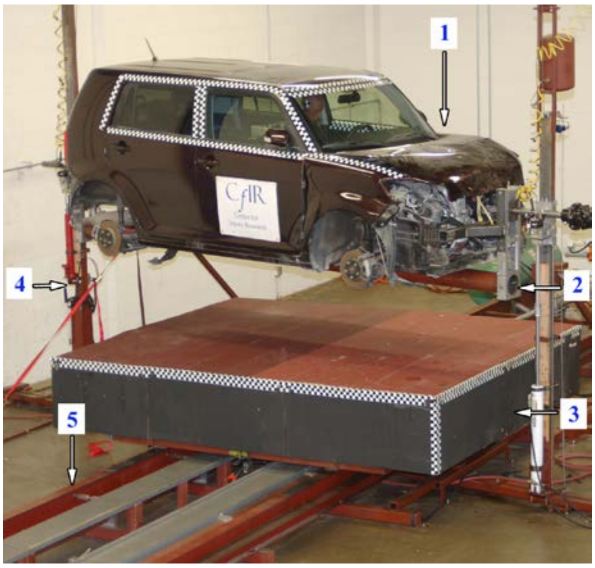

Figure 1. JRS-1 at C*f*IR
Key components of the JRS: (1) vehicle, (2) cradle/spit mount, (3) moving roadbed, (4) support towers, (5) coupled pneumatic-roadbed propulsion and roll drive

Figure 2. JRS-2 at UNSW/CrashLab

2. **Apply structural injury risk statistics;** Apply structural injury risk statistics using NASS/CIREN data and derive a “structural injury risk” criteria. Injury risk, as used here, is a statistical term relating structural crush (injury risk could be defined with other factors as well) to the probability of human real-world injury. A NASS/CIREN statistical analysis of more than 20,000 model year 1993 to 2007 vehicles identified that the probability of injury is a function of maximum residual crush at the front seat occupant position as shown in Figure 3 by Mandell, et al. [14]. It also shows the odds ratio as a function of residual crush. A rollover regulatory or NCAP injury measure system should match injury risk criteria and predict the predominant head, neck, and thorax injuries.

   The real-world rollover crash data files suggested that quadriplegia and paraplegia were residuals of lower neck bending injuries (bilateral locked facets), while death was usually attributed to head injury, upper neck cord damage affecting pulmonary and circulatory functions at C1 to C3, and/or thorax injury.

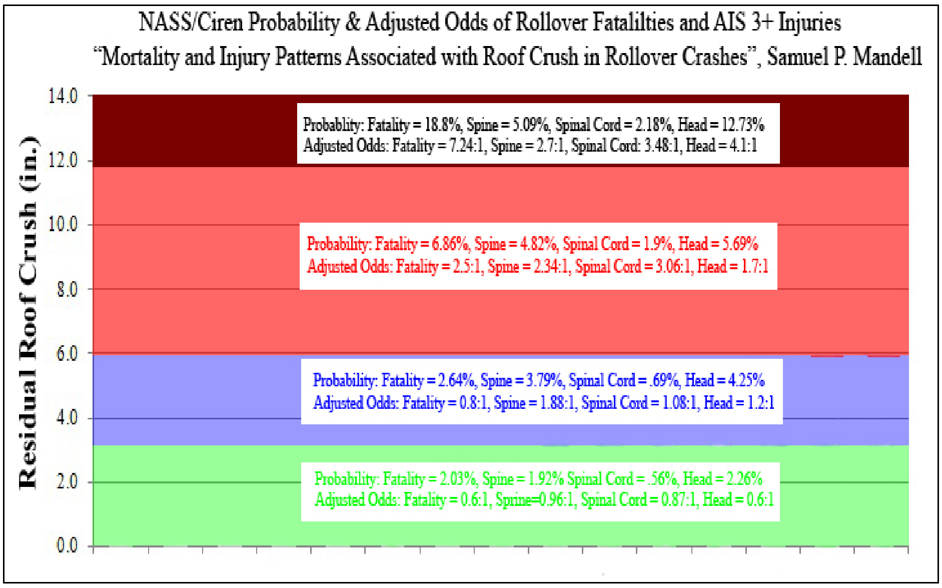

Figure 3. NASS/CIREN probability of rollover AIS 3+ injuries and adjusted odds [22]

3. **Evaluate the relative structural injury risk performance of production vehicles;** an example of an injury risk relationship was demonstrated by the IIHS analysis of the effect of SWR vs. injury rate shown in Figure 4. In 2008 the comparison of the results of 21 JRS tests to IIHS statistical structural injury risk data showed a substantial benefit from increased roof SWR [15]. Also shown on the chart is the NHTSA statistical analysis which indicated that, when roof crush exceeded headroom, injury was five times more likely [16-17].

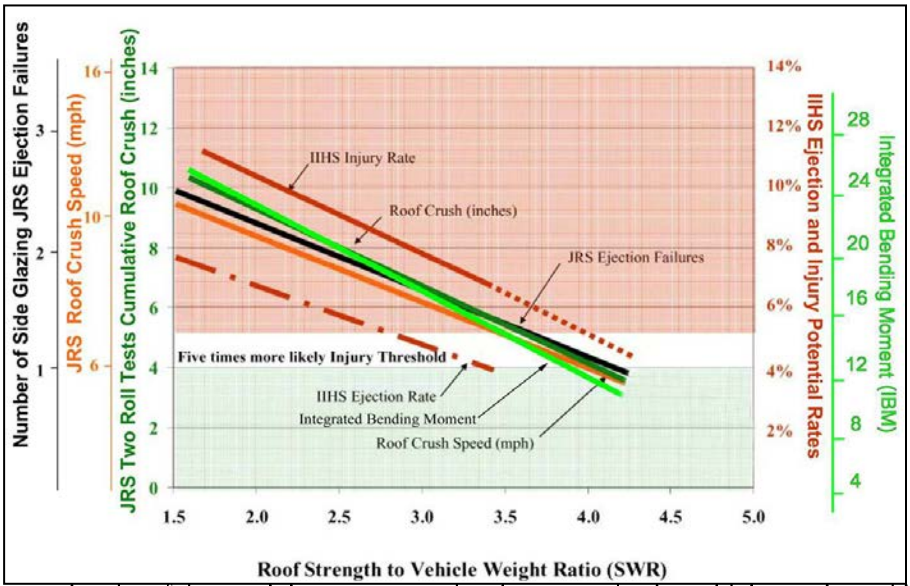

Figure 4. Composite plot of dummy injury measures showing rate reduction with increasing vehicle SWR

Figure 5 illustrates the structural injury risk probability as a function of residual crush as defined in Figure 3. The data shows that the probability of death and serious-to-fatal head, spine and spinal cord injury to belted occupants increases rapidly with cumulative vertical residual crush over the front occupant's seating position.

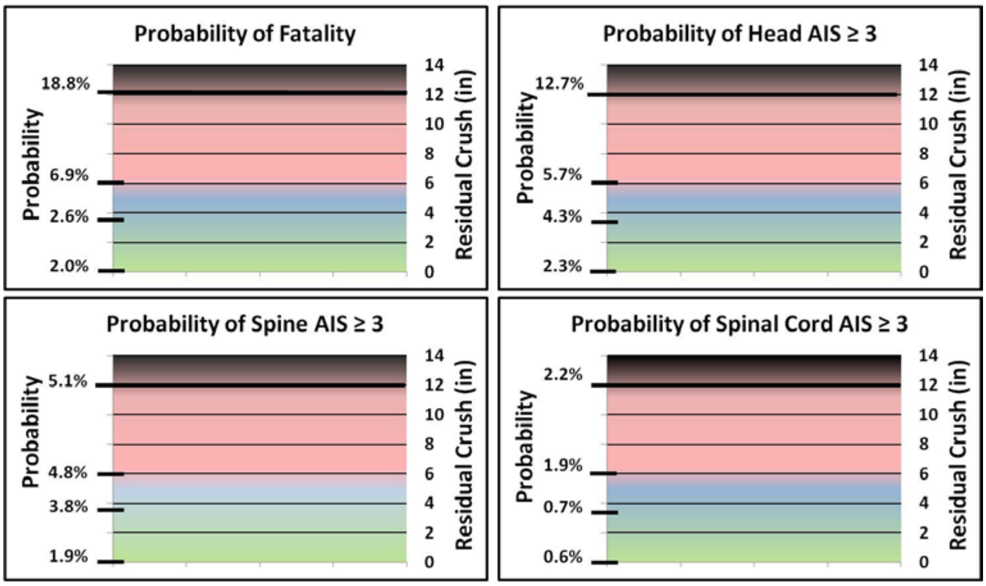

Figure 5. Probabilities of fatality, head, spine and spinal cord injuries

Using the Mandell chart, the structural injury risk performance was rated as:

- "GOOD" = non-injurious
  Residual crush < 8.9 cm (3.5 inches)
- "ACCEPTABLE" = 30% increased probability of death
  8.9 cm (3.5 inches) < Residual crush < 15.2 cm (6 inches)
- "POOR" = 3.5 times the probability of death
  15.2 cm (6 inches) < Residual crush < 30.5 cm (12 inches)
- "UNACCEPTABLE" = 9 times the probability of death
  30.5 cm (12 inches) < Residual crush

Figure 6 shows test results for production vehicles tested at a 15 mph, 5° pitch protocol in order of increasing residual roof crush. Basic recorded data parameters from these tests identified the relationship between vehicle design parameters that affect residual crush, such as SWR and MR.

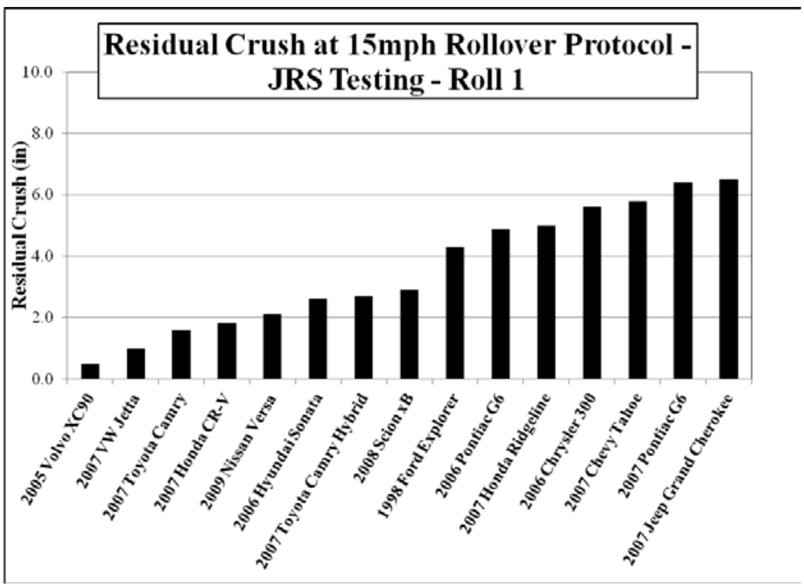

Figure 6. Vehicles tested in order of residual crush at a 15 mph, 5° pitch protocol

4. **Modify the production Hybrid III dummy to be more humanlike.** Few biomechanical engineers have had the opportunity to study instrumented dummies or post-mortem human subjects (PMHS) in a controlled rollover test environment. As a result there is a lack of consensus with respect to human spine injury mechanisms and dummy v. human head, neck, and torso alignment and the roof crush vector. Rollover simulations performed with Hybrid III dummy Madymo models [18] with and without untensed necks were found to be flexed about 30º, representative of the aligned Hybrid III neck. For this reason, Humanetics fabricated a 30° flexion lower neck attachment bracket and a low-durometer neck with about 30% of the stiffness of the production neck.

Comparison of human and dummy kinematics in drop tests. In 1998, kinematic responses were compared in 30, 50 and 90 cm (12, 19.7 and 36 inches) drop tests with belted head-at-the-roof human volunteers and anthropomorphic test dummies [19]. Figure 7a shows an inverted relaxed human volunteer with aligned torso, neck, and head, as well as an inverted dummy. In Figure 7b, 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 coming into view of the high-speed camera at 72 ms. In the 30 cm (12 inches) drop test, the roof contacted the ground at 250 ms.
- The middle frame shows the occupants with heads and necks in forward flexion (chin-to-chest) after the vehicle contacted the ground at 272 ms. The head target was 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 about 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 7a. Dummy (left) and human volunteer (right) in drop test fixture [19]

Figure 7b. High-speed video frames of human volunteer in 30-cm drop test [19]

5. **Develop momentum exchange dummy head, neck and spine injury measures and criteria.** The dummy injury measure representing the momentum exchange between roof contact and neck flexion, called the IBM, was derived by integrating the resultant of Mx and My lower neck bending moments. Correlating results with residual crush yielded the criteria as 13.5 (See Figure 8).

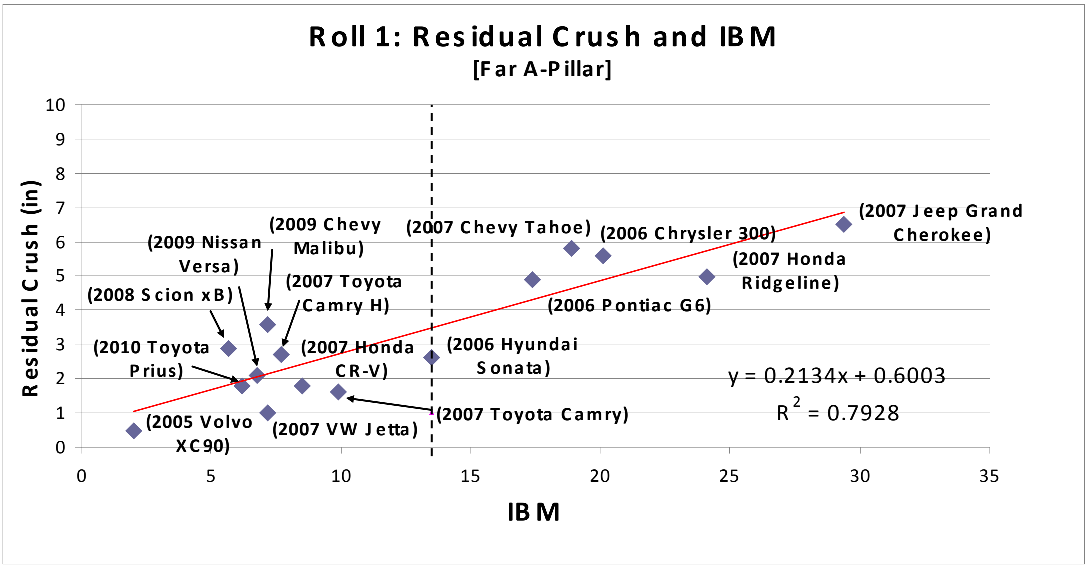

Figure 8. Residual crush v. IBM for various production vehicles

Residual crush is the only data available to an investigator after an accident. A specific injury is usually the result of a single impact not the result of a sequence of impacts. Dummy injury measures in a dynamic test provide the time history of roof crush and crush speed.

Consensus injury measures at 8 mph developed by McElhaney [20] and combined by Paver [21] are shown in Figure 9. It describes the combination of an impact speed and head displacement and establishes areas of AIS values. The first integration over 60 ms of the resultant head acceleration represents the head velocity and the double integration represents the head displacement. The product of head velocity and displacement is the IHA. For AIS 3+, the product of a 13 kph (8 mph) head impact velocity and a 15 cm (6 inches) head displacement yields an IHA criteria of 48.

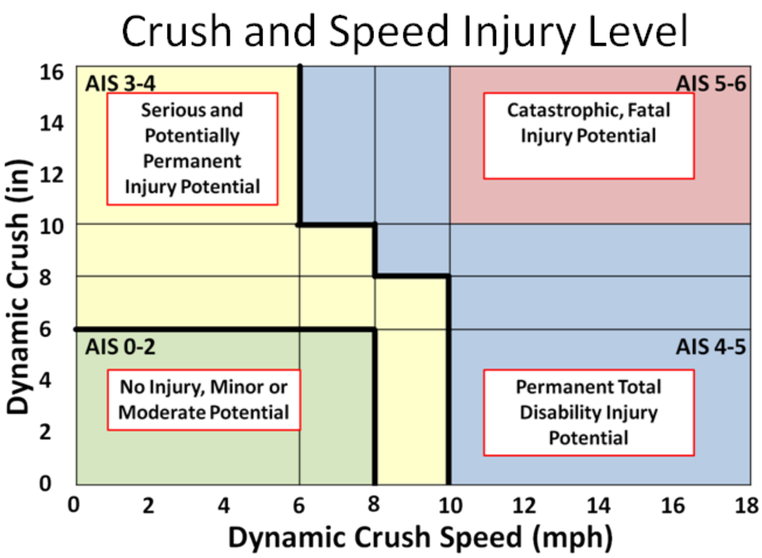

Figure 9. Dynamic crush and crush speed v. IHA for areas of AIS injury levels

6. **Demonstrate the match between structural injury risk relative to criteria and dummy injury measures relative to criteria** with a standard protocol. The ultimate value of a dynamic test is to assess not only vehicle structural injury risk, but also dummy injury measures compared to injury criteria from transducers mounted in a reasonably-humanlike anthropometric test device. At present, most laboratories and finite element models utilize the Hybrid III dummy as the human surrogate. In accordance with Section 4 we used a production Hybrid III dummy modified with a low-durometer neck oriented in 30º pre-flexion and instrumented with a six-axis lower neck load cell. The IBM bending criteria was derived from the lower neck My and Mx momentum exchange, and the IHA was derived from the dummy head impact speed and displacement.

   Figure 10 illustrates the percent of criteria corresponding to the structural injury risk parameters, the Injury Assessment Reference Values (IARV) and the neck and head measurements of a 2010 Ford F150 pickup [22]. The six bars in the figure are in sequence from left to right representing corrected residual crush, dynamic injury risk, peak lower neck axial compression, peak lower neck flexion moment, the IBM, and the IHA. In other words,
   - The royal blue (corrected from the string pot angle) and red (dynamic injury risk) bars represent residual roof crush and roof crush speed represent the percentage probability of a AIS 3+ structural injury risk.
   - The olive (peak axial lower neck compression) and purple (peak lower neck flexion moment) bars represent the percentage probability of AIS 3+ injury for traditional IARV's. The IARV injury measures and criteria applicable for frontal and side impacts substantially underestimate the injury potential, and
   - The turquoise (IBM) and orange (IHA) bars represent the percentage probability of AIS 3+ injury.

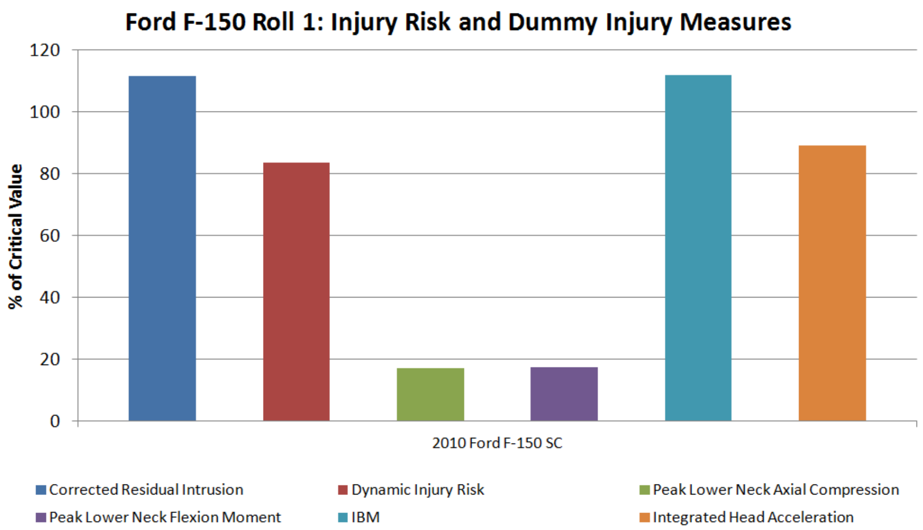

Figure 10. Structural injury risk and dummy injury measures for the 2010 Ford F-150

There were five tests conducted with the 15 mph, 5º pitch low-severity protocol. The structural injury risk relative to criteria was matched by the dummy injury measures relative to criteria (with variations associated with belt loadings and other measurable factors). Figure 11 is a bar chart of the five vehicles.

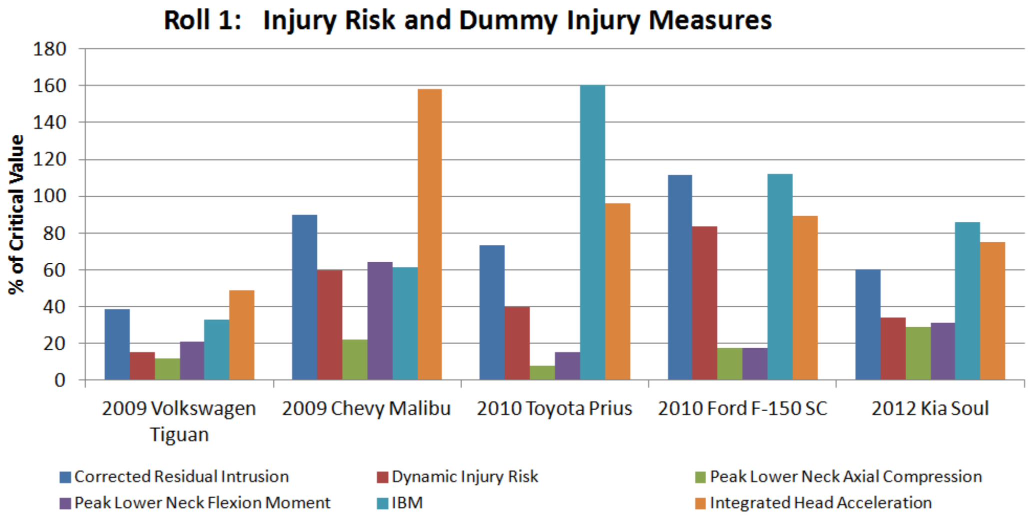

Figure 11. Structural injury risk and dummy injury measures of five production vehicles

7. **Identify a real-world test protocol;** identify the test parameters of 95% of real-world rollovers and serious AIS 3+ injuries. A five-year program was initiated to develop a dynamic test procedure and a JRS patent-based laboratory fixture at UVa and at UNSW. C*f*IR sought to identify the rollover segment with the greatest serious injury potential. This process required evaluating the injury potential sensitivity of each segment and its influence on the following segment. It has been shown that 95% of single vehicle rollovers and serious-to-fatal injuries occur within eight quarter-turns [23]. C*f*IR has taken a pragmatic view of a representative real-world protocol for a regulatory and/or NCAP occupant protection test, recognizing that the choice of protocol should represent the injury consequences of FMVSS 216 and 226 compliant vehicles.

   C*f*IR analysed the injury potential of each segment from case investigations, dolly rollover tests, 273 NASS case analyses of serious injury rollovers, and JRS experiments. The most harmful segment of potential injury was identified as the ballistic trajectory of the 1st roll. 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.

   For comparative purposes C*f*IR normalized the test protocols by road speed and roll rate to a 1-roll event at 33.6 kph (21 mph), 280°/sec roll rate, 10° of pitch, 145° contact angle and a drop height of 10 to 15 cm (4 to 6 inches) (See Table 1).

   In its initial JRS tests C*f*IR adopted a test protocol of 24.1 kph (15 mph) and a 190°/sec roll rate for each roll. Starting with the original roll moment of inertia and a lightweight compartment the amount of roof crush with a high SWR was assessed. Subsequent rolls with the same protocol gauged the effect of increased weight and more normal SWR. Observations from the first of these previously-unavailable dynamic repeatable tests were published in 2006 [26] and reviewed in the International Journal of Crashworthiness in 2010 [24]. Vehicles tested at the 24.1 kph (15 mph) protocol allowed direct comparisons of structural injury risk performance.

   Most of the continuing full-size vehicle tests were conducted using the 2-roll protocol at 24.1 kph (15 mph), 190°/sec roll rate, the 1st roll at 5° of pitch and the 2nd roll at 10° pitch.

   Studies of the vehicle trajectory preceding a near-side roll indicate that the far-side occupant experiences pre-trip yaw and trip accelerations of 0.7 to 1 G towards the near side. Experiments with human occupants and Madymo modelling (as part of the Far-Side Project) indicated that the subject leans to the nearside seat or center console so far that it is out of the shoulder belt [25]. For that reason in the protocol and JRS tests the dummy is tethered forward and towards the passenger side. This is accomplished by rotating the vehicle to -90° (passenger side down) exposing the dummy to 1 G and locking the tether from 30° forward of lateral, before resetting the initial roll angle for the test. The tether is electronically released at 30° of initial roll.

Table 1. The proposed real-world rollover protocol

Impact Road speed 33.8 kph (21 mph) ± 1.6 kph (1 mph)
Roll rate @ near-side impact 270°/sec ± 10%
Pitch 10° ± 2°
Roll angle at impact 145° ± 5°
Drop height 10 cm ± 2 cm (3 to 4.5 inches)
Yaw angle 10° ± 1°
Dummy initially tethered @ 1 g and 60° toward the nearside

8. **Demonstrate the real-world injury risk rating system;** Since the real-world protocol described in Section 7 involves a 21 mph 10º pitch protocol, C*f*IR used a normalization procedure previously published [26] to represent most vehicles tested and create Figure 14. The amplitude order of residual crush is shown overlaid on the Mandell chart of Figure 3. Validation of the normalization procedure is shown by the two bars corresponding to the 1999 Hyundai Sonata, marked with "x" where one bar is the normalized value and the other bar is the JRS test result using the real-world protocol with less than a 10% error. The demonstration characterizes the probability of structural injury risk resulting from the regulatory compliance testing of Section 9. Vehicles with "acceptable" compliance have less than 6 inches of residual crush (and corresponding dummy injury measures). The colour bands identify the rating system. Although many vehicles tested would rate "poor" none were unacceptable.

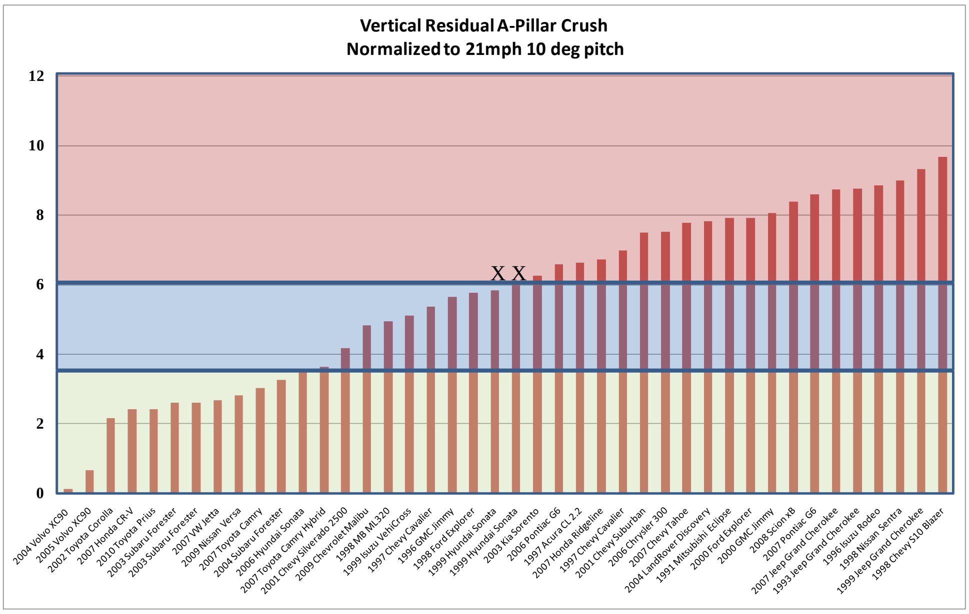

Figure 14. Normalized vertical residual A-pillar crush for various vehicles

Summary of Proposed Dynamic Rollover Compliance Test Regulation

Paraphrased from NHTSA, DOT § 571.208 Standard #208; Rollover Occupant crash protection and § 571.216 Standard No. 216; Roof crush resistance.

S1. Scope. This standard specifies performance requirements for the protection of vehicle occupants in rollover crashes.

S2. Purpose. The purpose of this standard is to reduce deaths and injuries and the severity of injuries due to the crushing of the roof into the occupant compartment in rollover crashes. Vehicle crashworthiness requirements are specified in terms of structural injury risk and corresponding forces and accelerations measured on the anthropomorphic dummy in test crashes.

S3. Application. This standard applies to passenger cars, multipurpose passenger vehicles, trucks, and buses to 2,725 kg (6,000 lbs) of maximum unloaded vehicle weight.

S4. Definitions.

- Injury risk performance is defined by the NASS-GES, CIREN probability of injury in Section 2 of this paper.
- Occupant protection performance shall be based on matching Dummy injury measures IBM and IHA relative to criteria (as defined in Section 6 of this paper) to within 30% of structural injury risk parameters relative to criteria. .
- The production Hybrid III dummy shall be modified as defined in Section 4 of this paper.
- The test fixture shall be based on the Jordan Rollover System patent as defined in Section 1 of this paper.
- Structural injury risk shall be defined by the statistical data of Method 2 of this paper.
- Production vehicle performance shall be evaluated in accordance with Method 3 of this paper.
- The real-world rating system shall be demonstrated by compiling real-world protocol test data as in Method 8 of this paper.

S5. Rollover Occupant crash protection requirements for the 50th percentile adult male dummy.

S5.1 Develop momentum exchange dummy, head, neck and spine injury measures and criteria as described in Method 5.

S5.2 Rollover Occupant Crashworthiness Requirements. The test dummy specified in S6 placed in each front outboard designated seating position shall meet the injury criteria of S6.1, S6.2, S6.3, S6.4, and S6.5 of this standard.

S5.3 Rollover. Subject a vehicle to the rollover test under the applicable conditions of S8 of this standard.

S6. Injury criteria for the prototype Part 572, Subpart E, Hybrid III rollover test dummy.

S6.1 All portions of the test dummy shall be contained within the outer surfaces of the vehicle passenger compartment.

S6.2 Head injury criteria: IHA shall not exceed 48.

S6.3 Neck injury: IBM shall not exceed 13.5.

S6.4 Thoracic injury: The resultant chest acceleration shall be calculated from the output of the thoracic instrumentation shown in drawing 78051.218, revision R incorporated by reference in Part 572, Subpart E of this chapter shall not exceed 60 g’s, except for intervals whose cumulative duration is not more than 3 ms.

S6.5 Thoracic Injury. Chest deflection. (a) Compressive deflection of the sternum relative to the spine shall not exceed 76 mm (3.0 in). (b) Compressive deflection of the sternum relative to the spine shall not exceed 63 mm (2.5 in).

S6.6 Leg Injury: Axial Femur Force. The force transmitted axially through each upper leg shall not exceed 2250#.

S6.7 Unless otherwise indicated, instrumentation for data acquisition, data channel frequency class, and moment calculations are the same as specified in Part 572, Subpart E Hybrid III dummy.

S6.8 Interior instrumentation shall include string potentiometers between the longitudinal roll axis and the A and B pillars on each side of the compartment and recorded by two opposing side high-speed colour cameras monitoring dummy motion and roof crush.

S6.9 The prototype Hybrid III rollover test dummy shall be placed in the outboard seating positions as specified in S5.2.

S8. Rollover test.

S8.1 The rollover test fixture shall meet the conditions of Method 1 as described in this paper.

S8.2 Real-world test protocol as described in Section 7 of this paper shall be used.

S8.3 Rollover test conditions.

S8.3.1 The vehicle is suspended with wheels and tyres removed on adjustable cradle mounts at the rear and at the front in a manner that allows it to be balanced, rotate freely and be dropped, passenger side (the nearside) leading onto the moving roadbed.

S8.3.2 The electrical system of the vehicle and its sensing and diagnostic module shall be powered to sense and activate pretensioners and airbags.

S8.3.3 Roadway: The roadway surface shall be level, rigid, of National Highway Traffic Safety Administration, DOT uniform construction, and of sufficient size to accommodate near and far-side roof contact at 135° of roll to 220° of roll and laterally from the hood to the rear of the mounted vehicle. It has a skid number of 75 when measured in accordance with American Society for Testing and Materials Method E–274–65T at 40 mph omitting water delivery as specified in paragraph 7.1 of that method.

S8.3.4 Roadway Instrumentation:

- Vertical and lateral load cells mounted on the roadway platform record the impact amplitude and coordinate the near and far-side impact times with the interior and dummy instrumentation.
- String potentiometers are placed on the fixture support towers to record vehicle vertical motion characteristics during the test. One string potentiometer is located in the front drop tower and the other is located in the rear drop tower. The potentiometers coordinate the vertical vehicle motion and drop timing with the interior instrumentation.
- ▪ A roll encoder is located on the cable pulley shows the roadway velocity throughout the roll.
- A roll-rate sensor in the vehicle shall be used to measure roll angle and roll rate during the test.
- The test vehicle identification and the test equipment shall be tabulated in tables of the report.

S8.3.5 Dummy: The prototype Hybrid III 50th percentile male rollover crash dummy specified in S6 shall be placed in the front outboard designated seating position. The test dummy shall meet the injury criteria of S6 of this standard.

- An instrumented, restrained test dummy in the outboard seat positions is monitored by seat belt load cells.
- The Hybrid III dummy shall be restrained using the vehicle's three-point harness with a non-deployed pretensioner. The Hybrid III is chalked before the test to locate impact marks. To make the Hybrid III dummy more humanlike, the cables in the lower spine were removed.

S10. Test dummy positioning procedures. The driver-side Hybrid III is tethered "out of position" with a light wire that electronically disconnected as the vehicle reached 30° past zero of roll. The "out of position" location of the dummy is found by rotating the vehicle by 90° toward the passenger side. This orientation simulated the dummy accelerating toward the passenger side door at 1 g.

CONCLUSION

Methodologies were developed to characterize a dynamic regulatory compliance test and acceptable performance criteria using a modified Hybrid III dummy. Rollover test performance is based on a match between the injury risk relative to criteria and momentum exchange dummy injury measures relative to criteria. Results of the five vehicles tested with an identical low-severity protocol, dummy modification and orientation demonstrated the match and the parameters affecting mismatch.

The primary benefit of the JRS dynamic tests compared to FMVSS 216 quasi-static tests is the ability to comparatively evaluate and rate vehicle performance with matched structural injury risk and dummy head, neck and spine injury measures relative to criteria. The secondary advantage is that the results identify anomalies between quasi-static and dynamic test methodologies. The tertiary advantage of the dynamic tests is the capacity to evaluate and optimize the effects of occupant protection features in rollovers.

Injury Assessment Reference Value (IARV) measures and criteria applicable to frontal and side impact events grossly underestimate rollover head and neck injury. A four-level injury risk rating system was demonstrated by normalizing 40 vehicles tested at various protocols to the regulatory test protocol, ordered by residual crush and plotted on the injury probability chart. A pilot series of production vehicles should be conducted with the proposed compliance test regulations. An analysis of these tests should be conducted to identify vehicle and restraint factors which result in a mismatch of injury risk and dummy injury measure performance relative to criteria.

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