Status of Comparative Dynamic Rollover Compliance Research and Testing

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Abstract – In the U.S., about 40,000 catastrophic and fatal injuries occur annually in rollover crashes. A strategy for injury mitigation is dynamic compliance testing with dummy-occupied vehicles and occupant protection requirements, similar to that required for frontal and side impacts. Presently, the CRIS and JRS dynamic vehicle rollover test devices realistically simulate the ballistic phase of real-world rollover crashes. A search for a typical serious injury test protocol is in progress.

Over 300 rolls and more than 50 two-roll JRS tests of mostly low severity ballistic trajectory protocols have been performed with the belted production Hybrid III dummy. These dynamic tests (as compared to static tests) identified significant roof strength, construction and crush effects of vehicle geometry, buckling structure, yaw and pitch impact angle, window breakage and their relationship to occupant injury and protection. A companion paper at this conference "Characterizing the Injury Potential of a Real World Rollover" details these effects.

It was also found that with roof crush, serious neck bending injuries predominated while head injuries and partial ejections did not occur, except with the very weakest roofs. Since the bending stiffness of the joint muscles of the human body during a rollover are unknowable, a Hybrid III dummy with a modified lumbar joint and reduced musculature neck has been developed as the best available surrogate for dynamic rollover tests. The Hybrid III neck is about 3 times stiffer in bending than a normal relaxed human neck and about one third as stiff as the tensed neck of a young soldier on which the production Hybrid III neck was based. Recent results with a yaw and trip derived initial out-of-position of this dummy indicated a 8 to 11 kph (5 to 7 mph) centrifugal erection rate. In combination with roof intrusion speeds of 11 to 21 kph (7 to 13 mph) more head injuries and partial ejections, consistent with crash statistics are predicted.

The JRS roof crush results of 40 production vehicles roughly normalized to a proposed real world severity test protocol has been matched to NHTSA's post crash negative headroom criteria and to a CDC serious injury risk to various body part analysis. A dynamic rollover crashworthiness compliance test based on a roof crush injury risk criteria with reported injury measures from an instrumented, belted, initially out-of-position dummy is available now.

In 2010, with resolving epidemiology and protocol parameter sensitivity data, our goal is a representative injury risk compliance pilot test series with occupant protection injury measure data demonstrated in 2011 and confirmed for an NPRM by VRTC in 2012. We firmly believe that a dynamic test will be ready for implementation long before the NHTSA plan.

INTRODUCTION

In the U.S., about 40,000 serious to fatal injuries occur annually in 258,000 rollover crashes. About 418,000 occupants are not seriously injured [1]. A strategy for injury mitigation is dynamic compliance testing with dummy-occupied vehicles and occupant protection requirements, similar to that required for frontal and side impacts. Presently, the CRIS and JRS dynamic vehicle rollover test devices can realistically simulate the ballistic phase of real-world rollover crashes [2].

C*f*IR submitted some 4,200 pages of comment and 5,200 pages of data to NHTSA roof crush dockets. Figures 1 and 2.

Figure 1. Docket submissions to NHTSA.

Figure 2. JRS testing data and reports.

The JRS came about as a result of NHTSA's request for comments on upgrading FMVSS 216 [3] in 2001. Its development was preceded by detailed review of the 1985 and 1990 Malibu tests [4-5], experimental lateral [6] and two sided quasi-static roof strength tests of more than 40 vehicles of 1990's vintage [7] as shown in Figures 3-6.

A key consideration in the compliance protocol development was the finding that a one-sided static test at 5º pitch/25º roll platen angles does not simulate the severe to fatal injuries evident in real world crashes. In contract, versus a sequential two-sided static test first at 10º pitch/25º roll and then 10º pitch/40º roll platen angles does simulate the severe to fatal injuries in real world crashes.

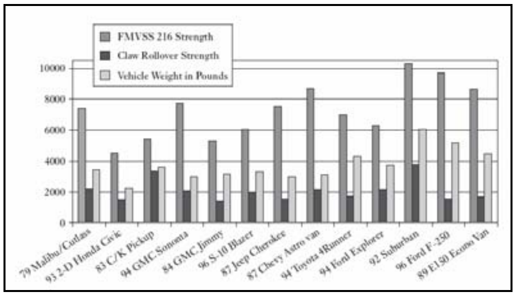

Figure 3. Comparative results of FMVSS 216 and 45º Survey tool lateral loading in 2000.

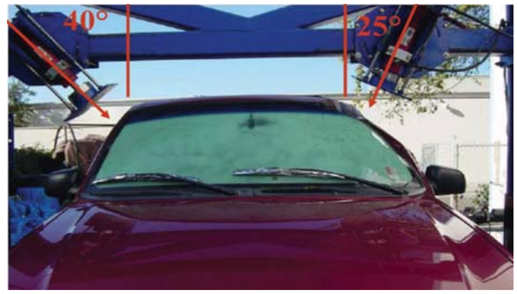

Figure 4. Vehicle in M216 test fixture indicating 25° and 40° platen angles.

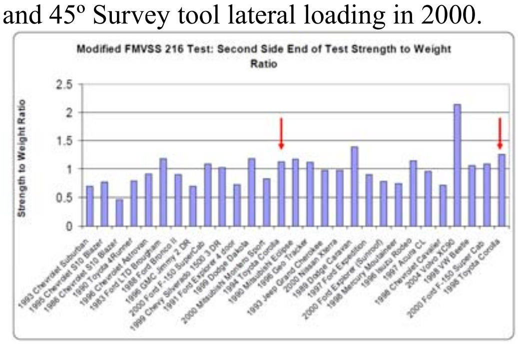

Figure 5. Second Side M216 Strength to Weight ratio highlighting 2 generations of Toyota Corollas.

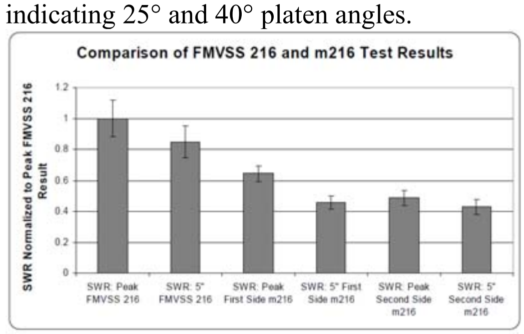

Figure 6. Comparison of FMVSS 216 and M216 tests at peak and at 18 cm (5") of displacement.

The lateral and two sided tests were prompted by the 1970 two-sided NTSB proposed roof strength rule [8], 1985 vintage GM studies of lateral loading [9] and the contribution of windshield bonding to static roof strength [10]. The results indicated that in a two sided test characteristic of a rollover, the roof was roughly half as strong as indicated by the standard FMVSS 216 test. Figure 5 also points out that strengthening the FMVSS 216 tested roof of a 1994 Toyota Corolla from an SWR of 2.5 to the SWR = 4.2 of the 1999 Corolla had comparatively little effect on its 10° of pitch M216 result.

NHTSA's static test angles are based on a vehicle's 5^o pitch and 25^o roll platen damage pattern matching the real world damage pattern of the same vehicle in a NASS case. Since almost all NASS case files do not involve serious injury, this comparison suggests that serious injury is equally likely in any vehicle which is platen tested at 5^o pitch and 25^o roll, although only about 9% of those rollover occupants were seriously injured. However, when searching the serious injury rollover data files selected by NHTSA to support their 2005 NPRM, 80% had damage from 10^o or more pitch [11]. Furthermore, at 10^o, pitch most vehicles were half as strong as shown by our modified or M216 tests. Most vehicles in the US fleet have an estimated average SWR of 2.2. All other things being equal an increase in the SWR of 50% to more than SWR = 3 will reduce serious injuries very little as NHTSA predicted. Hopefully by 2017 when manufacturers comply with FMVSS 216, they will have recognized through dynamic tests that adequate roof strength at 10^o of pitch is an important and easily implemented structural modification.

NHTSA interpreted C*f*IR's data submissions in the context of its historical one sided testing. In 2002 NHTSA conducted independent experiments (see Figure 7) comparing a one sided 5° of pitch and 25°

of roll test (black plot) on one Dodge Grand Caravan to a 10° of pitch and 45° of roll test on another identical vehicle (green plot). They concluded for these pitch and roll angles, pitch did not make any difference [12]. The peak values are similar. However, the 10º x 45º platen strength falls off sharply at 7 cm (3”) and is 40% lower at 12.5 cm (5”).

A similar pair of one sided tests was performed by NHTSA on two 2002 Ford Explorers. Figure 8 shows the 5° of pitch and 25° of roll test (purple plot) and the 10° of pitch and 45° of roll test (blue plot). After about 6 cm (2.5”) of stroke in the second test (blue plot) the platen edge contacted the base of the A-pillar and the force continued to rise inappropriately since the ground could not have contacted the base of the A-pillar at that depth and at those angles. Figure 8 also shows a data plot from a 2000 Explorer in an FMVSS 216 test, conducted by Exponent (black dash line). The 2000 and 2002 Explorer (purple plot) are supposed to be identical but obviously are not identical. An M216 test of the 2000 Explorer was conducted first on the near side with a 10º x 25º platen (green) and then on the far side with a 10º x 40º platen (orange). The Exponent 5º x 25º test force at 12.5 cm (5”) is about 15% lower than the comparable (purple) NHTSA test. The M216 (green and orange) tests at 12.5 cm (5”) are about 45% lower than the Exponent test.

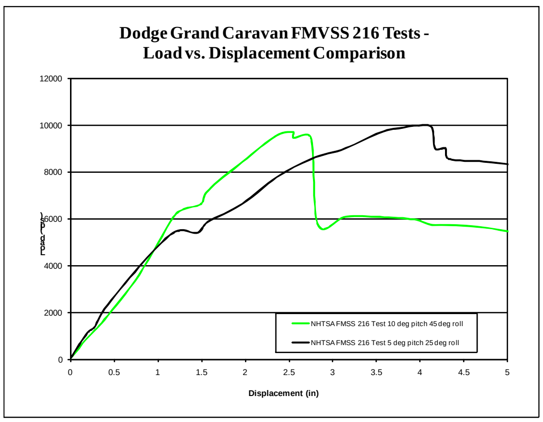

Figure 7. NHTSA Tests

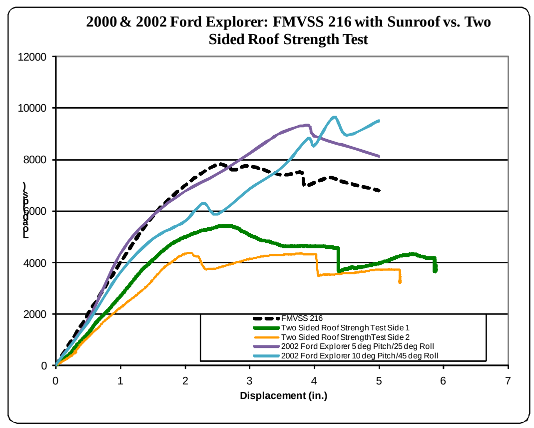

Figure 8. NHTSA, Exponent and M216 data

In a serious injury rollover crash both sides of the roof experience essentially the same 10° pitch. When the near side is displaced by the platen 12.5 cm (5”), the side glass and windshield break. This reduces the strength on the far side where the lateral loading collapses the structure so that the SWR is 0n the order of half of the FMVSS 216 result. Our tests have repeatedly and consistently demonstrated this result; we believe it is essentially the same for almost all similar geometry vehicles.

This difference in interpreting rollover roof strength is key to the inability to evaluate injury potential from static tests. Two other factors make dynamic testing essential to ferreting out roof failures: the effect of vehicle geometry and the potential for assessing occupant protection systems.

Dynamic JRS Test Considerations

Some 300 rolls of more than fifty (50) vehicles have been conducted with several protocols but most recently involving 10° of pitch. These tests have validated NHTSA’s and IIHS’ position that increased static roof strength to the SWR level of 3 or 4 or more will have a significant effect on reducing casualties. But as indicated by IIHS studies there is a wide disparity of the unadjusted data injury rates between vehicles of the same SWR as shown in Figure 9. That disparity is also seen in the JRS roof crush results of different vehicles with essentially the same SWR like the Honda CR-V and Honda Ridgeline. Also two identical tests with substantially different dynamic roof crush results illustrate the non-linearity of weak roofs like the Pontiac G6.

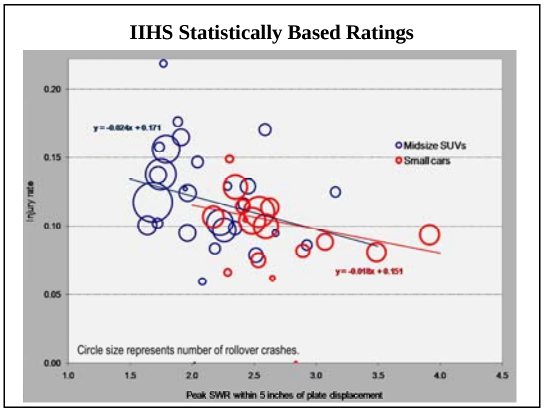

Figure 9. IIHS Injury Rates vs SWR

The US Rollover Injury Problem

- **258,000 Rollovers with 418,000 occupants and 40,000 (9.6%) are seriously injured or killed, 90% of which occur within two rolls.***

• **Interior Fatalities**	**5,400**	**(1.3%)**
• **Ejection Fatalities**	**4,800**	**(1.1%)**
• **Severe and critical injuries****	**12,000**	**(2.8%)**
• **Serious injuries****	**18,000**	**(4.3%)**
• **Not seriously injured**	**378,000**	**(90.5%)**

*NHTSA 2003 estimates. **estimated distribution from Ciren and GWU

"Ejection Mitigation using Advanced Glazing – Final Report", D Wilke, S Summers, J Wing, J Lee, C Harper, S Partyka, August 2001
"Initiatives to Address the Mitigation of Vehicle Rollover", National Highway Transportation Safety Administration, June 2003

Figure 10. Roughly Estimated Injury Statistics

Since the approximate accident statistics of Figure 10 suggest that less than 10% of the vehicles in rollover crashes are anomalous in injury potential, it is important to detect, reject or correct them. The only way to do that is through comparative dynamic rollover tests with derived parameters from real world rollover circumstances. We need to know the main contributors to far side injury potential with less than 10.2 cm (4") of roof crush, for a drop height of 10.2 cm to 30.5 cm (4" to 12") to the near side and an SWR of 3 to 4. Based on the JRS tests the most probable answers are initial pitch and roll angle and roll rate. However several ways of determining those parameters have been and are underway.

NHTSA suggests that the ballistic phase protocols ignore the potential for injury during the curb trips that precede the ballistic phase. Sixty percent of rollovers occur without a significant pre-roll crash [13]. Human experiments indicate the loss of control, yaw to trip, and the trip phases were not seriously injurious. Another aspect of the unlikely curb trip is a launch, pivoting over the near side wheels without yaw, which lofts the vehicle by a foot [14]. At the right traveling speed the roll rate can be such as to result in a first roof to ground contact on the flat of the roof panel [15] much like the CRIS tests of the Crown Victoria and the GM Blazer [16]. These result in spectacular roof crush and high potential for head/neck injury, but are unrealistic as the typical trip and touchdown characteristic. Nevertheless, the JRS can conduct such a test without the wheel trip mechanism but with the occupant injury potential kinematics.

The objective approach is illustrated by Parent [17] at the University of Virginia who performed a sensitivity study using the NCAC 2003 Ford Explorer model in LS-DYNA. This study evaluated the sensitivity of roof crush and vehicle kinematic response to variations in roof strength, roll angle, pitch angle, yaw angle, roll velocity, translational velocity, and drop height during the roof-to-ground interaction phase of the rollover event. A full-factorial design of experiments (DOE) array made up of three levels for each of the seven parameters was sub-sampled to a total of 129 simulations.

Based on these modeling results, for a vehicle like the 2003 Ford Explorer with an SWR of 2.2, peak roof crush is probably associated with drop height. However, drop height is not available from the NASS files. In essence, this UVa study seeks to find the key parameters resulting in the 10% of the people with serious to fatal injury, from the parameters which account for all rollover crashes including the 90% of uninjured.

A similar study is being performed at GWU / NCAC [18]. This study is based on 400 investigations of catastrophic rollover injury crashes and experimental evidence of rollover roof crush performance. The experimental studies were also based on Digges' two-roll event [13], Nash's 80% serious injury NASS cases at 10° pitch [19], Malibu roll rate gyros and end of track video drop heights [20-21] applied to JRS tests with a normalized protocol.

The Hybrid III dummy has historically been used as the human surrogate for dynamic rollover tests. The issue here is not whether the Hybrid III is or is not biofidelic. The Hybrid III neck was developed from testing of very strong young muscular tensed military personnel in the late 60's [22]. The Hybrid III neck is 10 times stiffer than a relaxed human neck. The neck is not characteristic of the unknowable and variable muscle tension of the general human population during the 3 or 4 second sequence of vehicle and occupant kinematics in a rollover. JRS research has shown that catastrophic head or neck injuries resulting from roof interaction and partial ejection in real-world rollover crashes are poorly replicated by dynamic rollover tests with the production Hybrid III dummy neck because of its stiffness.

Dynamic tests showed that the far-side human volunteer occupant's upper torso slipped out of the shoulder belt and moved laterally and forward during the pre-roll loss of control, yaw to trip, and the trip phases. The recently completed "Far Side Project" [23] confirmed these findings. This placed the occupant substantially inboard at the beginning of the ballistic phase of the rollover. Then, during the ballistic phase, centrifugal force erects the far side occupant, who develops a significant and injurious relative velocity as the head moves to and impacts the roof, roof rail, and header or goes out the side window.

METHODS

Development of the More Natural Hybrid III Spine

The Authors have developed a prototype neck and lumbar spine assembly for the Hybrid III dummy for use in rollover testing [24-28]. The design goals included decreased stiffness and a mechanism that represents the unknowable human muscle tension in rollover crash environments. The prototype neck was fabricated by Denton ATD using the production Part 572E Hybrid III neck mold. The stiff 67-durometer butyl rubber used in a production Hybrid III neck was replaced by "soft" 35-durometer butyl rubber discs and nodding blocks in the prototype neck. The angular limiting cables of the Hybrid III lumbar spine were removed to soften that joint and better duplicate the observed human kinematics. Preliminary rollover injury criteria have been proposed, and prototype and production Hybrid III and human cadaveric responses have been correlated [29].

Comparative dynamic platen drop and pendulum, and static torque tests of the standard production and a low durometer equivalent Hybrid III neck were conducted [28]. Tests were conducted at 0° to 60° neck to the impactor angle. Recognizing that the aligned dummy neck characterizes a human 30° neck to torso angle, the dummy neck in the most recent tests has been angled and set at 30°. These tests in effect established a transfer function of upper and lower neck bending moments relative to the established Injury Assessment Reference Values (IARV). These in turn were compared to the major lower neck injury moments established by Pintar et al. to derive peak bending moment injury criteria. In addition lower neck data from JRS tests were formulated into a proposed momentum exchange injury function which integrates the resultant bending moments into a comparative number called Integrated Bending Moment (IBM). [29-30]

Development of the Dynamic JRS Fixture

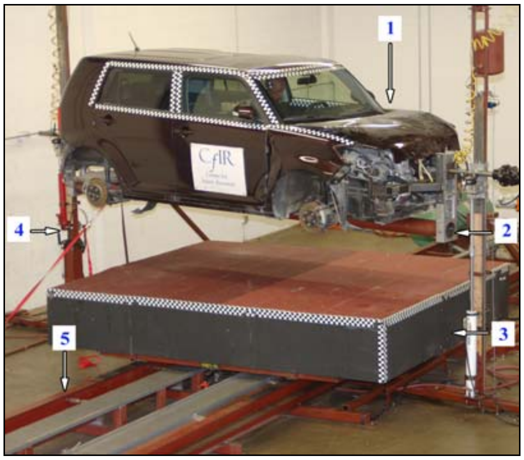

Figure 11. Key Components of The JRS: 1) Vehicle, 2) Cradle/Spit Mount, 3) Moving Roadbed, 4) Support Towers, 5) Coupled Pneumatic Roadbed Propulsion and Roll Drive

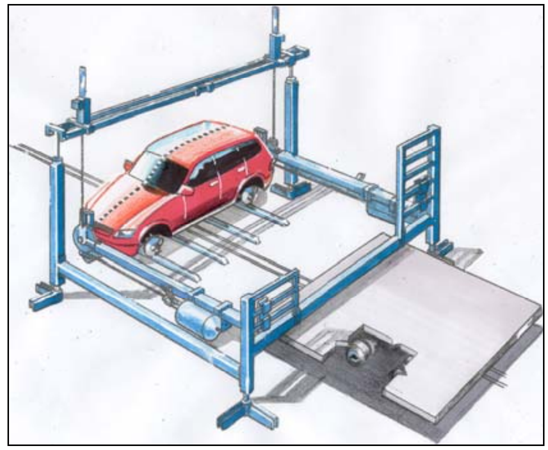

Figure 12. The UNSW/CrashLab JRS system: Gantry and Road Bed System.

The existing JRS fixture and its component parts are identified in Figure 11. The JRS fixture in fabrication for the UNSW/CrashLab in Sydney, Australia is shown in Figure 12. Both of these systems are more fully detailed in a companion paper at this conference [31].

In the course of more than 300 rolls and seven years of operation the JRS machine evolved from a simple dynamic rollover comparative development and evaluation device into a sophisticated research tool. The first tests used body-in-white compartments [32] on a cradle weighted to the vehicles roll moment of inertia and to the actual or any desired increased strength to weight ratio (SWR). Roof crush performance was measured by an array of string potentiometers. Concern for hood and fender contact with the ground affecting the roof deformation led to a larger road bed and complete vehicle tests with dummies. As larger and heavier, higher roll moment of inertia vehicles were tested the drive shaft and universal bearing joints increased in capacity. Instrumentation expanded to include dummy injury measures and high speed orthogonal color cameras with tracking software to supplement the string potentiometers. Lastly a method has been developed to use the JRS for parameter sensitivity tests by repetitive simulation of occupant kinematics with no roof crush. A companion paper at this conference [31] discusses the alternative design variations of the JRS now in fabrication or development for compliance testing, occupant protection equipment suppliers and vehicle manufacturers.

Development of Dynamic Protocols

The protocols used changed over time with the improvement of roof SWR from the 1.6 of the 1990 Chevrolet Blazer and Ford Explorer to current vehicles with SWRs of 2.4 to 6.8 [22]. The original tests were at 24.1 kph (15 mph), 5° pitch and 190°/sec. roll rate and 135° roll angle. It wasn't until those vehicle tests resulted in less than 10" of crush that the pitch angle was increased to 10° on the first or second roll of a test sequence where the expected roof crush was below 35.6 cm (14"). The retractor locked belted dummy (without cable limited lumbar bending) in the first roll is now set out-of-position by a 1G lateral force to the torso and is held by a 60º to the longitudinal axis tether which is released at the initiation of roll. A method has been developed to roughly normalize these protocols to the real world parameters for roof crush evaluation. The developed real world protocol for the first roll of a two roll sequence is 33.8 kph (21 mph) , 270°/sec., 10° pitch, 145° impact and 15° yaw angle, with a 10.2 cm (4") near side drop height [33].