MATCHING STRUCTURAL INJURY RISK STATISTICS AND DUMMY INJURY MEASURES FOR A DYNAMIC ROLLOVER RATING AND REGULATORY COMPLIANCE TEST

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ABSTRACT

A study was conducted on five different vehicles. Each vehicle was dynamically rollover tested using similar rollover test parameters. The study was performed to examine the major factors in a rollover that match structural injury risk to injury measures for occupants that were neither ejected nor partially ejected.

RESEARCH OBJECTIVES

Identify major factors in a rollover that match structural injury risk to injury measures for occupants that were neither ejected nor partially ejected.

INTRODUCTION

In recent years, efforts have been underway to develop a global full-scale dynamic rollover regulatory compliance test with instrumented anthropomorphic dummies. Compliance in this test is a function of both vehicle structural and dummy responses. In 2009, NHTSA amended the strength to weight ratio (SWR) requirement by increasing the criteria from 1.5 to 3.0 in the quasi-static FMVSS 216 Roof Crush compliance test. NHTSA also initiated research on a dynamic rollover compliance test. NHTSA pointed out that a regulatory compliance test be based on dummy injury measures and criteria that match the structural injury risk and criteria. Establishing the relationship between a vehicles structural performance and dummy injury measures became a primary objective of the (C*f*IR) Center for Injury Research recent research.

Until 2002 no direct measures of occupant responses and no data upon which to evaluate primary and supplemental restraint systems in a rollover environment have been available with the exception of virtual dummies. Virtual dummies are limited in that they cannot emulate the variable stiffness of human reactions over 0.9 seconds. A dynamic rollover test protocol can be used to determine the dummy kinematics in a rollover to better understand the relationship between the roof and occupant at the time of roof impact. Furthermore, the effectiveness of lap and shoulder belts in a rollover can be analyzed.

NHTSA has identified residual roof crush as the most important factor for determining structural injury risk in a rollover after an accident has occurred. Residual crush is the only data available to an investigator after a rollover 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 can provide the time history of roof crush and crush speed. Structural injury risk, as used here, is a statistical term relating structural performance in terms of crush to the probability of human real-world injury. The probability of human real-world injury, or injury risk, could be defined with other factors as well.

Structural injury risk statistics were obtained from NHTSA's NASS (National Automotive Sampling System) and CIREN (Crash Injury Research) data. The data was then used to derive the "structural injury risk" criteria for the proposed compliance test. The probability of injury for a belted occupant is based on residual roof crush as well as the dynamic speed of roof crush. This means that for the same amount of roof intrusion the injury risk can be much higher for a scenario where the roof intrusion speed is high versus a lower intrusion speed. 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 1 by Mandell, et al. [1]. A rollover regulatory or NCAP injury measure system should match structural injury risk criteria with the predominant head, neck, and thorax injuries. The real-world rollover crash data files suggested that quadriplegia and paraplegia were consequences 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.

Mortality (95% CI).

Roof crush	Probability	Weighted probability	Unadjusted odds	Adjusted odds[a]	Conditional odds[b] (hazard ratio)
0–3 cm	3.41%	0.38%	1.0	1.0	1.0
3–8 cm	2.03%	0.35%	0.588 (0.354, 0.977)	0.606 (0.362, 1.013)	0.577 (0.345, 0.963)
8–15 cm	2.64%	0.28%	0.769 (0.485, 1.218)	0.794 (0.497, 1.268)	0.759 (0.476, 1.210)
15–30 cm	6.86%	1.63%	2.089 (1.461, 2.987)	2.452 (1.684, 3.569)	2.253 (1.554, 3.267)
≥30 cm	18.18%	3.08%	6.301 (4.369, 9.087)	7.241 (4.895, 10.710)	6.548 (4.444, 9.647)

[a] Adjustment was done on (conditioning variables for adjusted logistic regression) age + age-squared, front seat v. rear seat, left seat v. right seat, gender.
[b] Conditional models were matched on body type (Auto, SUV, Truck, Van/Minivan), # rolls (2–3, 4–5, 6+ or lateral), curb weight (<> mean 1490 kg), rollover as primary event.

Spine Injury AIS ≥ 3 (95% CI).

Roof crush	Probability	Weighted probability	Unadjusted odds	Adjusted odds[a]	Conditional odds[b] (hazard ratio)
0–3 cm	1.96%	0.46%	1.0	1.0	1.0
3–8 cm	1.92%	0.37%	0.978 (0.566, 1.690)	0.958 (0.551, 1.665)	0.935 (0.538, 1.624)
8–15 cm	3.79%	0.94%	1.968 (1.273, 3.043)	1.883 (1.206, 2.940)	1.838 (1.179, 2.865)
15–30 cm	4.82%	1.38%	2.530 (1.634, 3.917)	2.341 (1.474, 3.718)	2.343 (1.480, 3.708)
≥30 cm	5.09%	1.01%	2.682 (1.474, 4.877)	2.690 (1.452, 4.983)	2.588 (1.399, 4.789)

[a] Adjustment was done on (conditioning variables for adjusted logistic regression) age + age-squared, front seat v. rear seat, left seat v. right seat, gender.
[b] Conditional models were matched on body type (Auto, SUV, Truck, Van/Minivan), # rolls (2–3, 4–5, 6+ or lateral), curb weight (<> mean 1490 kg), rollover as primary event.

Spinal cord injury (95% CI).

Roof crush	Probability	Weighted probability	Unadjusted odds	Adjusted odds[a]	Conditional odds[b] (hazard ratio)
0–3 cm	0.62%	0.06%	1.0	1.0	1.0
3–8 cm	0.56%	0.09%	0.911 (0.337, 2.460)	0.868 (0.320, 2.355)	0.854 (0.315, 2.315)
8–15 cm	0.69%	0.19%	1.113 (0.440, 2.812)	1.083 (0.425, 2.760)	1.071 (0.421, 2.724)
15–30 cm	1.90%	0.56%	3.104 (1.513, 6.366)	3.062 (1.457, 6.439)	3.195 (1.529, 6.673)
≥30 cm	2.18%	0.26%	3.579 (1.409, 9.092)	3.483 (1.338, 9.067)	3.434 (1.324, 8.906)

[a] Adjustment was done on (conditioning variables for adjusted logistic regression) age + age-squared, front seat v. rear seat, left seat v. right seat, gender.
[b] Conditional models were matched on body type (Auto, SUV, Truck, Van/Minivan), # rolls (2–3, 4–5, 6+ or lateral), curb weight (<> mean 1490 kg), rollover as primary event.

Head injury AIS ≥ 3 (95% CI).

Roof crush	Probability	Weighted probability	Unadjusted odds	Adjusted odds[a]	Conditional odds[b] (hazard ratio)
0–3 cm	3.82%	0.76%	1.0	1.0	1.0
3–8 cm	2.26%	0.84%	0.582 (0.359, 0.942)	0.603 (0.371, 0.981)	0.580 (0.357, 0.942)
8–15 cm	4.25%	0.77%	1.117 (0.764, 1.634)	1.188 (0.807, 1.749)	1.136 (0.773, 1.669)
15–30 cm	5.69%	1.05%	1.520 (1.045, 2.211)	1.678 (1.135, 2.480)	1.545 (1.049, 2.277)
≥30 cm	12.73%	2.11%	3.672 (2.456, 5.490)	4.088 (2.692, 6.209)	3.694 (2.442, 5.588)

[a] Adjustment was done on (conditioning variables for adjusted logistic regression) age + age-squared, front seat v. rear seat, left seat v. right seat, gender.
[b] Conditional models were matched on body type (Auto, SUV, Truck, Van/Minivan), # rolls (2–3, 4–5, 6+ or lateral), curb weight (<> mean 1490 kg), rollover as primary event.

Figure 1. *NASS/CIREN statistical analysis.*

Precrash headroom, the effect dynamic intrusion has on headroom, and belt forces were identified as major factors that can be used for determining neck and head injuries in rollovers. Using a hybrid III, dummy lap and shoulder belt forces measured in a dynamic rollover test can be used to reasonably determine dummy motion and the amount of headroom loss for a specific vehicle.

Computer simulations of dummies with tensed and untensed necks, human volunteer drop testing from 12 to 36 inches [2], and comparative tests between dummies and humans determined that to better match human characteristcs in flexion the dummy neck should be 1/3 as stiff as the production Hybrid III neck and inclined at 30 degrees to the torso [3]. The ultimate value of a dynamic test is to not only assess structural injury risk such as intrusion, but also dummy injury criteria measured 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. The Hybrid III dummy was 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.

A match between roof intrusion measures and dummy injury measures was identified in the five dynamic rollover tests using five different vehicles. The study determined that when the lap and shoulder belt forces were high the belts were effective in minimizing the dummy's motion towards the roof. When occupant motion towards the roof in a rollover, or diving, and low structural injury risk existed (low intrusion and low intrusion speed) the dummy injury measures were small. However, when high structural injury risk existed the reduction in the dummy diving motion was not sufficient to minimize dummy injury risk.

METHODS

Two generations of a mechanical rollover fixture called the Jordan Rollover System (JRS) were built and installed at C*f*IR, UVA (NHTSA), and UNSW. Over 50 vehicles have been evaluated for injury risk as defined by residual roof crush and crush speed using the JRS. The JRS rollover test protocol is used to examine the crash segment of a rollover that is further explained in ESV 11-0405 paper [4]. Moreover, it is used to assess what happens in a rollover crash after the vehicle begins to roll and two or more wheels of the vehicle have left the ground. Determining the factors such as vehicle handling and stability are assessed using other test methods.

Every rollover crash can be broken down into segments as defined by roll angle to evaluate the kinematics of a dummy/occupant. As a result the segment of the rollover crash with the greatest-injury potential was identified. The process of identifying the most serious injury potential required evaluating the injury potential sensitivity of each segment and its influence on the following segment. A real-world dynamic rollover test protocol should represent the injury consequences of FMVSS 216 and 226 compliant vehicles. This means that the injury criteria used in the protocol is not related to unbelted occupants or occupants that are partially ejected in a rollover. The test protocol is defined 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). The methodology for the development of the test protocol in Table 1 is explained in detail in ICrash paper ICR-14-33.

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

Consensus injury measures at 8 mph developed by McElhaney [5] and combined by Paver [6] are shown in Figure 2. The map of the injury measures was submitted to NHTSA in 2008. 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 integrated head acceleration (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. The only consensus injury measures were roof crush and roof crush speed based on criteria developed by McElhaney [6].

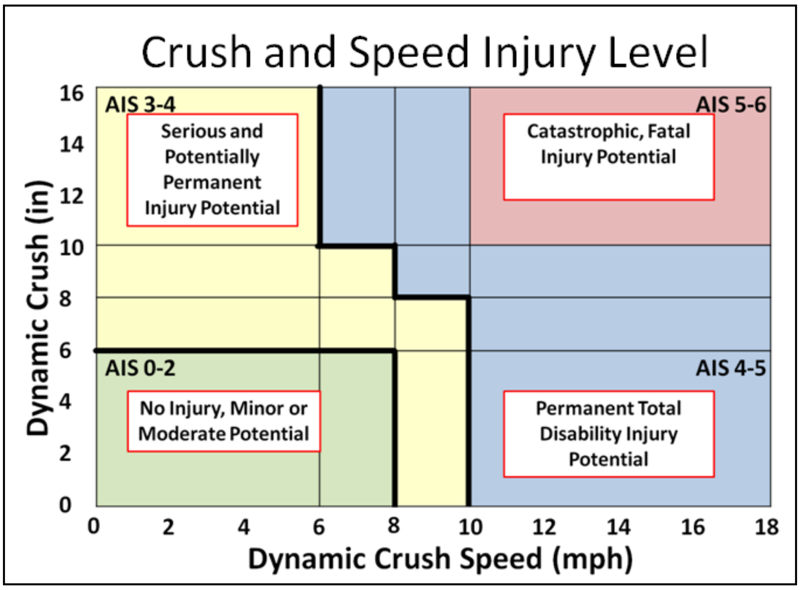

Figure 2. *Dynamic crush and crush speed in relation to AIS injury levels.*

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 values defined as injurious yielded the criteria as 13.5.

An example of an injury risk relationship was demonstrated by the IIHS analysis of the effect of SWR vs. injury rate. In 2008, C*f*IR compared the results of 21 JRS tests to IIHS statistical structural injury risk data which showed a substantial benefit from increased roof SWR [7]. NHTSA statistical analysis indicated that, when roof crush exceeded headroom, injury was five times more likely [8-9]. Moreover, the data indicated 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.

Since the real-world protocol described in Table 1 involves a 21 mph 10º pitch protocol, C*f*IR used a normalization procedure previously published [10] to represent most vehicles tested. The normalization procedure predicts the amount of residual crush based on SWR when a vehicle is tested using the real-world protocol. Validation of the normalization procedure is shown by the two bars corresponding to the 1999 Hyundai Sonata marked with an "x" as shown in Figure 3. 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 proposed dynamic rollover test.

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. The chart is normalized to the 1st roll of a 2 Roll rollover representing 95% of all rollovers and AIS 3+ rollovers. Vehicles with residual crush less than 3.5 inches would be read "good", vehicles with residual crush up to 6 would be rated "acceptable", vehicles with residual crush between 6 and 12 inches would be rated "poor", and vehicles with residual crush more than 12 inches would be rated "unacceptable".

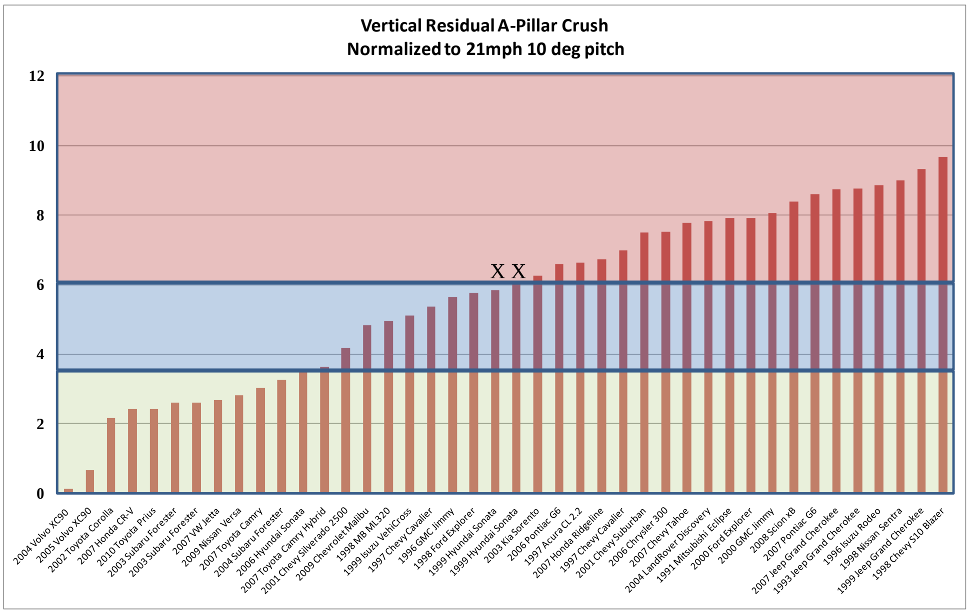

Figure 3. *Normalized vertical residual A-pillar crush for various vehicles.*

RESULTS

There were five tests conducted using a "low-severity" protocol. The low-severity protocol differed from the proposed real-world protocol (Table 1) in that the translational speed was 15 mph versus 21 mph and the pitch angle was 5º pitch versus 10º. The structural injury risk relative to dummy injury criteria was matched in Figure 4. Based on a hybrid III dummy configured with a soft neck angled at 30 degrees, the dummy injury measures were found to be a function of headroom and belt loading. Dummy configuration was the same for each vehicle test.

The six bars in the figure from left to right represent corrected residual crush, dynamic injury risk, peak lower neck axial compression, peak lower neck flexion moment, the IBM, and the IHA.

- The royal blue (corrected from the string pot angle) and red (dynamic injury risk) bars represent residual roof crush and roof crush speed. Based on the structural injury criteria as defined by NASS/CIREN data the percentage probability of a AIS 3+ structural injury risk is 100 percent of Critical Value.

- 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 Injury Assessment Reference Values (IARV). Traditional IARV measures and criteria applicable to frontal and side impacts substantially underestimate rollover injury potential as result of the dummy stiffness being attuned to crash modes other than rollover.

- The turquoise (IBM) and orange (IHA) bars represent the percentage probability of AIS 3+ injury in a rollover crash.

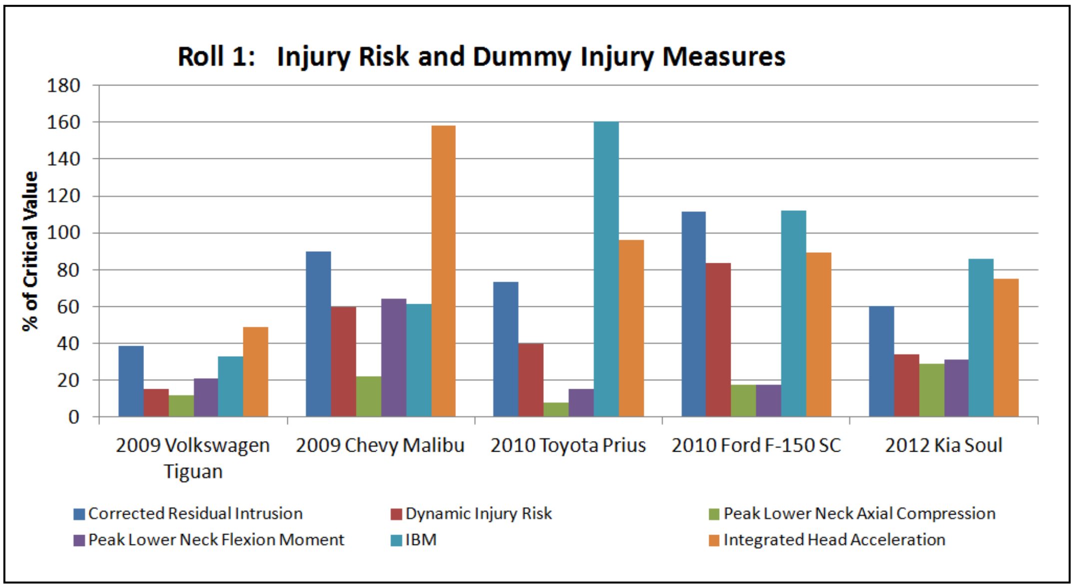

Figure 4. *Structural injury risk and dummy injury measures of five production vehicles.*

The 2009 Volkswagen Tiguan precrash headroom measured from the header was approximately 5 inches using the dummy configuration described earlier. The dynamic speed of intrusion is only 18% of structural injury criteria and the headroom was reduced to approximately zero during the rollover crash test. The peak lap belt force was 247 pounds and the shoulder belt force was 250 pounds. The peak lap and shoulder belt forces occurred during the roll segment that spanned from 180 degrees (completely inverted) through the far side impact roof crush.

The 2009 Chevrolet Malibu precrash headroom measured from the header was approximately 6 inches. The Malibu residual intrusion is 90% of the structural injury risk criteria. The bending moment is consistent with the roof intrusion. However, the IHA is more than twice the dynamic intrusion speed and as a result of this was over 150% of the critical value. The peak lap belt force was 245 pounds and the shoulder belt force was 171 pounds. The lap and shoulder belt provided the dummy with adequate resistance to falling immediately before and at the time of the far side impact. The test video shows the collapse at the top of the A-Pillar to be timed with the dummy's rotation about the seat due to gravitational forces. No dummy motion in the direction of the vehicle's z-axis was observed.

The 2010 Toyota Prius precrash headroom measured from the header was approximately 4 inches. In terms of structural injury risk the 2010 Toyota Prius measured slightly less than the Malibu. However, for the Malibu the

IBM is more than twice its residual intrusion and dynamic speed. The peak lap belt force was 207 pounds and the shoulder belt force was 401 pounds. The shoulder belt force diminished quickly at the time of peak intrusion.

The 2010 Ford F150 precrash headroom measured from the header was approximately 10 inches. The F150 exhibits residual crush and dynamic intrusion speed at the critical limit of the structural injury measures. The peak lap belt force was 246 pounds and the shoulder belt force was 597 pounds. The shoulder belt force diminished at the onset of the far side impact. Although the headroom for this vehicle is much higher than the other four, the structural injury measures are high enough to affect the dummy injury measures.

The 2012 Kia Soul precrash headroom measured from the header was approximately 5 inches. Although the dummy did contact the roof intrusion and intrusion speed was so low that the dummy injury measures remained below the critical injury values. The peak lap belt force was 387 pounds and the shoulder belt force was 261 pounds.

DISCUSSION AND LIMITATIONS

Precrash headroom for each vehicle is slightly higher than a typical seated 50^{th} percentile human because of the 30 degree soft neck angle used as an initial condition for the start of the rollover segment. The soft neck response to the dynamic forces involved in the rollover crash proved that the initial condition did not produce a negative effect on the test. Because the neck was able to respond quickly the dummy head position moved in the direction of the applied external forces. This meant that when the roof loading imparted an acceleration on the dummy and belts responded in the opposite direction the unrestrained head would move towards the roof as to be expected in a rollover.

The Tiguan showed correlation between relatively low residual crush and dynamic intrusion speed relative to dummy injury criteria. The values relative to criteria are so low that this vehicle is very safe in a rollover compared to the other four vehicles. Furthermore, the dynamic test validated the use of the lap and shoulder belts during the rollover. Because the belt provided the dummy with the necessary resistance to falling and the dynamic roof crush was minimal the magnitude of the impact with the header was minimized.

The Malibu vehicle as tested indicates a low force to the shoulder belt relative to other vehicles. In combination with a residual roof intrusion equal to 90% of the critical limit this allowed the upper torso of the dummy to rotate about the seat more rapidly and thus resulting in a high risk of serious head injury.

The Toyota Prius as a result of limited head room is very likely to result in a hyperflexion neck injury whenever the structural injury measures are close to the critical value. The small amount of headroom meant that the residual roof intrusion measure is more critical for the Toyota Prius to perform in terms of structural injury measures.

The Kia Soul has a little more than 5 inches of head room. With respect to the critical values, the residual intrusion and dynamic intrusion speed are not significally different from IBM and IHA measures. The peak lap belt force was 387 pounds and the shoulder belt force was 261 pounds. The belt forces diminished at the time of the far side impact indicating the roof was intruding on the occupant. The residual intrusion, IBM, and IHA support this finding. Because the intrusion measures were not exceeding the critical limit the IBM and IHA were also below the limit. The rollover test performed on the Kia Soul showed the vehicle to perform reasonably.

The F-150 has approximately 10 inches of headroom which is roughly 5 inches more than any of the other vehicles. The dummy injury measures match the structural injury risk measures. Furthermore, the structural injury criteria is near 100%. The peak lap belt force was 246 pounds and the shoulder belt force was 597 pounds. However, the belt forces diminished at the time of the far side impact indicating the roof was intruding on the occupant. The residual intrusion, IBM, and IHA support this finding. Figure 5 illustrates the percent of structural and dummy injury criteria for a 2010 Ford F150 pickup in a rollover [11].

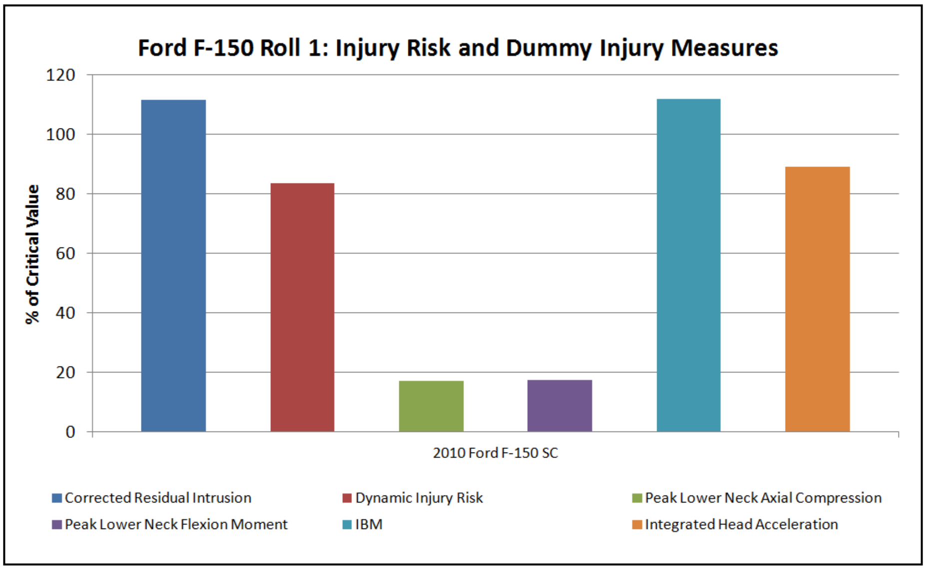

Figure 5. *Structural injury risk and dummy injury measures for the 2010 Ford F-150.*

There is a good match between structural and dummy injury measures which suggests that the vehicle is not safe. In a more severe rollover where the translational speed is 20 mph as opposed to 15 mph, the residual intrusion and dummy injury measures would well exceed criteria.

CONCLUSIONS

The five vehicle tests were conducted using a 24.1 kph (15 mph) translational speed, 190°/sec roll rate, and 5° of 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 [12]. Because of the occupant kinematics in a rollover lap belts need to be respond quickly to maintain the occupant seating position in a rollover. However, the loading associated with the lap belt can be excessive and therefore the best solution is one that maintains the occupant in its seating position by using both the shoulder and lap belt throughout the rollover segment. This can only be assessed using a dynamic test.

The JRS vehicle rollover dynamic testing apparatus has identified the 2010 Ford F150 as one of the vehicles which meets the most rigorous static roof strength criteria (SWR of 4 or greater) but fails to provide occupant protection from injury risk in a rollover consisting of more than one quarter turn. Results of JRS testing using a low-severity dynamic test protocol revealed it was possible for the side glazing to break causing a potential ejection portal in good SWR vehicles.

Because residual crush is measured post crash the factors that cause residual crush should be determined to better understand dynamic performance. Residual crush is found to be a function of vehicle strength to weight ratio, roof structure elasticity, and other geometric considerations [9]. When executing the IIHS roof strength protocol using a FMVSS 216 a roof crush test apparatus the elasticity of the roof structure can be measured as a second part of the roof crush test. The measurement would be added to the existing IIHS roof strength rating by measuring load and displacement (using the 13mm/sec speed) as the ram reverses direction until the load reading approached some number close to zero. This displacement value would then represent the elasticity of the roof structure.

An elasticity correction is necessary for better correlation of field data related to rollover injuries of late model vehicles with strong roofs. This is because the intrusion criteria was developed using earlier model vehicles with less elasticity. The NASS-CIREN files (Mandel probability of injury charts) are based on fleet average vehicles of the 90’s with SWR’s of about two and an elasticity of about 30%. Post 2005 vehicles have SWR’s greater than four and an elasticity of 60%. Elasticity is a function of roof structure elements being less deformed as a result of a stronger roof structure.

A vehicle that can provide protection for its occupants in a rollover should be defined by a dynamic rollover test that is based on both structural and dummy injury measures. By using a dynamic test procedure roof strength, effectiveness of primary and supplemental restraints, and the effect interior components have on an occupant in a rollover can all be measured. Historically rollover regulations have been less rigorous than frontal and side crashworthiness regulations. However, rollovers have the highest percentage of fatalities and make up 30 percent of all deaths associated with vehicle crashes inside the U.S.

Similar to the existing US regulatory side impact test FMVSS 214 the rollover compliance test regulation would be a two part test. The first part would assess the static structural performance of the roof structure. The second part would require validation in the form of a dynamic test of the performance of the roof structure, restraints, and occupant compartment interior in order to reduce the probability of an injury in a rollover. The proposed real-world rollover protocol outlined in Table 1 is associated with the most common serious injury rollovers and is explained in further detail in ICrash paper ICR-14-33.

The dynamic tests performed on the five vehicles outlined above shows the importance of validating the roof structure and seatbelt performance in a dynamic test environment. Furthermore, using only the static roof strength test and strength to weight ratio can be limiting when considering the relationship between headroom and dynamic performance of the roof structure are not taken into account. Rollover crash safety measures outlined in this paper can be expanded on by using a dynamic test for development primary restraints and roll activated side curtain airbags with respect to near side occupants.

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FIRST GENERATION OBESE ATD (FGOA)

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ABSTRACT

This paper sets forth the need for an Obese ATD. The goal of this study was to build a prototype that accurately represents an obese subject with a BMI of 35 kg/m^2, and also to explore new ATD flesh material options.

The prototype ATD was designed using a THOR-M platform and a 35 kg/m^2 BMI target. The finished prototype was then tested on a rear seat buck at 29 km/h and 48 km/h. The kinematic data from these tests was compared to the kinematic data from previous tests ran at the University of Virginia using a 35 kg/m^2 BMI PMHS. This comparison was used to evaluate the existing prototype and reform the next iteration of the ATD.

INTRODUCTION

The obesity rate has increased dramatically in the U.S. and many places in the world in recent years. From 1980 to 2000, the prevalence of obesity in Americans increased from 14.4% to 30.5% [1]. In 2009-2010, approximately 78 million adult Americans – over 35% of the adult U.S. population - were obese (defined as a Body Mass Index, BMI, greater than or equal to 30 kg/m2) [2].

Obese occupants pose unique challenges for restraint systems. In addition to the increased mass of the occupant, the increased amount of centrally-located subcutaneous tissue associated with obesity limits the ability of the lap belt to properly engage the pelvis. Depending on the anthropometry of the occupant, the increased depth of the subcutaneous tissue can result in the lap belt being located more anterior and more superior relative to the pelvis than would be observed in a non-obese occupant [3]. In many cases, the depth of tissue around the waist, thighs, buttocks, and abdomen may result in the lap belt being placed above the level of the anterior superior iliac spines. This sub-optimal belt position may result in limited-to-no engagement of the pelvis in frontal impacts, resulting in excessive forward motion of the occupants and direct loading of the lap belt into the abdomen [4][5]. In addition to the effect on abdominal injury risk, this may lead to increased injury risk to the lower extremities through striking the knee bolster [6][7], and increased risk of injury to the chest due to a greater portion of the restraining load being applied to the torso [8][9].

Current anthropomorphic test devices lack the ability to assess restraint interactions with obese occupants. The Hybrid III 95% male dummy – the only current ATD representation of a “large male” – has a height of 188 cm and a weight of 101 kg. This corresponds to a BMI of 28.6 kg/m^2. This is less than the 65th percentile BMI in U.S. adults (ages 20+) [2]. In addition, the Hybrid III 95th does not take into account changes in body mass distribution or increases in superficial soft tissue depth associated with obesity.

METHODOLOGY

ATD Development

The First Generation Obese ATD (FGOA) is built on an existing platform of the THOR 50th percentile male ATD. The conversion to an obese ATD is accomplished through a flesh jacket representing the superficial tissue of an obese male. The FGOA flesh jacket consists of chest, pelvis, and upper thigh fleshes. The flesh jacket is constructed from different molded materials that allow the flesh to be pliable enough so that the dummy buttock and thighs would fit and conform into a seat. The legs and arms were ballasted to meet their target weights (Table 1).

The external geometry of the current prototype of the FGOA jacket is based on the anthropometry of a selected obese male post mortem human surrogate (PMHS) previously reported in a series of frontal impact restraint sled tests [4][5]. That subject had a height of 189 cm, mass of 124 kg, and BMI of 35 kg/m^2. The internal skeletal dimensions of that subject (e.g., the internal diameter of the ribcage) were similar to those of a 50th percentile male PMHS [4]. Thus, the majority of the difference in the mass and exterior dimensions between this particular obese subject and a 50th percentile male occurred as a result of increased superficial tissue and abdominal fat. The finished ATD can be shown in Figure 1.

Figure1. Completed Obese ATD prototype

Once the Obese ATD prototype was complete, the external dimensions were measured and compared to the external dimensions of the PMHS (See Table 1). Furthermore an overlay picture of the 35BMI PMHS and Obese ATD is shown in Figure 1. Minor dimensional differences were noticed between the flesh jacket and PMHS, and will be corrected in the next version of the ATD. Also, differences in the seated height can be improved by using a slightly stiffer pelvic flesh material. Table 2 below indicates the target mass distribution weights; these distributions were based on a the THOR-M ATD.

Table1.
ATD VS. PMHS External Measurements

Location	ATD measurements (cm)	PMHS measurements (cm)
Chest Breadth - 4th Rib	42	40
Chest Breadth - 8th Rib	41	36
Chest Depth - 4th Rib	29	23.5
Chest Depth - 8th Rib	30	25.5
Hip Breadth	44.5	39.1
Chest Circumference - 4th Rib	130	110.7
Chest Circumference - 8th Rib	119	114.3
Waist Circumference - At Umbilicus	123.5	120
Waist Circumference - 8cm above Umbilicus	120	119.7
Waist Circumference - 8cm below Umbilicus	126	116.9
Thigh Circumference	65	68.6
Shoulder Breadth (Biacromial)	49	43
Seated Height	93.5	98

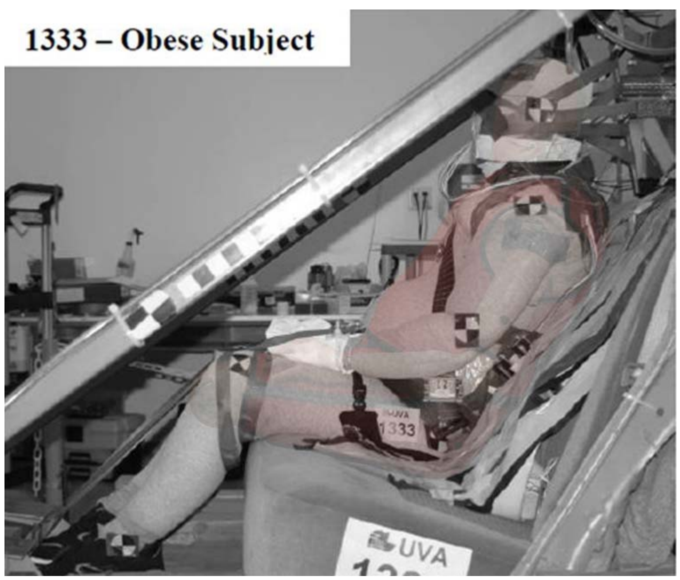

Figure2. Overlay of Obese ATD with 35BMI PMHS.

Table2.
Body Mass Distribution Targets

Segment	Hybrid III (lbs)	THOR (lbs)	Obese Design Targets (lbs)
Head	10 (5.8%)	10.2 (6.1%)	10.2
Neck	3.4 (1.9%)	3.64 (2.2%)	3.64
Upper Torso	37.9 (22.1%)	29.59 (17.9%)	49
Lower Torso	50.8 (29.7%)	62.3 (37.7%)	112
Upper Arm (each)	4.4 (5.1%)	4.4 (5.3%)	7.25
Lower Arm + Hand (each)	5 (5.8%)	5 (6.05%)	8.25
Upper leg (each)	13.2 (15.4%)	9.81 (11.9%)	16.2
Lower leg + feet (each)	12 (14%)	10.47 (12.7%)	17.4
Total Weight	171.3	165.15	273

Testing

Four tests, including two 48 km/h and two 29 km/h were performed with a sled buck representing the rear seat occupant component of a 2004 mid-sized sedan (See Figure 2.) Data was collected from accelerometers located in the head, neck and pelvis as well as angular rate sensors located in the head and T1 position. The tests were performed based on the test conditions of the obese PMHS test completed at the University of Virginia.

Figure3. Dummy sled test set-up, right side view.

RESULTS AND DATA

The trajectories shown below illustrate the trajectories from the 48km/h testing completed on a 23 kg/m^2 BMI PMHS (Figure 3), a 35 kg/m^2 BMI PMHS (Figure 4), and the obese ATD (Figure 5). As you can see from these comparisons, the ATD mimicked the substantially greater forward pelvis and knee motion caused by increased mass of the lower body and limited-to-no interaction between the pelvis (bone) and the lap belt that was seen in the 35 kg/m^2 PMHS.

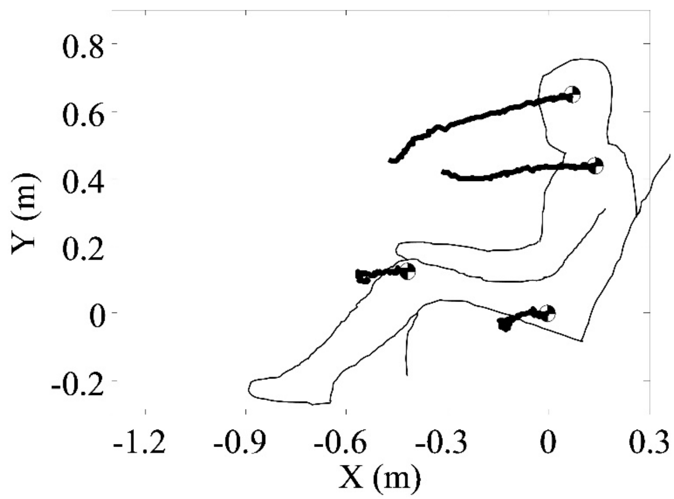

Figure4. Trajectory of the 23BMI PMHS [4].

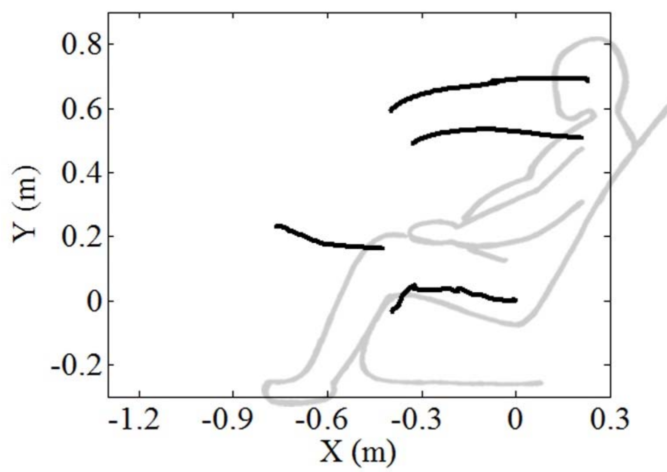

Figure5. Trajectory of the 35BMI PMHS [4].

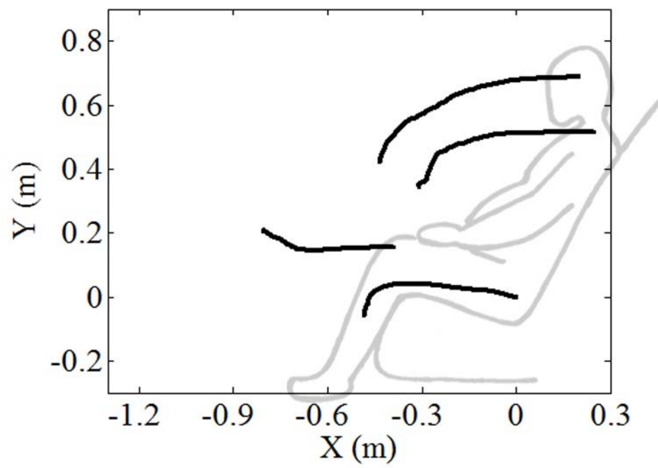

Figure6. Trajectory of the 35BMI Obese ATD.

Forward motion of head and knee of the dummy were 14 cm and 4 cm less than those of PMHS, and forward motion of pelvis of the dummy was 7 cm greater than PMHS. The mean peak of upper shoulder belt, lower shoulder belt, and lap belt tension in dummy tests were 6.5 kN, 6.7 kN, and 8.8 kN, and in PMHS tests, they were 6.4kN, 6.3 kN, and 8.3kN. Peak head, chest, and pelvis accelerations also tended to be greater with the dummy than with the PMHS.

CONCLUSIONS

The results suggest some differences in the kinematics and dynamics of the dummy compared to the PMHS that may be indicative of differences in the interaction of the posterior pelvis flesh and the seat, and a difference in mass distribution affecting relative loads on the various portions of the seatbelt. The differences in the head trajectories most likely stem from differences that already existed between the THOR ATD and the PMHS.

To correct the differences, next steps will be to create new flesh components for the arms and lower legs rather than ballasting the bones. More evaluation will be conducted on the stiffness of the material used for the flesh components as well.

Despite these differences, the obese dummy still exhibited the same kinematic characteristics that were highlighted as potentially challenging for restraint systems by the PMHS tests – most notably, both exhibited substantial forward motion of lower body and subsequent backwards rotation of the torso affected by limited engagement of the lap belt with the pelvis. This suggests that although further refinement may be warranted, this dummy may prove useful as a research tool to begin investigating the challenges of, and potential strategies for, the safe restraint of obese occupants.

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