A ROLLOVER HUMAN/DUMMY HEAD/NECK INJURY CRITERIA

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ABSTRACT

The human neck is a remarkable device for its function, flexibility and strength. It supports the head while permitting a wide range of motion and sustains itself under some vigorous head impacts in violent sports and accidents. Nevertheless, the neck has limits both of motion and of the forces it can sustain. In rollovers, the neck is usually loaded through the top or back of the head with the torso providing an inertial reaction mass. Skull fractures, head and brain injuries generally involve higher impact velocities than are necessary to fracture the cervical spine, but which can also load and critically injure the neck.

Accident injury statistics, tests of living and post-mortem human subjects (PMHS), analysis of athletic impacts, tests of anthropometric dummies and computer simulations of human and dummy kinematics, illustrate injury mechanisms and suggest injury criteria measurements for the human neck. Using this data a simple head impact measure as a neck injury criterion was developed to address the problem of neck injury in vehicle rollovers and to help identify appropriate vehicle design considerations for rollover occupant protection.

The analysis defines a head impact speed of 3 m/sec. (7 mph) which produces a neck load of 7,000 N in a 50th percentile male Hybrid III dummy, as the onset of serious neck injury, and that a head impact speed of 4.5 m/sec (10 mph) which produces a dummy neck load of 10,000 N represents the onset of severe to fatal neck injury. NHTSA has already accepted that a head impact velocity of 7 m/sec (16 mph) is the threshold for the onset of serious head and brain injury. These criteria are shown to reasonably represent available human injury accident and experimental statistical distributions.

DISCUSSION

The human neck is a remarkable device for its function, flexibility and strength. The cervical spine serves to transmit the brain's detailed instructions to the body that can provide the exquisite dexterity needed to play a musical instrument, the coordination for sports and dancing, and the capability of a myriad of motions used by people every day. It also transmits the feelings of touch and bodily pleasure back to the brain.

The neck is strong and flexible, supporting the head while permitting a wide range of motion and sustaining itself under some very vigorous head impacts in violent sports and accidents. Nevertheless, the neck has limits both of motion and of the forces it can sustain. Paraplegia and quadriplegia are consequences of the most severe, non-fatal injuries that the neck can sustain, and lesser injuries can result in substantial long-term disability and pain.

Critical neck injuries typically result from falling from heights, diving into a shallow pool and motor vehicle rollover accidents. In rollovers, the neck is usually loaded through the top or back of the head with the torso providing the inertial reaction mass. Skull fractures, head and brain injuries generally involve higher impact velocities or more concentrated loading. Neck injuries are generally a consequence of lower velocity, longer stroke forces on the head.

Despite the importance of head/neck injuries and fatalities in rollovers, there are no generally recognized injury criteria. NHTSA established head/neck injury criteria as part of its air bag

standard, but these were set at very conservative levels that can easily be met under the particular test conditions defined by the agency.

In a rollover the position and orientation of the human head (whether the occupant is belted or not) can only be specified as being in the vicinity of the seat, longitudinally between the A and B pillars and laterally between the outside of the roof rail and the middle of the seat. Roof impacts with the ground can result in very non-linear distortion and buckling of the roof panel and supporting structure. Therefore to chose a position and orientation for a dummy (or to presume that a restrained dummy will stay in the FMVSS 208 designated seat position) prejudices the ability of the test to evaluate the injury potential and risk of the roof design.

To circumvent these problems and facilitate dynamic rollover test evaluations, a simple head/neck injury criteria based on the best available data is necessary.

There is a substantial amount of data available based on tests of cadavers (post-mortem human subjects, or PMHS) and on experiments using anthropometric test devices (principally the 50th percentile male Hybrid III dummy). A recent, unpublished paper by Viano summarized and analyzed this data[1]. That paper summarized research conducted by a variety of biomechanics researchers and presented statistical summaries of the available data. In his paper, Viano estimated that a neck fracture was probable with a head impact speed in excess of 3 m/sec and an impact force of 4,000 N. In comparisons between cadavers and Hybrid III dummies that a 3 m/sec head impact will produce a reaction force of just under 4,000 N on the cadaver, but approximately 7,000 N on the dummy (see Figure 1). Viano's. His statistical conclusions were strongly challenged as having methodological flaws by a knowledgeable and experienced statistical academic analyst [2]. However, other studies including a review of dummy and specimen head/neck speeds and forces by Sances [3] the data from 16 Malibu rollover tests [4], volunteer human drop tests [5] and studies of NFL football impacts [6] all suggest that Viano's conclusion is reasonable, and suggest a 4.5 m/sec head impact (which would produce a 10,000 N neck force in a Hybrid III dummy) would be the limit for producing severe to fatal neck fractures.

Viano claimed that in general human head impact speed, neck force, and neck injury (classified only as serious or fractures) are poorly correlated. Nevertheless, he showed that the cadaver data demonstrated a low probability of a serious neck fracture for head impacts below 2 m/sec (4.5 mph) and high probability in head impacts above 4 m/sec (9 mph) as shown in his Figure 13 (our Figure 1).

In deriving the probability function Viano assumed all injuries were serious and did not differentiate among serious to fatal injuries. As can be seen, all of the cadavers that sustained a "serious" neck injury in the available data had a head impact at a speed greater than 4 m/sec, but there was a dearth of data from head impacts below this level.

The available PMHS (cadaver) data comes from a wide range of impact circumstances and a variety of head impact modes and mostly from the bodies of people who were older or diseased.

It is well known that the probability of serious injury increases dramatically with age. Thus, this data establishes a lower limit for the probability of serious injury as a function of resultant head impact speed. Viano describes his figure as follows:

"Figure 1 shows the 68 tests plotted with serious injury = **1** and no injury = 0. A Logistic regression model was fit to the data. This gives a sigmoidal injury risk function that is typically used in biomechanics research to determine human tolerances. The Logistic functions are plotted in Figure 1. For the upper curve, there is a weak relationship with a 32% probability for neck fracture at 2,000 N impact force, 50% at 3,472 N, 57% at 4,000 N and 85% probability of fracture at 7,000 **N."** Viano found no detailed relationship between head impact speed and neck force while classifying all the cadaver tests as either serious or non injuries.

Contrary to this general statistical analysis, single mode cadaver drop tests (most closely related to rollovers) of Sances, Yogananda and Nuscholz analyzed by Sances[3] found that severe to fatal (clinical fracture) injuries occurred at drop heights of 1 meter (4.4 m/s or 10 mph) and in tests of 1.2 to 1.5 meters (4.8 to 5.4 m/s or 11 to 12 mph) as shown in Viano's Figure 5 below, Figure 2.

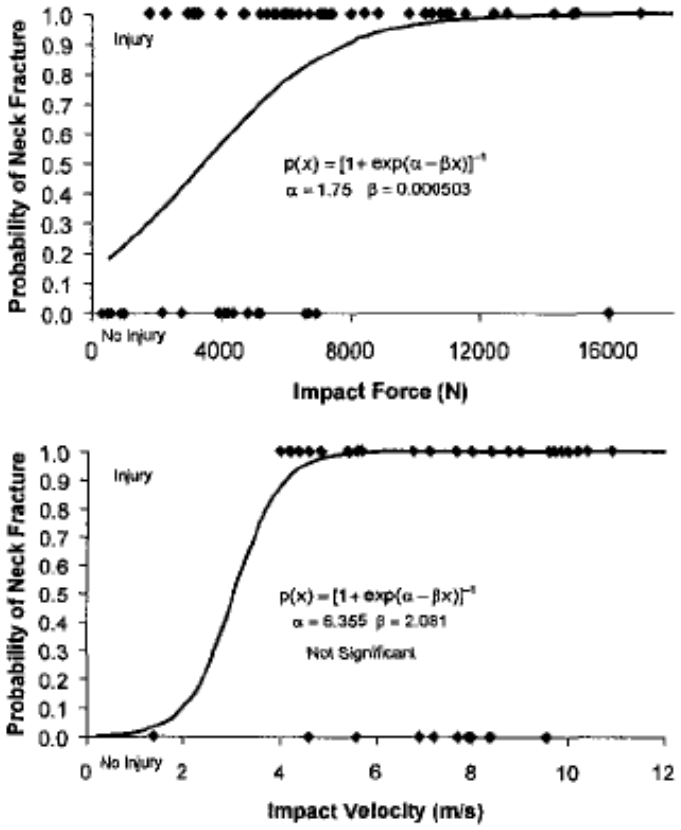


Figure 1 – PMHS data from Viano.

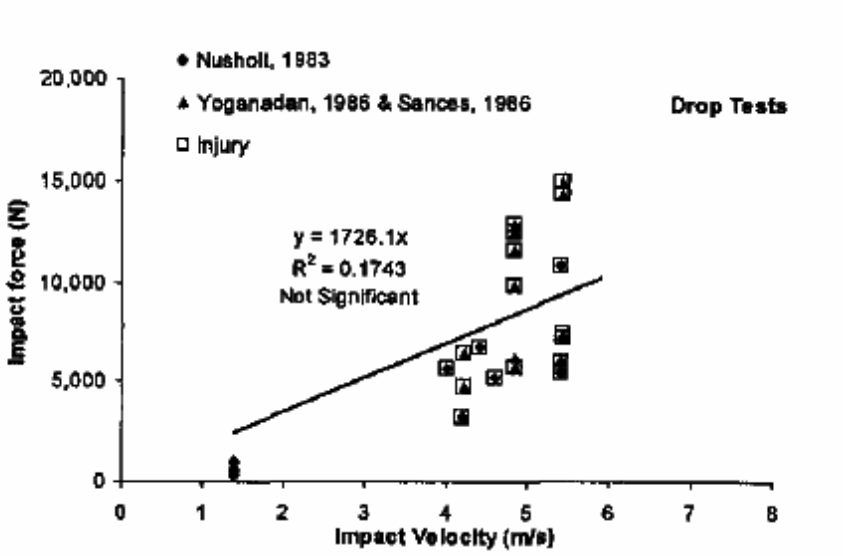


Figure 2. Figure 5 from Reference [1].

Viano also conducted research into football player injuries from head impacts.[4] For this work, videos of such impacts in actual football games were analyzed for impact speed, angle, point of contact, and other variables. Then, the impacts were emulated using fully instrumented Hybrid III dummies to determine the head acceleration and neck responses. Most important about this work is the insight it provides on the healthy human head impact velocity in which *no* head or neck injury occurs.

Although 22 of the 27 struck players whose impacts were studied suffered concussions (at 16.1 ± 4 mph) none sustained a neck fracture. Struck players were uninjured at impact speeds of 11.2 ± 2.5 mph. None of the striking players suffered significant head or neck injury at 9 ± 2.7 mph. As the study points out, "There are many reasons why the striking player is not injured, including the collision mechanics, strength and ability of the players and strength training of the neck musculature to maintain alignment during impact." These players were all young men.

We can conclude that these athletes define the opposite end of the spectrum of injury susceptibility from the cadavers discussed above. The impact velocities of the striking players involved ranged to above 11 m/sec and the change in velocity of their heads in most cases ranged from about 3 to over 6 m/sec (there were 4 with change in head velocity under 3 m/sec and one with a change in head velocity of 7.3 m/sec).

Another source of human non-injury data comes from tests conducted with volunteers in 1996[5] and 1998[6] in rigidized roof fixtures. In these spit and drop tests, belted occupants whose heads when inverted were at the rigidized roof, fell or were dropped at distances of 7.6 cm (3" producing an impact speed of 2.7 mph), 23 cm (9", 4.7 mph), 30.5 cm (12", 5.4 mph), 50 cm (20", 7 mph) and 91 cm (36", 9.5 mph). None was injured in these tests.

It is important that a neck injury criterion not be set at unrealistically low levels. To do so would unnecessarily constrain the design of products in which neck injuries might occur. In a motor vehicle rollover, for example, occupant head contact with the roof is likely, and the occupants of the vehicle may actually be falling toward the ground at a small velocity (rarely more than 1.5 m/sec) at the time of roof impact with the ground. Thus, the injury criteria should recognize that a human can survive such an impact without serious injury.

Because Hybrid III dummies are generally used in motor vehicle crash research and testing, it is important to understand the relationship between dummy measurements and the probability of human injury.

Viano's tests varied according to the impact surface, orientation and the use of helmets. Viano's Figure 22 (below) provides a summary of these previously reported test results.

Again Viano didn't differentiate between top/back impacts and more general orientations. Although these general results show substantial scatter, the data points obtained from tests with the same focused test conditions (top and back of the head impacts) are highly regular.

This suggests that for given test conditions, such as in a rollover, there is a linear relationship between dummy top/back of the head impact speed and neck force.

Sances[5], in 2002 addressed this problem. He compared his cadaver drop tests with Hybrid III dummy drop tests as well as various tests conducted to determine the neck compression force measured on the dummy as a function of head impact speed. He also considered recent evaluations under the similar rollover conditions of the Malibu dolly rollover tests, which measured and plotted the neck forces versus both neck compression velocity and roof intrusion velocity on the Hybrid III dummies. These results were also linear and of somewhat lower slope than the lower neck forces he originally measured.

He concluded that: "The data indicated that the hybrid III system transmits about 70 to 75% of the applied force from the head or upper neck to the lower neck area. In contrast, the cadaver studies showed for drops from 0.9 to 1.5 meters, about 20 to 30% of the applied force was transmitted from the head to the lower neck." In effect the human neck is at least twice as good an absorber of forces from the head as the dummy neck.

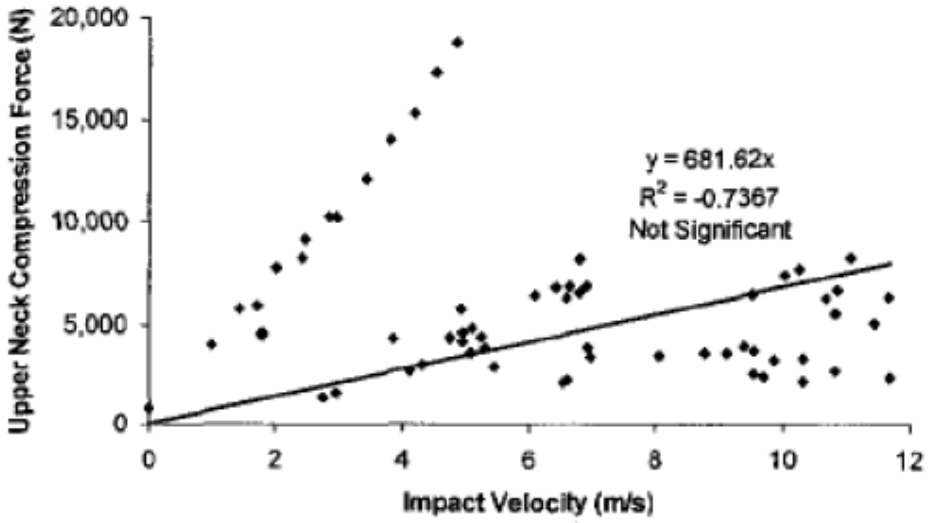


Figure 3. Figure 22 Dummy Tests: Neck Compression Force as a Function of Head Impact Velocity, from unpublished study [1].

To compensate when using the hybrid III dummy in rollover testing, the dummy force criteria at the upper neck sensor would be twice as high as the human criteria. Applying Sances cadaver to dummy conversion, an impact to a human at 3 m/sec would produce a force of around 3,500 N at the human neck while a dummy would measure a neck force of 7,000 N under the same head impact conditions.

Both of Sances' human and dummy comparisons were in drop tests to a solid surface, while the Malibu neck compression and intrusion velocity data was taken during vehicle rollovers. For rollover test purposes then, choosing the lower Malibu Hybrid III neck force versus velocity would err on the side of caution as shown below.

The data analyzed in the Viano paper strongly suggest that a simple, general mode, biomedical neck injury criterion, based on the probability of serious (AIS = 3) neck injury, is that the occupant's head not sustain an impact at a resultant speed greater than around 3 m/sec (7mph) and a force of 7,000 N. This is the level at which the probability of a *serious* neck injury or fracture (but not necessarily a spinal cord injury) to the most vulnerable members of society is around 50 percent. The probability of injury to a younger, healthier individual would be substantially lower than 50 percent.

Similarly, the single mode (rollover related) drop tests of Nuscholz, Yogananda and Sances as analyzed by Sances, establish the biomedical likelihood of *severe to fatal* neck injury or clinical fractures (involving spinal cord injury) occurring at 4.5 m/sec (10 mph) or more to more vulnerable members of society. The likelihood of such injury to a young, healthy individual would be lower.

A reality check on these criteria come from NHTSA accident data [2002 NASS] and the Malibu series of experimental rollovers. The accident data indicates that 91.4% or about 427,000 people are not seriously injured in rollovers, while about 18,000 (3.9%) are seriously injured, an estimated 12,000 (2.6%) are severely or critically injured and ten thousand are killed (2.1%). As shown in figure 5 and 6 there were 94 potentially injurious impacts among the two dummies in the 16 Malibu rollovers. In those tests, there were 87 (93%) impacts at less than 7,000 N (from a 7 mph impact), there were 3 (3%) impacts at over 7,000 N (7 mph) and 3 (3%) at over 10,000 N (10 mph), and 1 that was greater than the 16 mph head injury criteria. All of the impacts greater than 7,000 N (7 mph) were in production vehicles and their distribution is consistent with the accident data.

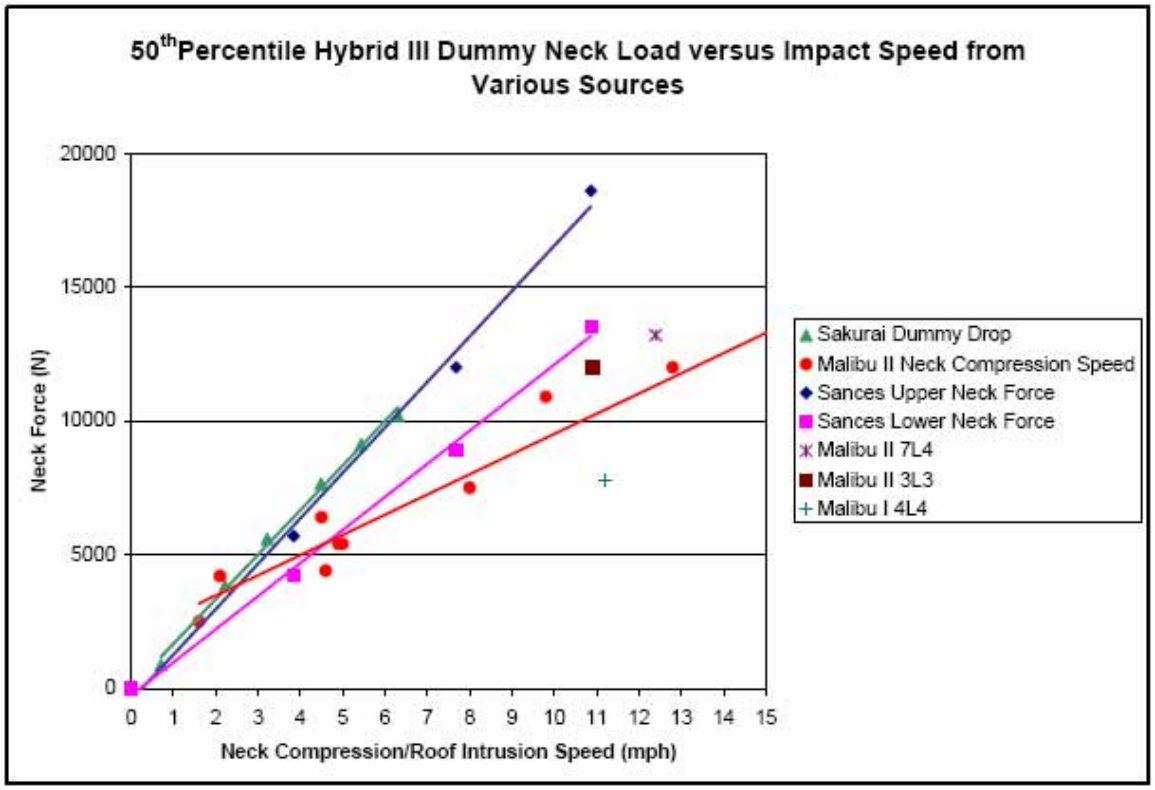
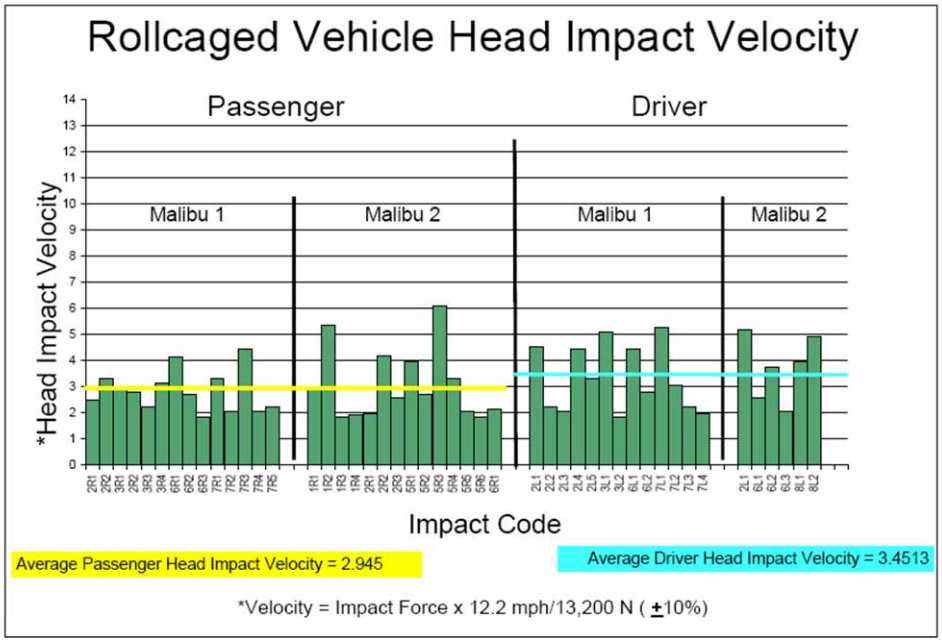
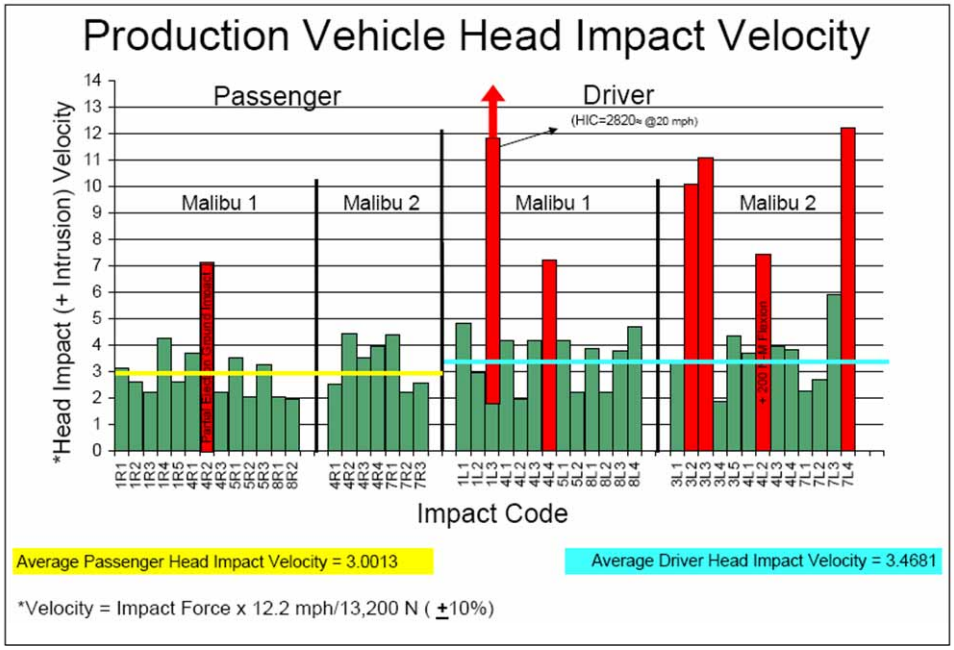


Figure 4. Various Hybrid III neck force vs. impact speed sources.



3 mph Head impact speeds with 2" or less intrusion

Figure 5. Malibu roll caged vehicle head impact speeds.



Red Bars are Head Impacts that Exceed 7 mph

Figure 6. Malibu production vehicle head impact speeds.

APPLICATION

Rollover crashes, according to NHTSA, account for about 10% of towaway accidents, but are 6 times more lethal and 3 times more serious than frontal and other accidents. There are about a quarter million rollover crashes involving cars, pickups, vans and SUVs with nearly a half million occupants, more than ninety percent of whom are not seriously injured. About 3% are seriously injured and recover, 3% are severely or critically injured and are permanently debilitated and 2% die.

Within each of those categories a significant number of occupants are partially or totally ejected. Cumulatively, eighty percent of all rollovers and 65% of the serious to fatal injuries occur in a one-roll event, and 95% of such injuries occur within 2 roll events.

In 2001, the non-profit Center For Injury Research and Xprts, LLC developed the Jordan Rollover System or JRS, a machine for conducting repeatable dynamic rollover roof impact tests. More than forty tests have been conducted on the JRS that have explored the effect of varying the test parameters and protocols.

The JRS holds the vehicle on an axis that goes through its center of gravity. It is rotated and dropped in coordination with the movement of a road segment under it. After impacts with the initially leading (near) side and the initially trailing (far) side, the vehicle is caught so that it sustains no further damage. In Figure 7, the vehicle rotates toward the left as the road surface moves along the rails below from left to right.

To quantify the roof crush during the roll there are thin cables that run from 6 points on the driver's side, the far side of the roof, to the center of rotation of the vehicle. Those cables measure the change in inches and the speed of the roof towards the vehicle center.

The JRS can facilitate the development and evaluation of occupant protection alternatives under a wide, but range of dynamic rollover conditions. With the proposed injury criteria, it can also provide comparisons and objective rankings of the injury potential of different vehicles and alternative designs.

The severity of the JRS test increases with the vehicle's pitch. We have conducted tests at both 5° and 10° of pitch. Increasing the roll rate of the vehicle increases the severity of the initially leading side (near) impact (which is less important because head and neck injuries rarely occur to occupants

seated on this side) but decreases the severity of the initially trailing (far) side.

The roll angle at initial impact strongly affects the far side impact. A greater roll angle will impose a greater force on the far side and is therefore a more severe impact. A lower roll angle will impose a greater force on the near side, but if the roof is strong, it will lift the vehicle and reduce the force on the far side.

We have tested vehicles that have minimal strength roofs (i.e. those that just meet the requirements of FMVSS 216) and vehicles with strong roofs on the JRS. A vehicle with a minimal strength roof, such as the 2000 Ford Explorer, show structural buckling and collapse even when tested at 5° of pitch and other lower severity conditions. The maximum intrusion speed was over 5 m/sec. Many other vehicles that we have tested show similarly poor performance in this test.

We have also tested vehicles with relatively strong roofs. The strongest production roof vehicle, the Volvo XC90, did well in a series of three runs. In the first two runs, at 5° pitch, there was no roof collapse or buckling and roof intrusion was only a couple of inches with an intrusion speed of only 1.4 m/sec. (3 mph), see Figure 8.

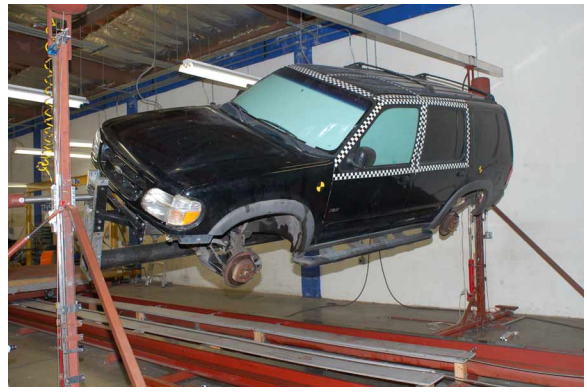


Figure 7. JRS Test Setup

Since the injury criteria is that serious injury is probable at head impact speeds of 3.6 to 5.4 m/sec (7 to 10 mph) and severe to fatal injury is probable at more than 5.4 m/sec (10 mph), it is easy to see which vehicle is safer.

2000 Ford Explorer 4dr Roll 1	Crush (in)		Peak Crush Speed
Location	Peak	End of Test	(mph)
A-Pillar	-8.7	-5.9	-6.3
Mid Point Between A and B Pillar	-9.1	-5.9	-6.7
B-Pillar	-6.7	-3.9	-5.5
Inboard of A-Pillar	-7.0	-4.9	-5.8
Inboard of Roof Rail Midpoint	-11.5	-8.5	-12.1
Inboard of B-Pillar	-8.7	-6.2	-9.1
Center of Roof	-8.2	-6.3	-7.6
Near Side A-Pillar	-4.2	-2.0	-3.8

2000 Ford Explorer 2 Roll JRS Test Series

Peak Dynamic Crush – 11.5 inches

Peak Cumulative Crush – 14.5 inches

Peak Crush Speed – 12.1 mph

2004 Volvo XC90 Roll 1	Crush (in)		Peak Crush Speed
Location	Peak	End of Test	(mph)
A-Pillar	-1.0	-0.1	-1.5
Mid Point Between A and B Pillar	-1.5	-0.3	-2.2
B Pillar	-1.2	-0.1	-1.9
Header Inboard of A-Pillar	-0.6	0.0	-1.2
Front of Sunroof	-1.1	-0.4	-1.8
Side of Sunroof	-1.5	-0.3	-2.3
Near Side A-Pillar	-2.1	-0.9	-3.3
Near Side B-Pillar	-3.2	-1.1	-3.7

2004 Volvo XC90 2 Roll JRS Test Series

Peak Dynamic Crush* – 2.6 inches

Peak Cumulative Crush* – 1.1 inches

Peak Crush Speed* – 3.0 mph

* Far side only

2000 Ford Explorer 4dr Roll 2	Crush (in)			Peak Crush Speed
Location	Peak	End of Test	Cumulative	(mph)
A-Pillar	-9.2	-6.4	-12.3	-9.6
Mid Point Between A and B Pillar	-9.9	-7.0	-12.9	-9.3
B-Pillar	-9.9	-6.7	-10.6	-8.8
Inboard of A-Pillar	-6.3	-4.2	-9.1	-7.0
Inboard of Roof Rail Midpoint	-9.5	-6.0	-14.5	-9.9
Inboard of B-Pillar	-8.9	-5.6	-11.8	-8.1
Center of Roof	-5.7	-3.1	-9.3	-8.5
Near Side A-Pillar	-2.4	1.0	-1.0	-4.1

2004 Volvo XC90 Roll 2	Crush (in)			Peak Crush Speed
Location	Peak	End of Test	Cumulative	(mph)
A-Pillar	-1.9	-0.5	-0.6	-2.0
Mid Point Between A and B Pillar	-2.6	-0.7	-1.0	-2.9
B Pillar	-2.6	-0.7	-0.9	-3.0
Header Inboard of A-Pillar	-1.2	-0.3	-0.3	-1.4
Front of Sunroof	-1.6	-0.5	-0.8	-2.1
Side of Sunroof	-2.5	-0.7	-1.1	-2.9
Near Side A-Pillar	-0.3	0.2	-0.7	-1.1
Near Side B-Pillar	-0.9	0.3	-0.8	-1.8

Figure 8. JRS Test Results.

CFIR and XPRTS have also conducted two roll, 15 mph JRS tests at 5° of 8 other production vehicles, see Figure 9. These equal severity tests provide the basis for an injury potential ranking system shown here. Note that a one mph allowance for the occupants falling speed has been made, higher rankings are not directly related to increased roof strength to weight ratio

(SWR), and that the best ranking is awarded only to those vehicles that meet the crush speed criteria and do not create ejection portals.

In conjunction with the proposed test injury criteria, the JRS can rank and compare the injury and ejection potential of vehicles in rollovers and can definitively identify vehicle safety component defects and their causal relationship to death and injury in accidents.

JRS 15 mph Low Severity Dynamic Rolls Ordered by Max. Roof Crush Speed at any Point for Injury Potential Evaluation

Model Years	Make/Models	216 SWR	Max Crush (Inches)	Maximum Speed (MPH)	Injury Probability	Case Injury
2002-2006	Volvo XC90 SUV	3.6	3.2	3.7	Best	NA
1999-2005	Hyundai Sonata Sedan	1.8	6.4	8.0	Fair	Quadriplegia
2003-2006	Kia Sorrento SUV	1.9	6.9	9.0	Poor	Quadriplegia
1995-1999	Nissan Sentra Sedan	3.2	9.1	9.6	Poor	Quadriplegia
1995-2001	GMC Jimmy SUV	2.4	6.7	9.8	Poor	Quadriplegia
1995-2005	Chevy Blazer SUV	2.4	9.6	10.1	Not Acceptable	Quadriplegia
1999-2001	Isuzu VehiCross SUV	NA	6.8	11.1	Not Acceptable	Brain Injury
2001-2006	C2500 HD Reg Cab Pickup	2.2	9.9	11.2	Not Acceptable	Fatal
1995-2001	Ford Explorer SUV	1.6	11.5	12.1	Not Acceptable	Quadriplegia
1994-1999	Mitsubishi Eclipse	2.5	7.6	12.1	Not Acceptable	Fatal

(Criteria: Best = < 6mph and no ejection portals; Good = < 6 mph; Fair = < 8 mph; Poor = < 10 mph; Not Acceptable = > 10mph)

Figure 9. JRS Test Results.

The proposed injury criteria is validated by being consistent with the actual injury suffered by the victim for whom the test was conducted.

CONCLUSIONS

These injury criteria are appropriate and valid for use in research, design and testing of a vehicle's injury potential in rollover accidents. Specifically, a 3.6 m/sec (7 mph, 7,000 N head impact as measured by a Hybrid III dummy) resultant head impact speed represents the onset of serious neck injury and a resultant 5.4 m/sec (10 mph, 10,000 N) represents the onset of severe to fatal neck injury. NHTSA specifies that a head impact velocity in excess of 15 mph must not produce a HIC that represents the onset of serious head and brain injury. On the other hand the head and torso may be tilted and the serious injuries are not just in Fz.

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