Proceedings of International Mechanical Engineering Congress and Exposition
IMECE2010
November 12-18, 2010, Vancouver British Columbia

IMECE2010-39032

MATCHED PAIR TESTING OF INJURY POTENTIAL IN REPEATABLE ROLLOVER TESTS WITH THE CRIS AND JRS

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ABSTRACT

The availability of repeatable dynamic rollover fixtures, like the Controlled Rollover Impact System (CRIS) and Jordan Rollover System (JRS), has changed the face of rollover structural and occupant protection development and evaluation. Tests performed with these devices have demonstrated scientific principles of occupant protection and injury potential which were previously resolvable only by expert rhetoric. Matched-pair experiments with instrumentation measuring dynamic roof crush and dummy injury metrics are now possible. The effectiveness of occupant protection features such as padding, window curtain airbags, belt pretensioners and headrests are qualitatively and quantitatively measureable. The sensitivity of rollover parameters themselves and their effect on injury potential can be determined by tests with different roll rates, pitch angles, impact angles and drop heights. Simulating injury potential to humans with ultimately biofidelic dummy musculature can also be demonstrated.

This paper presents two matched pair test sets performed on the CRIS and two matched pair test sets performed on the JRS. The matched pair test sets performed on the CRIS compare the dummy injury measures in reinforced and production versions of the 1998 Ford Crown Victoria and the 1996 Chevrolet Blazer. The CRIS test of the matched pair Crown Victoria vehicles has been presented previously in a paper by Moffatt et al [1].

The matched pair tests that were performed on the JRS were conducted to study the effect of a reinforced roof on dummy injury measures. These tests, performed on production and reinforced versions of the 1998 Ford Explorer and the 1999 Hyundai Sonata, included the measurements of road loads, roof crush and crush speed, dummy upper and lower neck loads, belt loads, as well as the movement of the vehicle during the test.

INTRODUCTION

In this study four matched pair, production vs. reinforced roof vehicle test sequences were performed and/or analyzed. Two sequences were conducted on the Controlled Rollover Impact System (CRIS) and two were conducted on the Jordan Rollover System (JRS). The sequences conducted on the CRIS consisted of tests of three matched pair 1998 Crown Victorias and tests of a matched pair of 1996 Chevrolet Blazers, all of which were conducted by Exponent [2,3]. The vehicles used in the matched pair testing conducted on the JRS were 1999 Hyundai Sonata and 1998 Ford Explorer vehicles.

There is much controversy concerning the threshold dummy head and neck loads that represent an injury potential, especially in the Hybrid III dummy with the very stiff, vertically oriented neck in a rollover circumstance. The lack of consensus makes it difficult to predict injury based strictly on peak neck loads. Nusholtz et al concluded that peak force was not found to be a reasonable predictor of cervical spine damage [4].

The vehicles in this study that exhibited large amounts of roof crush clearly showed a much more severe interaction between the roof and head of the dummy which caused major neck bending. This agrees with studies done by Allen which show that bending type injuries (flexion and extension) account for more than 90% of the neck injuries that occur in vehicle accidents [5]. According to Ridella, spine injuries involving "compression combined with flexion, extension, or lateral bending" are much more prevalent (2-6 times depending on the rollover crash mode) than head injuries, as can be predicted by Head Injury Criteria (HIC) calculations [6].

Mandell et al was able to show, with a statistical model of real world rollover accident data from the National Accident Sampling System (NASS) and the Crash Injury Research and Engineering Network (CIREN) databases, that head and spine injuries were more likely to occur in those rollover accidents involving more than 3.1” to 5.9” (8 cm to 15 cm) of roof crush [7].

Although Moffatt et al concluded that "there was no significant difference in the dummy head acceleration and [upper] neck loads" between the production and reinforced vehicles in CRIS, this study has found very prominent differences in the potential for injury between reinforced and production vehicles in rollover accidents. Moffatt et al has also said in the Malibu testing that peak neck loads occur before significant roof crush or that there was no significant difference in the number of potentially injurious impacts to the heads of dummies in production and roll caged vehicles [8].

Those statements are cleverly worded to imply that there was no difference in the potential for injury between vehicles with large amounts roof crush and those without. To support the contentions and deny proof to the contrary, the Malibu and CRIS tests do not include measurements of roof crush, occupant motion, belt forces or lower neck dummy instrumentation.

This study refutes these misleading non-sequiturs and instead looks for the characteristics of injury and the differences in those characteristics in the alternative configurations. This study attempts to analyze the differences in injury potential that are present between the reinforced and production vehicles by primarily looking at the duration and extent of neck bending caused by roof crush.

METHODS

The Controlled Rollover Impact System (CRIS), which has been described in other papers [1], consists of a cantilevered truss structure attached to the rear of a flatbed trailer which is pulled by a tractor show in Figure 1. The test vehicle is held at zero degrees of pitch and zero degrees of yaw by the truss structure and is rotated at a specified roll rate while the speed of the tractor determines the lateral speed of the test vehicle. Once at speed, the vehicle is released such that it contacts the road surface at a predetermined roll angle while the tractor and trailer combination continue forward.

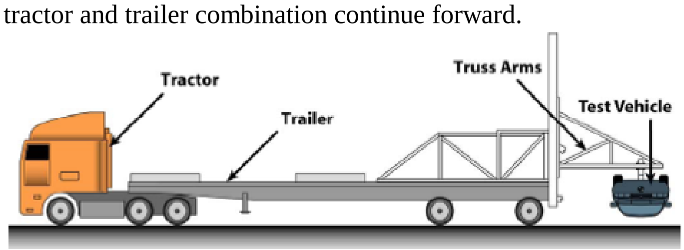

Figure 1: Schematic of CRIS

Six 1998 Crown Victoria vehicles were tested as matched pairs (production roof vs. reinforced roof) on the CRIS. Four tests were conducted at "low speed/low roll rate conditions" and two were tested at "medium speed/medium roll rate" conditions as shown in Table 1. Two 1996 Chevrolet Blazer vehicle were tested as matched pairs at the low severity test condition on the CRIS.

The rollcaged vehicles tested on the CRIS were reinforced with approximately 170 lbs (77.1 kg) of 2” (5.1 cm) diameter 3/16” (0.5 cm) wall steel tubing and mounting plates. The reinforcement and testing of the vehicles was performed by Exponent.

The JRS has been fully described elsewhere [9,10] but shown in Figure 2. It is capable of suspending a cradled vehicle, at its roll axis, over a track with a moving roadbed. The vehicle is rotated and pitched at a specified rate and angle and then dropped from a variable height onto the moving roadway. The rotating vehicle makes contact with the moving roadbed at a predetermined roll angle, usually on the near side (i.e. <180 deg of roll) and continues through its roll before its vertical motion is captured again at the end of the test.

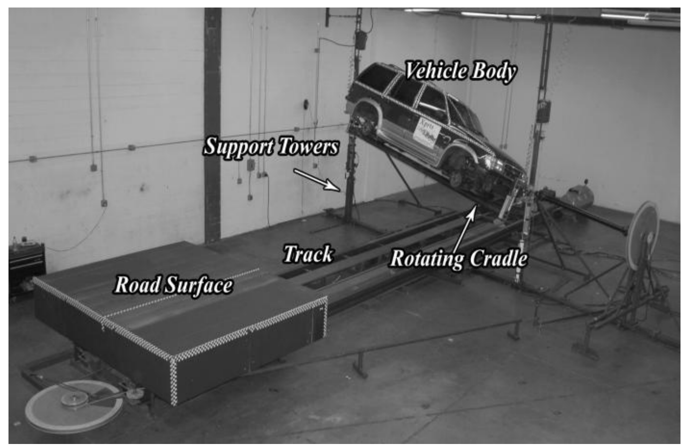

Figure 2: JRS test fixture

Three matched pair tests were conducted on the JRS. Two tests, with different protocols, were conducted on a matched pair of 1998 Ford Explorers. A matched pair of 1999 Hyundai Sonatas was tested once on the JRS. The protocols of the test conditions are detailed in Table 2.

The roofs of the reinforced vehicles tested on the JRS were modified by Safe Analysis and Forensic Engineering (SAFE). The vehicles were reinforced with 1.25” to 1.75" (3.2 cm to 4.4 cm) diameter tubing which was placed along the A and B pillars, roof header, roof rail and bows. Rigid polyurethane foam was also used to fill voids in the pillars, header, and roof rails. The total weight of the reinforcement was 127 lbs (57.6 kg) for the 1999 Hyundai Sonata and 145 lbs (65.8 kg) for the 1998 Ford Explorer.

Each test, conducted on both the CRIS and JRS, included a 50th percentile Hybrid III male dummy belted with production 3 point seat belt in the driver seat.

All of the tests were performed with the vehicle in a passenger side leading roll. The tests conducted on the CRIS caused the first ground impact on the vehicle to occur on the far (driver) side of the roof. The vehicles tested on the JRS impacted the roadbed first on the near (passenger) side of the roof. Tables 1 and 2 in the results section detail the test conditions for each set of tests.

Upper neck 6 axis load cells and head accelerometers were the only instruments used to measure dummy head and neck loads in the CRIS matched pair tests. Both upper and lower neck 6 axis load cells were used in the JRS tests in addition to string potentiometers at the A and B pillars on the driver's side of the vehicle which measured dynamic roof intrusion during the impact. High speed interior cameras were used in each test.

RESULTS

The headroom measured was 4" (10.2 cm) in the Crown Victoria and 6" (15.2 cm) in the Chevrolet Blazer. The lack of dummy lower neck loads and measurements of roof intrusion allows only for a qualitative analysis of the potential for neck bending injury in the CRIS tests, but which can be compared to the quantitatively evaluated JRS tests.

Test ID	Roll angle at impact [deg]	Roll Rate [deg/sec]	Horizontal Speed [kph(mph)]	Drop Height [mm(in)]
CRIS (low severity)	185	226	12.9 (8.0)	246 (9.7)
CRIS (high severity)	185	363	32.0 (19.9)	325 (12.8)

Table 1. CRIS test conditions*
***Specified test conditions. Actual conditions can be found in the Annex.**

Analysis of the high speed video from the interior of each vehicle showed significant differences in the amount of neck bending after the initial roof to ground contact between the rollcaged and production vehicles. Dummy movement was nearly identical up to the point of peak upper neck axial load. Then the distance between the roof and seat in the production vehicles reduced due to the deforming pillars and roof structure. The deformation of the roof structure and resulting reduction in headroom in the production vehicles forced the head of the dummy laterally and downward causing the neck to bend significantly. The neck of the dummy in the rollcaged vehicles showed no bending at all. Figures 3-6 show the difference in the amount the neck bending at the time of maximum roof crush for four of the 1998 Crown Victoria CRIS tests.

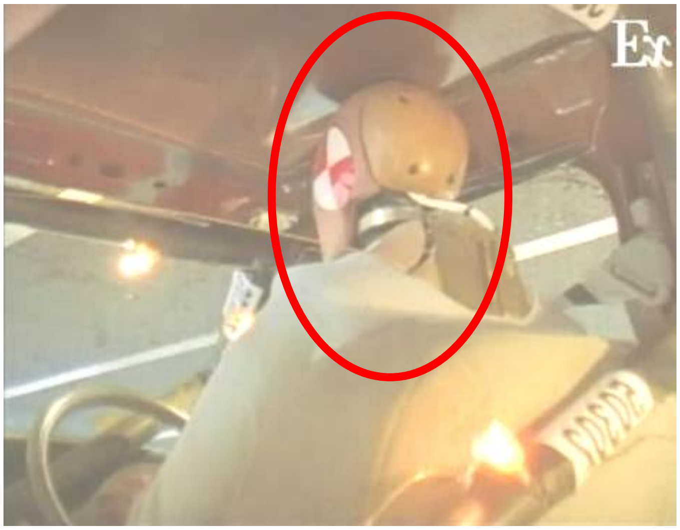

Figure 3. 1998 Crown Victoria (low severity rollcage 50302) max roof crush

Figure 4. 1998 Crown Victoria (low severity 51502) max roof crush

Figure 5. 1998 Crown Victoria (med. severity rollcage 61802) max roof crush

Figure 6. 1998 Crown Victoria (med. severity 62102) max roof crush

Figure 3 shows the orientation of the dummy head and neck at the time of maximum roof crush (estimated at less than 2” (5.1 cm)) for the rollcaged Crown Victoria. The neck of the dummy compressed about 0.5” (1.3 cm) and then bounced off the roof, but the lack of extensive roof crush precluded any bending of the neck. In Figure 4 we can see that the neck of the dummy in the production vehicle bent a significant amount due to the large amount of roof crush. The deformation of the roof trapped the head of the dummy in a position which recorded a residual upper neck moment Mx of 70 Nm. Similar results were obtained in the medium severity CRIS tests of the 1998 Crown Victorias as shown in Figures 5 and 6 and in the low severity CRIS tests of the 1996 Chevrolet Blazers as shown in Figures 7 and 8.

The primary direction of neck bending that was observed in the CRIS tests were in the lateral (Mx) direction. The neck has been identified as being only 70% as strong in the lateral direction of lower neck bending as it is in forward flexion.

Figure 7. 1996 Chevrolet Blazer (low severity rollcage 41103) max roof crush

Figure 8. 1996 Chevrolet Blazer (low severity 41703) max roof crush

The headroom for the 50th percentile Hybrid III male dummy in the JRS tests of the Ford Explorers and Hyundai Sonatas was 3” (7.6 cm) and 2” (5.1 cm) respectively.

Test ID	Roll angle at impact [deg]	Roll Rate [deg/sec]	Road Speed [kph(mph)]	Drop Height [mm(in)]	Pitch [deg]
1998 Ford Explorer Roll 1	145	180	24.1 (15.0)	102 (4.0)	5
1998 Ford Explorer Roll 2	145	180	24.1 (15.0)	102 (4.0)	10
1999 Hyundai Sonata	145	275	33.5 (20.8)	102 (4.0)	10

Table 2. Specified JRS test conditions (Actual conditions in Annex)

The dummy in the production Ford Explorer experienced lower neck bending moments 30-51% greater than those experienced by the dummy in the reinforced vehicle under the same conditions. The bending moment measured by the dummy in the production vehicle had a duration that was 2.8-3.6 times that of the dummy in the reinforced vehicle.

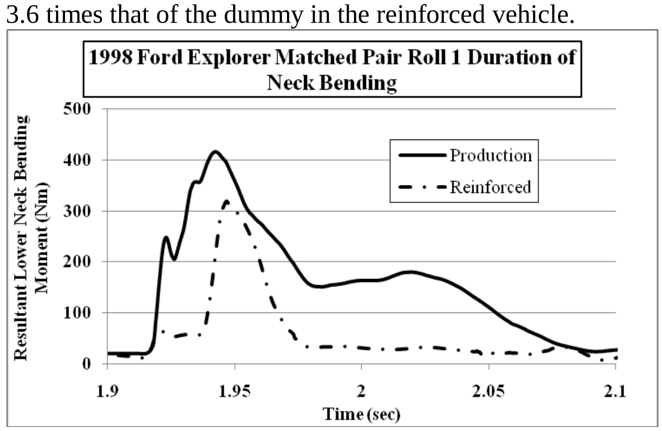

Figure 9. Duration of neck bending in matched pair Ford Explorer Tests

The areas under each curve in Figure 9 represent the interaction between the head of the dummy and the intruding roof. Although the peak lower neck bending moments measured in the reinforced and production Explorers are within 25% of each other, the peak load, on its own, is not significant. Looking at the resultant lower neck moment measured in the reinforced vehicle it is clear that the load was applied to the head very briefly (< 40 ms). The duration was not long enough for the neck to bend enough to produce an injury. The lack of lower neck bending can be seen in Figures 12 and 13. Also, the stroke of the roof was not sufficient enough to physically move the head into a position to bend the neck. The roof crush experienced by the Ford Explorers in the first and second roll resulted in dynamic negative headroom of 4” and 9” (10.2 cm and 22.9 cm) for the dummy in the production vehicle and a dynamic positive headroom of 1” and 0” (2.5 cm and 0 cm) for the reinforced vehicle. The reinforced roof was unable to produce neck bending because the roof did not deform far enough into the occupant space to do so.

The amount of neck bending seen in the high speed video frames of the reinforced vehicle is nearly unnoticeable. On the other hand, the resultant moment measured in the test of the production Explorer shows a lower neck bending duration of nearly 140 ms.

Figures 10-13 are frames from the high speed video that show the neck movement at the time of peak roof crush in each of the JRS tests of the 1998 Ford Explorers.

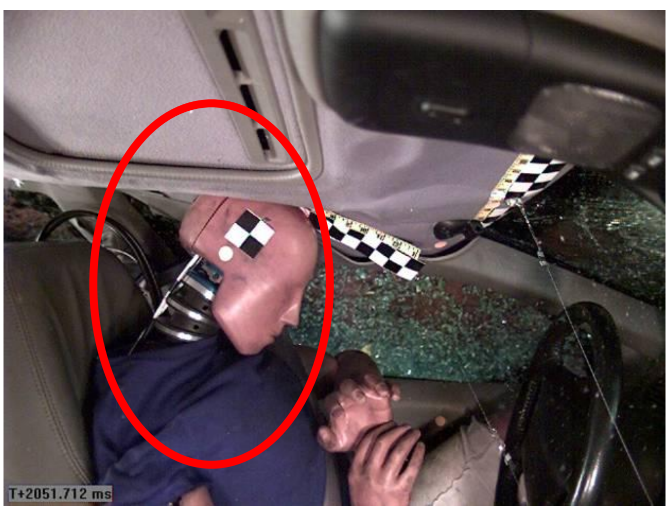

Figure 10. 1998 Ford Explorer (Production Roll 1) max roof crush


Figure 11. 1998 Ford Explorer (Production Roll 2) max roof crush

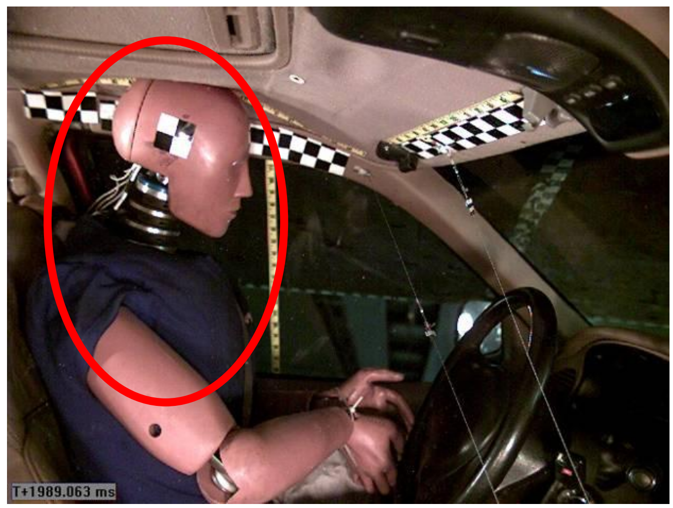

Figure 12. 1998 Ford Explorer (Reinforced Roll 1) max roof crush

Figure 13. 1998 Ford Explorer (Reinforced Roll 2) max roof crush

In Figure 11 the much reduced headroom has bent the neck of the dummy in a primarily lateral direction. The deformation of the roof in the second test of the production Ford Explorer was so great that the dummy was pinned in a position that placed a residual moment (Mx) of 55 Nm laterally on the lower neck of the dummy.

In the matched pair tests on the JRS the amount and duration of neck bending is related to the amount of headroom lost during the rollover event due to the deformation of the roof. In the JRS test of the reinforced roof Hyundai Sonata, the top of the driver side A-pillar moved 4.5” (11.4 cm) toward the center of the vehicle. Under the same test conditions, the roof of the production Sonata moved 10.9” (27.7 cm) toward the center of the vehicle. The initial headroom in the Sonata for a Hybrid III 50th percentile male dummy is approximately 4.5” (11.4 cm) which equates to a dynamic headroom loss for the reinforced and production vehicles of 0 and 6.4” (16.3 cm) respectively. The results after Roll 1 are shown in Figure 14 and 15. The dynamic intrusion of the roof left the reinforced and production Sonata vehicles with 2.2” (5.6 cm) and 7.3” (18.5 cm) of residual roof crush respectively.

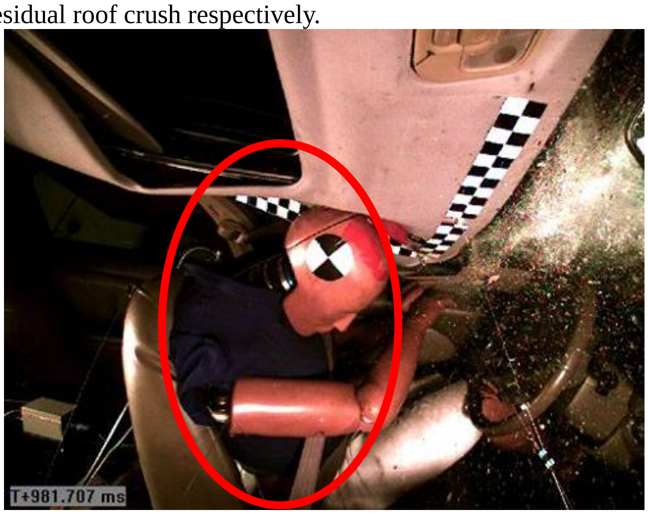

Figure 14. 1999 Hyundai Sonata (Production Roll 1) max roof crush

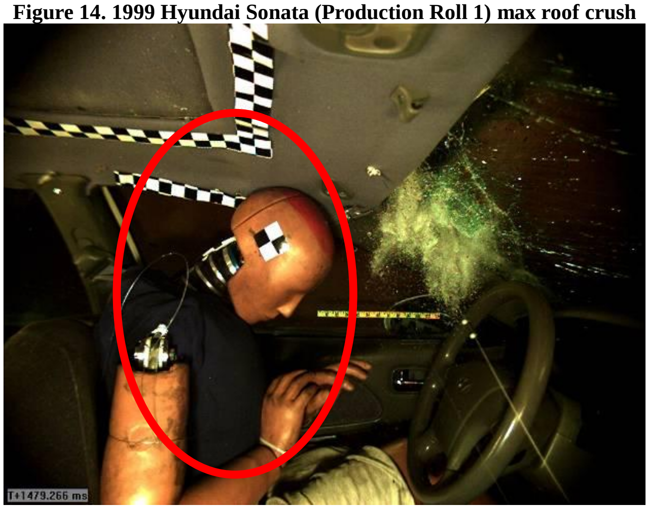

Figure 15. 1999 Hyundai Sonata (Reinforced Roll 1) max roof crush

DISCUSSION

Neck bending injuries in rollover accidents are causally related to roof intrusion. The stroke of the deforming roof applies forces to the head which cause the lower neck to bend and potentially become injured.

In an analysis, by Ridella et al, of rollover accidents with restrained occupants, consisting of 8 quarter turns or less as reported in the Crash Injury Research and Engineering Network (CIREN) database, it is shown that spine (neck bending) injuries are the most frequently occurring AIS 3+ injury, as shown in Figure 16.

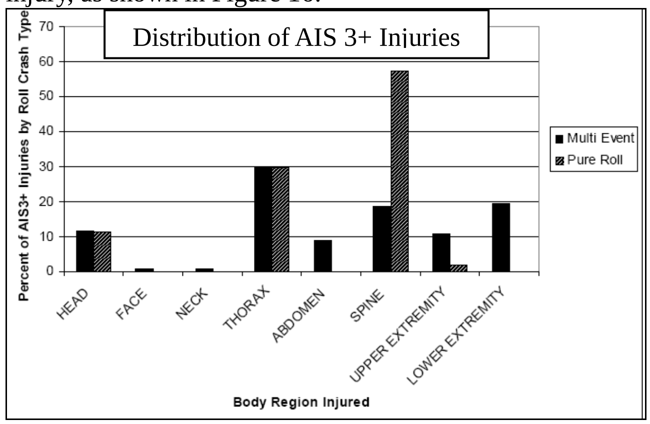

Figure 16. Distribution of injuries by body region for crash type [7].

Although seemingly trivial, it is worth noting that for a bending injury to occur there must exist a force applied to the head and/or neck which causes the neck bend as discussed by Nusholtz et al: "if compressive forces cause the spine to buckle, this is not in itself sufficient to cause damage to the cervical spine, and consideration should be given to […] a three-dimensional motion as a strong contributing factor in the mechanism of injury." and, "[bending] injuries [are] sustained because the head [is] bowed significantly … with a downward force, resulting in large bending moments at the base of the cervical spine" [4]. This has been observed to happen when an offset compression force displaces the head and causes the neck to bend. The two characteristics of a bending injury are a large bending moment and duration of loading by the large bending moment that provides sufficient time for the neck to bend. A large peak bending moment applied to the neck of the dummy is only able to cause injury if it has time produce enough bending to disrupt the spine.

The post crash negative headroom for the matched pair tests conducted on the JRS is plotted in Figure 17. Post crash negative headroom, as measured in these tests, is the distance the roof intruded beyond the original position of the head of the dummy. If the amount of post crash negative headroom is a positive value, the amount of residual roof crush was greater than the original amount of headroom the dummy had at the start of the test (i.e. the roof intruded into the occupant space and interacted with the head of the dummy). Negative values represent the distance remaining between the head of the dummy and the interior of the roof at the end of the test.

The resultant lower neck bending moment was calculated as the resultant value of the lower neck bending moments measured in the Mx and My directions. The duration of the resultant bending moment was calculated as the amount of time the dummy experienced a resultant lower neck bending moment greater than 50 Nm. The value of 50 Nm was chosen, not as an injury risk threshold, but as a way to distinguish between when the roof was interacting with the dummy head and when the head was freely moving under its own momentum.

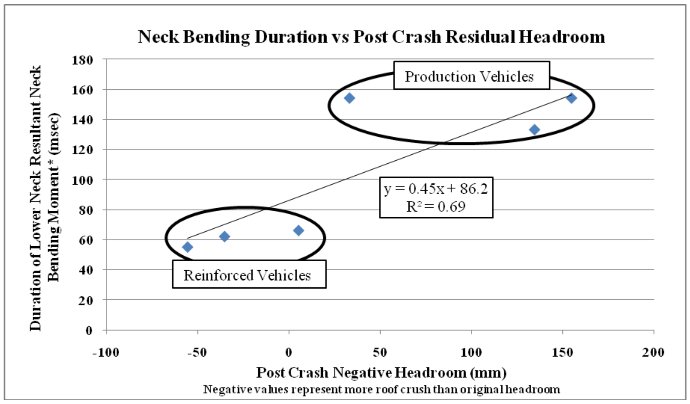

Figure 17. Relating neck bending duration and resid. roof crush.

The dummies in the production vehicles experienced bending of the lower neck for a duration which was, on average, 2.4 times longer than what was experienced by the dummies in the reinforced vehicles: 147 ms in the production vehicle and 61 ms in the reinforced vehicle.

CONCLUSION

Despite identical test protocol, the dummy measures recorded in the matched pair tests performed on the Jordan Rollover System (JRS) showed varying results. Although the peak forces measured showed only a slight difference between the dummy measures in vehicles with a large amount of roof crush vs. those without, there was a major difference in the duration of interaction between the roof and the head of the dummy. Specifically, the dummies in the production vehicles sustained loading to the head and neck directly from the roof of the vehicle for much longer than the dummies in the reinforced vehicles.

The JRS production vehicles experienced dynamic and residual roof crush from 2.4 to 6 times greater than the amount that was experienced by the reinforced vehicles. The amount of roof crush experienced in the production vehicles not only leads to direct injury but has the potential for creating ejection portals and trapping occupants in injurious positions that could limit breathing, and inhibit evacuation and safe rescue. In two tests of production vehicles, one on the Controlled Rollover Impact System (CRIS) and one on the JRS, the deformation of the vehicle roof pinned the dummy in a position with the neck bent and measuring a lower neck bending moment of more than 50 Nm.

The duration of neck loading is related to the amount of roof intrusion into the occupant space. The vehicles that experienced post crash negative headroom of more than 3" (7.6 cm) into the occupant space produced bending moments in the dummy necks that lasted an average of 147 ms.

Roof deformation in CRIS tested vehicles resembled match-boxing with the A-pillar and roof rail deforming in toward the passenger compartment in a mostly lateral direction. This direction of roof intrusion proved to bend the neck primarily in the lateral (Mx) direction. The roof deformation in the JRS tests was directed mostly inward toward the center of the vehicle and resulted primarily in flexion (My) bending. The one exception to this is the second roll of the production Ford Explorer in which the dummy neck was bent in the lateral direction.

This study supports the idea of developing a neck bending criteria which, like Head Injury Criteria (HIC), is based on the integrated time history of bending moments and therefore reflecting the effect of the extent of roof crush.

ACKNOWLEDGMENTS

The CRIS tests were conducted by Exponent and funded by Ford and General Motors. Similarly the JRS tests in this study were funded by the Center for Injury Research, a non-profit research organization in Goleta, CA.

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ANNEX A
ACTUAL TEST CONDITIONS

Test ID	Roll Angle at Impact [deg]	Roll Rate [deg/sec]	Horizontal Speed [kph (mph)]	Drop Height [mm (in.)]
50302 Rollcaged	184	227	12.9 (8.0)	269 (10.6)
50902 Rollcaged	182	226	12.7 (7.9)	269 (10.6)
51502 Production Roof	184	223	12.9 (8.0)	281 (11.1)
61102 Production Roof	185	227	13.0 (8.1)	297 (11.7)

Table 1. Low severity 1998 Crown Victoria matched pair CRIS test conditions

Test ID	Roll Angle at Impact [deg]	Roll Rate [deg/sec]	Horizontal Speed [kph (mph)]	Drop Height [mm (in)]
61802 (Rollcaged)	190	363	32.0 (19.9)	325 (12.8)
62102 (Production Roof)	186	361	32.0 (19.9)	322 (12.7)

Table 2. High severity 1998 Crown Victoria matched pair CRIS test conditions

Test ID	Roll angle at impact [deg]	Roll Rate [deg/sec]	Horizontal Speed [kph(mph)]	Drop Height [mm(in.)]
41103 Rollcaged	185	226	13.0 (8.1)	246 (9.7)
41703 Production	185	226	12.7 (7.9)	246 (9.7)

Table 3. Low severity 1996 Chevrolet Blazer matched pair CRIS test conditions

Test ID	Roll angle at Impact [deg]	Roll Rate [deg/sec]	Road Speed [kph (mph)]	Drop Height [mm(in)]	Vehicle Pitch [deg]	Vehicle Yaw [deg]
Roll 1						
1998 Ford Explorer	146	183	24.1 (15.0)	101.6 (4)	4.4	10
1998 Ford Explorer (Reinforced)	145	177	23.3 (14.5)	101.6 (4)	4.8	10
Roll 2						
1998 Ford Explorer	143	186	24.3 (15.1)	101.6 (4)	9.7	10
1998 Ford Explorer (Reinforced)	24.3 (15.1)	171	143	101.6 (4)	9.8	10

Table 4. 1998 Ford Explorer matched pair JRS test conditions

Test ID	Roll angle at Impact [deg]	Roll Rate [deg/sec]	Road Speed [kph (mph)]	Drop Height [mm(in)]	Vehicle Pitch [deg]	Vehicle Yaw [deg]
Roll 1						
1999 Hyundai Sonata	145	275	33.5 (20.8)	101.6 (4)	10.1	10
1999 Hyundai Sonata (Reinforced)	140	270	33.5 (20.8)	101.6 (4)	10.1	10

Table 5. 1999 Hyundai Sonata matched pair JRS test conditions