

Occupant Kinematics and Injury Mechanisms During Rollover in a High Strength-to-Weight Ratio Vehicle

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Michelle F. Heller, William N. Newberry, Janine E. Smedley, Senthil K. Eswaran, Jeffrey J. Croteau and Michael R. Carhart
Exponent Failure Analysis Associates

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ABSTRACT

Rollover events involving multiple revolutions are dynamic, high-energy, chaotic events that may result in occupant injury. As such, there is ongoing discussion regarding methods that may reduce injury potential during rollovers. It has been suggested that increasing a vehicle's roof strength will mitigate injury potential. However, numerous experimental studies and published field accident data analyses have failed to show a causal relationship between roof deformation and occupant injury. The current study examines occupant kinematics and injury mechanisms during dolly rollover testing of a vehicle with a high roof strength-to-weight ratio (SWR = 4.8). String potentiometers and high-speed video cameras were used to capture and quantify the dynamic roof motion throughout the rollover. Instrumented Anthropomorphic Test Devices (ATDs) in the front occupant positions allowed for the assessment of occupant kinematics, loading, and injury mechanics during the rollover event. The quantification of the roof motion over the complete time course of the rollover combined with ATD neck loads demonstrated that neck loads in excess of the relevant Injury Assessment Reference Value (IARV) occurred as a result of the dynamic rollover circumstances independent of the vehicle roof motion. Injurious neck loads were observed with relatively small amounts of roof deformation, while relatively small neck loads were observed during large elastic and plastic roof deformations. The results of this testing are discussed in the context of other experimental and field accident data studies examining roof deformation and occupant injury.

INTRODUCTION

According to Fatality Analysis Reporting System (FARS) data, rollovers accounted for 10,196 fatalities amongst light vehicle occupants in 2007, which represented 35% of all occupants killed that year in crashes ([U.S. NHTSA, 2009b](#)). Seatbelts have been shown to be highly effective in mitigating rollover occupant ejection, effecting occupant containment, and reducing the rate of serious and fatal injury. Recent National Highway Traffic Safety Administration (NHTSA) research estimates current seat belt use rates at an all time high of 84% ([U.S. NHTSA, 2009c](#)); however, seat belt use rates are much lower within the subset of crash events that result in fatality ([Malliaris and Digges, 1996](#)). Amongst belted rollover occupants, head-to-roof contacts have been identified as a significant source of injury to occupants that were found to remain inside the vehicle. Hence, the study of belted occupant kinematics and injury mechanisms in rollover is critical in finding ways to further mitigate injuries.

Vehicle rollovers resulting in serious injury are generally dynamic, high-energy, chaotic events, characterized by complex vehicle motions where rolling is superimposed with discrete ground impacts throughout the event. The vehicle often experiences multiple roof-to-ground impacts in different orientations. The laws of physics dictate and well-documented rollover crash tests have demonstrated that centripetal accelerations imposed by the vehicle's rotation tend to cause belted occupants to move away from the vehicle's center of gravity towards the vehicle perimeter during the airborne phases of high-energy rollovers ([Bahling et al., 1990](#)). Consequently, the head of a belted occupant can often be in contact with or in close proximity to the roof rail at various times throughout the event. During roof-to-ground

impacts, occupants tend to move in a direction parallel to the ground contact forces, and injurious head and neck loading may result. This injury mechanism involves the head being in contact with and constrained by the roof when the roof stops during a roof-to-ground impact. If the head, neck and torso are aligned during the roof-to-ground impact, the occupant's torso moves downward towards the roof and compresses the neck. This mechanism, often referred to as "torso augmentation", involves the neck being loaded in a "diving-type" loading scenario (i.e., the occupant essentially "dives" head first into the ground).

Roof-to-ground impacts often result in dynamic and plastic deformation of the roof structure. The data derived from numerous experimental rollover crash tests, where roof deformation and occupant loading have been simultaneously evaluated ([Orlowski et al., 1985](#); [Bahling et al., 1990](#); [Moffatt et al., 2003](#)), does not support the premise that there is a causal relationship between roof deformation and occupant injury; further, published field accident data analyses ([Moffatt and Padmanaban, 1995](#); [Padmanaban et al., 2005](#)) have not established a causal relationship between roof deformation and occupant injury. Nonetheless, debate persists as to whether increasing a vehicle's roof strength will mitigate injury potential associated with roof-to-ground contacts. A recent analysis of field accident data conducted by the Insurance Institute for Highway Safety (IIHS) concluded that "increased vehicle roof strength reduces the risk of fatal or incapacitating driver injury in single-vehicle rollover crashes" ([Brumbelow et al., 2008](#)). However, a review of this analysis by Padmanaban and Moffatt indicated that the IIHS work did not control for several factors such as belt use and ejection, which had previously been shown to be factors that influenced the likelihood of injury/fatality ([Padmanaban and Moffatt, 2008](#); [Moffatt and Padmanaban, 1995](#); [Padmanaban et al., 2005](#)). Although the Brumbelow analysis demonstrated a correlation between roof deformation and likelihood of incapacitating or fatal injury, it did not demonstrate a causal link. In addition, none of the statistical analyses of field rollover crash data have identified the origin of head, face, and neck injuries in those crashes. In the United States, the performance of a vehicle's roof structure is regulated by Federal Motor Vehicle Safety Standard (FMVSS) 216 ([U.S. NHTSA, 2009b](#)). Recently the NHTSA issued its final rule change for FMVSS 216 requiring performance for light vehicles (GVWR under 2,722 kg or 6,000 lbs) to have a SWR equivalent of 3.0 times the vehicle's unloaded weight.

The current study examines the occupant kinematics and injury mechanisms during rollover in a vehicle with a roof strength-to-weight ratio well in excess of the new requirement (SWR=4.8). Instrumentation and high-speed photogrammetry were used to document and quantify the roof motion throughout the rollover. Instrumented Anthropomorphic Test Devices (ATDs) in the front occupant positions were used to study the occupant kinematics and

neck loading during the rollover event. The role of roof deformation in the observed mechanics underlying injurious and non-injurious neck loading was evaluated by quantifying ATD loading and roof motion over the complete time course of the rollover. The results of this testing are discussed in the context of other experimental and field accident data studies examining roof deformation and occupant injury.

METHODS

The current study involved dolly rollover testing of a 2003 Subaru Forester. Prior to the dolly rollover, static inversion of the test vehicle was used to determine ATD/seatbelt fit to be used in the rollover test. The static inversions and the dolly rollover test were conducted at Exponent's Test and Engineering Facility in Phoenix, Arizona. In all evaluations, the driver and passenger outboard seats were adjusted consistent with FMVSS 208 specifications: seats were placed in the middle fore/aft position, seatbacks were reclined to detent 7 (full upright is detent 0), seat cushion vertical adjustments were placed in the lowest position, adjustable D-rings were positioned one detent below full-up, and the driver lumbar adjustment was fully retracted (no support) (D-ring and seatback positions matched positions documented in available FMVSS compliance tests of this make/model vehicle conducted by the NHTSA). The vehicle was drained of all fluids and the frontal supplemental restraint system was disabled. The front outboard seatbelt assemblies were removed and replaced with new service-replacement seatbelt assemblies. The upper interior trim was removed and markers were placed on the interior roof, windshield header, and upper pillars to facilitate visualization and quantification of roof displacement during the rollover event.

INVERSION STUDY

An inversion study was conducted utilizing the test vehicle. The vehicle was mounted in Exponent's roll spit fixture. A human surrogate approximately the size of a Hybrid III 50th-percentile male ATD was seated in the driver seat and restrained using the vehicle's three-point seatbelt restraint system. Head clearance and belt length measurements were recorded with the vehicle in the upright position ([Figure 1](#)) and with the vehicle inverted 180 degrees ([Figure 2](#)). This was repeated with the surrogate restrained in the right front seating position. Based on the findings of Moffatt et al (1997), which demonstrated that the Hybrid III equipped with a pedestrian pelvis exhibited less excursion during static and dynamic inversion testing than the ATD with a seated pelvis, the Hybrid III ATDs in the current study were equipped with the pedestrian pelvis and placed in the driver and right front seating positions. Head clearance measurements were recorded with the vehicle in the upright position. Belt length measurements were recorded with the vehicle in the upright and inverted positions. It was determined from the inversion study that the addition of 4.4 cm (1-3/4 inches) of webbing to

the driver restraint system and 2.5 cm (1 inch) of webbing to the right front restraint system allowed the ATD statically-inverted head clearances to match that of the human surrogate in the respective seating position. The additional webbing accounted for the difference in compliance of the human surrogate versus that of the ATD (Moffatt et al, 1997; [Moffatt and James, 2005](#)).



Figure 1. Head clearance and belt length measurements were recorded with the vehicle in the upright position for both the human surrogate (left) and ATD (right).

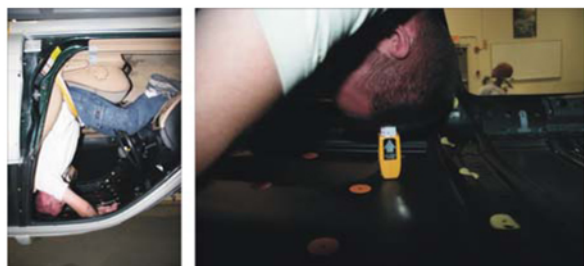


Figure 2. Head clearance and belt length measurements were recorded for the human surrogate with the vehicle inverted at a 180-degree roll angle.

DOLLY ROLLOVER TEST

The test vehicle had a production roof strength-to-weight ratio (SWR) of 4.8, as measured through testing conducted by the NHTSA's Vehicle Research & Test Center. [Croteau et al. \(2010\)](#) provides a comprehensive description of the dolly rollover testing protocols utilized for this study.

On-board vehicle instrumentation included two triaxial accelerometers and two triaxial angular rate sensors mounted along the vehicle centerline near the vehicle center of gravity. Additional triaxial accelerometers were mounted at the top of each A-pillar, and biaxial accelerometers were mounted at the top of each B-pillar to measure roof rail accelerations. Measurement of A-pillar displacement was obtained via video analysis of markers painted on the adjacent roof

structure, and B-pillar displacement was directly measured using string potentiometers mounted to the top of the pillars ([Figure 3](#)). All of the pillar measurements are reported relative to the respective pillar location prior to any roof deformation, and are measured and expressed in the vehicle reference frame. Hence, the reported displacement of the roof during roof-to-ground impact does not reflect the motion of the roof in the inertial reference frame. The vehicle was also instrumented with strain gauges on the roof structure in the area of the windshield header, A-pillar, B-pillar, C-pillar, and D-pillar. Two Hybrid III 50th percentile male ATDs with pedestrian pelvises were positioned in upright seated postures in the front outboard seating locations ([Figure 4](#)). The ATDs were instrumented with triaxial head accelerometers, six-axis upper neck load cells, and six-axis lower neck load cells ([Figure 5](#)). The ATDs were secured using new service-replacement three-point active restraints. Based on data gathered from the aforementioned inversion study, the restraints were calibrated to match the ATDs' inverted head clearance to a 50th-percentile-male human surrogate's inverted head clearance by adding 4.4 cm (1-3/4 inches) of webbing to the driver restraint and 2.5 cm (1 inch) of webbing to the front passenger restraint. Following positioning of the ATDs, load cells were installed on both the torso and lap portions of the webbing for both seating positions to record restraint loading during the test. All instrumentation data were acquired and filtered in accordance with SAE J211.

High-speed (250 frames per second) and real-time video cameras recorded the vehicle dynamics and ATD kinematics from both on-board and ground-based locations. Detailed pre- and post-test still photographs were taken of the test vehicle, ATDs, and rollover surface. Additionally, the rollover surface and debris field were mapped with ArcSecond's Vulcan System laser-based three-dimensional measurement tool following the test.

The six onboard high-speed video cameras were positioned as follows: one camera on the upper left dash panel with views of the right front ATD, right A/B pillars, and right roof; one camera on the upper right dash panel with views of the left front ATD, left A/B pillars, and left roof; one camera in the middle of row 2 with views of the right A/B pillars and roof; another camera in the middle of row 2 with views of the left A/B pillars and roof; one camera in the rear cargo area with views of the right A/B pillars and roof; and one camera in the rear cargo area with views of the left A/B pillars and roof ([Figure 4](#)).

Off-board video documentation included two ground-based panning real-time video cameras and two ground-based panning high-speed video cameras (front and rear panning views); six ground-based high-speed video cameras (overlapping lateral views capturing 0 to 15.2 m (0 to 50 feet), 15.2 to 30.5 m (50 to 100 feet), and 30.5 to 45.7 m (100



to 150 feet)); one ground-based high-speed video camera (downstream view); and one fixed-frame elevated high-speed video camera (upstream view).

The test vehicle was positioned on the FMVSS 208 dolly rollover fixture in a passenger-side leading configuration (Figure 6). The test vehicle was supported at a 23-degree roll angle, measured from the horizontal, and the leading side tires rested against an angled 10 cm (4-inch) steel flange. The bottom surfaces of the leading (passenger-side) tires were positioned 23 cm (9 inches) above the rollover surface. Following installation of the various instrumentation components, cameras, and mounting fixtures, the vehicle was ballasted to a target weight representing the received curb weight plus two 77.2 kg (170-lb) occupants. The dolly and test vehicle were accelerated up to a nominal speed of 71 kph (44 mph) via a continuous wire rope-driven crash rail system. Snubber tubes filled with energy-absorbing aluminum honeycomb were used to rapidly decelerate the dolly and initiate the vehicle rollover event onto a 15 cm (6-inch) deep compacted desert soil surface. The speed of the dolly and test vehicle at initiation of the rollover sequence was measured using the crash rail speed trap positioned just prior to dolly engagement at the snubber tubes.

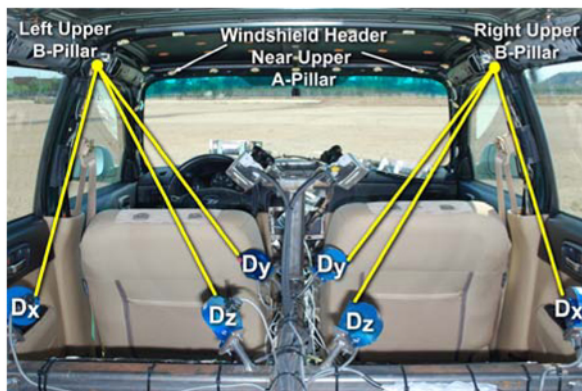


Figure 3. Depiction of markers painted on pillars, roof, and windshield header, as well as string potentiometers mounted to the top of the B-pillars.



Figure 4. Depiction of ATD and onboard camera positions.

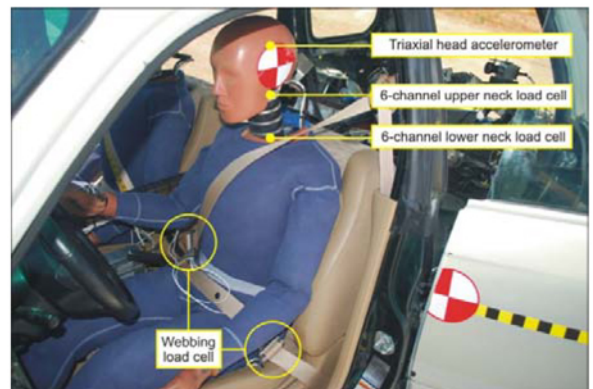


Figure 5. ATD and webbing instrumentation locations.



Figure 6. Still photographs of test vehicle on rollover dolly (top), and frame capture from high-speed video depicting vehicle at separation from rollover dolly (bottom).

RESULTS

The speed of the test vehicle at roll initiation was approximately 69.8 kph (43.4 mph). During the rollover sequence, the test vehicle underwent a total of 5-3/4 rolls over a distance of 42.1 meters (138 feet). Average roll rate over the event was 389 degrees per second, while the peak exceeded 700 degrees per second (Figure 7). There were several roof-to-ground contacts resulting in elastic and plastic deformation of the roof structures. During the roll sequence, both the passenger and driver experienced several discrete neck loading events (Figure 8, Tables 1 and 2).

During the first roll, the vehicle traveled approximately 14 meters (47 feet) with an average roll rate of 365 degrees per second and a peak roll rate of 610 degrees per second. The first vehicle-to-ground contact occurred when the passenger-side beltline area contacted the ground, followed by ground contact between the passenger-side pillars and roof rail. During this contact, all of the passenger-side glass was fractured and deposited on the ground. The vehicle remained in contact with the ground as it rolled from the passenger-side roof rail, across the roof, to the driver-side, contacting the

driver-side roof rail in a nose-down attitude. As the driver-side front wheel loaded against the ground at approximately 0.75 to 0.95 roll, the vehicle became airborne, and remained airborne through the completion of the first roll.

The peak compressive upper neck load measured for the passenger ATD (6,328 N or 1,423 lbs) occurred at approximately 0.49 seconds, during the first roof rail contact (passenger-side) with the ground. The highest passenger Head Injury Criteria (HIC_{15}) observed in the rollover also occurred during this roof-to-ground contact and was measured to be 162.6. The ATD's torso was in contact with the interior of the vehicle at approximately the 1/4-roll position. As the vehicle continued to roll, the passenger ATD's head moved toward the roof rail at a location just forward of the B-pillar junction. The peak passenger compressive neck loading resulted from torso augmentation when the vehicle was oriented just past the 1/4-roll position (0.31 revolutions), and thus the orientation of the passenger ATD's head and torso was closer to horizontal relative to the ground plane than vertical during this loading event. The vertical roof displacement, measured at the right B-pillar, was 1.9 cm (0.8 inch) at the time of the passenger ATD peak compressive upper neck load (Figure 9).

The peak vertical roof displacement observed at the right B-pillar during the first passenger-side roof impact occurred at approximately 0.55 seconds and measured 13.0 cm (5.1 inches) vertically downward (17.0 cm or 6.7 inches laterally inboard) relative to the B-pillar position in the non-deformed vehicle (Figure 9). This peak passenger-side B-pillar vertical displacement occurred over 60 milliseconds after the peak passenger ATD compressive upper neck loading (Figure 9). Further, at the time of peak downward roof displacement the passenger ATD upper neck was not loaded in compression but was, instead, in a state of neck tension (504 N, or 113 lbs) (Figure 9).

During the first passenger-side roof rail contact, the driver-side roof rail moved outboard. The driver ATD also moved outboard until its head contacted and loaded against the roof structure, compressing the neck (approximately 2,406 N, or 541 lb) in the absence of driver-side roof-to ground contact (Figure 10) and in the presence of outward roof motion relative to the chassis. The driver ATD subsequently experienced a peak compressive upper neck load (5,912 N, or 1,329 lb) during the first driver-side roof contact. During roof-to-ground contact, the motion of the driver ATD head was arrested against the roof rail while the torso continued to move toward the ground, resulting in neck compression. This torso augmentation occurred at approximately the 1/2-roll position, and the lateral and vertical roof displacements (measured at the left B-pillar relative to the position prior to any deformation) at the time of peak driver ATD compressive upper neck loading were approximately 3.2 cm (1.3 inch)

outboard and 2.8 cm (1.1 inch) downward respectively (Figure 10).

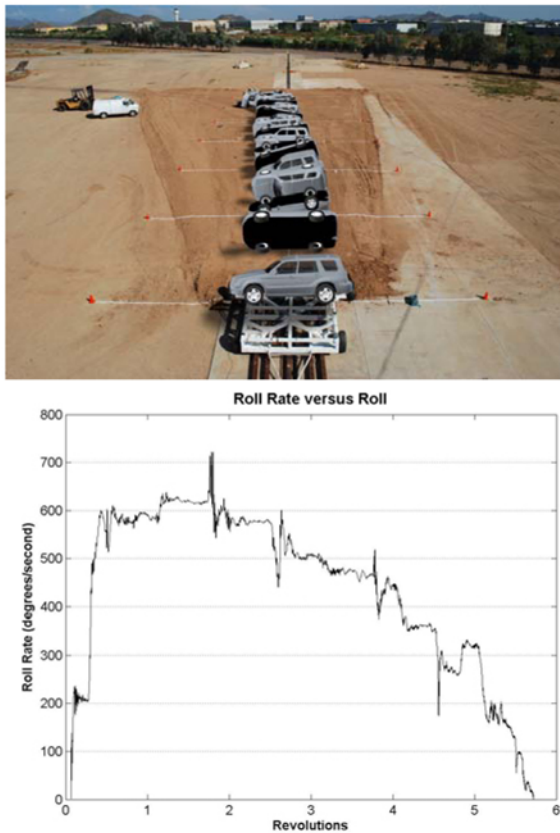


Figure 7. Vehicle rollover sequence re-created from video footage (top) and plot depicting vehicle roll velocity during the rollover event (bottom).

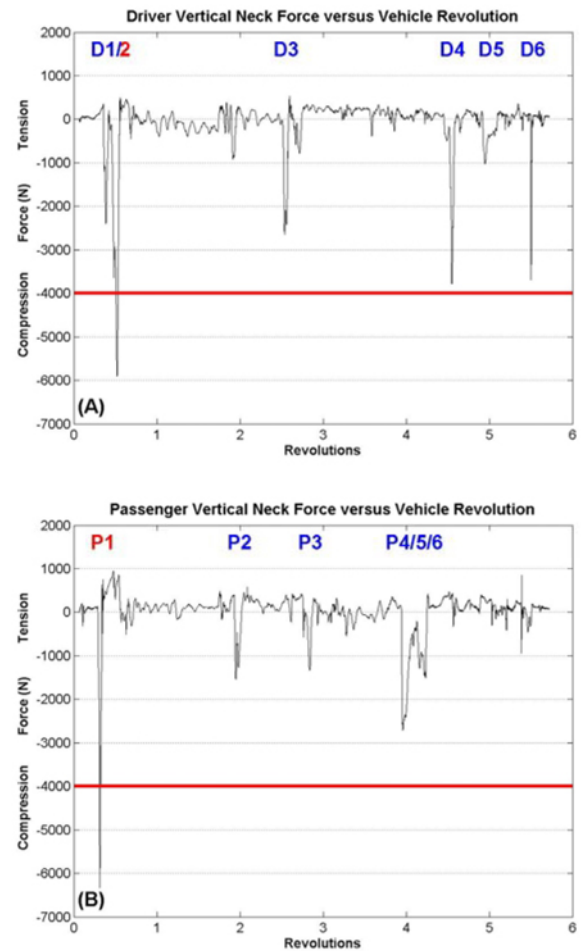


Figure 8. Driver (A) and Passenger (B) axial upper neck loads (F_z) versus vehicle revolution.

During the second roll, the vehicle traveled 7 m (22 feet) with an average roll rate of 610 degrees per second and peak roll rates in excess of 700 degrees per second. The second roll began with the vehicle airborne with a roll rate of approximately 590 degrees per second. The vehicle continued to roll through the 1-1/4-roll position as the right front wheel and fender made contact with the ground. The passenger-side roof rail did not make contact with the ground. The vehicle became airborne again after the 1-1/4-roll position, with a roll rate of approximately 630 degrees per second, until just prior to the 1-3/4-roll position when the driver-side contacted the ground. During this airborne phase both ATDs remained in an up-and-out position with their heads against the roof rails. The driver-side contact at the 1-3/4-roll position resulted in the highest driver HIC_{15} seen in the rollover sequence, with a value of 101.7. The passenger ATD's head came away from the roof rail following this contact, then moved back into contact with the roof inboard of the roof rail as the vehicle completed the roll. The vehicle was again airborne at the completion of roll 2.