

Occupant Kinematics and Injury Response in Steer Maneuver-Induced Furrow Tripped Rollover Testing

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ABSTRACT

Occupant kinematics during rollover motor vehicle collisions have been investigated over the past thirty years utilizing Anthropomorphic Test Devices (ATDs) in various test methodologies such as dolly rollover tests, CRIS testing, spin-fixture testing, and ramp-induced rollovers. Recent testing has utilized steer maneuver-induced furrow tripped rollovers to gain further understanding of vehicle kinematics, including the vehicle's pre-trip motion.

The current study consisted of two rollover tests utilizing instrumented test vehicles and instrumented ATDs to investigate occupant kinematics and injury response throughout the entire rollover sequences, from pre-trip vehicle motion to the position of rest. The two steer maneuver-induced furrow tripped rollover tests utilized a mid-sized 4-door sedan and a full-sized crew-cab pickup truck. The pickup truck was equipped with seatbelt pretensioners and rollover-activated side curtain airbags (RSCAs). The RSCAs were a prototype next generation design. The sedan was not equipped with these technologies. Each test vehicle contained two restrained instrumented 50th-percentile male ATDs in the front outboard seating positions. The vehicles were accelerated using a tow system, released, and then maneuvered onto a dirt test surface by an automated steering controller resulting in a passenger-side-leading soil-tripped rollover. The RSCAs and seatbelt pretensioners in the pickup truck deployed prior to the first vehicle-to-ground contact. Occupant kinematics and ATD injury metrics were evaluated for the duration of the roll events.

The results of the study demonstrated two neck-loading events wherein the compressive loads in the upper neck and the Nij were well in excess of the Injury Assessment Reference Values (IARV). Both of these neck-loading events involved the driver ATD in the sedan. The vertical deformation of the driver side roof structure at the time of the first neck-loading event that exceeded the IARV was 4.4 cm (1.7 inches). The second of these events involved direct head-to-ground contact. Compressive neck loading events were preceded by a pattern of a peak in the filtered axial head acceleration, followed by a peak in the filtered axial chest acceleration. A statistically significant positive correlation was observed between axial chest acceleration and axial compressive neck force. The interaction of the RSCAs with the two ATDs in the pickup truck was also investigated. The ATD loading and airbag interaction differed between the leading-side and trailing-side of the pickup truck. Occupant ejection was not observed to occur in this test.

Both tests showed multiple incidences when the occupants' heads were in proximity to the roof. The current study provides insight into occupant kinematics and injury potential during steer maneuver-induced furrow tripped rollover events, including the effects of RSCAs and seatbelt pretensioners.

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INTRODUCTION

Researchers have evaluated occupant kinematics and injury potential in vehicle rollovers over the last thirty years. Several methodologies have been employed in rollover research, including dolly rollover tests, CRIS testing, spin-fixture testing, inversion tests, and ramp-induced rollovers (e.g., [6, 8, 9]). Additionally, “tip up” testing and “on road” testing has been used to evaluate how an occupant moves in response to vehicle maneuvering and the pre-trip phase of rollover [10, 11]. However, these prior test paradigms were not designed to evaluate vehicle and occupant dynamics during both the pre-trip phase as well as the entire rollover event. The current testing involves steer maneuver-induced furrow tripped rollovers wherein occupant dynamics throughout the entirety of the rollover sequence, from pre-trip vehicle motion to the position of rest, can be investigated within a single test event.

The literature has documented the complex nature of vehicle motion (and consequently the occupant motion) throughout the rollover event, using phrases such as, “unique, violent crash events” [1], “not entirely reproducible by a single test event” [1], “not possible to predict the vehicle dynamics” [12], “large variations in the vehicle rolling motions” [13], “identical vehicles roll differently from test to test” [13], “impacts occur at various and random orientations” [7], “unpredictable vehicle and occupant kinematics” [15], “dynamic, high-energy, chaotic events” [8], “rollover testing was unrepeatable” [16], “no consistent or repeatable deformation patterns observed” [16], and “chaotic, unpredictable and unrepeatable nature of rollovers” [22], and other similar statements [also see 2, 14, 17, 18, 19, 20, 21]. With the advent of new technologies such as seatbelt pretensioners and rollover-activated side curtain airbags (RSCAs), it is especially important to continue to investigate occupant kinematics and occupant loading during rollover collisions to ascertain how these new technologies might affect occupant dynamics and injury potential during such events.

Since the initial introduction of RSCAs into the United States automotive market in 2002, increasing numbers of vehicles have become available with this technology. The National Highway Traffic Safety Administration (NHTSA) issued Federal Motor Vehicle Safety Standard (FMVSS) No. 226 in January 2011, which requires all new vehicles sold in the United States be equipped with standard feature ejection mitigation countermeasures by September 1, 2017.

According to NHTSA: “To meet the requirements of FMVSS No. 226, vehicle manufacturers will avail themselves of the side curtain air bag technologies that are already being installed in vehicles to meet FMVSS No. 214, ‘Side impact protection.’ In response to the 2011 final rule, manufacturers will enhance these side curtain air bags to make them larger to cover more of the window opening, more robust to remain inflated longer, and more advanced to deploy in side impacts and in rollovers.” [Federal Register/Vol. 78, No. 174/September 9, 2013/Rules and Regulations]. One of the primary goals driving the implementation of RSCAs into vehicles is the mitigation of full and/or partial occupant ejection. However, the agency has recognized that this objective must be balanced against the need to “do no harm” to occupants that may be too close to deploying devices [Federal Register/Vol. 64, No. 56/March 24, 1999/Rules and

Regulations]. Occupants may be in the deployment zone of a RSCA as a result of a variety of pre-event seating position and occupant postures. Further, the near-side occupant in a furrow-tripped rollover will be projected toward the deployment path of a RSCA as a result of inertia. Therefore, the interaction between the occupant and the RSCA at deployment, and throughout, a multiple rollover sequence is of interest to researchers.

The current study examines occupant kinematics and occupant loading during both pre-trip vehicle maneuvers and the vehicle rollover sequence to rest in a pickup truck equipped with seatbelt pretensioners and RSCAs, as well as in a sedan not equipped with these technologies. Onboard high-speed and real-time video as well as instrumentation was used to assess occupant kinematics, occupant-to-vehicle interactions, occupant-to-seatbelt interactions, occupant-to-RSCA interactions, and occupant injury response throughout the. The results from the sedan and pick-up truck rollovers in this testing are discussed in the context of other studies examining occupant motion and neck loading during the pre-trip and rolling phases of a rollover collision. To the authors' knowledge, this is the first publicly available steer maneuver-induced furrow tripped rollover test series in which occupant dynamics in the presence of a deployed RSCA was evaluated throughout the entire rollover sequence.

METHODS

The current study involved two steer maneuver-induced furrow tripped rollover tests utilizing a mid-sized 4-door sedan and a full-sized crew-cab pickup truck. Testing was conducted at Exponent's Test and Engineering Facility in Phoenix, Arizona. [Larson et al. \(2015\)](#) provides a comprehensive description of the rollover testing protocols utilized for this study as well as detailed vehicle kinematics and dynamics [23].

Both test vehicles were modified from their production condition in preparation for testing. Each vehicle had a pivoting tow-wagon tongue attached to the front sub-frame and left steering knuckle to guide the vehicle during acceleration to test speed. The rear seats were removed and fixtures were installed to provide mounting locations for instrumentation equipment, video equipment, a steering controller, and a brake test abort system. Most of 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. The equipped Electronic Stability Control (ESC) was deactivated in both vehicles to prevent brake application during the steering maneuver that preceded the soil trip event. The headrests were removed and the frontal airbags were deactivated to prevent obstruction of the video. The sedan was not equipped with a rollover sensing system; the vehicle's side curtain airbags were removed, and its side impact sensors and seatbelt pretensioners were deactivated. The pickup truck was equipped with a rollover sensing system that activated the retractor based pyrotechnic pretensioners and prototype side curtain airbags. The pickup prototype RSCAs were exposed due to the removal of the interior upper trim ([Figures 1 and 2](#)).

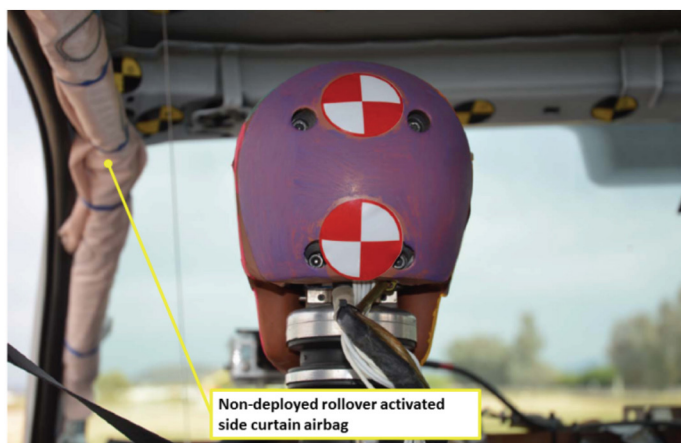


Figure 1. Stowed prototype RSCA on driver side of pickup truck

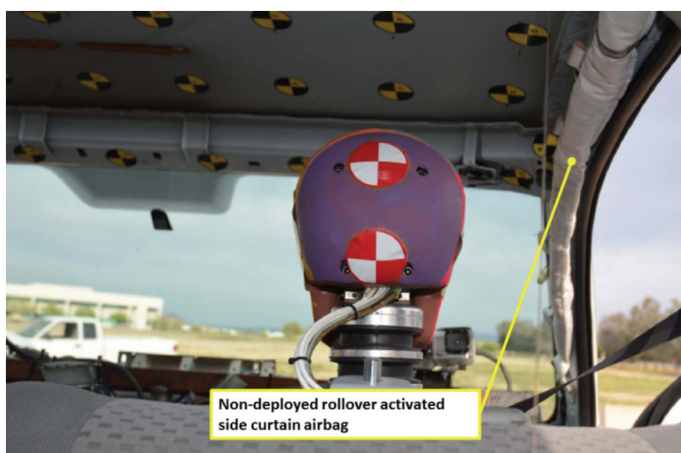


Figure 2. Stowed prototype RSCA on passenger side of pickup truck

Onboard vehicle instrumentation for both vehicles included a nine-accelerometer package, two triaxial accelerometer sets, two triaxial angular rate sensor sets, a two-axis tilt sensor, and an inertial/GPS measurement system were mounted near the vehicle center of gravity. String potentiometers were mounted on the vehicle to measure the displacements of the roof rail/B-pillar junctions. String potentiometers were also mounted to measure suspension travel. Additional sensors were installed to measure wheel speeds and steering wheel angle and torque.

Two Hybrid III 50th-percentile male ATDs were positioned in upright seated postures in the front outboard seating locations consistent with the procedures of Federal Motor Vehicle Safety Standard (FMVSS) 208. The two ATDs in the pickup truck test were equipped with pedestrian pelvises. The two ATDs in the sedan test were equipped with seated pelvises with the gap between the molded pelvis flesh and the molded thigh flesh filled with open-cell foam and spanned with gaffer tape to prevent the seatbelt from entering the gap. The ATDs were instrumented with head accelerometers, six-axis upper neck load cells, six-axis lower neck load cells, two triaxial chest accelerometer sets, triaxial chest angular rate sensors, two-axis chest tilt sensors, and triaxial lumbar load cells (Figure 3). The ATD in the driver position was instrumented with a nine-sensor array head

accelerometer set and the ATD in the front passenger position was instrumented with a triaxial head accelerometer set and a triaxial head angular rate set.

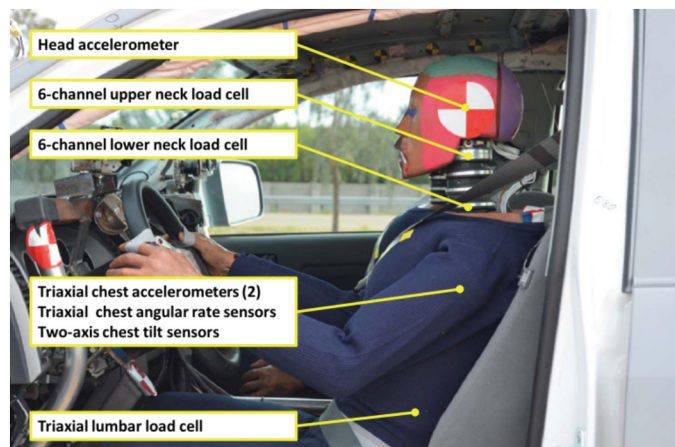


Figure 3. Driver ATD instrument arrangement, which was typical for all ATDs utilized in the test series.

The ATDs were secured using the three-point active seatbelt restraint systems, which utilized a continuous webbing, single retractor system with a single-slotted sliding latch plate, seat-mounted end-release buckle and dual-sensitive locking retractor. Load cells were installed on both the torso and lap portions of the webbing for both seating positions (Figures 4 and 5). String potentiometers were attached to the webbing between the D-ring and retractor mouth opening to evaluate webbing movement. In the pickup test, restraint cables were installed from the shoulders of each ATD to release pins mounted at the top of the upper seat backs to limit ATD lateral motion leading up to trip (Figure 4). The restraint cables were automatically released using a programmable event sequencer upon deployment of the RSCAs.

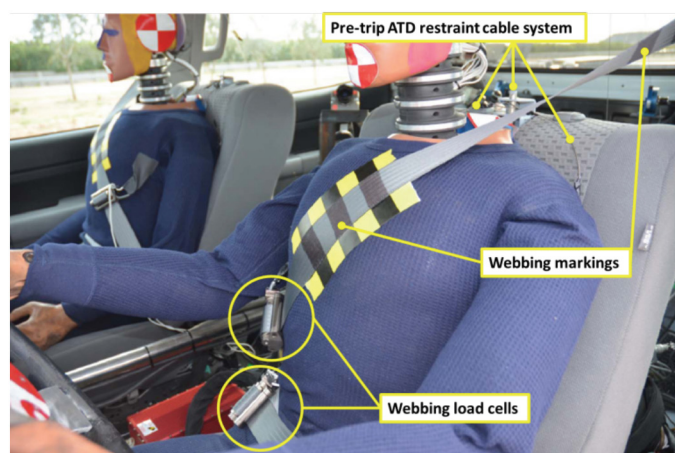


Figure 4. Webbing load cell locations and pre-trip ATD restraint cable system for pickup ATDs.

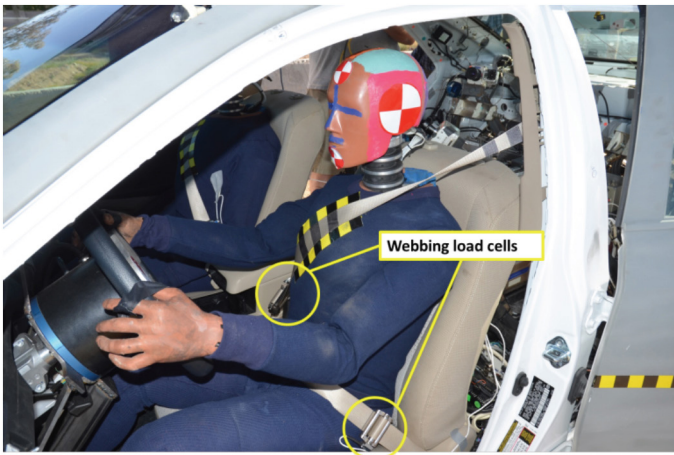


Figure 5. Webbing load cell locations for sedan ATDs.

All data were acquired at 10 kHz and were anti-alias filtered at 2.5 kHz. Time zero was defined as the vehicle release from the tow system. Noise spikes, defined as triangular transients with short duration timescales and high amplitudes that were clearly distinguishable from signal activity, were removed from the data using a peer-reviewed and published technique [27]. Spikes that occurred near signal peaks of interest, had longer time durations, or were indistinguishable from surrounding signal were not removed. Data were then digitally filtered in accordance with the SAE J211 recommended practice.

Each vehicle was tested with the ignition on, the engine running, and the transmission in neutral. The vehicles were attached to a tow system and accelerated to the test speed on a paved tow lane. The vehicles were then released and an automated steering controller input a right-left steer maneuver. The right steer caused the vehicle to yaw clockwise and travel off the paved tow lane and onto the prepared off-road soil surface. The off-road soil surface consisted of a 6-inch layer of mortar sand treated with stabilizer and was designed to provide a homogeneous off-road surface to drive on and furrow into while minimizing camera view interference due to airborne dust. Once the vehicles entered the off-road soil surface, the automated steering controller next input a rapid left steer that caused the vehicle to yaw counter-clockwise into a passenger-side leading orientation. The passenger-side tires furrowed into the soil inducing a soil-tripped rollover.

The tests were documented to record vehicle and ATD kinematics using high-speed (250 frames per second) and real-time video cameras, including: 10 ground-based off-board video cameras, 3 elevated off-board video cameras, and 12 onboard video cameras. The ground-based off-board video cameras included 3 panning real-time, 2 panning high-speed, and 5 static real-time. The elevated off-board video cameras included 1 panning real-time, 1 panning high-speed, and 1 static real-time. The onboard video cameras included 4 real-time and 8 high-speed. The sedan test was also documented by three overhead real-time video cameras attached to two helicopter drones. Videos and data were synched using a simultaneous flash visible in the on- and off-board videos and data event trigger, which occurred at vehicle release from the tow system. Ground-based still camera photographs were also taken from various

vantage points. Detailed pre- and post-test still photographs were taken of the test vehicles, ATDs, and rollover ground surfaces. The vehicles were also mapped using EOS Systems Photomodeler software and scanned using a FARO 3D laser scanner. The rollover surface and debris field were mapped using a FARO 3D laser scanner following the tests.

Upper neck compressions were analyzed against the axial ATD head and chest accelerations. Timing and amplitudes of neck compression local maxima exceeding 1000 N were compared to corresponding head accelerations measured by the center-mounted head accelerometer and chest accelerations measured by the high-level chest accelerometer. The measured acceleration pulses were subject to high frequency content, short duration spikes, and asymmetries, thereby making identification of a standardized point on the pulse (such as the pulse peak or the pulse midpoint) hard to determine across all events. To account for such asymmetries and minimize unwanted signal, a systematic method was established in which the axial acceleration pulse was filtered with a 50-Hz low-pass 1st-order Butterworth filter and the time at which the local maxima occurred was identified. The acceleration was then identified at this filtered peak time, which we will refer to as the Filtered Maximum Analysis (FMA) acceleration (Figure 6). The FMA acceleration point is therefore influenced by both the pulse peak and pulse mid-point. We note that for many of the acceleration pulses analyzed the peak of the acceleration pulse corresponded with the FMA acceleration. This analysis allowed us to compare consistent times across all acceleration events. Polar plots were used to visualize the magnitudes of axial head acceleration, axial chest acceleration, and neck compression as a function of vehicle roll angle with FMA acceleration timing represented on the plots by a dashed line.

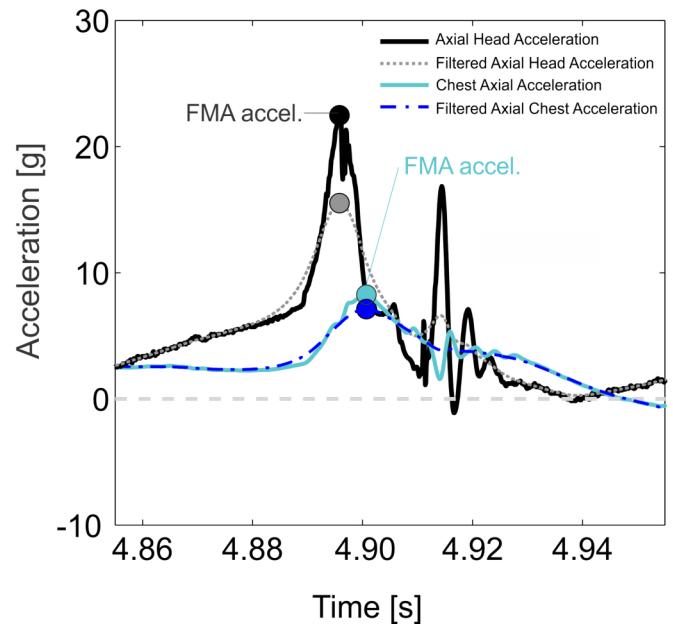


Figure 6. Representative example of filtering maximum analysis (FMA), used to compare axial acceleration timing with axial neck compression timing. The circles represent the time at which the filtered trace is maximal for the axial head (black and gray) and axial chest (blue and cyan) acceleration. The FMA acceleration is the acceleration at the time

RESULTS

Sedan Driver Kinematics and Loading

The sedan was accelerated to a speed of 105 kph (65 mph) prior to release and the subsequent steering maneuvers. After the right and left steer inputs, the sedan's tires began to furrow into the soil surface. The speed at trip was 55 kph (34 mph) and occurred 2.65 s after the vehicle was released from the tow system. The sedan completed 3-1/2 revolutions in a passenger side leading direction over a distance of 29 m (95 ft) and came to rest on its roof. The average roll rate during the event was 251 deg/s with a peak roll rate of 548 deg/s during the second roll.

An overview of the sedan driver kinematics during the steer maneuver, soil furrowing, and at each 1/8th roll position of the rollover sequence is provided in the [Appendix](#) (Figures 39, and 41, 42, 43, 44), with the latter illustrated in the context of the vehicle dynamics (roll angle, roll rate, and vehicle acceleration). As the sedan began to steer towards the right, the driver ATD moved slightly outboard relative to the vehicle interior and the torso belt moved closer to the ATD's neck. As the vehicle steered towards the left, the driver ATD moved rightward (inboard), and the torso belt moved towards the ATD's left shoulder. As the vehicle furrowed into the soil, the driver ATD leaned inboard and the torso belt moved off of the ATD's left shoulder. As the vehicle began to roll through the first quarter roll and into the inverted position, the ATD moved outboard relative to the vehicle, and the torso belt once again moved into a position over the outboard shoulder towards the ATD's neck. The ATD head became positioned against the underside of the roof rail and against the glass. The driver's side roof rail and front window glass made contact with the ground and onboard video showed that the glass had fractured by 3.220 s. The glass likely fractured due to a combination of occupant loading and contact with the ground. The ATD peak compressive upper neck load of 4972 N (1118 lbf) occurred shortly thereafter at 3.223 s with the vehicle roll angle at 190 degrees (0.53 revolutions) ([Figure 7](#)). A transient negative (upward) head acceleration of 21.7 g occurred at 3.224 s due to the release of the head from the constraint of the window glass as it fractured. The compressive neck load associated with this event was in excess of Injury Assessment Reference Value (IARV) of 4000 N and resulted from the torso's continued motion towards the head when the vehicle was oriented just past the 1/2-roll position. The loading of the neck due to motion of the torso toward the head after the head's motion has been arrested is referred to as "torso augmentation" and has been well described in previous rollover literature (e.g., [Raddin et al., 2009](#)). The peak N_{ij} associated with this event was 1.13 in compression-extension (N_{ce}) with a compressive force of 4964 N (1116 lbf) and an extension moment of 42.8 N-m (378.8 lbf-in). The peak extension moment was 44.0 N-m (389.0 lbf-in) and occurred 3.9 ms after the peak compressive neck load. The peak lateral neck moment in rightward bending was 104.5 N-m (926.3 lbf-in) and occurred 9.2 ms prior the peak compressive neck load. The vertical roof displacement, measured at the left B-pillar, was 4.4 cm (1.7 inches) downward at the time of the driver ATD peak compressive upper neck load ([Figure 8](#)), and the lateral deformation was 7.3 cm (2.9 inches) inboard at the same time. The peak

compressive lower neck load was 4111 N (924 lbf) and occurred at 3.224 s. The highest Head Injury Criteria (HIC_{15}) that occurred during the first roll was 49.9, well below the IARV of 1000.



Figure 7. Exterior view of sedan position (top) and interior driver ATD position (bottom) that corresponds to neck loading event during the first roll (roll angle = 190°, roll rate = 404°/s).

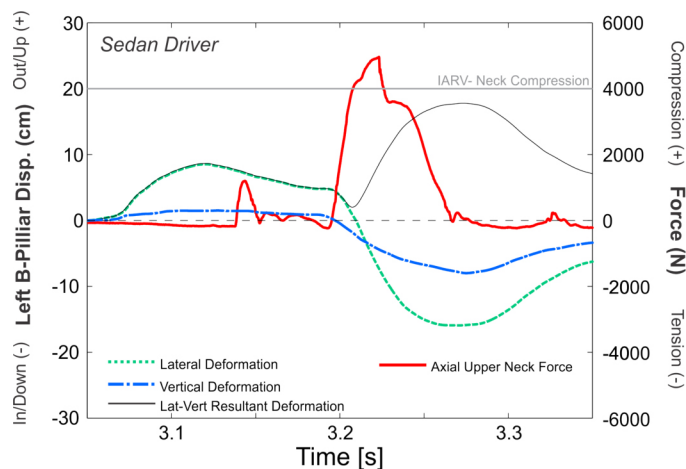


Figure 8. Time history of upper neck force and lateral, vertical, and resultant roof deformations at the left B-pillar for the sedan during the first roll. The peak compressive load exceeds the IARV of 4000 N.

The accelerations acting on the head and the chest of the sedan driver ATD near the time of the peak compressive neck load during the first roll were investigated (Figure 9). Note that for head and chest accelerations the downward direction relative to the ATD is positive, and upward is negative. The axial head acceleration pulse lasted for approximately 45 milliseconds with a FMA acceleration of 21.3 g occurring at 3.205 seconds. The acceleration pulse acting on the chest lasted for approximately 74 milliseconds, with a FMA acceleration of 17.1 g occurring at 3.211 seconds. There was a lag of approximately 5.6 ms between the acceleration pulses of the head and chest, which corresponded to the compliance between the head and torso and the resulting compressive neck load. The negative transient that occurs during the pulse is due to the release of the head from the constraint of the window glass as it fractured.

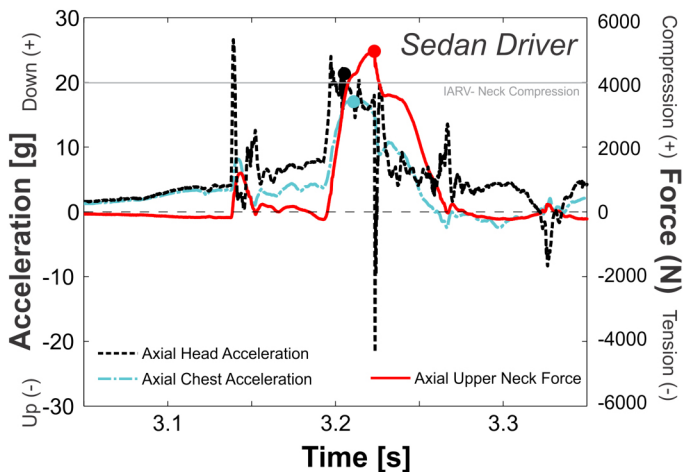


Figure 9. Sedan driver ATD axial head acceleration, axial chest acceleration and axial upper neck loading that correspond to the neck loading event during the first roll. The circles indicate FMA accelerations (21.3 g and 17.0 for the head and chest, respectively) and peak neck compressive loading (4972 N). See appendix (Figure 37) for longitudinal, lateral, and axial head and chest accelerations. The neck compressive load exceeds the IARV of 4000 N.

During the first roll, the vehicle traveled approximately 11.6 m (38 ft) with an average roll rate of 333 degrees per second. Following fracture of the driver door window glass, the ATD's head moved outside the plane of the driver side window. As the vehicle completed the first roll, it became airborne until the passenger-side wheels made contact with the ground at approximately the 1 1/8-roll position. Just beyond the 1 1/2-roll position, the ATD head stopped due to direct contact with the ground and the torso continued to move, resulting in a compressive neck load that also exceeded the IARV. The ATD's upper neck was loaded to 5984 N (1345 lbf) at 3.970 s (Figure 10). The peak N_{ij} associated with this event was 1.01 in compression-flexion (N_{cf}) with a compressive force of 5978 N (1344 lbf) and a flexion moment of 10.7 N-m (94.6 lbf-in). The peak flexion moment was 32.4 N-m (286.8 lbf-in) and occurred 16.5 ms after the peak N_{ij} . The peak lower neck compressive load was 4607 N (1036 lbf). The maximum HIC_{15} during the second roll was 54.2. The torso belt was located over the ATD's shoulder, adjacent to the neck, throughout this contact and loading event.



Figure 10. Exterior sedan orientation (top) and interior view of driver ATD position (bottom) that corresponds to neck loading event during the second roll (roll angle = $360+200^\circ$, $461^\circ/s$).

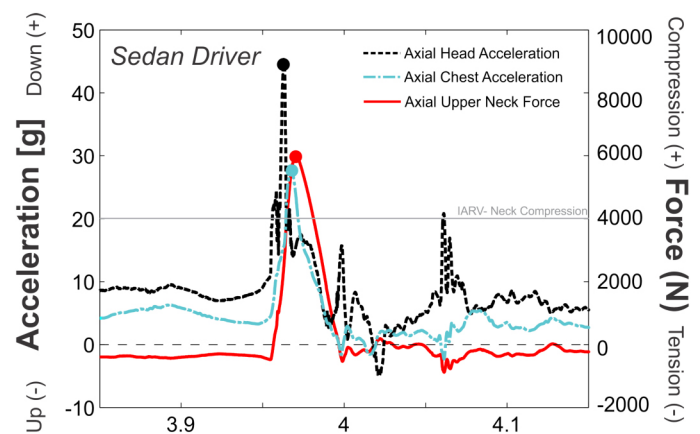


Figure 11. Sedan driver ATD axial head acceleration, axial chest acceleration and axial upper neck loading that correspond to the neck loading event during the second roll. The circles indicate FMA accelerations (44.5 g and 27.7 g for head and chest acceleration, respectively) and peak neck compressive loading (5984 N). See appendix (Figure 38) for longitudinal, lateral, and vertical head and chest accelerations. The neck compressive load exceeds the IARV of 4000 N.

The acceleration pulse acting on the ATD head during the second roll lasted for approximately 36 ms with a FMA acceleration of 44.5 g occurring at 3.963 s. The acceleration pulse acting on the chest lasted for approximately 43 ms, with a FMA acceleration of 27.7 g occurring at 3.968 s. Again, we observe a lag of 5.2 ms between the FMA timing of the acceleration pulses of the head and chest, which corresponded to the compliance between the neck and torso and the resulting compressive neck load (Figure 11). This neck loading event occurred due to direct contact between the ATD head and the ground as the driver's head was positioned in the upper window opening and the driver side roof rail and made direct contact with the ground.



Figure 12. Exterior view of the sedan orientation (top) and interior view of the driver ATD position (bottom) that corresponds to the neck loading event during the third roll (roll angle = $720+212^\circ$, roll rate = $315^\circ/\text{s}$).

During the second roll, the vehicle traveled 6.4 m (21 ft) with an average roll rate of 470 degrees per second. As the vehicle completed the second roll, it again became airborne until the right rear wheel made contact with the ground. The windshield separated from the vehicle as the sedan completed the second roll and came to rest in the roll path. The driver ATD maintained an upward and outward position relative to a nominal seated position during the airborne phase of roll 3. As the sedan moved just past the $2\frac{1}{2}$ -roll position (2.6 rolls), the ATD head was positioned such that it was in contact with pinch weld of the roof rail as the vehicle approached ground contact. The driver head was decelerated by contact with the pinch weld and the ground

as the torso continued to move resulting in a compressive neck load of 2945 N (662 lbf) (Figure 12); however, it was below the IARV. The maximum HIC_{15} during the third roll was 5.0.

The third roll involved a roll distance of approximately 7.0 m (23 ft) with an average roll rate of 318 degrees per second. The vehicle completed the third roll and transitioned to the fourth while airborne until both right side wheels contact the soil at 3.1 rolls. The laterally-directed forces due to this contact caused the driver ATD head to re-enter the vehicle and the ATD to move inboard, towards the vehicle centerline. The torso belt moved off the ATD's left shoulder and interacted with the upper part of the ATD's left arm. As the vehicle continued to roll, the ATD moved outboard and then inboard again. As the sedan came to rest at the $3\frac{1}{2}$ rolls position, the ATD was inverted and supported by the lap belt, with the torso belt located on the ATD's upper left arm.

The HIC_{15} for the driver ATD remained well below the IARV of 1000 throughout the rollover sequence. The driver ATD experienced six neck loading events that exceeded 1000 N (two of which exceeded the IARV of 4000 N) that were further evaluated. The axial head acceleration magnitude, axial chest acceleration magnitude and neck compressive loading were plotted as a function of roll angle with the use of polar plots (Figures 21, 22, 23, 24, 25, 26). This technique, first introduced by Croteau et al. (2010), is useful given the cyclic nature of the vehicle roll position during a rollover event [7]. The magnitudes of the accelerations and compression force are plotted radially outward, spaced at 10 g/division or 1000 N/division, respectively, with the zero degree vehicle roll angle (upright) at the 12 o'clock position. Due to the passenger-side leading nature of these rollovers, demonstrative graphics show the 45-degree positions in the CCW direction as viewed from the front of the vehicle. The polar plot analysis revealed that neck-loading events were associated with axial chest and head accelerations pulses. The accelerations and loading events were also compared as a function of time (Figures 21, 22, 23, 24, 25, 26). In all six sedan-driver ATD loading events, the head FMA acceleration occurred first, followed by the chest FMA acceleration, and then the neck compression peak (Table 1). This pattern corresponds to torso augmentation as described in [6]. Furthermore, at or just proceeding the head FMA acceleration, there was alignment of the head and chest axis, creating an environment in which inertial forces from the torso are transmitted to the head and create a scenario in which neck compression can occur. At the time of the two neck compressive loading events that exceed the IARV (Figures 22 and 23), the vehicle was oriented near the 180 degree roll position (inverted), at which time the vehicle structures in close proximity to the ATD's head were interacting with the ground.

Sedan Passenger Kinematics and Loading

The sedan passenger kinematics during the steer maneuver, furrow and rollover sequence are illustrated in the Appendix (Figures 39 and 45, 46, 47, 48). When the sedan experienced a steer input to the right prior to the rollover event, the passenger ATD moved slightly inboard, with the torso belt maintaining its relative initial position on the ATD chest. As the vehicle began to steer to the left, the ATD moved outboard, towards the passenger-side door. The right torso belt moved leftward on the ATD's shoulder and neck as the

vehicle began to furrow. As the passenger-side roof rail of the vehicle made contact with the ground at approximately the 3/8-roll position (0.37 rolls), the ATD experienced a compressive neck load of 2760 N (620 lbf) prior to the peak lateral and vertical roof deformation associated with this ground contact (Figures 13 and 14). This neck load was below the IARV.

As the vehicle continued rolling through the inverted 1/2-roll position to the driver-side roof rail ground impact, the ATD moved inboard relative to the torso belt such that the ATD's right shoulder slipped out of the torso belt. The ATD moved upward relative to its seat and its neck flexed into a chin-to-chest position. This contact between the top/back of the ATD's head and the roof did not cause an appreciable compressive neck load or bending moments in the passenger ATD.

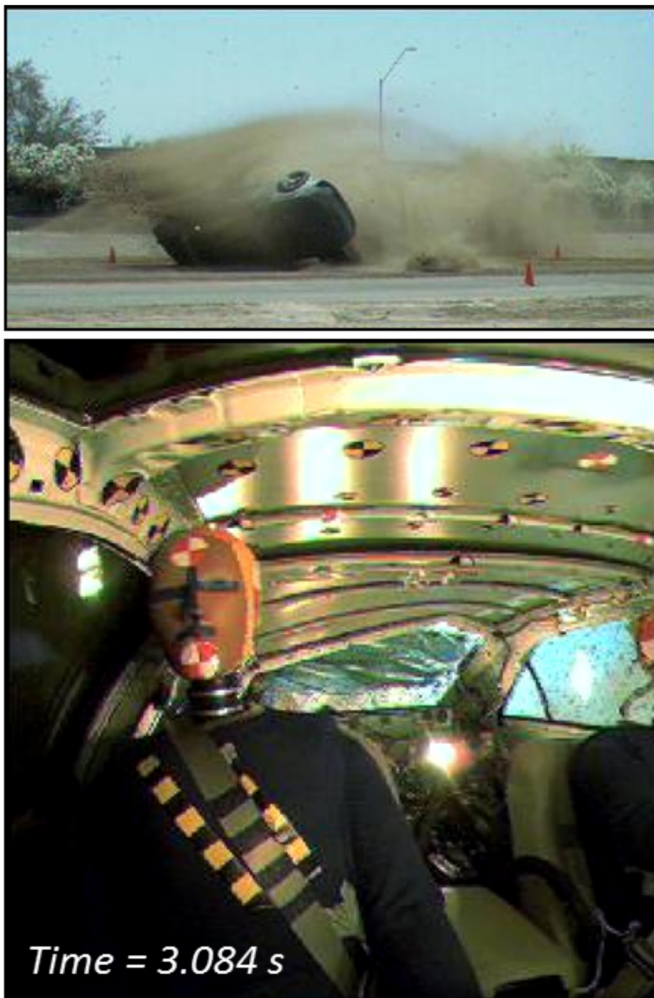


Figure 13. Exterior view of sedan orientation (top) and interior view of passenger ATD position (bottom) that corresponds to neck loading event during the first roll (roll angle = 134°, roll rate = 290°/s).

As the vehicle continued to roll into a wheels-down position as it completed the first roll, the ATD moved relative to the restraint system such that the torso belt was located across the lower chest and abdomen of the ATD and engaged the right arm just above the elbow joint. As the vehicle began the second roll, the ATD's neck was bent to the left as the head continued to engage with the interior roof structures. Vertical and lateral roof deformation occurred while the vehicle was inverted during the second roll, beginning just before the 1 1/2-roll position. The right front window glass fractured at 1.3 rolls,

at which time the ATD was positioned such that its head and body were angled away from the window portal. The right side of the ATD's head was against the roof during this time, and there was again no appreciable axial compression or bending measured within the ATD neck.

As the vehicle vaulted towards the end of the second roll and began the third roll, the passenger ATD engaged the seatbelt in a similar manner to the beginning of the prior roll. The ATD did not experience an axial compressive neck load spike in the inverted vehicle position during the third roll. As the passenger side wheels touched down at 3.1 rolls, the passenger ATD moved towards the passenger door window and the ATD head impacted the roof rail and the torso impacted the B-pillar. The ATD experienced a sub-IARV neck compressive load of 2802 N (630 lbf), a leftward load of 915 N (206 lbf), and a lateral neck moment of 84.0 N-m (743.4 lbf-in) associated with a leftward rotation. The resultant chest acceleration during the contact was 47.4 g, which was below the IARV of 60 g resultant acceleration. The HIC₁₅ associated with the head contact was 319.9, below the IARV of 1000.

As the vehicle came to rest after 3 1/2 rolls, the ATD was positioned upside down in the vehicle, the torso belt was positioned closer to the right shoulder, and the ATD head was in contact with the roof structure of the sedan. The N_{ij} remained below the IARV and the HIC₁₅ remained below the IARV throughout the roll sequence. The passenger ATD experienced two compressive neck loading events that exceeded 1000 N that were further evaluated using the polar plot analysis as described previously (Figures 27 through 28 and Table 1). As with the driver ATD, the passenger ATD loading events revealed a timing pattern in which the head FMA acceleration occurred first, the chest FMA acceleration occurred second, and the neck compression peak occurred third. Furthermore, head-neck-chest body segments were aligned during the events. The second event (Figure 28) occurred near the 45-degree roll orientation. At that time, the vehicle's right side tires impacted the ground and altered the vehicle motion such that the ATD head moved into the passenger side roof rail. This event demonstrates that neck loading can occur in non-inverted vehicle orientations as discussed in Heller, et al. [8].

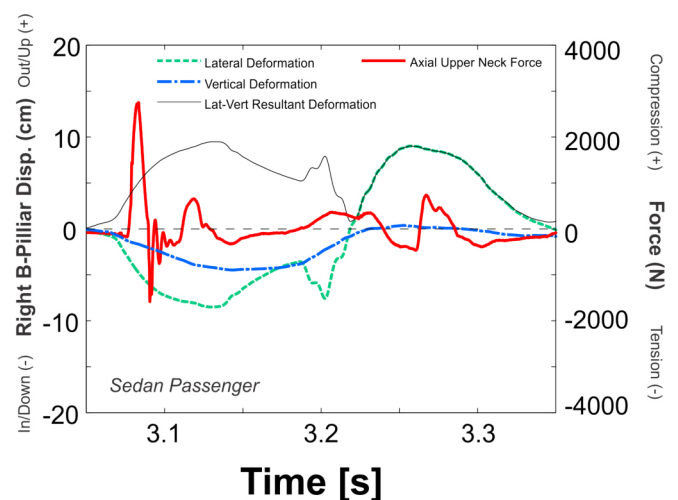


Figure 14. Time history of upper neck force and lateral, vertical, and resultant roof deformations at the right B-pillar for the sedan passenger during the first roll.

Pickup Driver Kinematics and Loading

The pickup was accelerated to a speed of 116 kph (72 mph) prior to release and the subsequent steering maneuvers. After the right and left steer inputs, the pickup's tires began to furrow into the soil surface. The speed at trip was 71 kph (44 mph) and occurred 2.55 s after the vehicle was released from the tow system. The pickup completed four revolutions in a passenger side leading direction over a distance of 44 m (144 ft) and came to rest upright on its wheels. The average roll rate during the event was 329 deg/s with a peak roll rate of 617 deg/s during the second roll.

The pickup driver kinematics during the steer maneuver, furrow and rollover sequence are illustrated in the [Appendix](#) (Figures 40 and 49, 50, 51, 52). As the vehicle began to steer to the right, the driver ATD moved slightly to the left (outboard) relative to the vehicle. As a result, the torso belt moved slightly towards the ATD's neck. As the vehicle began to steer to the left, the ATD moved back through its nominal seating position and then continued to move to the right (inboard) relative to the vehicle. As the right side tires began to furrow and the left wheel began to lift off of the ground, the driver ATD was located just inboard relative to the seat centerline, and the torso belt was located on the ATD's left shoulder. This lateral ATD excursion was limited by the tethering of the ATD torso to simulate the effect of human counter-posturing. The vehicle's RSCAs deployed at 2.439 s after tow release with the vehicle at the 32.3-degree roll angle and roll rate of 128 degrees per second. Refer to [Figure 15](#) for a sequence of interior frame captures that document side curtain airbag deployment; the sequence starts at pre-deployment and documents inflation at 4 ms (250 fps) intervals until it is fully inflated.

The activation of the seatbelt pretensioner and ATD tether release occurred simultaneously to the RSCA deployment. Prior to the pretensioner activation, the torso webbing load was 156 N (35 lbf) and the lap belt webbing load was 89 N (20 lbf). Activation caused a short transient spike in the torso webbing load that was approximately 81 ms in duration and had a peak of 1824 N (410 lbf). Similarly, activation caused a spike in the lap belt webbing load that had a peak of 727 N (164 lbf) and duration of approximately 67 ms. The string potentiometer located between the D-ring and retractor mouth measured 8.3 cm (3 1/4 in) of webbing movement, while analysis of the onboard video indicated the torso portion of the seatbelt moved approximately 5 cm (2 in) towards the D-ring with respect to the ATD chest ([Figure 15](#)).

At the time of RSCA deployment, the ATD's head and left shoulder were inboard of the airbag. The deployment event was associated with a tensile neck load of 324 N (73 lbf) and a resultant chest acceleration of 10.3 g, neither of which approached their associated IARV. The resultant acceleration of the ATD head was less than 9 g.

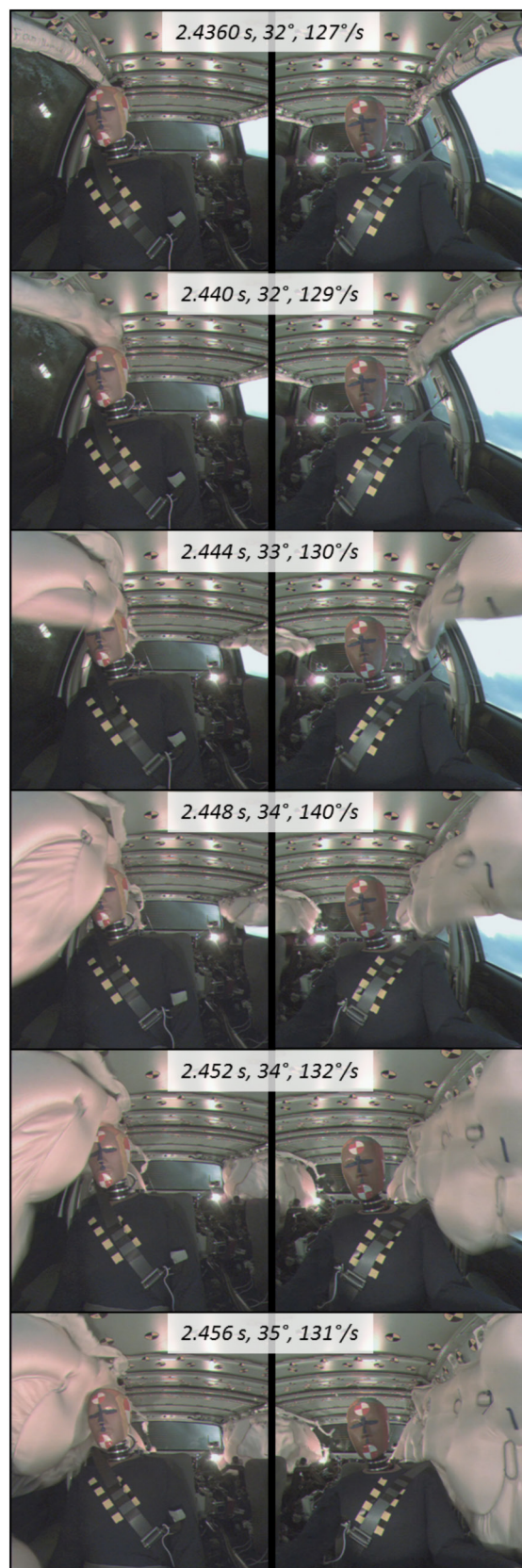


Figure 15. Sequence of frame captures from a rear facing on-board camera depicting deployment of (right) driver and (left) passenger RSCA in pickup truck. Time, roll angle, and roll rate are shown for each frame capture.

As the vehicle continued to move through the $\frac{1}{4}$ roll position, the driver ATD moved up and out relative to the vehicle, such that it moved into the RSCA. As the vehicle was inverted (approximately 0.6 rolls), the ATD moved further outboard and interacted with the deployed RSCA such that the ATD head assumed a rightward lateral bending position and the torso belt maintained a position close to its initial location relative to the ATD torso. The vehicle completed the first roll by vaulting with four wheels off the ground and with the driver ATD interacting with the RSCA. The vehicle traveled 15.5 m (51 ft) between trip and the completion of the first roll, and the average roll rate was 348 degrees per second.

During the second roll, the vehicle traveled 8.2 m (27 ft), and the average roll rate was 549 degrees per second. The passenger side roof structures made contact with the ground between the approximate $1\frac{1}{4}$ and $1\frac{1}{2}$ roll positions. This roof-to-ground contact resulted in the driver ATD head impacting the RSCA/roof rail and was associated with a HIC_{15} of 231.7 and an upper neck compressive load of 1681 (378 lbf). The vehicle completed the second roll by vaulting with four wheels off the ground and with the driver ATD interacting with the RSCA. The vehicle traveled 8.2 m (27 ft) during the third roll and experienced an average roll rate of 438 degrees per second. The inverted position (approximately $2\frac{1}{2}$ rolls) did not involve contact between the vehicle roof and the ground until the driver's side hood made ground contact and produced a HIC_{15} of 73.9 and a compressive neck load of 592 N (133 lbf).

The vehicle's fourth roll involved an average roll rate of 187 degrees per second, and the vehicle traveled 11.9 m (39 ft) before coming to rest. The fourth roll began as the two rear wheels made ground contact while the vehicle was nose pitch up. The driver ATD responded to the impact by moving rearward into its seat and the head and neck moved into extension. In a production vehicle, the neck motion likely would have been mitigated due to contact with the head restraint, which was removed for testing to allow for camera visualization from the rear of the vehicle. Again, the vehicle did not make ground contact in the inverted position until approximately 3.6 rolls, when the driver-side hood contacted the ground. The ATD moved into the curtain during this ground contact.

The vehicle came to rest, wheels up, after impacting the ground with the passenger-side wheels. The driver ATD moved inboard as the vehicle came to rest and the torso belt slipped off the ATD's left shoulder. The ATD came to rest leaning inboard with the torso belt located slightly proximal to the elbow joint. The N_{ij} never exceeded the IARV of 1.0 throughout the roll sequence, and the compressive neck loading never exceeded the IARV of 4000 N throughout the crash event.

Pickup Passenger Kinematics and Loading

The pickup passenger kinematics during the steer maneuver, furrow and rollover sequence are illustrated in the [Appendix](#) (Figures 40 and 53, 54, 55, 56). When the pickup truck experienced a steer input to the right, the passenger ATD moved slightly to the left, with the torso belt maintaining its nominal position. As the vehicle's steer input shifted to the left, the ATD moved to the right such that the torso belt moved along the ATD shoulder towards the neck. The vehicle's two

left wheels lifted, and the RSCAs deployed. The RSCA deployed down onto and then outboard of the ATD's head, with the deployed airbag properly inflated between the ATD head and the window (Figure 15).

The airbag deployment and interaction with the passenger ATD head was associated with an upper compressive neck load of 3159 N (710 lbf) at 2.447 seconds, which was followed by a tensile neck load of 742 N (166.7 lbf) only a few milliseconds later. The duration of this compressive neck loading event was 11 ms and was several times shorter than the duration of compressive neck loading measured in the sedan driver ATD neck loading events that exceeded the IARV. The HIC_{15} was 47.1 from the deployment, with a resultant head acceleration of 88.6 g. A resultant chest acceleration of 19.3 g was also measured at this time.



Figure 16. Exterior view of the pickup orientation (top) and onboard view of passenger ATD position (bottom) at time of vehicle-to-ground contact during first roll (roll angle = 207° , and roll rate = $442^\circ/s$).

The activation of the passenger seatbelt pretensioner and tether release occurred simultaneously to the RSCA deployment. Prior to the pretensioner activation, the torso webbing load was 351 N (79 lbf) and the lap belt webbing load was 476 N (107 lbf). At activation, there was a transient spike in torso webbing load with a peak of 1690 N (380 lbf) and duration of approximately 63 ms and a transient spike in the lap belt webbing load with a peak of 810 N (182 lbf) and

duration of approximately 20 ms. The string potentiometer located between the D-ring and retractor mouth measured 7 cm (2 ¾ in) of webbing movement, while analysis of the onboard video indicated the torso portion of the seatbelt moved approximately 4 cm (1 ½ in) towards the D-ring with respect to the ATD chest (Figure 15).

The vehicle continued to roll with the passenger ATD maintaining a position upward and outboard relative to the vehicle's center of mass. The vehicle experienced a contact to the driver's side roof rail when the vehicle was inverted that caused the passenger ATD to move towards the driver's side roof rail (Figure 16). This motion resulted in the passenger torso belt slipping off of the passenger ATD's right shoulder during the first roll. The passenger ATD also moved rearward relative to the seat during this contact. As the vehicle moved past the ¾ roll position, the torso belt was located in the right elbow joint of the ATD, and the ATD's head was against the roof, with the face presented to the roof surface (Figure 17).



Figure 17. Exterior pickup orientation (top) and passenger ATD position (bottom) after movement of seatbelt relative to ATD shoulder (roll angle = 316°, and roll rate = 535°/s).

The ATD maintained a position such that its face was against the roof structures as the vehicle completed the first roll and began the second roll. The vehicle contacted the ground on the passenger side and rolled through the driver side during the second roll, and the ATD's upper neck compressive loads and flexion/extension moment

oscillated as the ATD's motions were dictated by the vehicle kinematics. The peak compressive neck load during the roll sequence was 2642 N (594 lb) at 1.9 rolls (3.992 s), and the peak extension moment during the roll sequence was 45.2 N-m (400.3 lbf-in) at 1.0 rolls (3.4461 s). The ATD maintained the face-to-roof position as the vehicle vaulted from the second roll into the third roll, moved forward due to the driver's side roof contact at approximately 2 ¾ rolls, and moved rearward back into its seat as a result of the contact between the rear wheels and the ground. Throughout the first half of the fourth roll, the ATD was positioned with the top of its head against the roof structures. The vehicle impacted the driver's side, at which time the passenger ATD moved inboard and its motion was ultimately restricted due to engagement with the lap belt and the torso belt, which was still located around the ATD's right elbow joint. As the right wheels made final ground contact, the passenger ATD moved into the RSCA and came to rest in the passenger seat in an upright position as the vehicle came to rest.- t

The compressive neck loading events that exceeded 1000 N in the two pickup truck ATDs were selected for further evaluation utilizing polar plots and time histories of the relevant ATD measurements.

Eight such events were identified for the two pickup truck ATDs, with the driver experiencing a single neck loading event and the passenger experiencing seven compressive neck loading events. For the pickup driver ATD, neck loading occurred at 155 degrees. Similar to the sedan events, pickup driver event 1 showed a pattern of head axial FMA acceleration occurring first, then chest axial FMA acceleration, followed by neck compression (Figure 29 and Table 1). For the sedan passenger (Figure 30, 31, 32, 33, 34, 35, 36), five of the seven neck loading events demonstrated a similar timing pattern. One of those five events was associated with interaction of the head with the deploying prototype RSCA. Review of the remaining two events revealed that the head and torso were not aligned; the timing pattern as described for the other fourteen events in the four ATDs was not seen in these two events.

DISCUSSION

The current study involved two steer maneuver-induced furrow tripped rollover tests using two vehicles, a sedan and a pickup truck. The pickup truck was equipped with non-production, prototype RSCAs. In each test, the rollover event was induced by a steer-reversal maneuver wherein the vehicle rapidly steered first to the right and then to the left on a soil surface. The instrumented vehicle and front seat ATDs utilized in each test allowed for a detailed analysis of the occupant kinematics and injury response throughout the pre-trip phase as well as the entire rollover sequence.

Yamaguchi et al. (2005) used a series of tip-up tests in a vehicle equipped with a steer controller and outriggers to examine the response of ATDs and human volunteers to steering maneuvers and vehicle tip-up [10]. While the ATD's kinematics did not fully capture the active posturing of the volunteers, the authors concluded that the ATD's motion reasonably reflected the volunteer posture during the pre-trip phase an on-road rollover. The positions of the passenger ATD, at the time of driver-side wheel lift, in the sedan and the pickup truck tests in the current work were found to be similar to the position

of the passenger ATD after a right/left steering maneuver in the Yamaguchi study. This indicates that the pre-trip position and posture of the ATDs in the current work were reasonably comparable to the volunteer and ATD positions observed in [10] (Figure 18).

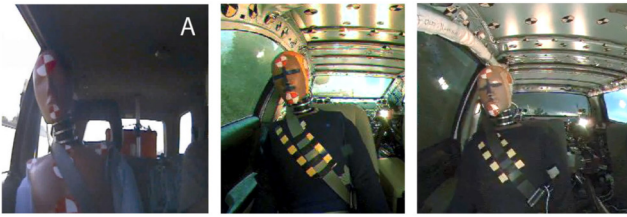


Figure 18. (Left) Partial Figure 9 from Yamaguchi study ([10]) showing the ATD position after a passenger side leading tip-up produced by a right steer followed by a left steer. (Middle) Sedan passenger ATD position after driver's side wheels had lifted. (Right) Pickup truck passenger ATD position after driver's side wheels had lifted.

The ATDs in the pickup test of the current study were loosely tethered to their seatback during rollout and pre-trip vehicle motions prior to deployment of the RSCA. This methodology is not typical of rollover testing. However, it is important to note the steer maneuver-induced test paradigm used in the current study involves a complete set of pre-trip vehicle dynamics. While real-life rollover accidents can involve various occupant positions and postures, it was the goal of the current study to first examine occupant positions and postures that are reasonable examples of postures that might be adopted by a human occupant during a steer maneuver-induced furrow tripped rollover.

In 2011, the NHTSA issued Federal Motor Vehicle Safety Standard (FMVSS) No. 226, which requires that by September 1, 2017 all new vehicles produced be equipped with ejection mitigation countermeasures as a standard feature. The NHTSA's stated "Purpose and Scope" for FMVSS 226 was: "This standard establishes requirements for ejection mitigation systems to reduce the likelihood of complete and partial ejections of vehicle occupants through side windows during rollovers or side impact events. [CFR §571.226.S1]" A review of the occupant kinematics in both the RSCA-equipped pickup truck and the non-RSCA-equipped sedan in the context of the associated vehicle dynamics throughout the rollover events of the current study allows for some observations regarding the potential efficacy of RSCAs.

Neither ATD in the RSCA-equipped pickup truck experienced a complete or partial ejection. Neither ATD in the RSCA-equipped pickup truck sustained loading in excess of the established IARVs in the head, cervical spine, chest, or lumbar spine. The driver ATD in the sedan that was not equipped with RSCAs experienced two neck loading events in excess of the compressive IARV and a partial ejection of the ATD's head. One of the two neck loading events occurred simultaneously with the partial head ejection. Per the evaluation of the sedan's vehicle kinematics and associated occupant kinematics, the presence of a RSCA might provide benefit in the form of mitigating partial ejection of the driver ATD's head during this particular rollover sequence.

Detailed analysis of the two compressive neck loading events that exceeded the IARV (both in the sedan driver ATD) demonstrated that the ATD axial head acceleration related to each impact preceded the

axial chest acceleration (as determined using the filtered maximum analysis), with the chest lagging the head by several milliseconds. In addition, these FMA accelerations immediately preceded the peak neck compressive load in each event and are associated with the sudden deceleration of the head (Raddin et al., 2009). The lag of the chest acceleration relative to the head acceleration demonstrated in the current study, followed by the neck loading, supports the conclusions of previous research that compressive neck injuries occurring during rollover events are a result of neck loading produced by motion of a torso mass toward a stopped head [4, 6, 8, 20]. Injuries resulting from this mechanism are often referred to as "diving" injuries, and have been well established in the biomechanical literature [24, 25, 28]. Nightingale et al. (1996) described how cervical spine injury occurs within 2.2 to 18.8 milliseconds of head impact [25]. The timing between the FMA head acceleration and peak compressive neck loading observed in the current study was consistent with those described by Nightingale and coworkers in the human spine.

The neck loading events presented in the current study were primarily compressive in nature, especially those exceeding the IARV. Biomechanical testing on cadaveric specimens indicated that the presence of a moment on the neck affected the axial tolerance. The N_{ij} neck injury criteria were developed to take into account a linear combination of axial loads (i) and bending moments (j): tension-extension (N_{te}), tension-flexion (N_{tf}), compression-extension (N_{ce}), and compression-flexion (N_{cf}) [29]. Specifically, N_{ij} are calculated as shown below (Equation 1).

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (1)$$

In Equation 1, F_z is the axial load (compression or tension), M_y is the bending moment (flexion or extension), F_{int} is the critical axial load intercept and M_{int} is the critical bending moment intercept. When plotted with the axial load on the abscissa and the moments on the ordinate, the N_{ij} corridor forms a kite shape with the boundary having N_{ij} equal to 1.0. The N_{ij} is used in conjunction with overall tolerances for neck compression and tension (i.e., FMVSS 208) such that the top and bottom are 'cutoff' of the corridor, kite (Figure 19).

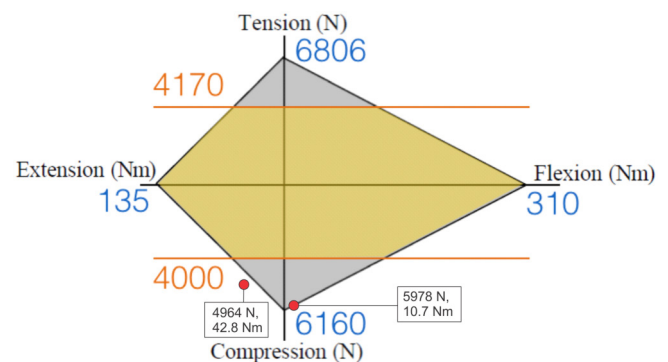


Figure 19. N_{ij} "kite" with overall axial load limits superimposed (FMVSS 208). The intercept values (blue) and axial load limits (orange) are those used for the 50th-percentile male ATD. The effective IARV corridor is shown in brown. The red circles show the loading conditions (compressive load and bending moment) at peak N_{ij} for the two sedan driver ATD neck loading events that exceeded the compressive IARV.

Therefore, for neck loading events dominated by axial force and having small values of bending moment compared to the critical intercepts, like those discussed above, the IARV is essentially governed by the overall axial load limits. Hence, the focus in the current study was on the compressive neck loading.

The biomechanical literature has also established conditions that need to be met in order for a diving-type compressive cervical spine injury to occur [24, 25]. The head and neck need to be in a very specific alignment such that the torso continues its motion into the neck once the head's motion has been arrested, and in such a way as to cause compressive loading of the spine, as is described by Raddin et al. (2009) as "torso augmentation." In addition to the required body alignment, the torso must also have enough velocity to create loading of sufficient magnitude to cause injury (as measured by the established IARVs for ATDs as detailed in [26]). The occupant kinematics during a rollover event are governed by initial positioning and vehicle dynamics, including the magnitude and direction of the vehicle accelerations during ground contact events. While ATD neck loading has been documented at various vehicle orientations, including ones in which the wheels are down, in previous rollover research [8], compressive neck loading in excess of the IARV was most likely to occur when roof structures were in contact with the ground. A combination of the vehicle's acceleration magnitude and direction throughout a rollover sequence, the ATD's head and neck alignment at each acceleration spike, and the proximity of the ATD's head to vehicle interior structures will contribute to determining whether an occupant would likely be injured. Despite the high-speed rollover in both vehicles, injurious neck loading events were rare; these tests demonstrate the required combination of factors that must be present in order to generate injurious loading. The sixteen compressive neck loading events identified as being in excess of 1000 N (including the two compressive neck loading events considered injurious due to exceeding the IARV of 4000 N) were analyzed in greater detail to gain further insight as to what factors during a loading event may increase the likelihood of injury to an individual (Figures 21, 22, 23, 24, 25, 26 and Table 1). This analysis revealed that 15 of 16 events demonstrated a lag time between the axial head FMA acceleration and the neck loading of between 3.0 and 17.9 milliseconds, consistent with the time between peak axial head acceleration and axial neck force in the cadaver test described by Nightingale [25]. The only event that fell outside of the aforementioned range was Pickup Passenger Event 3, in which the ATD was positioned with its forehead presented to the roof structures during the maximum compressive neck load. In that event, the peak neck compression preceded both the peak head acceleration and peak chest acceleration (Figure 32). Biomechanical research has demonstrated torso augmentation in the presence of head constraint and head-neck-torso alignment produces injurious neck loading in a human. In Pickup Passenger Event 3, the ATD's head and torso were not aligned and constrained in a manner that would produce the greatest compressive loading of the spine. Consequently, the head

moved out of the way of the torso mass so as to mitigate the compressive neck loading. When compared to the other neck loading events, the difference in relative loading times between the head, chest, and neck seen in Pickup Passenger Event 3 appear largely attributable to the lack of head and torso alignment.

There was one compressive neck-loading event in which the chest FMA acceleration occurred after the peak neck-loading event (Pickup Passenger Event 2, Figure 31). This event was also characterized by the ATD's forehead and face presenting to the roof structures of the vehicle, as occurred in Pickup Passenger Event 3. Furthermore, Pickup Passenger Event 2 resulted in the longest time between the axial head FMA acceleration and the axial chest FMA acceleration (28 ms) and was one of only two events in which the measured head acceleration was less than the chest acceleration. Similarly to Pickup Passenger Event 3, the ATD in Pickup Passenger Event 2 did not have head, neck and torso aligned and the head constrained to produce high levels of compressive loading.

In the pickup truck equipped with RSCAs, there were events in which the neck loading was greater than 1000 N, although none exceeded the IARV. While all eight neck-loading events in the pickup truck occurred in the presence of the RSCA, there were only two events in which the ATD head interacted directly with the airbag (Pickup Driver Event 1 and Pickup Passenger Event 1). Pickup Driver Event 1 (Figure 29) occurred during the first roll, and the top and left side of the head were in contact with the RSCA at that time, resulting in an upper neck compressive load of 1680 N. Although RSCA deployment path could be influenced by interior trim structures not present in the test vehicle, Pickup Passenger Event 1 (Figure 30) occurred during the deployment of the RSCA and resulted in an upper neck compressive load of 3153 N. This event reinforces the challenges presented by the design of a RSCA that meets FMVSS 226 while mitigating the loading to the occupant's head and neck in the event that they are in the path of the deploying RSCA.

Further examination of the collection of neck-loading events revealed that the upper compressive neck load was correlated with the magnitude of the axial chest acceleration experienced by the ATD for the sixteen neck loading events. Specifically, the chest acceleration magnitude is a significant ($\alpha = 0.05$) predictor of compressive axial load when considering all 16 instances when dummy neck load exceeded 1000 N (two-tailed t-statistic: 3.57, $p < 0.05$). In addition, a statistically significant positive correlation between chest acceleration and axial compression neck force was shown (Figure 20). Eight of the events involved neck loading between 1000 N and 2000 N. Of these eight events, several involved ATD alignment and head constraint that mitigated the production of compressive neck loading. With head, neck and torso alignment and head constraint, the axial FMA chest acceleration influenced the magnitude of the compressive neck load experienced by the ATD consistent with torso augmentation.

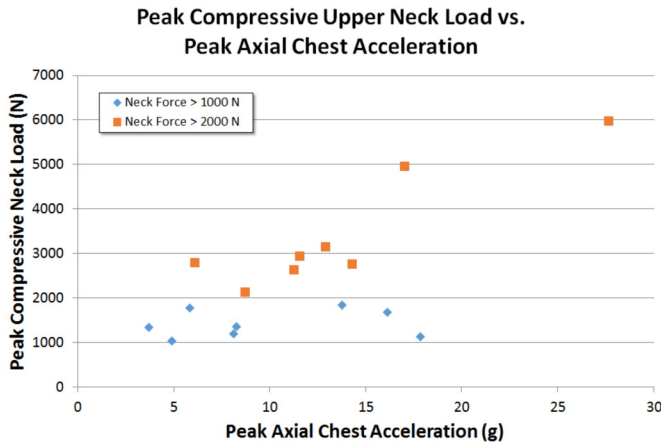


Figure 20. Peak compressive upper neck load versus axial FMA chest acceleration for all events and for compressive loading events greater than 2000 N (orange squares).

While there were no neck-loading events that exceeded the upper compressive neck loading IARV of 4000 N (899 lb) in the pickup truck ATDs, the results of this single test should not be interpreted to indicate that the presence of a combination of a seatbelt pretensioner and a RSCA will prevent the potential of a neck injury in all rollovers involving similarly equipped vehicles. In fact, the combination of a seatbelt pretensioner and a RSCA did not prevent head-to-roof contact in the pickup test. Newberry et al. (2014) used a spin-fixture to investigate how RSCAs influence the excursion and ATD head and-neck loading during the airborne phase of rollover [9]. They found that the presence of a RSCA might influence the occupant lateral head excursion and resulting occupant loading but that the RSCA can direct the head into contact with upper vehicle structures located inboard relative to the RSCA as a result of the occupant's up and out motion during the rollover event. Further they showed that the presence of the RSCA cannot prevent the head from coming into contact with or close proximity to the roof, and cannot prevent head, neck and torso alignment. McCoy (2010), utilizing the ROCS fixture to simulate curb-tripped rollovers found that the presence of pretensioners and curtain airbags did not prevent head-to-roof contact and had a limited effect on the magnitude of neck loads at roof-to-ground impact [30]. This research found several instances of neck loading in excess of the IARV of 4000 N, even in the presence of these safety features.

Other studies have focused on the effects of seatbelt pretensioners on head excursion during rollover. Using a validated computational model, Newberry et al. (2006) simulated a maneuver-induced rollover and found that pretensioners, having characteristics similar to those in production vehicles at the time of the study, only modestly affected occupant kinematics and head excursion [33]. This finding was attributed to the limited capacity of the pretensioners to retract webbing in the presence of webbing tension. Cassatta, et al. (2010) utilized a rigid fixture to simulate curb-trip rollovers and found that seatbelt pretensioner deployment time played a primary role on the occupant kinematics. The authors indicated that while the effectiveness of seatbelt pretensioners appeared to increase at earlier deployment times this fact needs to be balanced with unnecessary deployment of pretensioners and rollover curtains. Similarly, White, et al. (2011) found that “with deployment times prior to occupant belt

loading, certain pretensioner combinations were able to reduce the lateral and vertical motion of the trailing side ATD head when compared to non-pretensioner baseline tests”. The authors indicated that the amount of webbing retracted and its effect on occupant kinematics were decreased with belt load, and that real-world rollovers are often preceded by vehicle motions that can result in loading of the belts before rollover initiation. In the current study, the furrow-tripped rollover involved prolonged lateral decelerations in excess of 1 g. Although the occupants in the RSCA-equipped pickup were tethered to limit lateral excursion, the pre-trip vehicle dynamics produced lateral occupant motions and lap- and torso-belt loading prior to pretensioners and RSCA deployment.

In general, the occupant kinematics and injury mechanics observed in the current study of steer maneuver-induced furrow tripped rollovers were akin to those documented in prior dolly rollover and CRIS testing. However, because rollovers are unpredictable and chaotic events, and because additional variables such as pre-trip occupant position and seatbelt routing can influence occupant excursion, position, and alignment throughout the rollover sequence, it is important that more research be done to further characterize how occupant motion and injury potential may be influenced by various designs of these safety measures under a wide variety of conditions.

SUMMARY/CONCLUSIONS

The current study utilized vehicle and occupant data from two vehicle rollovers: a pickup truck that was equipped with RSCAs and seatbelt pretensioners and a sedan that was not equipped with these technologies. The occupant kinematics and loading were examined for the two front outboard seating positions and were related to vehicle kinematics and loading. These analyses yielded the following results:

1. Of the four ATDs involved in the testing, only one ATD (sedan driver) sustained any loading that exceeded the established IARVs. There were two events during the course of the sedan rollover that resulted in upper neck compressive loading that exceeded the IARV of 4000 N (899 lb). These neck-loading events occurred as a result of combined head-to-vehicle and head-to-ground contact.
2. During the peak neck load for the sedan driver ATD, where its head was inside the vehicle, the vertical roof deformation at the driver's side B-pillar was 4.4 cm (1.7 inches) and the lateral deformation was 7.3 cm (2.9 inches) rightward.
3. The RSCA deployment resulted in discernable loading to both the passenger and driver ATD in the pickup truck but did not exceed existing IARVs, including loading to the head, neck, chest, and lumbar spine. Due to the inertial loading on the ATD and the roll angle of the vehicle at deployment, there was a greater interaction and consequently loading between the passenger (leading side) ATD and the RSCA than there was between the driver (trailing side) ATD and the RSCA.
4. Of the sixteen compressive neck loading events identified that exceeded 1000 N, fourteen events demonstrated a clear pattern of a FMA head acceleration, followed by FMA chest acceleration, followed by a peak compressive neck load. This

finding supports previous rollover and biomechanical literature that describes how neck compressive loads develop in an ATD due to the arrest of the head motion followed by loading of the torso into the neck.

5. A statistically significant positive correlation was observed between axial chest acceleration and axial compressive neck force.
6. In the single rollover event that involved deployment of RSCA, the ATDs were not partially or completely ejected from the vehicle. The presence of a seatbelt pretensioner and RSCA during a rollover event did not prevent the occupant's head from moving into proximity of, or in contact with, the roof.

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