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# Biomechanical Investigation of Injury Mechanisms in Rollover Crashes from the CIREN Database

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## ABSTRACT

*Previous research has described the types of injuries suffered by belted occupants of vehicles involved in rollover crashes. There has been much debate concerning these injuries, in particular the head, spine and thoracic injuries. Since rollovers may result in complex occupant kinematics, this paper analyzed extensive crash field and descriptive injury data from 55 belted occupants involved in 51 rollover crashes taken from the Crash Injury Research Engineering Network (CIREN) database. The paper discusses a methodology to deduce specific body region injury mechanisms of occupants in rollover crashes selected for crash as well as occupant characteristics.*

## INTRODUCTION

Numerous publications have attempted to understand the nature and mechanisms of occupant injuries as a result of rollover crashes. Early field analysis work by Huelke et al. (1973, 1976) and Hight et al. (1972) indicated a dominance of head and brain injuries in rollover crash occupants, however, most of these injuries occurred in unbelted, ejected occupants. When examining belted, unejected occupants, Huelke and Compton (1983), Digges et al. (1993), Parenteau and Shah (2000) and Bedewi et al. (2003) found the head and spine to be the most seriously injured body regions. The majority of these studies characterized the crash and occupant outcomes based on potential contact the belted occupant could have made with the vehicle interior. The head and neck regions are of most interest due to their typically severe outcomes and long recovery.

Digges et al. (2005) reported on injury outcomes for restrained and unrestrained occupants in various rollover crash conditions. They found that the severe injury (AIS => 3) rate for occupants in multiple-event rollover crashes (e.g., a planar crash followed by a roll) was double the rate for occupants in single vehicle rollover crashes. Additional analysis by Digges and Eigen (2006, 2007) examined injury severity in occupants involved in single vehicle or “pure” rollover crashes compared to these multi-event rollovers. They found that injury distributions were different for the two groups with the pure roll (single vehicle) cases having more head injury and the multi-event rollover crashes having more thoracic injury.

Others have attempted to identify injury causation with respect to rollover head and neck injuries. The National Highway Traffic Safety Administration (NHTSA) has published a significant body of rollover injury and fatality analysis using the National Automotive Sampling System (NASS) and Fatality Analysis Reporting System (FARS) databases. In their most recent work, Strashny (2007a) described rollover injuries in belted, unejected occupants relative to roof intrusion from single vehicle rollover crashes in the National Automotive Sampling System Crashworthiness Data System (NASS CDS) database. The analysis indicated that the maximum severity of head, neck (cervical spine and/or spinal cord) and face injury was significantly related to the amount of roof intrusion into the occupant compartment and the remaining post-crash headroom in the vehicle. Alternatively, Padmanaban's (Padmanaban et al., 2005) analysis of NASS CDS indicated no association of pre-crash effective headroom with serious head or neck (cervical spine and/or spinal cord) injury in belted occupants in single vehicle rollover crashes.

These unresolved associations have led some to test belted anthropometric test devices (ATDs) in rollover crashes to determine kinematics and potential for injury based on contact. Bahling et al. (1990) found high axial neck loads in belted ATDs subjected to severe rollover crashes in both production and roof-strengthened vehicles as a result of the ATD's interaction with the roof during the event. Further analysis of this data by Friedman and Nash (2001) concluded that human cervical neck injury could occur from pure compressive forces on the top of the head aligned with the neck as a result of head contact to the roof during the roll event. Young et al (2007) reanalyzed the Bahling data to calculate a neck injury criterion, Nij (Eppinger et al., 1999), originally developed for assessment of neck injury potential in frontal impact. He suggested that this criterion could be used to predict the likelihood of neck injury between the production and roof strengthened vehicle in the rollover crash tests studied.

Brumbelow et al. (2008) used police-reported, multi-state crash injury data to compare rollover crash injury severity to vehicle roof strength. While he concluded that injury risk was associated with roof strength, he was unable to derive injury mechanisms due to the type of data analyzed. Bedewi et al.(2003) analyzed more detailed rollover crash case data from NASS CDS, but did not indicate specific mechanisms of injury to the belted occupants. Young et al. (2007) pointed out that more research is required to understand the specific injury mechanisms as a result of occupant contact to interior structures during rollover.

The research described above has relied on large sample databases, severe crash tests, or other sources to illustrate the rollover injury issue. This study intends to further the understanding of the underlying biomechanical processes that may describe the rollover crash injuries by examining specific cases from the CIREN database and applying a new tool within the CIREN program, the Biomechanics Table, or BioTab. The rich nature of the CIREN data, such as detailed medical injury and imaging information, coupled to extensive crash engineering data, can provide a unique perspective on the mechanisms for a particular injury. The BioTab tool provides an objective methodology to assess the injury and assign a specific injury mechanism based on factual evidence from the crash, clinical data, and prior biomechanical research.

## METHODS

### CIREN Description

This study is based on information drawn from the NHTSA-sponsored CIREN database. This database, now over 10 years old, has collected information from over 3500 crashes of late model year vehicles where at least one serious (AIS => 3) or two moderate (AIS = 2) injuries occurred to one of the vehicle occupants. Other selection criteria are involved, but the crashes are selected based upon injury severity of the occupant. A complete list of CIREN inclusion criteria may be found in the United States Federal Register (2004). The related vehicles are studied in a detailed crash investigation, forming the basis of the CIREN vehicle parameters, linked to the detailed medical records of the occupant's injuries. This includes radiological images and reports, clinical progress, notes during treatment, operating room reports, clinical photographs, occupant interviews, discharge reports, one year follow-up recovery assessment and other descriptions of the injuries. A thorough, multidisciplinary review of each case occurs to derive a biomechanical basis for the injuries based on physical evidence. A review team at each of the eight CIREN centers consists of an experienced NASS-trained crash investigator, a board-certified trauma physician, biomechanical engineer, data coordinator, and emergency response personnel. Other physicians (surgeon or radiologist) and engineering personnel may be consulted on individual cases. These reviews confirm the crash and injury assessment (including AIS coding) as well as complete the BioTab process (to be discussed below) for all AIS 3+ injuries suffered by the case occupant.

## Case Selection/ Data Extraction

Data was extracted from the master CIREN data repository. Case selection was based on the following occupant and vehicle crash parameters: occupant was at least 16 years of age and older seated in the right/left front outboard seating position, confirmed wearing lap/shoulder belt and sustained serious and/or disabling injury, per CIREN requirement. The injury level provides injury source, confidence in the assignment of injury source, and AIS 90 injury coding (1998 update), with related disaggregation by injury severity, body region, and injury aspect. The vehicle rollover was characterized as either a pure rollover event or a multiple event rollover crash. The pure rollover crashes were characterized by a single-event non-planar crash of at least one quarter turn. The multiple event rollover crashes consisted of at least one planar event and one rollover event and generally experienced a planar crash event followed by a rollover event. Only rollovers up to eight quarter turns (two roof contacts) were selected to avoid uncertainty in injury mechanism analysis from extremely violent crashes. Generally, the multiple event rollover crashes sustained a planar event that precipitated the rollover crash. In these cases, the maximum injuries were disaggregated by event to determine when it was experienced. It was noted that cases did exist with a planar event following the rollover event. These were usually interrupted rollover crashes. The arrested rollover crash at the first event might be deemed as more injurious, from energy dissipation standpoint, than multiple quarter turn rollover events.

The data was received in Excel spreadsheets, as extractions from the master CIREN data repository. These data sets were then imported into SAS for analysis. This paper considers crash and vehicle parameters of a similar specificity to NASS CDS. The occupant and injury parameters, however, benefit from detailed injury reporting and review inherent in CIREN analysis. A synthesis of engineering and medical expertise comprises the conclusions reported in this data set and on which the conclusions of this paper are predicated. The BioTab, reports the disaggregation of injuries based upon the separate crash events. This concept is absent in the NASS CDS, however, with less detail, this system provides the national estimates of tow-away crashes occurring on public roadways in the United States. While CIREN cannot be used to generate nationally-representative crash statistics, the use of CIREN and associated BioTab allows crash events to be analyzed individually as opposed to en masse where all injury are assigned to the most harmful event. In multi-event crashes, especially involving rollover, clear and distinct injury patterns can be differentiated with the appropriate data and expertise.

Upon dissagregation, the cases were subjected to a review of the crash summary, scene diagram, occupant contact points, collision deformation classification (CDC), and relevant injury radiology. This review is done initially by the case crash reconstruction and injury review team at the individual CIREN centers. From the case crash reconstruction and injury review done by the CIREN center for that case, consideration of the injury ranking was undertaken. The ranking was not necessarily the sole predictor of the maximum injury for the case. The authors gave consideration to whether the injury might be produced during the rollover event. Typically, this injury ranking resulted in the most severe injury, known as the Rank 1 injury, to be selected for further analysis. For this analysis in this paper, the Rank 1 injury was usually the highest AIS injury that occurred as a result of a rollover or a frontal or side collision. The data tables in the Appendices give the Rank 1 injury and associated crash information.

The data from the Excel extractions, as well as the full CIREN report were integrated to form a master workbook of crash data for each relevant occupant. The case was identified as a pure or multiple event rollover as described above. Basic demography relevant to occupant size and seating location, as well as vehicle roll direction and crash severity were included. The Rank 1 injury was assigned to the planar or rollover phase of the crash based upon the occupant kinematics, as described, scene diagram, photographs, and radiological evidence. This injury was then subjected to additional analysis using the BioTab which will be described below.

## BioTab Description

The BioTab provides a means to completely and accurately analyze and document the physical causes of injury based on data obtained from detailed medical records and imaging, in-depth crash investigations, and findings from the medical and biomechanical literature. The BioTab was developed because the terminology and methods currently used to describe and document injury causation from crash investigations are vague and incomplete. For example, the terms direct and indirect loading are often used to describe how an injury occurred. However, there are situations where these terms are unclear, e.g., is a femoral shaft fracture from knee-to-knee bolster loading from direct loading of the knee or indirect loading of the femur through the knee. In addition, the term inertial loading is often used to describe how tensile neck injuries occur, however, using this terminology fails to document that neck tension would not have occurred unless the torso was restrained. The BioTab removes these ambiguities by providing a consistent and well-defined manner for coding injuries and recording the biomechanics of injury in crash injury databases.

Coding in the BioTab revolves around the definition of an Injury Causation Scenario (ICS), which is the set of crash, vehicle, occupant, and restraint conditions that were necessary for an AIS 3+ injury to have occurred as well as the factors that affected the likelihood and severity of the injury. The elements of an injury causation scenario will identify and describe the following:

1) Whether the injury was caused by another injury (e.g., a rib fracture causes a lung laceration),
2) The Source of Energy (SOE) that led to the occupant loading that caused the injury,
3) The Involved Physical Component (IPC) that caused injury by contacting the occupant and the body region contacted by the IPC,
4) The path by which force was transmitted from the body region contacted, through body components, to the site of injury, and
5) All other factors that contributed to the severity or likelihood of injury.

The BioTab documents the evidence supporting these elements and uses it to determine confidence levels for each IPC and ICS.

The BioTab also documents the specific "mechanisms" by which an injury is believed to have occurred. Importantly, the BioTab distinguishes between injury causation scenarios and injury mechanisms. While the latter are necessarily a function of a particular ICS, the mechanisms that produced an injury are specific descriptions of the physical response of an occupant to the applied loading. In the BioTab, mechanisms can be documented at the body-region and organ/component level and include physical events such as compression, torsion, acceleration, and bending. As with IPCs and ICSs, evidence for injury mechanisms is documented in the BioTab and may include specific injury data obtained from the crash investigation (e.g., an avulsion fracture of a long bone due to a tension mechanism), as well as information in the biomechanical and medical literature (e.g., ribs break in bending). As with ICSs and IPCs, confidence levels are assigned to injury mechanisms based on evidence. A flowchart of the process and further discussion on BioTab may be found in Scarboro (2005).

The BioTab process described was applied to Rank 1 (or most serious) injury of the occupant from all the cases meeting the inclusion criterion for this study. In several cases, the BioTab injury mechanism analysis was already completed by the CIREN center team and these results were confirmed by the authors and support. In other cases, the BioTab process was completed by the authors and the CIREN dataset extended to reflect this analysis. The master workbook of all the vehicle and occupant data was summarized into a single-page dataset (including BioTab Involved Physical Component and injury mechanism) that could sustain integrated queries and forms the basis for the findings to follow. This data is found in Appendices 1 and 2 and forms the basis for the results to be presented.

## RESULTS

### Demographics (Occupant)

Sixty four occupants in 59 vehicles involved in a rollover crash met the criteria for inclusion in this study. However, after review of each case, 3 occupants were eliminated from further analysis since the rollover was associated with a second, non-planar event that arrested the roll of the vehicle. These types of rollovers were not the intent of this study. An additional six occupants were eliminated from further analysis since their Rank 1 injury was an AIS 2 injury and the BioTab was designed especially for AIS 3+ injury mechanism analysis. Of the remaining 55 occupants in 51 vehicles, 19 were in a single event, or pure rollover crash and 36 were in a multiple event crash with rollover. Sample representative demographics for these 55 occupants are listed in Table 1 and additional details may be found in Appendices 1 and 2.

For the pure roll cases, 11 of the 19 occupants were male and 8 of 19 were female. Eight of the 11 males were considered overweight by Body Mass Index (BMI > 25) calculation and Centers for Disease Control tables while 5 of the 8 females were overweight. It should be noted that mean BMI for adult males and females, based on 1999-2002 NHANES data, was 27.9 and 28.1, respectively (Ogden et al., 2004). The males in the pure roll cases had the oldest average age for either gender by roll event categories. For the multi-event roll case occupants, 19 were females and 17 were males and about half of each gender group was overweight.

Table 1. Case Occupant Demographics.

| Occupant | Pure Roll | MultiEvent |
|---|---|---|
| Males | Mean | Mean |
| Age (years) | 49 | 35 |
| BMI | 28 | 25 |
| Females | Mean | Mean |
| Age (years) | 40 | 42 |
| BMI | 26 | 25 |
| Drivers | N | N |
| Near Side | 4 | 11 |
| Far Side | 10 | 18 |
| Passengers | N | N |
| Near Side | 2 | 2 |
| Far Side | 3 | 5 |

Drivers made up nearly 80% and right front seat passengers comprised about 20% of the occupants sampled. For both event types, more occupants experienced a far side rollover, that is, the roll was initiated on the opposite side of the occupant's seated position. Although not statistically significant, 64% of the multiple event rollover crash occupants experienced far side rollover orientation. Of the multiple event rollover crash occupants, 25% resulted in far side orientation with one quarter turn, zero vehicle inversions. Another 25% of the multiple event rollover crash occupants sustained one vehicle inversion, producing a far side orientation and 13% of the occupants experienced 2+ vehicle inversions. For the pure rollover occupants, approximately three-quarters of the occupants experienced far side rollover crashes. Nearly 60% of these crash occupants experienced one vehicle inversion while the rest experienced two inversions.

## Demographics (Vehicle)

Fifty-one rollover crashes were identified from the CIREN database. These selected crashes were of at least one quarter turn and did not exceed eight quarter turns. These crashes were disaggregated by single event, or pure, and multiple event rollover crashes as well as by vehicle type.

Nineteen (19) pure and 32 multi-event rollover crashes were identified. In terms of crash severity, none of the pure roll vehicles had a reported longitudinal delta-V due to the rollover damage indicated by the crash investigator. The average reported delta-V for the vehicles in the 32 multievent rollovers, inherent to the planar component of the crash and based upon damage measurements, was 37 kph, indicating a moderate to severe crash experience. Rollover severity, defined either as number of ¼ turns or roof inversions, was greater for the pure roll vehicles regardless of vehicle type. The pure roll cases averaged nearly 6 quarter turns (2 roof inversions) versus an average of 3 quarter turns (1 roof inversion) for the multi-event rollovers.

## Injuries

For the 55 occupants in this analysis, a total of 842 injuries at all severity levels (AIS 1 to 6) were reported. Twenty-nine percent of the 842 injuries were AIS 3+, however, the distributions of injuries were different between the pure roll and multiple event roll cases (Figure 1). Injuries to the spine, largely involving the cervical bony structure, accounted for 57% vs. 19% of the AIS 3+ injuries to pure roll event vs. multiple event roll occupants. Neck injuries in this analysis refer only to the soft tissue structures of the neck and accounted for less than 1% of the serious injuries for either group. The percentage of spine injuries in the pure roll group is in contrast to the 11.5% figure for all AIS 3+ injuries in belted, single vehicle rollover occupants derived from figures in Digges and Eigen (2005) in their NASS CDS analysis. This is indicative of the CIREN sampling process for more severe injuries. Thoracic injuries were the dominant severely injured body region for the multi-event roll group, accounting for just below 30% of all the AIS 3+ injuries for that group. The same percentage of the AIS 3+ injuries to the pure roll occupants were thoracic injuries. Nearly equal percentages of serious head injuries were evident in both groups and lower extremity and abdominal injury were the remaining serious injury regions for the multi-event rollover occupants. It is interesting to note that the pure roll serious injuries fall mainly in the head, spine, and thorax regions while the multi-event occupant injuries are distributed to all body regions.

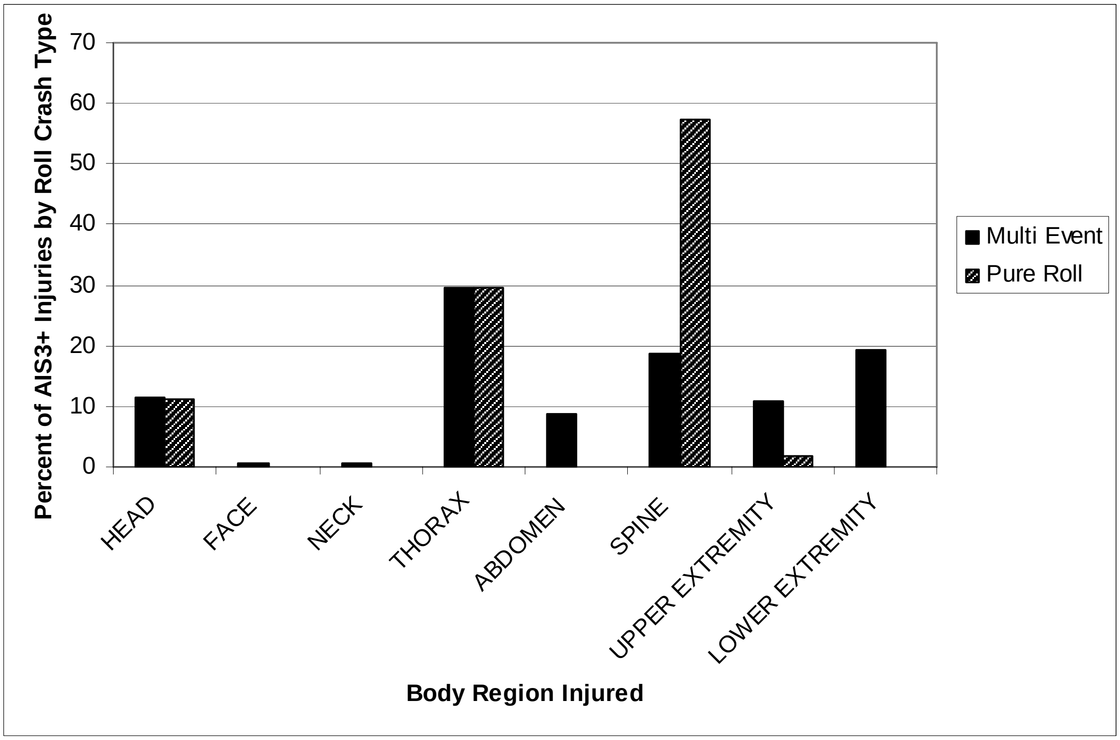

Figure 1: Distribution of AIS3+ Injuries by Body Region for Occupants by Rollover Crash Type.

## BioTab Analysis

The Rank 1 or most severe AIS 3+ injury for each occupant was evaluated by the BioTab process. Appendices 1 and 2 give a complete listing of the relevant occupant and injury variables for the pure roll cases and the multiple event roll cases respectively, including the results of the BioTab analysis (Injury Event, i.e., the source of the energy for the injury, Involved Physical Component, and Regional Injury Mechanism) for the Rank 1 injury in the case. Appendix 1 lists the occupants involved in a pure roll only and Appendix 2 lists the occupants in a multi-event rollover crash. It is apparent from Appendix 1 that the fracture of the cervical spine is the most frequent Rank 1 injury in this set accounting for eight of the nineteen Rank 1 injuries. Head injury accounted for six of the nineteen Rank 1 injuries with chest, thoracic, and lumbar spine injuries in the remaining five cases. The cervical injuries occur throughout the cervical spine structure from C2 to C7 and even involving T1. All of these eight cervical injury cases involved a complex kinematic and combined loading condition of the cervical spine during the injury event as the head interacted with either the roof or roof rail as the indicated IPC. The regional mechanism for all of the spinal injuries included compression combined with a flexion, extension, or lateral bending. The six head (brain) injuries involved a head-to-roof impact and a regional (head) compression mechanism of injury. There was insufficient information to deduce the organ level (brain) injuries which could be a shearing or tension mechanism. The three chest injuries were from compression mechanism as a result of a direct thorax interaction with the roof or side interior.

For the multi-event rollover cases, BioTab analysis implicated twenty-nine of thirty-six (80%) Rank 1 injuries to the planar crash event (FI: frontal impact; or SI: side impact) as the injury event or source of energy for the injury. The roll event was the injury producing event in eight cases and involved injuries from all the other body regions with no specific pattern. Chest and abdominal injuries accounted for 12 of the 36 Rank 1 injuries. This involved either rib fracture, lung contusion, or other organ injury. The head and entire spinal column each accounted for six Rank 1 injuries. There were four cases with severe femur fracture as the Rank 1 injury and the remaining Rank 1 injuries were distributed to the arm and lower leg. All of the chest, abdomen, and femur injuries involved a compression regional injury mechanism, usually due to interaction with the side door structure, belt, or air bag depending on the injury event. Of the six cases of spinal injury as the Rank 1 injury, only one involved the cervical spine bony structure. The spinal injuries were mainly lower thoracic and lumbar spine burst fractures caused by compression from loading the seat or seat belt during one of the planar events other than the rollover.

## Case Description

To better inform the reader of the analysis process involved for each case, the following example describes the crash, occupant kinematics and injuries, and BioTab analysis of an occupant from the pure roll event list in Appendix 1.

*Case example (Appendix 1, Case 8).* A 4-door sport utility vehicle (SUV) was traveling south in the left southbound lane of a rural, four-lane divided freeway (two lanes southbound, unprotected median, two lanes northbound). It was daylight, snowing, and the road was slush covered. The driver of the SUV was overtaking a slower vehicle in the right lane when he lost control due to the slippery road surface. The SUV departed the left side of the road and entered the median. The driver attempted to regain control by steering to the right, but the vehicle began to rotate in a clockwise manner. The SUV tripped over its left wheels/tires and rolled six quarter turns (2 roof inversions) before coming to rest on its roof facing north-northwest. The impact was classified as severe but no WinSmash reconstruction was attempted due to the rollover nature of the crash. Figure 2 shows the post-crash condition of the vehicle and the interior space at the case occupant seating position.

The case occupant is the 155 cm (5' 1"), 86 kg (190 lb), 44-year-old female right-front passenger who was using the available three-point seat belt, but the dash-mounted air bag did not deploy. The case occupant was transported via ground ambulance to a local hospital and was later transferred to a regional level-one trauma center. The occupant kinematics were deduced such that she moved up and outboard, relative to the vehicle interior as the vehicle rolled. Evidence indicated her head interacted with the roof where she sustained a loss of consciousness, fractures to the left facets of C5 through C7, a left C6 lamina fracture, and a cervical spinal cord contusion resulting in quadriplegia. A computed tomography (CT) scan of her cervical spine (Figure 3) indicates the location and extent of the injuries. Note the asymmetry of the fracture pattern. Her other injuries included minor contusions to the neck and upper and lower extremities. For the BioTab process, the Injury Causation Scenario was defined and indicated the rollover as the source of energy. Based on the physical evidence of head contact to the roof, the roof was identified as the involved physical component (IPC). The path of the force was transmitted from the head to the lower cervical spine. Based on her kinematics and analysis of the fracture pattern of her cervical spine injuries from the CT scan (Figure 3), a compression/lateral bending mechanism to the region resulted in failure of the lower cervical spine structures. This pattern is consistent with mechanisms reported by Pintar et al. (1989, 1995).

## DISCUSSION

This paper discusses an approach using the results of queries from NASS CDS (others like the German In-Depth Accident Study (GIDAS) could also be used) to describe the vehicle crash modes and injuries of interest and then derives the comprehensive injury detail from CIREN cases to understand the body region injury mechanisms. In studies cited above by Digges and Eigen (Digges et al., 2005; Digges and Eigen, 2006), the use of large sample databases such as NASS CDS provided perspectives on rollover crashes to begin the understanding of what types of injuries are associated with these crashes and what vehicle components may be involved in the injury process. However, the conclusions on specific body region injury mechanisms, as defined in this paper, can only be derived from a more detail-oriented (though more limited in cases) database such as CIREN. This paper clarifies the definition of injury mechanism based on biomechanical analysis of the entire crash event. The CIREN database offers a unique opportunity to expand upon the aggregate injury numbers and use evidence-based, objective methods to deduce injury mechanisms in all crash types, including rollover. CIREN data mimics other large sample data bases by indicating the severe injuries in rollover occur to the head, neck, thorax, and extremities as shown in Figure 1. However, when further analyzed using the BioTab process, there are significant differences in what body regions are injured between pure roll and multiple roll events as well as the injury mechanisms indicated.


[redacted]

Figure 2: Post-Crash Vehicle Photo of Pure Roll Case 8 (Appendix 1).

The majority of the injuries in the multi event rollovers was attributed to the planar crash and not the rollover and indicated a compression mechanism to the region of injury whether it was head, chest, abdomen, or femur. Thoracic injuries were dominant and almost always indicated the planar event as the source of the energy. In contrast, complex injury mechanisms were noted in the injuries suffered by the occupants in a pure roll crash. Most often, these injuries were cervical spine injuries. The mechanisms identified for these cervical spine injuries involved compression combined with bending, extension, or flexion based on the physical vehicle evidence and the analysis of radiographic and other medical information on the occupant. Pre-crash maneuver, roll severity, and other occupant factors may play a role in the occupant's position and injury mechanism. Conroy et al. (2006) compared occupant, crash, and vehicle characteristics in rollover crashes that involved seriously injured occupants from the CIREN database to a control group of minor or uninjured occupants in rollover crashes from the NASS database. They found that the roof and side interior structures were a significant source of injury for seriously injured occupants, but did not employ the BioTab process to look at injury mechanisms.

Occupants involved in pure rollover crashes in this study had slightly more severe rollovers than multiple event rollover occupants based on the number of vehicle ¼ turns and inversions and this may have affected the injury distributions and patterns between the groups. These occupants were usually male and generally overweight, as defined by their BMI, however no meaningful statistics could be applied due to sample size. Strashny (2007b) calculated injury severity rates for occupants in single vehicle rollovers (relative to age, gender, and BMI). He found that restrained drivers, fatally injured in a rollover, had a higher BMI than unrestrained drivers. Since all occupants in this study were restrained, it was not possible to compare to unrestrained.

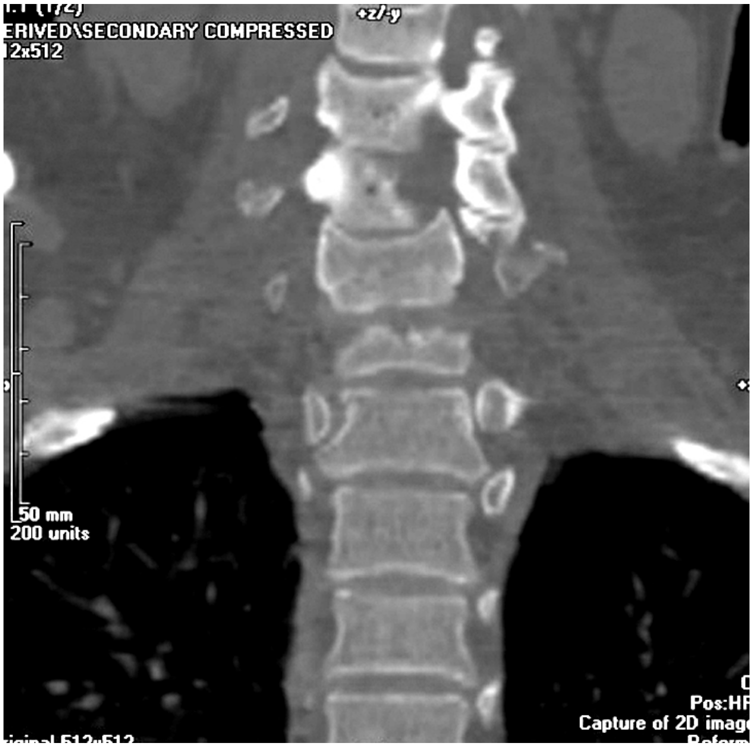

Figure 3: Radiology of Pure Roll Case Vehicle Occupant Showing Multiple Cervical Spine Injuries.

The dominance of cervical spine injuries among the pure roll occupants bears further inspection. The rollover crash severity, indicated by number of inversions, was higher for the crashes that involved cervical spine injury. This led to the roof or some roof structure being the involved physical component for these injuries. Biomechanics investigators have attempted to characterize the response of the human cervical spine under loading through the head. This paper is not an exhaustive review of this literature, but uses those conclusions to support the complex kinematic and biomechanical processes that contribute to the injuries observed in the occupants of this paper. Moffatt et al. (1978) and Patrick (1987) have provided good overviews of automotive cervical trauma. Their observations of fracture patterns indicate the loading modes responsible for the injury. The work of Nusholtz et al. (1981), Pintar et al. (1989, 1995), and Nightingale et al. (1997) derived the cervical spine failure modes based on initial orientation and loading of the head. A conclusion from this body of work can be that the complex loading of the neck through the head can induce buckling and injury in a variety of locations and mechanisms depending on initial occupant orientation and load path. The CIREN occupants in this study had failures along the entire cervical spine and even into the thoracic region, and a variety of mechanisms were derived from the BioTab analysis based on the physical evidence. To derive surrogate predictors of injury that characterize these injuries would require additional analysis of existing biomechanical data and development of test surrogates that could mimic the occupant kinematics predicted in these crashes.

## Limitations of Study

The results of this study and conclusions drawn were from a highly selective subset of the CIREN database, which by design, is a censored sample of severely injured occupants admitted to one of eight participating Level-1 trauma centers in the USA. One cannot conclude the trends indicated are nationally representative based on the disparity of injury distributions between NASS and CIREN for the belted occupants in a pure rollover. In addition, this small sample of rollover cases limits some possible direct comparisons of non-injured to injured occupants since all the occupants had at least one severe injury.

## CONCLUSIONS

Vehicular rollover is a result of a complex, chaotic crash event that results in a unique set of circumstances for each occupant injury. Conclusions on body region injury mechanisms, as defined in this paper, cannot be drawn from large sample databases. This study provides a unique opportunity to utilize the CIREN database coupled with powerful analysis tools to deduce specific injury mechanisms. The data in this study reveals that rollovers need to be disaggregated based on number of crash events. The resulting dissimilarity in injury distribution helps to better understand how to describe the scenario that led to the injury. Thoracic, not just head and neck injury mechanisms need to be considered in these analyses. Also, this study indicates that cervical spine injury mechanisms are the result of complex loading combining compression with flexion, extension, or lateral bending as a result of interaction with vehicle components, primarily during a pure rollover event. Thoracic injury mechanisms were compression-based as a result of interaction with vehicle components during the planar (frontal or side impact) event of the multiple event roll crashes. This understanding could help describe a modeling or test environment for countermeasures, such as belt improvements described by Moffatt (Moffat et al., 1997; Moffat and James, 2005) to mitigate such injuries. Further analysis of CIREN case data as well as research and development of appropriate surrogates to mimic human kinematics and injuries in rollover is required.

## ACKNOWLEDGEMENTS

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## Appendix 1. Demographic Data, Injury, and BioTab Analysis for Pure Roll Event Occupants.

| Obs | Age | Gender | Height(cm) | Weight(kg) | BMI | Seat Pos | Near/Far | R/L | Inversions | AIS_Rank1 | Rank 1 Injury | Rank 1 Injury Description | Body Region | INJ_EVENT | IPC | Regional Mechanism |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 64 | Male | 188 | 129 | 36 | Row 1 Left | Near side | Roll left | 1 | 3 | 4502143 | Rib cage fracture 1 rib with hemo-/pneumothorax (OIS Grade I) | Chest | Roll | Roof | Compression |
| 2 | 30 | Female | 165 | 69 | 25 | Row 1 Left | Near side | Roll left | 2 | 3 | 4414063 | Lung contusion unilateral with or without hemo-/pneumothorax | Chest | Roll | Left side interior surface | Compression |
| 3 | 19 | Male | 173 | 61 | 20 | Row 1 Left | Far side | Roll right | 2 | 4 | 4414104 | Lung contusion bilateral with or without hemo-/pneumothorax | Chest | Roll | Roof | Compression |
| 4 | 76 | Male | 180 | 82 | 25 | Row 1 Right | Near side | Roll right | 2 | 3 | 6502263 | Cervical Spine fracture pedicle | C-spine | Roll | Roof | Compression/extension |
| 5 | 53 | Male | 175 | 66 | 22 | Row 1 Right | Far side | Roll left | 1 | 3 | 6502283 | Cervical Spine fracture odontoid (dens) | C-spine | Roll | Roof | Compression/extension |
| 6 | 73 | Male | 182 | 130 | 39 | Row 1 Left | Far side | Roll right | 1 | 4 | 6402184 | Cervical Spine Cord contusion incomplete cord syndrome with fracture and dislocation | C-spine | Roll | Roof | Compression/extension |
| 7 | 33 | Female | 170 | 50 | 17 | Row 1 Left | Far side | Roll right | 2 | 3 | 6502223 | Cervical Spine fracture facet | C-spine | Roll | Roof | Compression/lateral bend |
| 8 | 44 | Female | 155 | 86 | 36 | Row 1 Right | Far side | Roll left | 2 | 5 | 6402285 | Cervical Spine Cord contusion complete cord syndrome C-4 or below with frac.and dis. | C-spine | Roll | Roof | Compression/lateral bend |
| 9 | 21 | Male | 183 | 79 | 24 | Row 1 Right | Near side | Roll right | 1 | 4 | 6402184 | Cervical Spine Cord contusion incomplete cord syndrome with fracture and dislocation | C-spine | Roll | Roof | Compression/lateral bend |
| 10 | 51 | Male | 191 | 95 | 26 | Row 1 Left | Far side | Roll right | 1 | 3 | 6502103 | Cervical Spine dislocation facet unilateral | C-spine | Roll | Left roof rail | Compression/flexion |
| 11 | 78 | Female | 157 | 86 | 35 | Row 1 Left | Far side | Roll right | 1 | 3 | 6402083 | Cervical Spine Cord contusion with transient neurological signs with fx/dis | C-spine | Roll | Sunroof | Compression/flexion |
| 12 | 41 | Male | 180 | 102 | 31 | Row 1 Left | Far side | Roll right | 2 | 4 | 1406404 | Cerebrum hematoma/hemorrhage intracerebral small | Head | Roll | Left roof rail | Compression |
| 13 | 60 | Male | 183 | 86 | 26 | Row 1 Left | Far side | Roll right | 1 | 5 | 1406545 | Cerebrum hematoma/hemorrhage subdural small bilateral | Head | Roll | Ground | Compression |
| 14 | 20 | Female | 163 | 61 | 23 | Row 1 Left | Near side | Roll left | 1 | 5 | 1406285 | Cerebrum diffuse axonal injury (white matter shearing) | Head | Roll | Roof | Linear acceleration |
| 15 | 38 | Female | 152 | 54 | 23 | Row 1 Left | Near side | Roll left | 1 | 4 | 1406524 | Cerebrum hematoma/hemorrhage subdural small | Head | Roll | Roof | Compression |
| 16 | 42 | Female | 165 | 68 | 25 | Row 1 Right | Far side | Roll left | 1 | 3 | 1406843 | Cerebrum subarachnoid hemorrhage | Head | Roll | Roof | Compression |
| 17 | 36 | Male | 175 | 84 | 27 | Row 1 Left | Far side | Roll right | 1 | 3 | 1908063 | Scalp avulsion blood loss > 20% by volume | Head | Roll | Roof | Shear |
| 18 | 47 | Male | 180 | 84 | 26 | Row 1 Left | Far side | Roll right | 2 | 3 | 6506343 | Lumbar Spine fracture vertebral body major compression | L-spine | Roll | Seat | Compression/flexion |
| 19 | 34 | Female | 157 | 68 | 28 | Row 1 Left | Far side | Roll right | 2 | 5 | 6404685 | Thoracic Spine cord laceration complete cord syndrome with fracture and dislocation | T-spine | Roll | B-pillar | Compression/flexion |

## Appendix 2. Demographic Data, Injury, and BioTab Analysis for Multi-Event Roll Occupants.

| Obs | Age | Gender | Height(cm) | Weight(kg) | BMI | Seat Pos | Near/Far | R/L | Inversions | AIS_Rank1 | Rank 1 Injury | Rank 1 Injury Description | Body Region | INJ_EVENT | IPC | Regional Mechanism |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 29 | Male | 190 | 100 | 28 | Row 1 Left | Far side | Roll right | 1 | 4 | 5442264 | Spleen laceration major (OIS Grade IV) | Abdomen | FI | Seat | Compression/flexion |
| 2 | 32 | Female | 157 | 47 | 19 | Row 1 Left | Near side | Roll left | 0 | 4 | 5442264 | Spleen laceration major (OIS Grade IV) | Abdomen | SI | Left side interior surface | Rate of compression |
| 3 | 27 | Male | 183 | 91 | 27 | Row 1 Left | Far side | Roll right | 0 | 3 | 5442243 | Spleen laceration moderate (OIS Grade III) | Abdomen | SI | Left armrest | Compression |
| 4 | 66 | Female | 171 | 68 | 23 | Row 1 Left | Near side | Roll left | 0 | 4 | 5442264 | Spleen laceration major (OIS Grade IV) | Abdomen | SI | Left armrest | Compression/Rate of compression |
| 5 | 40 | Female | 163 | 59 | 22 | Row 1 Right | Far side | Roll left | 1 | 3 | 8534183 | Tibia fracture posterior malleolus open/displaced/comminuted | Ankle | FI | Floor | Compression |
| 6 | 40 | Male | 180 | 90 | 28 | Row 1 Left | Far side | Roll right | 1 | 3 | 7532043 | Ulna fracture open/displaced/comminuted | Arm | FI | A-pillar | Compression |
| 7 | 30 | Female | 163 | 64 | 24 | Row 1 Left | Near side | Roll left | 0 | 3 | 7528043 | Radius fracture open/displaced/comminuted | Arm | FI | A-pillar | Compression |
| 8 | 54 | Female | 168 | 98 | 35 | Row 1 Right | Near side | Roll right | 1 | 4 | 4502644 | Rib cage flail chest with lung contusion (OIS Grade III or IV) | Chest | FI | Belt | Compression |
| 9 | 21 | Female | 165 | 54 | 20 | Row 1 Left | Far side | Roll right | 2 | 3 | 4414063 | Lung contusion unilateral with or without hemo-/pneumothorax | Chest | FI | Air bag | Rate of compression |
| 10 | 39 | Male | 183 | 86 | 26 | Row 1 Left | Near side | Roll left | 0 | 3 | 4502503 | Rib cage fracture open/displaced/comminuted (any or combination; >1 rib) | Chest | FI | Belt | Compression |
| 11 | 41 | Male | 175 | 104 | 34 | Row 1 Left | Far side | Roll right | 0 | 3 | 4414063 | Lung contusion unilateral with or without hemo-/pneumothorax | Chest | SI | Left side interior surface | Rate of compression |
| 12 | 49 | Female | 168 | 79 | 28 | Row 1 Left | Near side | Roll left | 1 | 6 | 4410146 | Heart (Myocardium) laceration perforation complex or ventricular rupture | Chest | FI | Air bag | Compression |
| 13 | 42 | Male | 188 | 93 | 26 | Row 1 Left | Far side | Roll right | 0 | 6 | 4410166 | Heart (Myocardium) multiple lacerations | Chest | FI | Air bag | Compression |
| 14 | 62 | Female | 163 | 82 | 31 | Row 1 Left | Near side | Roll left | 1 | 3 | 4502143 | Rib cage fracture 1 rib with hemo-/pneumothorax (OIS Grade I) | Chest | FI | Belt | Compression |
| 15 | 57 | Female | 155 | 61 | 25 | Row 1 Left | Far side | Roll right | 0 | 4 | 4502324 | Rib cage fracture >3 ribs on one side and <=3 ribs on other side, stable chest or NFS == with hemo-/pneumothorax | Chest | SI | Left side interior surface | Compression |
| 16 | 51 | Female | 163 | 57 | 21 | Row 1 Left | Far side | Roll right | 2 | 3 | 6502263 | Cervical Spine fracture pedicle | C-spine | Roll | Roof | Compression/lateral bend |
| 17 | 25 | Female | 170 | 63 | 22 | Row 1 Left | Near side | Roll left | 0 | 3 | 7532043 | Ulna fracture open/displaced/comminuted | Elbow | Roll | Ground | Compression |
| 18 | 60 | Male | 183 | 64 | 19 | Row 1 Left | Far side | Roll right | 1 | 3 | 1502023 | Base (basilar) skull fracture without CSF leak | Head | SI | Left side interior surface | Compression |
| 19 | 51 | Female | 160 | 68 | 27 | Row 1 Left | Near side | Roll left | 1 | 4 | 1406304 | Cerebrum hematoma/hemorrhage epidural or extradural NFS | Head | Roll | Roof | Compression |

## Appendix 2. Demographic Data, Injury, and BioTab Analysis for Multi-Event Roll Occupants (con't).

| Obs | Age | Gender | Height(cm) | Weight(kg) | BMI | Seat Pos | Near/Far | R/L | Inversions | AIS_Rank1 | Rank 1 Injury | Rank 1 Injury Description | Body Region | INJ_EVENT | IPC | Regional Mechanism |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 59 | Female | 173 | 75 | 25 | Row 1 Left | Far side | Roll right | 1 | 3 | 1502503 | Base (basilar) skull fracture with CSF leak | Head | Roll | Ground | Compression |
| 21 | 17 | Male | 178 | 52 | 16 | Row 1 Left | Far side | Roll right | 0 | 5 | 1406285 | Cerebrum diffuse axonal injury (white matter shearing) | Head | SI | Left side interior surface | linear acceleration |
| 22 | 18 | Male | 180 | 79 | 24 | Row 1 Right | Near side | Roll right | 0 | 5 | 1406285 | Cerebrum diffuse axonal injury (white matter shearing) | Head | SI | Other occupant | Compression/linear acceleration |
| 23 | 41 | Male | 175 | 84 | 27 | Row 1 Left | Far side | Roll right | 2 | 4 | 1406524 | Cerebrum hematoma/hemorrhage subdural small | Head | Roll | Roof | Angular acceleration |
| 24 | 17 | Male | 191 | 69 | 19 | Row 1 Left | Near side | Roll left | 0 | 3 | 8534223 | Tibia fracture shaft open/displaced/comminuted | Lower leg | Roll | Foot controls | Compression/bending |
| 25 | 56 | Male | 183 | 87 | 26 | Row 1 Left | Far side | Roll right | 1 | 3 | 4502303 | Rib cage fracture >3 ribs on one side and <=3 ribs on the other side, stable chest or NFS | L-spine | Roll | Seat | Compression |
| 26 | 20 | Female | 152 | 43 | 19 | Row 1 Left | Near side | Roll left | 2 | 3 | 6506343 | Lumbar Spine fracture vertebral body major compression | L-spine | FI | Seat | Compression |
| 27 | 23 | Female | 163 | 50 | 19 | Row 1 Right | Far side | Roll left | 1 | 3 | 6506343 | Lumbar Spine fracture vertebral body major compression | L-spine | FI | Belt | Compression/flexion |
| 28 | 66 | Male | 183 | 91 | 27 | Row 1 Left | Far side | Roll right | 0 | 3 | 8518223 | Femur fracture supracondylar | Thigh | FI | Knee bolster | Compression |
| 29 | 33 | Female | 163 | 77 | 29 | Row 1 Left | Near side | Roll left | 1 | 3 | 8518143 | Femur fracture shaft | Thigh | FI | Knee bolster | Compression |
| 30 | 20 | Male | 180 | 68 | 21 | Row 1 Left | Far side | Roll right | 1 | 3 | 8518143 | Femur fracture shaft | Thigh | FI | Knee bolster | Compression |
| 31 | 39 | Male | 173 | 88 | 29 | Row 1 Left | Far side | Roll right | 1 | 3 | 8518143 | Femur fracture shaft | Thigh | FI | Knee bolster | Compression |
| 32 | 62 | Female | 165 | 78 | 29 | Row 1 Right | Far side | Roll left | 0 | 5 | 6404645 | Thoracic Spine cord laceration complete cord syndrome with fracture | T-spine | FI | Belt | Compression/flexion |
| 33 | 31 | Female | 150 | 57 | 25 | Row 1 Right | Far side | Roll left | 0 | 3 | 6504343 | Thoracic Spine fracture vertebral body major compression | T-spine | FI | Belt | Compression/flexion |
| 34 | 19 | Male | 193 | 76 | 20 | Row 1 Right | Far side | Roll left | 1 | 3 | 1602043 | Length of Unconsciousness known to be <1 hr. with neurological deficit | Up arm | SI | Console | Compression |
| 35 | 25 | Male | 188 | 86 | 24 | Row 1 Left | Far side | Roll right | 0 | 3 | 7526043 | Humerus fracture open/displaced/comminuted | Up arm | SI | Left side interior surface | Compression |
| 36 | 25 | Female | 163 | 73 | 27 | Row 1 Left | Far side | Roll right | 2 | 3 | 7526043 | Humerus fracture open/displaced/comminuted | Up arm | FI | Air bag | Compression |

# DISCUSSION

PAPER: **Biomechanical Investigation of Injury Mechanisms in Rollover Crashes from the CIREN Database**

PRESENTER: ***Steve Ridella, National Highway Traffic Safety Administration, USDOT***

**Q**UESTION: *Guy Nusholtz, Daimler Chrysler*
It looked like you had sort of quantum mechanical phenomena with your injury causation system where you have multiple possible scenarios, so you're predicting all sorts of different things. How do you collapse your weight function in that case? And, what is the methodology that's used?

**A**NSWER: How do I collapse my weight function? Can you translate them?

**Q:** Well, you have multiple scenarios.

**A:** You can have multiple scenarios. You prefer to have one, but you can have up to two.

**Q:** Okay. Let's say you have two scenarios. So either it happened one way or it happened another way, and somehow you have two.

**A:** Right.

**Q:** What is the methodology you use to decide which scenario is a—First of all, how do you come up with a scenario? I mean is there an analytical approach? And two: How do you decide between your multiple scenarios?

**A:** That was the whole purpose of creating this process was to try to get away from sort of—as I heard it used to be called—biomechanics by proxy. I think this did it. The scenarios are by confidence level. When you go to CIREN Review and you sit around with a bunch of people, you might have half the group saying, "I think it's this way," and the other one says, "No. I think it's this way." But, you start to look at the evidence and say, "Okay. This is probably a probable. This one might be just possible." So you put that in there because there was enough evidence, perhaps, to at least put it in as a possible scenario, but there's no waiting factor that we use. So when you go in and look at these online, you may only see "probably" scenarios for your analysis as opposed to a "possible". We want to document that just in case we want to go back and look at our case later. So there's no waiting factor.

**Q:** So it's a bunch of people who make a decision and say, "Okay. This is what we think it is," and sometimes it's wrong and sometimes it's right."

**A:** Yes, a bunch of smart people.

**Q:** That's subjective!

**A:** But it is weighing of the evidence. So you have a higher confidence level if you have, let's say—If you're saying the head hit the roof and if you have evidence that you have, like, hair marks on that spot, that bumps it up. So if you didn't have it, but you're still thinking, "Okay. It's logical that the head hit the roof, but you don't have the contact," then you drop it down a confidence level. So it is adding up the evidence. The more evidence that you have that says the same thing, the higher confidence you have. So it's not just arbitrary. You really do add up the pieces of evidence for that particular causation scenario.

**Q:** So are you doing it through a Basian calculation where you upgrade your prior probability?

**A:** It's not that. It's not that statistical.

**Q:** Okay. So it's still subjective. Thank you.

**Q:** *Jingwen Hu, UMTRI*
I noticed that you have more of an amount of rollover than the pure rollover in the CIREN database. But as I remember, the pure rollover is more common than the multi rollover if you're considering the whole crash database. So my question is: When you select the crash for the CIREN database, are you considering the percentage of different types of crash?

**A:** No, we don't. We enroll the occupant in a crash. It's different from NASS. NASS actually looks at the police reports and looks at tow-aways so they understand the vehicle first. The occupant comes to the ER, the ED; and we select them and enroll them there, and then go look at the vehicle. So we have no apriority knowledge about how severe, what that crash was or what some of the kinematics of that crash were. So that's what we get. We don't select that. We try not to.

**Q:** Actually, I have another question. What the controversy here is was whether the roof crush caused the injury during rollover. I'm wondering whether this CIREN can contribute to that question.

**A:** We have all that information in our database, like NASS. We have these critical intrusions. I didn't put them here. I was more interested in just documenting the process. Down the road, I'm sure we'll be able to look at that data and understand what each occupant had. I have that information.

**Q:** Okay. Thank you.

**Q:** *Anthony Santago, Virginia Tech*
What do you think the mechanism is that's causing the more neck injuries in the pure rolls than in the frontal impact and then pure rolls?

**A:** I think it's 1) probably severity. As you saw, they were a little bit more severe. There were at least two roof inversions for some of those cervical fractures. So if people were getting up in those regions—getting their heads somewhere and causing those complex mechanisms that we had identified, that's what we found from the CT data that we've got. So I'm thinking that they're really just more severe rollovers.

**Q:** So the impact, you think, takes away the severity of the rollover initially? Your graph that you had that showed the neck injuries: It was a lot higher with the pure rollover than with the impact and then the rollover? Do you think the impacts [are] actually strapping the occupant down--?

**A:** I think if it's a frontal or side impact, that's where they're getting their injuries. So the kinematics might be totally different. I think that's what we've got to start understanding in the future what dummies can do, and we're going to have some sort of rollover test in the future to understand it. Maybe it's got to have just a pure roll thing; or if we do an impact, we kind of understand how that affects the roll kinematics of the vehicle.

**Q:** Thank you.