An Evaluation of the Association Between Vertical Roof Crush and Head, Neck and Spine Injury in Rollover Motor Vehicle Crashes: NASS-CDS 1997 through 2007

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CERTIFICATE OF APPROVAL

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Abbreviations

AIC	Akaike Information Criterion
AIS	Abbreviated Injury Scale
ATD	Anthropometric Testing Device
BAC	Blood Alcohol Content
BIC	Bayesian Information Criterion
FMVSS 216	Federal Motor Vehicle Safety Standard 216
GEE	Generalized Estimating Equation
GM	General Motors
GVWR	Gross Vehicle Weight Rating
HNS-NISS	Head, Neck and Spine – New Injury Severity Score
IIHS	Insurance Institute for Highway Safety
IRB	Institutional Review Board
ISS	Injury Severity Score
MVC	Motor Vehicle Crash
NASS-CDS	National Automotive Sampling System – Crashworthiness Data System
NASS-GES	National Automotive Sampling System – General Estimates System
NCSS	National Crash Severity Study
NHTSA	National Highway Traffic Safety Administration
NISS	New Injury Severity Score
OHSU	Oregon Health & Science University
QIC	Quasilikelihood Under the Independence Model Information Criterion
SWR	Strength-to-Weight Ratio

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Abstract

The mechanism of injury to the head, neck and spine in motor vehicle rollover crashes is a contentious topic of research. Most studies sponsored by the automotive industry have concluded that the magnitude of vehicle roof deformation (vertical roof crush) resulting from a rollover crash is not causally associated with these types of injuries. A growing body of evidence suggests that there is an association. The results of this study based on data from the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) lend support to a statistical association between roof crush and injury.

The odds of injury (vs. no injury) to the head, neck and spine increased by 44% (95% CI: 8-91%) with each 10 cm increase in roof crush. The odds of severe injury to the head, neck and spine (as measured by a Head, Neck and Spine New Injury Severity Score or 'HNS-NISS') increased by 64% (95% CI: 26-114%) with each 10 cm increase in roof crush.

This study utilizes both cross-sectional and case-control designs and provides support for the intrusion hypothesis, the theory that stronger vehicle roof construction that is better able to resist intrusion into the occupant compartment in rollover crashes can reduce head, neck and spine injuries.

Background and Significance

Despite considerable efforts to improve safety, motor vehicle crashes (MVC) remain the number one cause of death among those 5-34 years of age in the US [1]. There were 33,808 MVC fatalities in 2009, of which 8,296 were occupants of vehicles involved in rollover crashes [2]. The financial burden of injury, fatality and property damage resulting from MVCs is significant. In the US, for 2008, the estimated monetary cost of MVCs and the resultant 2.1 million disabling injuries was $255 billion [3]. It has been estimated that MVCs, both on and off the job, cost US employers $41.5 billion in benefits and $18.4 billion in wage-risk premiums in 2000 [4]. The most costly injuries resulting from MVCs are those to the head, spine and lower extremities [5].

A rollover crash involves a vehicle that experiences at least two quarter turns (≥ 180°) about its long axis. Although rollover crashes are less common than frontal, side, or rear impact collisions, they are associated with a higher rate of injury and fatality than any other crash type. Rollovers comprised only 4% of MVCs in 2005, however they accounted for 34% of all motor vehicle occupant deaths [6]. When compared to planar crashes, occupant kinematics in a rollover are chaotic and difficult to predict. Costly, debilitating and sometimes fatal injuries to the head, neck and spine are common in rollover crashes [7]. For this reason, a great deal of effort has gone into studying injury mechanisms in rollovers over the past 35 years.

The issue that has generated the most controversy in the literature is the phenomenon of roof crush (vertical and/or lateral intrusion of the vehicle roof/ceiling into the occupant compartment) and how it may or may not relate to the risk of head and spine injury. The source of the controversy is largely due to the fact that the auto manufacturing industry has sponsored research and publications that indicate that roof crush is not related to head and neck injury, whereas non-industry researchers, some of whom serve as consultants for plaintiffs who claim that a faulty roof design was the cause of their head and/or neck injury in a rollover crash, assert the opposite viewpoint.

Attempts to reduce injuries by strengthening vehicle roof structure are not a recent trend and began in the 1930’s when steel roll cages were first used in rollover crash tests. Significant gains in understanding occupant kinematics (movement within the vehicle) during a rollover were made in the 1960’s with the adoption of intravehicular high speed cameras for viewing anthropometric testing device (ATD or commonly known as a ‘crash test dummy’) movement, resulting in improvements in vehicle design and crash performance in the 1970’s [8]. A key improvement was the implementation of crush zones, which allowed for deformation of the vehicle with preservation of the occupant compartment [8].

In the process of performing crash tests automotive industry researchers have postulated a “diving theory” injury mechanism, in which injury to the head, neck and spine is thought to result from the occupant moving towards the vehicle roof during a rollover, while the roof, which is in contact with the ground, temporarily remains stationary relative to the inverted occupant. Edward Moffatt, a General Motors (GM) engineer, originally introduced the theory in 1975 as a result of crash testing performed with ATDs [9]. The implication of the diving theory is that roof crush (and thus roof strength) is unrelated to injury risk in rollover crashes.

In the competing explanation to the diving theory, called the "intrusion theory," it is maintained that during roof-to-ground contact in a rollover that produces roof crush, the vehicle roof is momentarily stationary against the ground, while the rest of the vehicle continues to move downward, thus reducing occupant headroom. Implicit in the intrusion hypothesis is the conclusion that increasing the strength of the roof and thus its ability to resist intrusion into the occupant compartment is key to reducing occupant head and neck injury risk [10]. The words of Viano et al. in a 2009 crash test study best describe the opinion that industry sponsored research has maintained since Moffatt's 1975 paper: "increasing roof strength would not reduce neck loads" [11].

The studies that are referred to as the basis for the diving theory of injury are primarily those using ATD kinematic and body part load analysis, the best known of which are two studies referred to as "Malibu I" and "Malibu II." [12] [13] [14]. These studies involved 16 rollover crash tests with 1983 Chevrolet Malibus that were launched into a lateral roll from a rolling dolly [13]. Half of the vehicles were reinforced with a rigid roll cage and half were production vehicles. Vertical roof crush was considerable among production vehicles and absent in those that were modified. Peak neck loads (a proxy for injury potential) were nearly identical between both vehicle types. Thus investigators concluded that vertical roof crush has no effect on head and neck injury. Furthermore, in these tests investigators observed that the maximum ATD neck load during the inversion of the vehicle occurred prior to vertical intrusion of the vehicle roof into the occupant compartment. Because the moment with the (presumed) highest potential for injury (maximum neck load) and the moment of maximum roof intrusion were temporally distinct, it was concluded that roof crush is not a cause of injury to the head or neck. Rather, it was concluded that it is the momentum of the occupant torso, which continues to move towards the roof after the head is stationary, that loads the neck and head and causes injury.

More recently, Raddin et al. [15] and Viano et al. [11] have replicated these ATD findings using more elaborate testing procedures. The former test used the Controlled Rollover Impact System (CRIS). The CRIS is tractor-trailer with a specially designed trailer that spins a vehicle about its long axis. The vehicle is then released and it strikes the ground. The roll rate and angle of impact can be controlled thus the CRIS creates repeatable crash test conditions with six degrees of freedom (forward/backward, up/down, left/right, pitch, yaw and roll). The crash experience is monitored via accelerometers (sensors) attached to ATDs and intravehicular cameras. This study involved crash tests with 10 vehicles, half production and half with a reinforced roof. Similar to Malibu I and Malibu II, investigators found that injurious forces exerted on the neck of an ATD were not concurrent in time with maximum roof crush and these forces were no different between reinforced and production vehicles [15]. The latter study involved a single Saab 9-3 sedan launched from a rolling dolly and researchers drew the same conclusions [11].

However, crash tests utilizing ATDs may not always be an accurate representation of real world rollover crash dynamics. A recent reexamination of the Malibu I and Malibu II crash test data (including slow motion video footage) by Grzebieta and Young [16][17][18], utilizing Newtonian physics, suggests that intrusion, not diving is indeed the primary source of injury, and what is more, the deformation mechanism that Malibu I and Malibu II proposed "bears no comparison to a 'real world' crash test." They determined that calculating the neck load based on factors associated with the diving theory alone results in a significant underestimate of neck load, indeed the effects of roof crush and diving actually *combine* to produce neck load [16]. Furthermore, Friedman et al. [10] point out that the Malibu studies "assumed that when the roof strikes the ground, it lays flat against the ground and slides with low friction across the ground, neither buckling nor deforming laterally." This is not accurate, lateral (sideways) intrusion does occur in rollovers and has been shown to significantly increase the odds of an injury to the head and face [19].

Crash tests conducted in 2007 at the request of the Ford Motor Corporation by Bidez et al. [6], utilizing ATDs, did not support the diving theory. These tests used three 1998-1999 Ford Explorer SUVs that were launched into a lateral roll with a rolling dolly. These crash tests observed the same temporal dissociation between peak neck load and maximum roof crush that prior research had noted. However they found that the neck loads resulting from occupant diving were not sufficient to cause spinal cord injury. Similarly Friedman et al. [10] explained that injuries to the head and neck that occur in a rollover happen in about 10 milliseconds, in which time the torso typically moves toward the head less than 2 cm. This is far less distance than is necessary to cause injury. Thus torso movement or "augmentation" in the diving theory is not a valid explanation for injury. Bidez et al. [6] also pointed out that force measurements of neck loading on the cervical spine in Malibu I and Malibu II were inaccurate. These measurements were taken on ATDs at the lower cervical spine. However choosing this location to place a sensor and assess force neglects the kinetic energy absorption associated with vertebral fracture or subluxation in the upper cervical spine. In a human, high-energy impacts can cause damage to the upper cervical spine. However this force may dissipate before reaching the lower cervical spine with the collapse of the upper region. Thus measures of force to the lower cervical spine are a poor indicator of injury to the rest of the cervical spine, above the sensor.

In 2009, Brumbelow et al. [20] with the Insurance Institute for Highway Safety (IIHS) performed roof crush testing on eleven midsize SUV roof designs according to the standards mandated by Federal Motor Vehicle Safety Standard 216 (FMVSS 216). These tests involved roof crush of up to 25 cm. They also gathered data from police reported rollover crashes in 14 US states. Logistic regression was used to evaluate the association between occupant injury and roof crush, as well as other variables. They found that a one-unit increase in the roof strength-to-weight ratio (SWR), as mandated by FMVSS 216, was associated with a 24% (95% CI 15-33) reduction in the risk of fatal or incapacitating injury. These findings are in agreement with Burns et al. [21] who determined that a reduction of roof intrusion to a maximum of 8-15 cm for belted occupants would result in the prevention of 134 cases of spinal cord injury and annual savings of approximately $97 million.

While interesting and arguably useful from an engineering perspective, crash tests, including those employing ATDs are not necessarily a reliable proxy for injury mechanism or risk in human populations exposed to real world rollover crashes. Thus validation of these experimental findings with observational (epidemiological) studies is helpful. Some epidemiological (or population based) studies have also failed to find an association between roof crush and injury. Based on data gathered from 1977-79 in the National Highway Traffic Safety Administration's (NHTSA) National Crash Severity Study (NCSS) Huelke et al. [22] found no association between roof crush and injury severity in rollover crashes. With data collected from the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) from 1992 to 1996, Parenteau et al. [23] concluded: "spinal injuries in a rollover are often associated with a 'diving-type' injury mechanism." Moffatt and Padmanaban [24] used police reported data from the National Automotive Sampling System – General Estimates System (NASS-GES) regarding 60,758 single vehicle rollovers in Florida, Michigan, North Carolina and Texas. They concluded that there was no association between vehicle roof strength and severe roof damage or occupant injury. They did find that vehicle roof shape was associated with both these outcomes.

However, Brumbelow et al. [20] described potential sources of bias and confounding which were inadequately addressed in Moffat and Padmanaban. This epidemiological study based on the NASS-GES included nonproduction vehicles. These vehicles are not representative of the national fleet. Brumbelow et al. also pointed out that while it may seem logical to control for seatbelt and alcohol use, as Moffat and Padmanaban did, these variables are inconsistently accounted for and poorly defined in the NASS-GES. The NASS-GES is a nationally representative sample of MVCs that relies on police reporting of seatbelt use and alcohol use, among other variables. It has been demonstrated that a significant amount of misclassification occurs in law enforcement reporting of seatbelt use. A comparison of NASS-CDS to police reported data showed that misclassification of seat belt use was related to the severity of injuries in vehicle occupants [25]. This misclassification has the potential to artificially inflate the efficacy of seatbelt use in studies such as Moffatt and Padmanaban, thus obscuring the effect of other factors, such as roof crush. The way in which alcohol use was accounted for in their study also raises doubts about its implications. The record of alcohol use is based on inconsistent application of blood alcohol content (BAC) testing and the judgment of law enforcement that tends to vary with the severity of the crash [26].

In stark contrast to epidemiological studies supporting the diving theory, Rains et al. [27] used data from the NASS-CDS and found that reduced headroom (as determined by both roof crush and initial headroom) was associated with increased risk of head injury. More recently, by applying weighted logistic regression modeling to eleven years of NASS-CDS data, Hu et al. [19] determined that increased roof crush is associated with elevated odds of injury to the head, face and neck.

Subsequent research based on the NASS-CDS database has found that the odds of mortality, traumatic brain injury (TBI), and spine injury increase with increasing measures of vertical roof crush. Mandell et al. [28] searched the NASS-CDS for occupants involved in rollover crashes from 1993 to 2006. This yielded a robust weighted sample of 10,921 occupants. Using logistic regression researchers were able to determine the odds of injury given various types of exposure. Vertical roof crush was by far the most useful predictor. Relative to occupants with less than 15 cm of roof crush, investigators noted a 52% increase in the odds of TBI for occupants with 15-30 cm of roof crush and a 267% increase with more than 30 cm. Using the same reference group, the odds of spine injury increased by 153% with roof crush of 15-30 cm and 168% above 30 cm. The odds of death among occupants with more than 30 cm of roof crush are 7.2 times the odds among those with 0-15 cm.

When designing an epidemiological study of rollover risk it is critical to account for variables that are predictive of injury so that they are controlled for. Vehicle occupant position relative to the rotation of the rollover is such a variable. When a vehicle rolls towards its left side, the driver (front-left seat) is termed the “leading” or “near-side” occupant, whereas the passenger (front-right seat) is termed the “following” or “far-side” occupant. Based on epidemiological data from the NASS-CDS, in this scenario the passenger or far-side occupant has a significantly higher risk of injury and fatality [29] [30] [31] [32]. This is likely due to the greater acceleration and rotational torque experienced by the far-side occupant [33]. Jewkes [34] expanded on these prior findings by determining that near-side occupants had a higher risk of sustaining head injuries while far-side occupants had a higher risk of injuries to the neck and spine.

Similarly, other researchers have indicated that the number of vehicle inversions or rolls is an important metric for determining risk of injury, regardless of seatbelt use [35]. This makes intuitive sense from a mechanical perspective. The more times a vehicle rolls, the more opportunity there is for occupants to make contact with vehicle components (roof, windshield, A pillar, B pillar, etc.), objects outside the vehicle, or to be ejected if they are not properly wearing a seatbelt. Furthermore, vehicles that experience a greater number of rotations are likely traveling at a higher rate of speed, and thus there is an inherent increased potential for injury, irrespective of other roll characteristics.

Although the debate regarding whether or not vertical roof crush is causally associated with risk of head, neck and spine injuries in rollover crashes continues in the literature, the NHTSA appears to have embraced this theory. FMVSS 216 which was updated by the NHTSA in 2009, doubling the roof SWR for light vehicles, represents an acknowledgement by the federal government that roof strength is an aspect of motor vehicle design worthy of adjusted regulation [28]. The original version of FMVSS 216 was implemented in 1971 “to reduce deaths and injuries due to the crushing of the roof into the passenger compartment in rollover accidents” [36]. This standard involves a quasi-static test and requires that when a steel plate called a “platen” is pressed downward on a vehicle roof with increasing force until a force equal to 1.5 times the weight of the vehicle is reached, the distance the plate has traveled from the point of initial contact must be no greater than 127 mm or 5 inches. This applied to all vehicles with a gross vehicle weight rating (GVWR) of 6,000 pounds or less. The minimum SWR for this test referred to as “platen travel” was 1.5 times the weight of the vehicle, up to 5,000 pounds [37]. After amendment of FMVSS 216 in 2009, the SWR was increased to 3.0 and the 5 inch platen displacement standard was replaced by the requirement that the minimum strength (5000 pounds or 3.0 times the vehicle weight) is reached before head-to-roof contact occurs for an ATD seated in the outboard (front-side) position [38]. This new SWR standard applied to all vehicles with a GVWR of 6,000 pounds or less and the prior SWR of 1.5 was applied to vehicles greater than 6,000 but less than 10,000 pounds [39].

Despite these federal regulations, the forces involved in motor vehicle travel will always constitute some risk of injury to occupants. This is an inevitable consequence of surrounding oneself with a cage made of steel, glass and plastic, weighing thousands of pounds and capable of moving at high speeds. However, efforts to improve safety through intelligent engineering and government regulation have been successful and will continue to be a salient goal. The recent adjustment of FMVSS 216, the observed decline in annual MVC fatalities, widespread adoption of airbags, electronic stability control and anti-lock bakes are examples of success [40]. Our hope is that this study will contribute to the growing body of literature regarding risk of injury and roof crush in rollover crashes. Ideally any resultant improvements in the understanding of injury causation in this scenario will lead to decreased morbidity and mortality in rollover crashes.

Relevance and Objective

MVCs are a substantial contributor to national morbidity and mortality. Though comparatively rare, rollover crashes impart the highest risk for injury and death. Vehicle roof strength, and thus the magnitude of roof deformation in a rollover crash may be associated with increased odds of injury to the head, neck and spine. This study employed NASS-CDS data regarding rollover MVCs to determine the strength of association between roof crush and odds of injury to these three body regions, while controlling for potential confounders. Exploring this association will help inform future regulation of vehicle manufacturing and potentially reduce injury.

Methods:

1) Data Source

The data for these cross-sectional and matched case-control analyses were abstracted from the NASS-CDS for the years 1997 through 2007. The NASS-CDS investigates about 5,000 MVCs every year in 36 geographic Primary Sampling Units (PSU) at a cost of approximately $10,000 per investigation. A record of over 800 variables including weather conditions, road conditions, injury to occupants or pedestrians and vehicle damage is kept for each crash. Trained crash investigators and medical examiners record these variables. In order for an MVC to be recorded in the NASS-CDS it must meet several criteria: a police report was generated; it was located within a primary sampling unit; it involved at least one passenger car, van or light truck; and at least one vehicle was towed from the crash scene. In turn, these data are weighted to represent all police reported MVCs occurring in the US and involving passenger cars, light trucks, and vans that were towed due to damage [41]. The dataset employed in this study was abstracted by Garthe Associates (Marblehead, MA) using proprietary software.

2) Subject Selection

To reduce possible sources of bias or confounding, exclusion and inclusion criteria were applied in the abstraction of these data. Rollovers that involved multiple vehicles, vehicles that experienced an arrested roll, major vehicle fires, immersions and end-over-end rollovers were excluded. Doing so reduced possible sources of confounding. Only front-left and front-right occupants were included in this analysis. No center or second-row occupants were included. Abbreviated Injury Scale (AIS) scores of “0” and “7” were omitted. The reasoning for this is explained in 3) Dependent Variable in the Methods. Deployment of side-curtain airbags was not included in this study due to the comparatively low number of vehicles with them in the national fleet. Furthermore the NASS-CDS has only recently begun to record data regarding side-curtain airbags.

Table 1: Exclusion and Inclusion Criteria

Exclusion Criteria
Under 13 years of age
Center seated occupants
Major Vehicle Fires
Vehicle immersions
Arrested rollovers
Convertibles
Unknowns
AIS "0" and "7"

Inclusion Criteria
Single vehicle rollovers
Autos[1], SUVs, minivans and pickups
Front-left and front-right (outboard) occupants
Type M occupants[2]
Type O occupants[3]

Occupant ejection from a vehicle is a significant source of injury in many rollover MVCs [22] [42]. Controlling for this variable is highly pertinent. Ejections were not excluded from or accounted for in this dataset. However, the definition of an injured occupant (type M) in the NASS-CDS implies that crash investigators determined that the injuries of interest were caused by specific vehicle roof components. Controlling for ejection becomes irrelevant under such constraints. If indeed an occupant was ejected, intruding vehicle roof components, not ejection, caused injuries to the head, neck and spine.

Of the 3,088 vehicle occupants abstracted with the inclusion and exclusion criteria listed above, 1,118 were injured occupants (type M) and 1,970 were uninjured (type O). The following occupants were removed from the type M group: those for whom death, airbag deployment, seat belt use and roll direction (necessary for determining leading vs. following position) were unknown. All occupants of convertibles were removed because this vehicle type lacks a proper roof, and roof crush is the primary outcome of this analysis. After these exclusions, 960 type M occupants remained.

Among these 960 injured occupants, 155 were matched to 155 uninjured occupants who were in the same vehicle at the time of a rollover. These 155

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[1] "Auto" denotes the following vehicle types: 2dr sedan/hardtop/coupe/3dr/2dr hatchback, 5dr/4dr hatchback, 4dr sedan/hardtop and station wagon

[2] Intrusion of a specified vehicle component occurred at the occupant's seating position, and a specified component caused an AIS injury in the head, neck or spine.

[3] Intrusion of a specified intruding component occurred at the occupants seating position, BUT either no injury was caused by a specified component OR the injury(s) caused were NOT in the head, neck or spine.

matched pairs (a total of 310 occupants) served as the sample for the matched case-control analysis.

3) Dependent Variable

The Abbreviated Injury Scale (AIS) is used in the NASS-CDS to record injury severity. The AIS indicates probability of survival for 30 days from the time of injury and says little about long-term survival or health effects, see Figure 1 [43]. The AIS is divided into 8 categories regarding injury:

0: None
1: Minor
2: Moderate
3: Serious
4: Severe
5: Critical
6: Maximum
7: Injured, Unknown Severity

The “0” and “7” categories were excluded from our analysis to reduce potential misclassification bias. If occupants are marked “uninjured” by law enforcement in a police report and no AIS coding is later conducted by crash investigators, the occupants will remain marked “uninjured” in the NASS-CDS. There is no true AIS 0 category in the NASS-CDS. The 0 category includes individuals with no AIS codeable injuries (potentially individuals who did not sustain an injury), individuals for whom injury data are missing and sometimes those who are dead. This latter scenario results when a police report finds an individual dead on arrival and never bothers to record injury status and investigators later fail to do so as well. If an injury occurred but no data regarding the severity of injury are available, some investigators leave the injury status blank, rather than the correct code of “7” to represent injured but severity unknown.

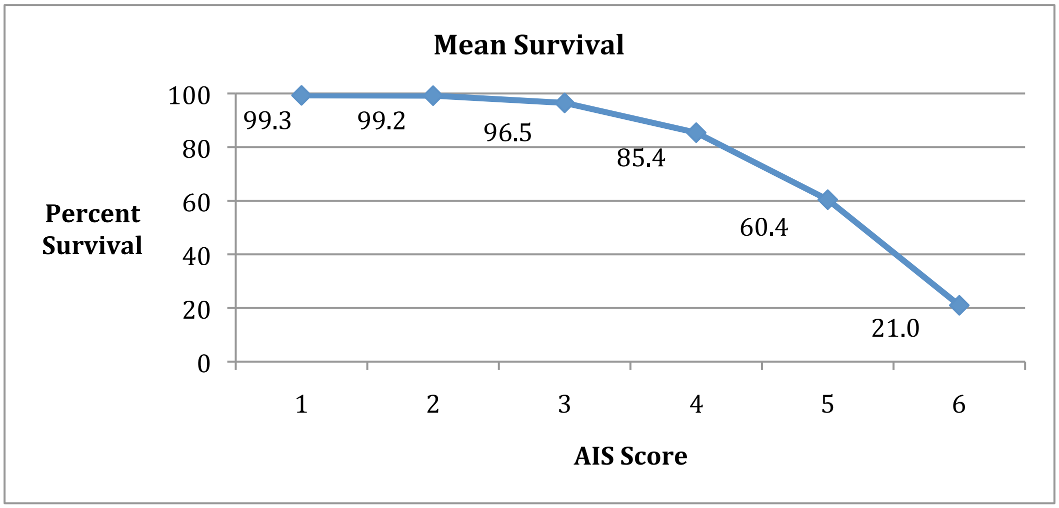

Figure 1: AIS as a predictor of injury survival

Thus, it is possible that a substantial proportion of individuals in the 0 category have injuries that were not documented. Although the proportion of misclassified observations cannot be precisely estimated, we suspect it to be large. For this reason, we excluded all AIS 0 scores from the analysis dataset, and relied upon categories 1, 2, and 3 to represent individuals with injuries that were judged to be substantially less life-threatening. Individuals with AIS 7 were also excluded from the analysis dataset.

Injuries recorded in the NASS-CDS are assigned a body region code. The body regions and their corresponding codes are:

1: Head
2: Face
3: Neck[4]
4: Thorax
5: Abdomen
6: Spine[5]
7: Upper Extremity
8: Lower Extremity
9: Unspecified

The Injury Severity Score (ISS) is defined as the sum of the squares of the single highest AIS score in each of the three most severely injured body regions [44].

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[4] "Neck" refers to all tissue between the head and thorax excluding the spinal column.

[5] "Spine" refers to the cervical, thoracic and lumbar regions of the spinal column.

This system of scoring was created to allow for the calculation of a single composite score indicating severity of more than one injury in multiple body regions ("polytrauma"). However Osler et al. [45] have demonstrated that the New Injury Severity Score (NISS) or the sum of the squares of the AIS scores of an occupant's three most severe injuries, regardless of the body region in which they occur, is a better predictor of survival than the ISS.

Although injuries to all body regions are possible in a rollover crash, those to the head, neck and spine are common and often severe. This study employed a modified NISS score that is specific to the head, neck and spine. This modified NISS is the sum of the squares of the AIS scores of an occupant's three most severe injuries, regardless of whether they occurred in the head, neck or spine. The cut-point for the ISS and NISS is usually a score of 15. However, our modified NISS is restricted to injuries to the head, neck and spine, validating a logical cut-point based on death is necessary. This is to say, a NISS cut-point based on all body regions may not be the same as a head, neck and spine NISS (HNS-NISS) cut-point, with respect to predicting survival. Similar to Osler et al. [45], we constructed an ROC curve to determine a threshold or "cut-point" to divide HNS-NISS scores into "low mortality" and "high mortality" while maximizing sensitivity and specificity. Figure 2 displays an ROC curve for a weighted GEE model with death as the dependent variable and HNS-NISS as the independent variable. The un-weighted model had similar results. By simultaneously balancing sensitivity (72.54%) and specificity (71.88%) we calculated a cut-point of HNS-NISS = 9 for defining the outcome. Occupants with a score ≥ 9 are considered "high mortality" and those with a score < 9 are considered "low mortality."

Table 2: Dependent Variable

Dependent Variable	Details	Rationale
Modified Head, Neck and Spine NISS (HNS-NISS)	0: <9 1: ≥9	HNS-NISS indicates severity of injury with respect to survivability.

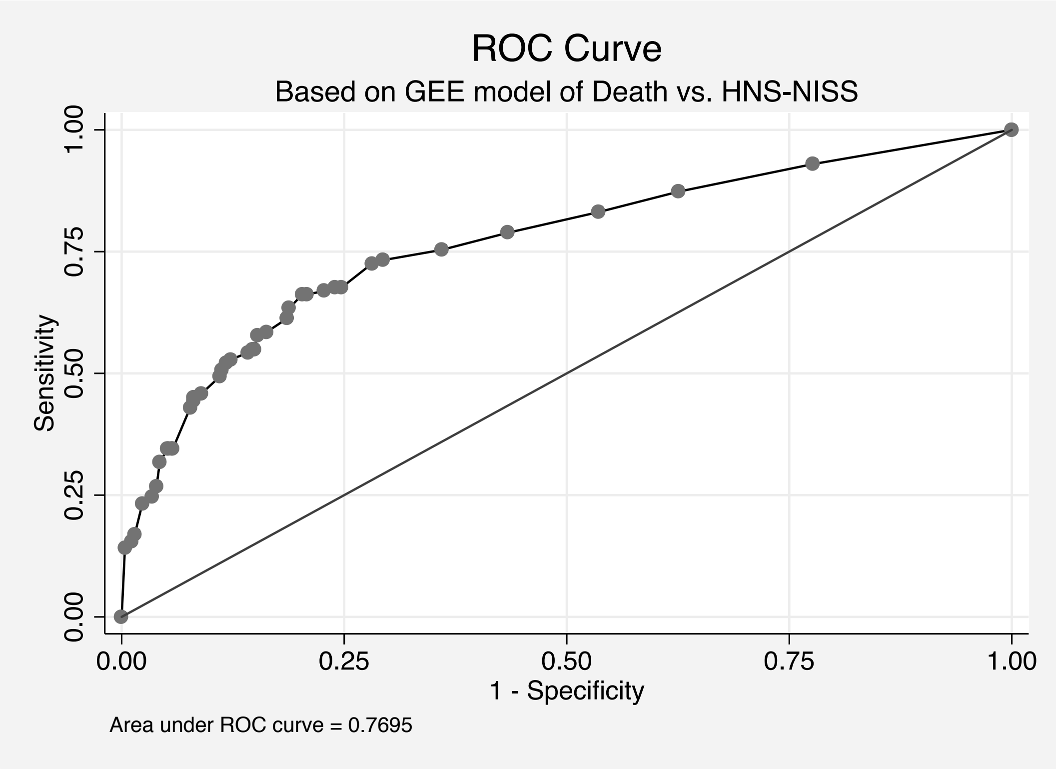

Figure 2: ROC curve of death vs. HNS-NISS

4) Independent Variables

The primary independent or main effect variable was the magnitude of vertical roof crush measured in centimeters. This variable was recorded for intrusion of the roof, roof rail and windshield header. The NASS-CDS condenses this roof crush into six categories that can be seen in Table 3. However, taking the midpoint of the range of measurements for each stratum can create a continuous version of roof crush. For example strata 1 or ≥ 3 but < 8 cm became 5.5 cm, stratum 2 became 11.5 cm, and so on. By dividing these values by 10, a variable was created for which each unit represents an increment of 10 cm.

Several other variables in Table 4 were candidates for inclusion in the final model. Only front airbag deployment was included in the analysis, and side airbags were not. This is due to the relatively low frequency of vehicles equipped with side airbags in the national fleet. Change in velocity (ΔV) is commonly used to assess crash severity in planar crashes. However, this variable is not helpful for rollover MVCs and is often not recorded at all, thus it was not included [46].

Table 3: Primary Independent Variable

Primary Independent Variable	Details	Rationale
Roof Crush (Categorical)	1: ≥ 3 but < 8 cm 2: ≥ 8 but < 15 cm 3: ≥ 15 but < 30 cm 4: ≥ 30 but < 46 cm 5: ≥ 46 but < 61 cm 6: ≥ 61 cm	The effect of this variable is of primary interest.
Roof Crush (Continuous)	10 cm increments	

Table 4: Other Independent Variables

Other Independent Variables	Details	Rationale
Vehicle Body Type	1: Auto 2: Minivan 3: Pickup 4: SUV	Vehicles behave differently, these effects can be controlled for.
Quarter Rolls	1-16: quarter rolls 17: more than 16 quarter rolls	This is a demonstrated predictor of crash severity.
Front Airbag	0: Deployed 1: Not Deployed/Equipped	Airbags mitigate injury in most crashes.
Seat Belt (Three point manual automatic, or manual lap)	0: Properly Used 1: Not used	Proper seatbelt use reduces injuries in most crashes.
Roll Arc Side	0: Near-side (leading) occupant 1: Far-side (following) occupant	Occupants in the following side have an increased risk of injury.
Seating Position	0: Right-Front Seat 1: Left-Front Seat	This dataset contains only front-left and -right occupants, this allows us to control for occupant seating position.
Age	Years	Age may affect injury potential.

Statistical Analysis

Each observation in this dataset represents a single vehicle occupant. Each MVC involves only one vehicle, while each vehicle has one or two occupants, and each occupant can have one or many injuries to the head, neck and spine (see Figure

3). The HNS-NISS combines all injuries for these body regions to one score for an occupant.

We recognized the grouping or clustering relationship in these data whereby two occupants of the same vehicle should not be treated as independent because they are both subject to conditions of the same vehicle in the same rollover crash. To adjust for these correlated observations, we used GEE.

The cross-sectional analysis employed a generalized estimating equation (GEE) with a logit link for odds ratios and semi-robust standard error to determine the odds of HNS-NISS ≥ 9. Per Hardin and Hilbe [47] we used an exchangeable correlation structure because observations were clustered, not collected over time.

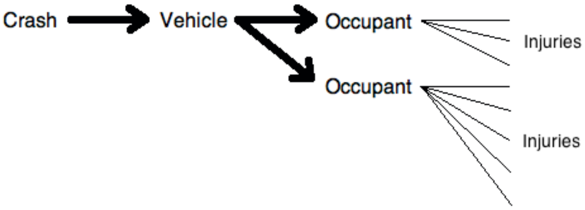

Figure 3: Dataset Structure

The data employed in this study provided the opportunity to also perform a matched case-control analysis. Occupant pairs in which one occupant sustained an injury (occupant type M, i.e. "case") and one occupant did not sustain injury (occupant type O, i.e. "control") were isolated based on the same selection criteria as the 960 type M occupants used in the historical cohort study. Because roof crush measurements as well as several other covariates in this study are occupant specific, not vehicle specific, we were able to compare these disparate type occupant pairs using conditional fixed-effects logistic regression to model the odds of being injured.

Prior to performing a multivariable analysis, univariable GEE models were created for each independent variable. Univariable fixed effects logistic models were used for the matched case-control study. Variables that achieved a level of significance p ≤ 0.20 were retained for multivariable modeling. A more inclusive level of significance of 0.20 was used at this stage in the analysis to prevent exclusion of variables with borderline significance in univariable analysis that become significant at $p = 0.05$ in a multivariable model.

We started with a multivariable model including all covariates that attained $p \leq 0.20$ in univariable modeling. Among covariates with $p > 0.05$, those with the highest p-value were removed by backwards elimination until all covariates in the model achieved $p \leq 0.05$. Then, each eliminated variable was re-added one-at-a-time to see if it achieved significance. Any variables that were not statistically significant but appear mechanistically intrinsic to injury were retained in the model. To check for interaction between airbag and seatbelt use in the cross-sectional study modeling HNS-NISS, GEE models were stratified by these two variables. Quasilikelihood under the independence model information criterion (QIC) was used to help determine the best fitting and most parsimonious, yet mechanistically feasible model to describe the relationship between the outcome and the independent variables.

To help pick the best model in the matched case-control study Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were employed as well as a method proposed by Nagelkerke for calculating an R^2 like measure models fit via maximum likelihood [48]. The formulas used for calculating R^2 are displayed below.

$$R^2 = 1 - \exp\left[-\frac{2}{n}\{l(\hat{\beta}) - l(0)\}\right] = 1 - \{L(0)/L(\hat{\beta})\}^{2/n}$$

Where $l(\hat{\beta}) = \log L(\hat{\beta})$ and $l(0) = \log L(0)$ represent the log likelihood of the fitted and null models respectively and n is the number of matched case-control pairs.

$$\max(R^2) = 1 - \exp\{2n^{-1}l(0)\} = 1 - L(0)^{2/n}$$

$$\overline{R}^2 = R^2/\max(R^2)$$

The NASS-CDS is a nationally representative sample with weighted observations. Each MVC in this dataset has a ratio inflation factor weight that indicates the estimated national frequency of that MVC. These weights are generated by the NHTSA. Two separate analyses, one weighted the other un-weighted, were carried out for the cross-sectional and matched case-control studies modeling HNS-NISS (four final models in all). STATA version 11.2 was used for all GEE and logistic regression modeling.

Results – Cross-Sectional Study

1) Descriptive Data

Data regarding 1,118 injured vehicle occupants involved in rollover MVCs investigated and recorded in the NASS-CDS during the study period were initially abstracted for analysis. After removing those with missing data, 960 (86% of original sample) occupants remained.

Tables 5 and 6 describe the characteristics of these individuals. There were 333 occupants with an HNS-NISS ≥ 9, and 627 with HNS-NISS < 9. The mean modified HNS-NISS value of the sample was 12, while the median was 4, indicating that the distribution of these values was skewed towards higher scores. This is consistent with Figure 4 displaying a histogram of modified NISS scores. The mean roof crush for all occupants was 23.5 cm, 27.3 cm for those with HNS-NISS ≥ 9, and 21.5 cm for those with HNS-NISS < 9. Only 28 occupants had a roof crush value ≥ 61 cm (2.9%) while most were ≥ 15 but < 30 cm (38.4%).

Slightly more than half of all occupants were in the following side of the roll arc. Of the occupants in the following side, 38.83% had HNS-NISS ≥ 9, as compared to 29.23% of those in the leading side. This observation is consistent with theory that occupants in the following side of the roll arc experience more rotational torque and are at an increased risk for injury.

The majority of occupants were in the driver's seat, the front-left seating position (77.4%). Further, 838 occupants or 87.29%, were alone in a vehicle when it rolled. Thus most of the individuals in our analysis were drivers and were the only vehicle occupant. There were 61 occupant pairs (one driver and one passenger) present in the analytic data set for a total of 122 occupants.

Table 5: Characteristics of cross-sectional occupants – categorical variables stratified by HNS-NISS ≥ 9 vs. HNS-NISS < 9

	HNS-NISS ≥ 9			HNS-NISS < 9			Total	% Total
	N	Row %	Col. %	N	Row %	Col. %		
Vehicle Occupants	333	34.7	100	627	65.3	100	960	100
Roof Crush								
≥3, <8 cm	26	18.8	7.8	112	81.2	17.9	138	14.4
≥8, <15 cm	53	26.4	15.9	148	73.6	23.6	201	20.9
≥15, <30 cm	141	38.2	42.3	228	61.8	36.4	369	38.4
≥30, <46 cm	73	41.2	21.9	104	58.8	16.6	177	18.4
≥46, <61 cm	24	51.1	7.2	23	48.9	3.7	47	4.9
≥61 cm	16	57.1	4.8	12	42.9	1.91	28	2.9
Vehicle Group								
Auto	155	34.0	46.6	301	66.0	48.0	456	47.5
Minivan	6	33.3	1.8	12	66.7	1.9	18	1.9
Pickup	70	32.6	21.0	145	67.4	23.1	215	22.4
SUV	102	37.6	30.6	169	62.4	27.0	271	28.2
Quarter Rolls								
1-4	297	34.8	62.2	388	65.2	61.9	595	62.0
5-8	99	33.6	29.7	196	66.4	31.3	295	30.7
≥9	27	38.6	8.1	43	61.4	6.9	70	7.3
Front Airbag								
Deployed	98	44.8	29.4	121	55.3	19.3	219	22.8
Not Deployed/Equip.	235	31.7	70.6	506	68.3	80.7	741	77.2
Seatbelt Use								
Used	195	32.4	58.6	407	67.6	64.9	602	62.7
Not Used/Equip.	138	38.6	41.4	220	61.5	35.1	358	37.3
Roll Arc Side								
Leading	121	29.2	36.3	293	70.8	46.7	414	43.1
Following	212	38.8	63.7	334	61.2	53.3	546	56.9
Seat Position								
Front-Right	67	30.9	20.1	150	69.1	23.9	217	22.6
Front-Left	266	35.8	79.9	477	64.2	76.1	743	77.4

Table 6: Characteristics of cross-sectional occupants – continuous variables stratified by HNS-NISS ≥ 9 vs. HNS-NISS < 9

		Roof Crush (cm)[6]	Quarter Rolls[7]	Age (years)	Weights
HNS-NISS ≥ 9 (N=333)	Mean	27.3	4.4	34.4	84.6
	Std. Dev.	15.7	3.0	15.4	209.2
	Min.	5.5	1	14	2.3
	Max.	69	16	83	2,446.6
HNS-NISS < 9 (N=627)	Mean	21.5	4.5	31.6	243.7
	Std. Dev.	14.0	2.8	14.5	533.3
	Min.	5.5	1	13	2.4
	Max.	69	17	82	7,274.8
Total (N=960)	Mean	23.5	4.5	32.6	188.5
	Std. Dev.	14.9	2.8	14.9	454.5
	Min.	5.5	1	13	2.3
	Max.	69	17	83	7,274.8

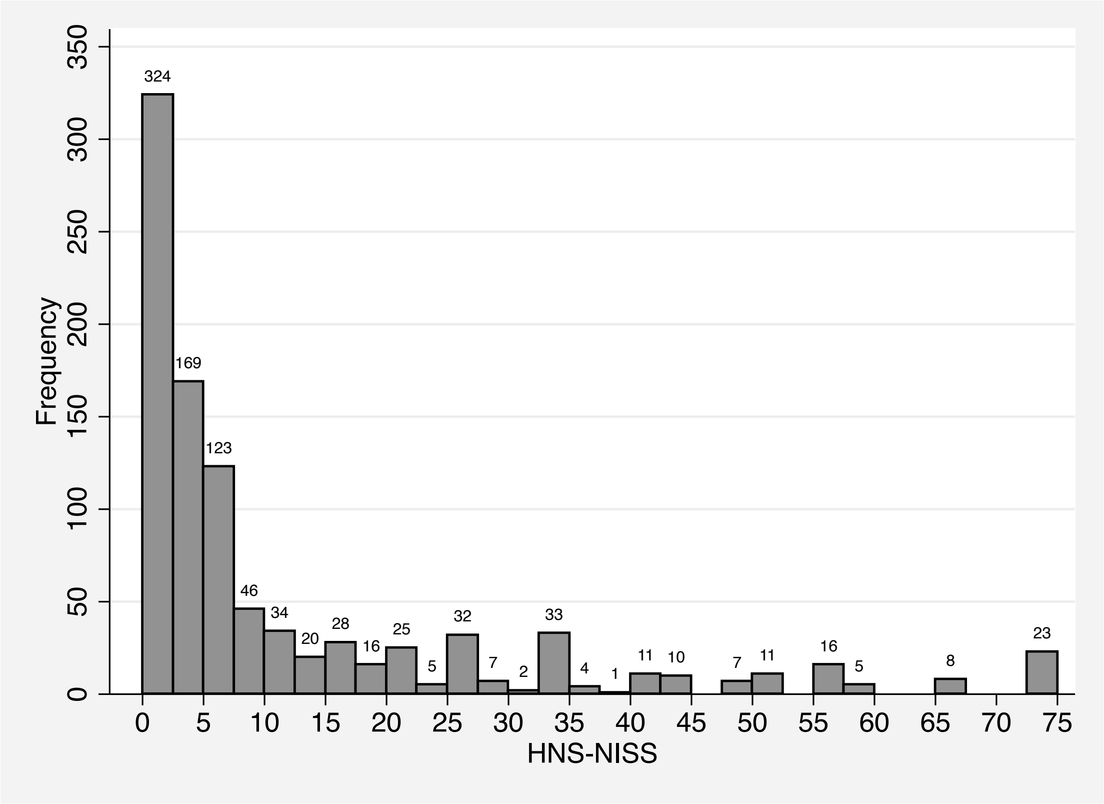

Figure 4: Histogram of HNS-NISS scores

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[6] Categorically recorded in the NASS-CDS

[7] 17 denotes ≥ 17

2) Univariable GEE Modeling

The results of all univariable GEE models, both un-weighted and weighted, can be seen in Tables 7 and 8. These odds ratios represent crude measures of association between each covariate and the primary outcome of HNS-NISS ≥ 9. When weighting was accounted for, the following variables were found to be associated with this outcome at $p \leq 0.20$: roof crush (both continuous and categorical), airbag deployment, seat belt use, roll arc side and age. When weighting was excluded, roof crush (both continuous and categorical), airbag deployment, seat belt use, roll arc side, seat position and age met the same criterion of significance.

Table 7: Un-weighted univariable models – odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE	N
Roof Crush (Continuous)					
Plus 10 cm	1.30	1.19 - 1.42	<0.001	0.060	960
Roof Crush (Categorical)			<0.001		
≥3, <8 cm	Ref.	-	-	-	138
≥8, <15 cm	1.56	0.92 - 2.65	0.102	0.422	201
≥15, <30 cm	2.69	1.67 - 4.31	<0.001	0.648	369
≥30, <46 cm	3.05	1.81 - 5.14	<0.001	0.812	177
≥46, <61 cm	4.50	2.21 - 9.17	<0.001	1.635	47
≥61 cm	5.88	2.42 - 14.26	<0.001	2.657	28
Vehicle Group			0.662		
Auto	Ref.	-	-	-	456
Minivan	0.98	0.35 - 2.74	0.975	0.514	18
Pickup	0.98	0.66 - 1.32	0.710	0.164	215
SUV	1.17	0.86 - 1.61	0.322	0.188	271
Quarter Rolls (Continuous)					
Plus 1/4 roll	0.99	0.94 - 1.04	0.646	0.024	960
Quarter Rolls (Categorical)			0.721		
1-4	Ref.	-	-	-	595
5-8	0.95	0.71 - 2.27	0.712	0.142	295
≥9	1.17	0.71 - 1.93	0.528	0.299	70
Front Airbag Deployment					
Deployed	Ref.	-	-	-	219
Not Deployed/Equipped	0.57	0.42 - 0.78	<0.001	0.090	741
Seatbelt Use					
Used	Ref.	-	-	-	602
Not Used/Equipped	1.31	1.00 - 1.71	0.053	0.181	358
Roll Arc Side					
Leading	Ref.	-	-	-	414
Following	1.54	1.18 - 2.02	0.002	0.214	546
Seat Position					
Front-Right	Ref.	-	-	-	217
Front-Left	1.24	0.90 - 1.72	0.189	0.205	743
Age					
Plus 1 year	1.01	1.00 - 1.02	0.005	0.005	960

Table 8: Weighted univariable models – odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE	N
Roof Crush (Continuous)					
Plus 10 cm	1.68	1.30 - 2.17	<0.001	0.220	960
Roof Crush (Categorical)			<0.001		
≥3, <8 cm	Ref.	-	-	-	138
≥8, <15 cm	1.86	0.76 - 4.54	0.175	0.848	201
≥15, <30 cm	2.74	1.17 - 6.41	0.020	1.187	369
≥30, <46 cm	6.45	2.49 - 16.73	<0.001	3.136	177
≥46, <61 cm	37.60	8.69 - 162.50	<0.001	28.089	47
≥61 cm	6.70	1.35 - 33.38	0.020	5.490	28
Vehicle Group			0.516		
Auto	Ref.	-	-	-	456
Minivan	2.24	0.56-8.98	0.253	1.588	18
Pickup	1.14	0.45 - 2.87	0.782	0.538	215
SUV	0.82	0.38 - 1.74	0.597	0.315	271
Quarter Rolls (Continuous)					
Plus 1/4 roll	0.98	0.85 - 1.13	0.762	0.071	960
Quarter Rolls (Categorical)			0.415		
1-4	Ref.	-	-	-	595
5-8	1.45	0.71 - 3.00	0.310	0.538	295
≥9	0.64	0.16 - 2.54	0.530	0.451	70
Front Airbag Deployment					
Deployed	Ref.	-	-	-	219
Not Deployed/Equipped	0.30	0.14 - 0.63	0.001	0.113	741
Seatbelt Use					
Used	Ref.	-	-	-	602
Not Used/Equipped	1.78	0.88 - 3.61	0.110	0.642	358
Roll Arc Side					
Leading	Ref.	-	-	-	414
Following	1.55	0.81 - 2.97	0.186	0.514	546
Seat Position					
Front-Right	Ref.	-	-	-	217
Front-Left	1.45	0.78 - 2.72	0.240	0.463	743
Age					
Plus 1 year	1.02	1.01 - 1.04	0.012	0.009	960

3) Multivariable GEE Modeling

After a process of backwards elimination, two preliminary multivariable models were generated: one un-weighted and the other weighted. To facilitate testing for interaction, continuous rather than categorical roof crush was used in multivariable modeling. The weighted model included the following variables: roof crush (continuous), airbag deployment, seatbelt use and age. The un-weighted model included all of the above covariates plus roll arc side. Although seat belt use was not statistically significant (p=0.056), the magnitude of the odds ratio (OR=1.90) and the intrinsic nature of this covariate in MVCs lead us to retain it in the weighted model.

To evaluate the possibility that airbag deployment and/or seatbelt use could modify the effect of roof crush on injury or, that airbag deployment and seatbelt use could modify one and other's effect, with respect to injury, GEE models were carried out by subgroups. The four resultant models can be seen in Tables 9 and 10. Each model considered occupants from one of the four following groups: airbag deployed and seatbelt was used (group 1); airbag deployed and seatbelt was not used (group 2); airbag did not deploy or was not equipped and seat belt was used (group 3); and airbag did not deploy or was not equipped and seatbelt was not used (group 4). Because the point estimate ORs vary across these groups for both un-weighted and weighted models, further investigation of potential interaction between airbag deployment and roof crush as well as seat belt use and roof crush was necessary.

Four additional models were constructed to evaluate potential effect modification (Tables 11, 12, 13 and 14). Neither airbag deployment or seat belt use appear to modify the effect of roof crush, with respect to the odds of HNS-NISS ≥ 9. However, the weighted model for group 3 does have a protective odds ratio (OR=0.27 95% CI (0.10, 0.69), p=0.007) when compared to group 1. The result was similar for an un-weighted model (OR=0.55, 95% CI (0.36, 0.83), p=0.004). Group 2 appears harmful and group 4 appears protective, both relative to group 1, though neither odds ratio is statistically significant.

Table 9: Un-weighted multivariable models stratified by airbag deployment and seat belt use – odds of HNS-NISS ≥ 9

		OR	95% CI	p	Semirobust SE
Group 1: Airbag Deployed, Seatbelt Used (N=128)	Roof Crush				
	Plus 10 cm	1.42	1.11 - 1.83	0.006	0.184
	Roll Arc Side				
	Leading	Ref.	-	-	-
	Following	0.76	0.36 - 1.62	0.480	0.293
	Age				
	Plus 1 year	1.02	1.00 - 1.05	0.054	0.012
Group 2: Airbag Deployed, Seatbelt Not Used (N=91)	Roof Crush				
	Plus 10 cm	1.28	0.99 - 1.65	0.063	0.167
	Roll Arc Side				
	Leading	Ref.	-	-	-
	Following	1.63	0.67 - 3.95	0.280	0.736
	Age				
	Plus 1 year	1.02	0.98 - 1.06	0.265	0.019
Group 3: Airbag Not Equipped/ Non-deployed, Seatbelt Used (N=474)	Roof Crush				
	Plus 10 cm	1.35	1.17 - 1.56	<0.001	0.099
	Roll Arc Side				
	Leading	Ref.	-	-	-
	Following	2.74	1.74 - 4.30	<0.001	0.630
	Age				
	Plus 1 year	1.01	1.00 - 1.03	0.018	0.006
Group 4: Airbag Not Equipped/ Non-deployed, Seatbelt Not Used (N=267)	Roof Crush				
	Plus 10 cm	1.21	1.03 - 1.42	0.022	0.099
	Roll Arc Side				
	Leading	Ref.	-	-	-
	Following	0.95	0.56 - 1.60	0.833	0.253
	Age				
	Plus 1 year	1.01	0.99 - 1.03	0.276	0.011

Table 10: Weighted multivariable models stratified by airbag deployment and seat belt use – odds of HNS-NISS ≥ 9

		OR	95% CI	p	Semirobust SE
Group 1: Airbag Deployed, Seatbelt Used (N=128)	Roof Crush				
	Plus 10 cm	2.10	1.01 - 4.36	0.048	0.784
	Age				
	Plus 1 year	1.03	0.99 - 1.07	0.161	0.022
Group 2: Airbag Deployed, Seatbelt Not Used (N=91)	Roof Crush				
	Plus 10 cm	1.56	1.02 - 2.40	0.041	0.342
	Age				
	Plus 1 year	1.00	0.96 - 1.05	0.978	0.024
Group 3: Airbag Not Equipped/ Non-deployed, Seatbelt Used (N=474)	Roof Crush				
	Plus 10 cm	1.56	1.25 - 1.94	<0.001	0.174
	Age				
	Plus 1 year	1.03	1.01 - 1.05	0.007	0.011
Group 4: Airbag Not Equipped/ Non-deployed, Seatbelt Not Used (N=267)	Roof Crush				
	Plus 10 cm	1.63	0.99 - 2.70	0.057	0.420
	Age				
	Plus 1 year	1.03	0.99 - 1.07	0.198	0.022

Table 11: Un-weighted interaction between airbag/seatbelt and roof crush with respect to odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE
Roof Crush				
Plus 10 cm	1.43	1.11 - 1.85	0.006	0.187
Age				
Plus 1 year	1.02	1.01 - 1.03	0.001	0.005
Roll Arc Side				
Leading	Ref.		-	-
Following	1.51	1.13 - 2.00	0.005	0.219
Airbag*Seat Belt			0.023	
Group 1	Ref.		-	-
Group 2	1.95	0.73 - 5.23	0.182	0.981
Group 3	0.62	0.27 - 1.43	0.266	0.265
Group 4	1.22	0.52 - 2.90	0.646	0.539
Airbag/Seatbelt*Roof Crush			0.579	
Group 1*Roof Crush	Ref.		-	-
Group 2*Roof Crush	0.89	0.62 - 1.26	0.502	0.160
Group 3*Roof Crush	0.95	0.71 - 1.28	0.738	0.143
Group 4*Roof Crush	0.84	0.62 - 1.13	0.253	0.130

Table 12: Un-weighted interaction model between airbag and seatbelt with respect to odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE
Roof Crush				
Plus 10 cm	1.31	1.19 - 1.43	<0.001	0.061
Age				
Plus 1 year	1.02	1.01 - 1.03	0.001	0.005
Roll Arc Side				
Leading	Ref.		-	-
Following	1.50	1.13 - 1.99	0.005	0.216
Airbag*Seat Belt			<0.001	
Group 1	Ref.		-	-
Group 2	1.45	0.84 - 2.51	0.181	0.405
Group 3	0.55	0.36 - 0.83	0.004	0.116
Group 4	0.79	0.50 - 1.23	0.288	0.179

Table 13: Weighted interaction model between airbag/seatbelt and roof crush with respect to odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE
Roof Crush				
Plus 10 cm	2.10	1.01 - 4.37	0.048	0.786
Age				
Plus 1 year	1.03	1.01 - 1.04	0.001	0.009
Airbag*Seat Belt			0.076	
Group 1	Ref.		-	-
Group 2	3.67	0.50 - 26.96	0.202	3.733
Group 3	0.57	0.09 - 3.39	0.534	0.517
Group 4	0.96	0.13 - 6.99	0.967	0.972
Airbag/Seatbelt*Roof Crush			0.900	
Group 1*Roof Crush	Ref.		-	-
Group 2*Roof Crush	0.77	0.33 - 1.84	0.564	0.343
Group 3*Roof Crush	0.74	0.34 - 1.60	0.448	0.291
Group 4*Roof Crush	0.78	0.32 - 1.89	0.581	0.353

Table 14: Weighted interaction model between airbag and seatbelt with respect to odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE
Roof Crush				
Plus 10 cm	1.64	1.27 - 2.13	<0.001	0.218
Age				
Plus 1 year	1.03	1.01 - 1.04	0.001	0.009
Airbag*Seat Belt			<0.001	
Group 1	Ref.		-	-
Group 2	1.93	0.65 - 5.71	0.234	1.068
Group 3	0.27	0.10 - 0.69	0.007	0.130
Group 4	0.51	0.18 - 1.43	0.199	0.268

In summary, the effect of roof crush with respect to the odds of HNS-NISS ≥ 9 is not modified by either airbag deployment or seatbelt use. However, there is statistically significant interaction between one strata of airbag deployment and seat belt use (group 3 - airbag did not deploy or was not equipped and seat belt was used) with respect to this outcome.

Two un-weighted models and two weighted models became candidates for selection as the final model. Table 15 displays the covariates in these models as well as their respective QIC values. Both un-weighted and weighted versions of Model 2 included the interaction between airbag deployment and seat belt use observed with group 3. The QIC values for the un-weighted and weighted versions of Model 1 were lower indicating a better fitting model. These models were chosen for the final multivariable GEE models. Tables 16 and 17 display the odds ratios for the final un-weighted and weighted models.

Table 15: Final model candidates for cross-sectional cohort study and QIC scores – odds of modified NISS ≥ 9

	Un-weighted		Weighted	
	Model 1	Model 2	Model 1	Model 2
Variables	Roof Crush Age Roll Arc Position Airbag Deployment Seat Belt Use	Roof Crush Age Roll Arc Position Groups 1-4	Roof Crush Age Airbag Deployment Seat Belt Use	Roof Crush Age Groups 1-4
QIC	1182.07	1184.03	1188.13	1190.06

Table 16: Un-weighted final model – odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE
Roof Crush				
Plus 10 cm	1.31	1.19 - 1.43	<0.001	0.061
Front Airbag Deployment				
Deployed	Ref.	-	-	-
Not Deployed/Equipped	0.55	0.40 - 0.75	<0.001	0.089
Seatbelt Use				
Used	Ref.	-	-	-
Not Used/Equipped	1.44	1.08 - 1.91	0.013	0.209
Roll Arc Side				
Leading	Ref.	-	-	-
Following	1.50	1.13 - 1.99	0.005	0.216
Age				
Plus 1 year	1.02	1.01 - 1.03	0.001	0.005

Table 17: Weighted final model – odds of HNS-NISS ≥ 9

	OR	95% CI	p	Semirobust SE
Roof Crush				
Plus 10 cm	1.64	1.26 - 2.14	<0.001	0.221
Front Airbag Deployment				
Deployed	Ref.	-	-	-
Not Deployed/Equipped	0.27	0.13 - 0.54	<0.001	0.096
Seatbelt Use				
Used	Ref.	-	-	-
Not Used/Equipped	1.90	0.98 - 3.68	0.056	0.640
Age				
Plus 1 year	1.03	1.01 - 1.04	0.002	0.009

Results – Matched Case-Control Analysis

1) Descriptive Data

Of the 2,843 vehicle occupants, both type M and O (injured and not injured) a total of 310 were occupants who shared a vehicle with an opposite occupant type. In other words vehicles with one injured and one uninjured occupant. These 155 crashes served as the units of observation for the matched case-control analysis. Tables 18 and 19 describe these occupants. Those variables that were vehicle specific and thus identical for both occupants (vehicle group and quarter rolls) were omitted.

The distribution of occupants in the matched case-control study was similar to that in the larger cohort of injured occupants. The mean HNS-NISS among cases was 7.3. All controls had a score of 0. Similar to the historical cohort study occupants, very few matched case-control occupants had ≥ 61 cm of roof crush (2.6%), while 30.3% had ≥ 15 but < 30 cm. Among cases, 60% were in the following roll arc position while among controls, 40% were. Among cases 60.6% were in the front-left seating position while among controls only 39.4% were similarly seated.

Table 18: Characteristics of matched case-control occupants – categorical variables stratified by cases and controls

	Cases Injured (N=155)			Controls Uninjured (N=155)				
	N	Row %	Col. %	N	Row %	Col. %	Total	% Total
Roof Crush								
≥3, <8 cm	25	45.5	16.1	30	54.6	19.4	55	17.7
≥8, <15 cm	29	40.9	18.7	42	59.2	27.1	71	22.9
≥15, <30 cm	54	57.5	34.8	40	42.6	25.8	94	30.3
≥30, <46 cm	30	49.1	19.4	31	50.8	20.0	61	19.7
≥46, <61 cm	12	57.1	7.7	9	42.9	5.8	21	6.8
≥61 cm	5	62.5	3.2	3	37.5	1.9	8	2.6
Front Airbag Deployment								
Deployed	33	50.0	21.3	33	50.0	21.3	66	21.3
Not Deployed/Equipped	122	50.0	78.7	122	50.0	78.7	244	78.7
Seatbelt Use								
Used	87	48.9	56.1	91	51.1	58.7	178	57.4
Not Used/Equipped	68	51.5	43.9	64	48.5	41.3	132	42.6
Roll Arc Side								
Leading	62	40.0	40.0	93	60.0	60.0	155	50.0
Following	93	60.0	60.0	62	40.0	40.0	155	50.0
Seat Position								
Front-Right	61	39.4	39.4	94	60.7	60.7	155	50.0
Front-Left	94	60.7	60.7	61	39.4	39.4	155	50.0

Table 19: Characteristics of matched case-control occupants – continuous variables stratified by cases and controls

		Roof Crush (cm)[8]	Age (years)	Quarter Rolls[9]	HNS-NISS[10]
Cases Injured (N=155)	Mean	24.6	30.0	4.5	7.3
	Std. Dev.	16.0	15.6	2.9	10.4
	Min.	5.5	14	1	1
	Max.	69	79	17	57
Controls Uninjured (N=155)	Mean	22.0	29.3	4.5	-
	Std. Dev.	15.4	14.5	2.9	-
	Min.	5.5	14	1	-
	Max.	69	80	17	-
Total (N=310)	Mean	23.3	29.7	4.5	3.7
	Std. Dev.	15.7	15.0	2.9	8.2
	Min.	5.5	14	1	0
	Max.	69	80	17	57

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[8] Categorically recorded in the NASS-CDS

[9] 17 denotes ≥ 17

[10] All controls have HNS-NISS = 0

2) Univariable Fixed-Effects Logistic Regression

No weighted analysis could be carried out for the matched case-control study as occupants within a pair had identical weight values. Un-weighted univariable logistic regression models can be seen in Table 20.

Table 20: Univariable models for matched case-control study occupants – odds of head, neck and spine injury

	OR	95% CI	p	SE
Roof Crush (Continuous)				
Plus 10 cm	1.41	1.07 - 1.86	0.014	0.198
Roof Crush (Categorical)			0.091	
≥3, <8 cm	Ref.	-	-	-
≥8, <15 cm	0.83	0.36 - 1.89	0.660	0.349
≥15, <30 cm	2.33	0.99 - 5.46	0.053	1.012
≥30, <46 cm	2.34	0.81 - 6.78	0.117	1.271
≥46, <61 cm	5.03	0.85 - 29.62	0.074	4.550
≥61 cm	8.72	0.70 - 108.54	0.092	11.216
Front Airbag Deployment				
Deployed	Ref.	-	-	-
Not Deployed/Equipped	1.00	0.20 - 4.95	1.000	0.816
Seatbelt Use				
Used	Ref.	-	-	-
Not Used/Equipped	1.24	0.65 - 2.34	0.517	0.403
Roll Arc Side				
Leading	Ref.	-	-	-
Following	1.50	1.09 - 2.07	0.013	0.246
Seat Position				
Front-Right	Ref.	-	-	-
Front-Left	1.54	1.12 - 2.13	0.009	0.253
Age				
Plus 1 year	1.01	0.98 - 1.05	0.348	0.016

3) Multivariable Fixed-Effects Logistic Regression

Only variables that achieved a $p \leq 0.20$ in univariable modeling were considered for inclusion in a multivariable model. Roof crush (continuous and categorical), roll arc position and seating position all satisfied this criterion. Continuous rather than categorical roof crush was used in multivariable modeling so as to be consistent with the cross-sectional analysis.

After backwards elimination two potential models emerged (Tables 21 and 22). The first (Model 1) included roof crush and seat position, while the second (Model 2) included roof crush and roll arc position. Both models had very similar AIC and BIC values (AIC=205.06, BIC=212.53 and AIC=207.76, BIC=215.24 respectively). Both seat position (p=0.008) and roll arc position (p=0.036) were statistically significant in their respective models.

Using the Nagelkerke method, the $\overline{R}^2$ value was 0.1137 for the model with seat position and 0.0922 for the model with roll arc position. In the former model 11% of the variation in the outcome can be explained by the explanatory variables, as compared to 9% in the latter model. Based on the p-values, AIC, BIC and coefficient of determination, a final model including seat position is preferable by a narrow statistical margin. In this model, a 10 cm increase in roof crush is associated with a 44% increase in the odds of being an injured occupant (OR=1.44 95% CI (1.08, 1.91), p=0.014). Relative to occupants in the front-right seat position, those in the front-left have a 56% increase in the odds of being injured (OR=1.56 95% CI (1.12, 2.17), p=0.008).

Table 21: Multivariable model 1 for matched case-control study occupants – odds of head, neck and spine injury

	OR	95% CI	p	SE
Roof Crush (Continuous)				
Plus 10 cm	1.44	1.08 - 1.91	0.014	0.2103
Seat Position				
Front-Right	Ref.	-	-	-
Front-Left	1.56	1.12 - 2.17	0.008	0.2629

Table 22: Multivariable model 2 for matched case-control study occupants – odds of head, neck and spine injury

	OR	95% CI	p	SE
Roof Crush (Continuous)				
Plus 10 cm	1.35	1.03 - 1.77	0.033	0.1887
Roll Arc Side				
Leading	Ref.	-	-	-
Following	1.42	1.02 - 1.98	0.036	0.2388

Discussion and Conclusions

This study sought to determine if increased measurements of vertical roof crush by a roof component at an occupant's seating position were associated with increased odds of head, neck and spine injury in a rollover MVC. The injuries considered were caused by vehicle roof components, as determined by crash investigators recording information for the NASS-CDS. If indeed vertical roof crush is not associated with injury, increased measurements of roof crush by these injurious roof components should not be associated with increased odds of injury. This was not observed. Increased measurements of roof crush were associated with increased odds of injury. We found a 64% (95% CI: 26-114%) increase in the odds of HNS-NISS ≥ 9 for each additional 10 cm of vertical roof crush. Similarly we found that a 10 cm increase in vertical roof crush was associated with a 44% (95% CI: 8-91%) increase in the odds of any injury (vs. no injury) to the head, neck and spine.

All occupants in the cross-sectional analysis using HNS-NISS were injured and experienced roof crush at their seating position. It is important to stress that the odds ratio for roof crush represents a relative difference comparing less life-threatening injury to more life-threatening injury. It does not describe absolute difference between no injury versus injury.

For both outcomes evaluated in this study (injury vs. no injury and HNS-NISS ≥ 9) roof crush was a statistically significant predictor. In univariable models even low levels of roof crush were associated with increased odds of injury. Measurements of roof crush in the NASS-CDS are taken along a vehicle's vertical axis. This study does not account for roof crush in the lateral (sideways) direction.

This is a potential limitation because this form of roof crush may also be predictive of injury.

A statistically significant interaction between airbag deployment and seatbelt use with respect to the odds of HNS-NISS ≥ 9 was also observed. In weighted modeling, the absence of front airbag deployment while properly wearing a seatbelt was associated with a 27% (95% CI: 10-69%) reduction in the odds of HNS-NISS ≥ 9 relative to having a front airbag deploy while properly wearing a seatbelt. The results were similar in un-weighted modeling. Airbag deployment may be indicative of more severe crash conditions. It is also plausible that a belted occupant who has also been subjected to an airbag deployment will be in a more erect position in his or her seat at the time of the roof crush, and thus more prone to injury from intruding roof components. No other statistically significant interactions were observed between air bag deployment and seat belt use, between airbag deployment and roof crush, or seatbelt use and roof crush, with respect to the outcome.

This study accounted for occupant age but not height. In the cross-sectional analysis increased age was associated with increased odds of HNS-NISS ≥ 9 in both weighted and un-weighted final multivariable models. Each additional year of age was associated with a 3% (95% CI: 1-4%) increase in the odds of the outcome in weighted modeling. This suggests that increased age imparts a greater propensity for injury as the body loses its ability to resist injurious forces and recover from their effects. Occupant height may be a useful variable for inclusion in future research. Pre-crash headroom is partially a result of occupant height, and omission of this variable is a potential limitation of the present study.

Weighted and un-weighted models did differ. Compare the weighted univariable odds ratios for categorical roof crush (Table 7) to their un-weighted counterparts (Table 8). Both variables display a dose-response curve whereby increased roof crush measurements are associated with increased odds of HNS-NISS ≥ 9. However, the fifth stratum of roof crush (46-61 cm) in the weighted model has an unusually large odds ratio (37.60). This is due to several observations with very large weights. If outliers with weights > 1000 are removed from this model the dose-response becomes more uniform and closely follows the un-weighted univariable models. However, including these weight outliers does not change the overall statistical significance of roof crush or the implications of the model. The implications of weighted and un-weighted models did not differ meaningfully with respect to the association between vertical roof crush and the outcome.

Other limitations related to measurement should be considered in the interpretation of our findings. How a rollover MVC is defined may vary depending on the aspect of vehicle or occupant dynamics an investigator wishes to evaluate. Many studies use the criterion that a vehicle must have experienced at least two quarter turns (≥ 180°) about its long axis. The present study included vehicles that experienced at least one quarter turn (≥ 90°) about the long axis, or a "roll". Inclusion of these vehicles in our data set provides representation of additional MVCs with the potential for impact forces which may result in vertical roof crush and injury to occupants, and therefore may have higher generalizability to the full range of MVCs involving rolls. Differences in our estimates of association with prior studies which included only rolls with two quarter turns or more are expected to be small because only 53 vehicles or 5.5% of our total sample experienced less than two quarter turns.

AIS injuries to the head, neck and spine that were coded as either a "0" (no injury) or a "7" (injured, severity unknown) were omitted from this analysis due to potential misclassification. The rational for this decision is described in the Methods section. Knowledge of the degree of misclassification in AIS, particularly values of 0, is absent. Omission of these outcomes could introduce bias, though the authors do not believe this is the case. Indeed inclusion of AIS 0 scores could bias the results of this analysis towards the null.

The NASS-CDS is a weighted sample of all MVCs for which a police report was filed. This type of MVC tends to be more severe and thus this data source is skewed towards more severe MVCs. However, given the nature of rollover crashes this is less of a concern. Nearly all rollover MVCs are severe and there are likely very few single vehicle rollovers in which the vehicle involved was able to leave the scene without a police report being filed. Thus the sample of single vehicle rollover crashes in the NASS-CDS is probably more representative of all single vehicle rollover crashes in the nation, when compared to other crash types that are recorded.

To date, the authors are unaware of any other studies that have used GEE to control for the correlated nature of individuals occupying the same vehicle. Furthermore, this study employs a matched case-control design that has not been used in prior epidemiological rollover studies. Both these methods allow for the control of variables that were not included in the analysis and thus a reduction in potential confounding. The GEE analysis employed semirobust standard error. This more conservative approach reduces the possibility of a Type I error or making a spurious association.

With regard to the effect of roof crush on the outcome of interest, the present analysis is in agreement with many epidemiological and ATD based studies [6][10][16][17][18][19][20][27][28][38]. However it contrasts starkly with prior research sponsored by the automotive industry [9][11][12][13][14][15][22][24]. There are many more studies on both sides of the debate that were, for the sake of brevity, not reviewed in the present study.

Future research should focus on evaluating the efficacy of amendments to FMVSS 216, to ascertain if increased SWR standards have resulted in a reduction of injury or death. Increasing roof strength may necessitate more steel or alternate designs in the manufacture of vehicle roofs. These changes must be balanced with competing, and arguably valid concerns, such as fuel economy, center of gravity (which influences the propensity to roll) and cost to both manufacturers and consumers. Defining a reasonable degree of protection should be a consideration in future research. However, before any such research can be conducted, significant time must transpire before a large enough proportion of the national fleet is composed of vehicles that comply with these new standards.

Though this study concentrates on what occurs after a rollover crash is initiated, the importance of crash prevention must not be overlooked. Efforts to improve driver education, reduce speed limits, lower vehicle center of gravity, and increase the adoption of electronic stability control and anti-lock brakes may help prevent rollovers, as well as other crash types, from occurring in the first place. From a public health standpoint, achieving this end is desirable. Injuries resulting from MVCs are a substantial and costly contributor to national morbidity and mortality.

In conclusion, this study presents a statistical association between vertical roof crush and injury to the head, neck and spine that constitutes a public health concern. Furthermore, the results of this study suggest that increasing roof strength (and as a corollary decreasing roof crush) may reduce injury, death and monetary cost to society associated with both these outcomes.

References

[1] Centers for Disease Control. (2010) WISQARS (Web-based Injury Statistics Query and Reporting System). [Online]. http://www.cdc.gov/Motorvehiclesafety/index.html

[2] Insurance Institute for Highway Safety. (2009) Occupants of cars, pickups, SUVs, and vans. [Online]. http://www.iihs.org/research/fatality_facts_2009/occupants.html

[3] National Safety Council. (2010) Summary from Injury Facts, 2010 Edition. [Online]. http://www.nsc.org/news_resources/injury_and_death_statistics/Documents/Summary_2010_Ed.pdf

[4] Ted R. Miller and Eduard Zaloshnja, "What Do US Traffic Crashes Cost Employers?," *Association for the Advancement of Automotive Medicine*, vol. 47, pp. 607-610, 2003.

[5] Delia Hendrie, Greg Lyle, and Brian Fildes, "The Cost of Injuries Sustained in Road Crashes," *Association for the Advancement of Automotive Medicine*, vol. 47, pp. 605-607, 2003.

[6] Martha W. Bidez, John E. Cochran, Dottie King, and Donald S. Burke III, "Occupant Dynamics in Rollover Crashes: Influence of Roof Deformation and Seat Belt Performance on Probable Spinal Column Injury," *Annals of Biomedical Engineering*, vol. 35, no. 11, pp. 1973-1988, 2007.

[7] Narayan Yogonandran et al., "Epidemiology and Injury Biomechanics of Motor Vehicle Related Trauma to the Human Spine," *SAE Technical Papers*, 1989.

[8] David C Viano, "Causes and Control of Spinal Cord Injury in Automotive Crashes," *World Journal of Surgery*, vol. 16, pp. 410-419, 1992.

[9] E. Moffatt, "Occupant Motion in Rollover Collisions.," in *19th Conference of the American Association of Automotive Medicine*, San Deigo, CA, 1975.

[10] D Friedman and C E Nash, "Advanced Roof Design for Rollover Protection," in *17th International Tehcnical Conference on the Enhanced Safety of Vehicles*, 2001.

[11] David C Viano and Chantal S Parenteau, "Vehicle and Occupant Responses in a Friction Trip Rollover Test," *Society of Automotive Engineers*, 2009.

[12] G S Bahling et al., "Rollover and Drop Tests - The Influence Roof Strength on Injury Mechanics Using Belted Dummies," *SAE Technical Papers*, 1990.

[13] Garry S Bahling, Thomas R Bundorf, Edward A Moffatt, and Kenneth F Orlowski, "The Influence of Increased Roof Strength on Belted and Unbelted Dummies in Rollover and Drop Tests," *Journal of Trauma, Injury Infection and Critical Care*, 1995.

[14] M B James, R P Nordhagen, D C Schneider, and S W Koh, "Occupant Injury in Rollover Crashes: A Reexaination of Malibu II," *SAE Technical Papers*, 2007.

[15] James Raddin, Joseph Cormier, Brian Smyth, Jeffery Croteau, and Eddie Cooper, "Compressiv Neck Injury and its Relationship to Head Contact and Torso Motion during Vehicle Rollovers," *Society of Automotive Engineers*, 2009.

[16] Raphael Grzebieta, David Young, Michael Bambach, and Andrew McIntosh, "Rollover Crashes: Diving Versus Roof Crush," in *Enhanced Safety of Vehicles Conference*, Lyon, 2007.

[17] David Young, Raphael Grzebieta, Andrew McIntosh, Michael Bambach, and Bertrand Frechede, "Diving versus roof intrusion: a review of rollover injury causation," in *International Crashworthiness Conference*, vol. 12, 2007.

[18] R H Grzebieta et al., "Rollover Crashworthiness: The Final Frontier for Vehicle Passive Safety," in *Australasian Road Safety Research Policing and Education Conference*, Melbourne, 2007.

[19] Jingwen Hu, Clifford C Chou, Yang H King, and King I Albert, "A Weighted Logistic Regression Analysis for Predicting the Odds of Head/Face and Neck Injuries During Rollover Crashes," *Annual Proceedings Association for the Advancement of Automotive Engineering*, vol. 51, pp. 363-379, 2007.

[20] Matthew L. Brumbelow, Eric R. Teoh, David S. Zuby, and Anne T. McCartt, "Roof Strength and Injury Risk in Rollover Crashes," *Traffic Injury Prevention*, vol. 10, pp. 252-265, 2009.

[21] Stephen P. Burns, Robert P. Kaufman, Christopher D. Mack, and Eileen Bulger, "Cost of Spinal Cord Injuries Caused by Rollover Automobile Crashes," *Injury Prevention*, vol. 16, pp. 74-78, 2010.

[22] Donald F. Huelke and Charles P. Compton, "Injury Frequency and Severity in Rollover Car Crashes as Related to Occupant Ejection, Contacts and Roof Damage," *Accident Analysis and Prevention*, vol. 15, no. 5, pp. 395-401, 1983.

[23] Chantal S Parenteau and Minoo Shah, "Driver Injuries in US Single-Event Rollovers," *Society of Automotive Engineers*, 2000.

[24] E A Moffatt and J Padmanaban, "The Relationship Between Vehicle Roof Strength and Occupant Injury in Rollover Crash Data," *39th Annual Conference of the Association for the Advancement of Automotive Medicine*, pp. 245-267, 1995.

[25] Melissa A Schiff and Peter Cummings, "Comparison of Reporting of Seat Belt Use by Police and Crash Investigators: Variation in Agreement by Injury Severity," *Accident Analysis and Prevention*, vol. 36, pp. 961-965, 2004.

[26] James H Hedlund, Robert G Ulmer, and Veronika Shabanova Northrup, "State Laws and Practices for BAC Testing and Reporting Drivers Involved in Fatal Crashes," US Department of Transportation, Washington, DC, 2004.

[27] Glen C. Rains and Joseph N. Kanianthra, "Determination of the Significance of Roof Crush on Head and Neck Injury to Passenger Vehicle Occupants in Rollover Crashes," *SAE Technical Papers*, 1995.

[28] Samuel P. Mandell, Robert Kaufman, Christopher D. Mack, and Eileen M. Bulger, "Mortality and Injury Patterns Associated with Roof Crush in Rollover Crashes," *Accident Analysis and Prevention*, vol. 42, pp. 1326-1331, 2010.

[29] Jele Dietrich, Joseph Kuebler, and Peggy Auinger, "Risk of Injury and Fatality in Single Vehicle Rollover Crashes: Danger for the Front Seat Occupant in the "Outisde Arc"," *Academic Emergency Medicine*, vol. 14, pp. 899-902, 2007.

[30] Claire D. Gloeckner et al., "Implications of Vehicle Roll Direction on Occupant Ejection and Injury Risk," *Association for the Advancement of Automotive Medicine*, vol. 50, pp. 155-169, 2006.

[31] O. Jr. Keifer, O. Sr. Keifer, and M. Woodhouse, "Sport Utility Vehicle (SUV) Rollover Collisions: An Analysis of NASS-CDS Injury Data for 1998 through 2004," *SAE Tehcnical Papers*, 2004.

[32] C. Parenteau, M. Gopal, and D. Viano, "Near- and Far-Side Adult Front Passenger Kinematics in a Vehicle Rollover," *SAE Technical Papers*, 2001.

[33] G. T. Yamaguchi et al., "Occupant Mechanics in Rollover Simulations of High and Low Aspect Ratio Vehicles," *SAE Technical Papers*, 2006.

[34] Dagmar Buzeman Jewkes, "The Effect of Roll Velocity and Roof-to-Ground Impact Angle on Injuries in Lateral Rollovers," *SAE Technical Papers*, pp. Paper No. 2009-01-0823, 2009.

[35] K. Diggs and A. Eigen, "Classification of Rollovers According to Crash Severity," *Association for the Advancement of Automotive Engineering*, vol. 50, pp. 141-153, 2006.

[36] Office of the Federal Registrar, vol. 36, no. 236, pp. 23299-23300. National Highway Traffic Safety Administration - Final Rule. Docket no. 2-6, Notice 5; 49 CFR Part 571 - Motor Vehicle Safety Standards, 1971.

[37] Department of Transportation, 49 CFR Part 571 Docket No. NHTSA-2008-0015 RIN 2127-AG51 Federal Motor Vehicle Safety Standards; Roof Crush Resistance, 2008, Saved as: Federal Motor Vehicle Safety Standards; Roof Crush Resistance.

[38] Mathew L. Brumbelow and Eric R. Teoh, "Roof Strength and Injury Risk in Rollover Crashes of Passenger Cars and SUVs," Insurance Institute for Highway Safety, Paper No. 09-0502 2009.

[39] Office of the Federal Registrar, vol. 74, no. 90, pp. 22348-22393. National Highway Traffic Safety Administration, 2009.

[40] National Highway Traffic Safety Administration. (2010, September) NHTSA. [Online]. http://www.nhtsa.gov/PR/DOT-165-10

[41] National Center for Statistics and Analysis - National Highway Traffic Safety Administration, "National Automotive Sampling System (NASS) Crashworthiness Data System - Analytical User's Manual," US Department of Transportation, Washington, DC, 2009.

[42] David J Thurman, Cindy L Burnett, Deinse E Beaudoin, Lew Jeppson, and Joseph E Sniezek, "Risk Factors and Mechanisms of Occurance in Motor Vehicle-Related Spinal Cord Injuries: Utah," *Accident Analysis and Prevention*, vol. 27, no. 3, pp. 411-415, 1995.

[43] AAAM, "2000 NASS Injury Coding Manual," Department of Transportation, NHTSA, Washington, DC, 2000.

[44] S P Baker, B O'Neill, and W B Long, "The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care," *The Journal of Trauma*, vol. 14, no. 3, pp. 187-196, March 1974.

[45] Turner Osler, Susan Baker, and William Long, "A Modification of the Injury Severity Score that Both Improves and Simplifies Scoring," *The Journal of Trauma: Injury, Infection, and Critical Care*, vol. 43, no. 6, pp. 922-926, 1997.

[46] Carol Conroy et al., "Rollover crashes: Predicting serious injury based on occupant, vehicle, and crash characteristics," *Accident Analysis & Prevention*, vol. 38, pp. 835-842,

2006.

[47] James W. Hardin, *Generalized Estimating Equations*. Boca Raton, Florida: Chapman & Hall/CRC, 2003.

[48] N. J. D. Nagelkerke, "Miscellanea: A note on a general definitionof the coefficientof determination," *Biometrika*, vol. 78, no. 3, pp. 691-692, 1991.