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MACHINE AND VEHICLE SYSTEMS

The Contribution of Vehicle, Occupant and Crash Factors to the Risk of Injury as a Result of Vehicle Rollover -
New approaches to data and modeling analysis

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THE CONTRIBUTION OF VEHICLE, OCCUPANT AND CRASH FACTORS TO THE RISK OF INJURY AS A RESULT OF VEHICLE ROLLOVER -
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ABSTRACT

Injuries and deaths as a result of vehicle rollover remain a consistently large contributor of the overall crash fatalities in the United States. While more new vehicles are becoming equipped with electronic stability control and rollover ejection countermeasures as well as increased roof strength, it will take several years of production before these newer vehicles permeate the fleet and the effectiveness of these technologies can be fully assessed. In the interim, continued vigilance on assessment of rollover injury causation is recommended. This can be done through systematic analysis of aggregate field crash data and specific case studies. Also, mathematical modeling studies can be done to assess the contributions of vehicle, occupant and crash factors to the injury risk of rollover involved occupants.

The major aims of the research in this thesis are to determine how rollover crash investigations and crash field data analysis can determine the most frequent types of injuries and their mechanisms that occur to belted, unejected occupants involved in rollover crashes and, once determined, identify the role of vehicle, occupant and crash factors that can predict injury risk. The first aim can be achieved through case studies and aggregate national crash data analysis while the second aim uses finite element and multi-body modeling of rollover crashes.

Aggregate rollover field data was taken from the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS). Head, spine (cervical) and thoracic injuries dominated the injury with specific injury types in each body region indicating areas of further interest to investigate regarding injury causation. Analysis of specific case studies taken from the Crash Injury Research Engineering Network (CIREN) indicated that single event, single vehicle (pure) rollovers were associated with complex mechanisms of cervical spine injuries that were associated with vehicle roof strength (strength to weight ratio), and the amount of vertical as well as lateral intrusion at the injured occupant location. Occupant body mass index was a possible contributor to injury risk.

A finite element model of a contemporary sedan was used in a simulation of a Controlled Rollover Impact System (CRIS) test to identify vehicle and crash parameters that were most associated with high cervical neck forces in the Hybrid III dummy occupant model. The variables that contributed the most to the occupant and vehicle structural response were pitch angle, roll angle, and drop height. These factors determine where and with what force the vehicle roof impacts the ground. The analysis showed that proper selection of a crash dummy model is also a critical step in the interpretation of effects of the factors used in analysis. Subsequent MADYMO modeling of the CRIS test with the models of the Hybrid III and THOR advanced frontal crash dummy and a facet model of the human body were performed with imported finite element nodal vehicle model outputs representing vehicles with the strongest and weakest roof. When coupled with a parameter analysis of advanced vehicle seat belt restraints, the analysis showed that stronger roofs will reduce injury risk, and that restraint systems can provide additional protection to reduce the potential for occupant head impact to the roof.

The analysis approach to both data and modeling in this thesis provided results through innovative combined crash field data analysis, parametric computer modeling methods and statistical and human body modeling techniques to arrive at the conclusions reached. As future vehicle design evolves with respect to automation and other propulsion systems, designers and engineers need to be aware of the

structural and occupant restraint requirements these vehicles will need as they interact with the fleet and are exposed to potential rollover situations.

KEYWORDS: Rollover, CIREN, NASS-CDS, Injury Causation, CRIS, Intrusion, Restraints, Kinematics, Roof Inversions, THOR, Global Sensitivity Analysis

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Ridella, S.A. and Eigen, A.M. (2008) *Biomechanical Investigation of Injury Mechanisms in Rollover Crashes from the CIREN Database*. In: Proceedings of the International IRCOBI Conference on the Biomechanics of Injury. Bern, Switzerland.

Division of work between authors: Ridella made the outline of this study. Eigen developed the code to extract the relevant CIREN cases based on selection criteria. Ridella and Eigen jointly reviewed all cases used in the study. Ridella completed the data summary tables and presented all data included in the paper. The paper was written and reviewed by Ridella and Eigen.

PAPER II

Ridella, S.A., Eigen, A.M., Kerrigan, J.R. and Crandall, J.R. (2017) *Vehicle and occupant factors in spine injuries of belted, non-ejected occupants involved in rollover crashes.* In review for publication in *Traffic Injury Prevention*.

Division of work between authors: Ridella made the outline of this study. Eigen developed the code to extract the NASS data based on selection criteria as well as generating the weighted data used in the NASS tables and figures. Ridella, Kerrigan and Crandall jointly reviewed all cases used in the study. Ridella completed the CIREN data summary tables and prepared the figures for all the CIREN data included in the paper. The paper was written and updated by Ridella and was reviewed by all authors.

PAPER III

Ridella, S.A. and Bojanowski, C. (2015) *Sensitivity Analysis on the Influence of Vehicle Factors on the Kinematic Response of a Mid-Sized Male Crash Dummy During a Simulation of a Controlled Rollover Crash.* In: Proceedings of the International IRCOBI Conference on the Biomechanics of Injury. Lyon, France.

Division of work between authors: Ridella made the outline of this study and developed the input parameters. Ridella provided the vehicle and dummy models model and worked with Bojanowski to develop input files for analysis. Ridella and Bojanowski jointly reviewed and created tables and figures from output. The paper was written by Ridella and was reviewed by all authors.

PAPER IV

Ridella, S.A. and Bojanowski, C. (2017) *Comparison of Response Variation of THOR and Hybrid III Dummy Models in a Controlled Rollover Impact Model.* Submitted to International Journal of Crashworthiness.

Division of work between authors: Ridella made the outline of this study and determined variables for analysis. Bojanowski used vehicle file from paper three and THOR dummy model provided by Ridella to develop and run input files for analysis. Bojanowski and Ridella jointly reviewed output and created data tables and charts of output. The paper was written by Ridella and was reviewed by all authors.

PAPER V

Ridella, S.A., Cochran, J, Bojanowski, C. and Kerrigan, J. (2017). *Evaluation of Effectiveness of Restraint and Vehicle Factors to Mitigate Injury Measures in Three Occupant Models Involved in Controlled Rollover Crash Simulation*. Submitted to Stapp Car Crash Conference.

Division of work between authors: Ridella made the outline of this study. Bojanowski provided the exported nodal outputs of the models selected for analysis by Ridella. Cochran created and ran MAYDMO input files with imported vehicle files and restraint configurations provided by Ridella. Ridella, Cochran and Kerrigan jointly reviewed initial data and Ridella completed all final analysis of dummy data in Diadem and Hyperview. The paper was written by Ridella and was reviewed by all authors.

Conference Presentations of the Present Work

Ridella S.A., Eigen A.M. *Biomechanical Investigation of Injury Mechanisms in Rollover Crashes from the CIREN Database*. International IRCOBI Conference on the Biomechanics of Injury, 2008.

Ridella, S.A., Eigen, A.M., Kerrigan, J.R., Crandall, J.R. *An Analysis of Injury Type and Distribution of Belted, Non-Ejected Occupants Involved In Rollover Crashes*. 53rd Conference of the Association for Advancement of Automotive Medicine Conference (AAAM), 2009. 53.

Ridella, S.A., Eigen, A.M., Kerrigan, J.R. and Crandall, J.R. *An Analysis Of Injury Type And Distribution Of Belted, Non-ejected Occupants Involved In Rollover Crashes*. Society of Automotive Engineers Government/Industry Meeting, 2010.

Ridella S.A., Bojanowski C.*, Sensitivity Analysis on the Influence of Vehicle Factors on the Kinematic Response of a Mid-Sized Male Crash Dummy during a Simulation of a Controlled Rollover Crash,* International IRCOBI Conference on the Biomechanics of Injury, 2015.

DEFINITIONS AND ACRONYMS

Active Human Model	A modified facet model representing human body geometry and capable of muscle activation.
AIS	Abbreviated Injury Scale. An ordinal scale (1-6) of threat to life associated with an injury.
BioTab	A systematic process to determine the causation of crash injury based on objective analysis of field evidence and comparison to experimental results
BMI	Body Mass Index. Mathematical formula describing a ratio of a person's weight to their height.
Cervical Spine	Referring only to the bony aspects of the cervical area of the spine.
CIREN	Crash Injury Research Engineering Network. Administered by NHTSA since 1996, CIREN is a convenience sample of injured occupants from recently made (less than 6 model years old) vehicles involved in qualifying crashes in the United States.
CRIS	Controlled Impact Rollover System. A test procedure to evaluate the rollover response of a vehicle in a repeatable manner.
Drop Height	The vertical distance the vehicle's center of gravity travels during a CRIS test.
FARS	Fatal Accident Reporting System. A census of all on road fatalities (died within 30 days of the crash) occurring yearly in the United States.
FE	Finite Element
GSA	Global Sensitivity Analysis. Method for evaluation of relative contributions of individual input parameters as well as the interactions between these parameters to the response of a system.
HARM	A measure of societal cost of an injury based on maximum AIS level. It includes both medical costs to treat the injury and indirect costs such as lost income (Malliaris et al, 1982)
Hybrid III	A crash test dummy designed for evaluation of occupant response in a frontal impact mode.
ICS	Injury Causation Scenario. Used in BioTab process to describe the causation of a particular injury.
IPC	Involved Physical Component. The vehicle component that interacted with the occupant in the injury causation scenario.
IIHS	Insurance Institute for Highway Safety.
Intrusion	The interior deformation of a vehicle component into the occupant space. Specified as lateral or vertical in the NASS and CIREN data.

Inversion	Number of times that the roof faced or contacted the ground by the time the rollover is complete. E.g., 2 quarter turns are 1 inversion, 6 quarter turns are 2 inversions.Usually counted as integers.
ISS	Injury Severity Score – sum of the squares of the highest AIS score from 3 different body regions.
LS-DYNA	Finite element software code developed for analysis of component and system response to dynamic input.
MADYMO	Mathematical Dynamic Modeling. Software code developed for multi-body analysis of occupant and vehicle crash responses.
NASS-CDS	National Accident Sampling System – Crashworthiness Data System
NHTSA	National Highway Traffic Safety Administration
Pitch Angle	Angle the between the logitudinal axis of the vehicle and the road.
Pure rollover	A rollover comprising a single vehicle, single event crash as defined in the NASS database.
Quarter turn	A unit of rollover "severity" indicating the vehicle has rolled through at least a 90 degree angle about its longitudinal axis.
Roll Angle	Angle between lateral axis of vehicle and the road at impact
Roll Rate	Rate of angular rotation around the vehicle's longitudinal axis during a rollover event.
Rollover	A vehicle crash resulting in a rolling motion of the vehicle around its longitudinal axis and involving intermittent ground contact with the sides, roof or bottom of the vehicle.
Sobol	A method of Global Sensitivity Analysis to determine the contribution of input parameters to the variation of the output of a system.
SWR	Strength-to-Weight Ratio. The ratio of the peak force relative to unloaded vehicle mass before 125mm of crush is achieved in an FMVSS216 quasi-static roof crush compliance test.
THOR	Test device for Human Occupant Restraint. An advanced crash test dummy developed for use in frontal and oblique crash modes.

1. INTRODUCTION

The deleterious effects of vehicular rollover crashes continue to be a significant contributor to overall crash fatality and calls for continued research from a variety of disciplines. Over the last 40 years, data has been generated from rollover crash field data analysis, crash injury analysis, vehicle testing, and computer modeling. Reviewing and summarizing relevant historical and current literature related to rollover injuries is important. The combined knowledge of rollover testing, assessment of vehicle and occupant factors and the role of computer modeling related to rollover are essential to determine what approaches are still required to mitigate the injuries and deaths that are still occurring. The following sections detail the field data and magnitude of the rollover issue, with a bias for information from the United States, where rollover crashes and countermeasures have been more extensively researched compared to the rest of the world. Then the rollover testing, regulation, simulation efforts and countermeasures will be summarized as they relate to the aims of the specific research results that follow and the recommendations for future work.

1.1 Field Data Analysis - The Rollover Issue

A significant amount of media, governmental and academic attention in the United States has been given to the vehicle rollover issue recently, and is has not done so without basis. The number of vehicles involved in a rollover or has rollover as part of a crash event, represents a substantial part of the overall crash and injury picture in the U.S. According to the National Highway Traffic Safety Administration (NHTSA), of the 6.3 million police-reported vehicle crashes that occurred in the United States in 2015, approximately 2%, or just over 300,000, involved rollover (NHTSA 2015b). In 2004, the annual toll of rollover crashes included 10,591 fatally injured occupants and over 225,000 injured occupants (NHTSA, 2004). Broken down by vehicle type, approximately 28% of the fatalities occurred in passenger cars and over 60% occurred in sport utility vehicles (SUVs) and pickup (P/U) trucks. The difference in fatalities by vehicle type is due to a somewhat higher propensity for SUVs to roll than passenger cars. This is related to a vehicle's resistance to rollover that can be expressed as the relationship between the track width of the vehicle and the vehicle's center of gravity (CG) height. NHTSA expressed this relationship as a Static Stability Factor (SSF) and uses the factor to grade rollover injury risk in its New Car Assessment Program (NCAP). SUVs typically have a higher rollover risk as their CG heights are greater than passenger cars. NHTSA has observed that SSF values have reduced for the fleet in the US thus contributing to reductions in rollover crashes and fatalities (NHTSA, 2005).

Between 2006 and 2010, impressive reductions in overall crash fatalities in the United States as well as in Europe and Asia have been demonstrated. In 2006, 42,708 total fatalities were recorded in the US, however, these had reduced to 32,999 by 2010. The annual number of fatalities remained stable for next four years, however, fatalities increased in 2015 by 7.2% to 35,092. In 2006, 10,442 fatalities were attributed to rollover of light vehicles (vehicles weighing less than 4,500kg) representing about 25% of the overall crash-related fatalities in the US. For 2015, there were 6,990 rollover related fatalities of light vehicle occupants in the US, representing approximately 20% of all crash-related fatalities (Figure 1.1), but a 33% reduction from 2006. This consistent reduction may be attributable to wider spread use of rollover curtain airbags, electronic stability control and stronger roofs. However, when looking at rollover fatalities of unejected occupants in light vehicles as a percentage of all rollover fatalities, the number has risen steadily since 2006 to represent 47% of all occupants killed in a rollover crash (Figure 1.1). This represents a yearly number of approximately 3,400 fatally injured occupants in light vehicles that were not ejected during the roll event. Presumably, most of those occupants were belted and this continued rise indicates an area of research needing additional analysis.

Vehicle rollover crashes have also been studied in other parts of the world, but mainly in Europe. Mackay (1993) published information on urban rollovers in the United Kingdom (UK) and Otte (2005) published an extensive analysis of rollover crashes in Germany. Parenteau et al. (2001) compared rollover crash characteristics between the US and the UK. These papers will be summarized below. Little research has been published in Asia, however, there has been recent research activity in Australia as a result of high profile rollover crashes. Those papers will also be summarized in Paper 2.

The most definitive work in rollover outside the United States was undertaken by the European Community in the 2002-2005 timeframe. A forty-two month project called Rollover: Improvement of Rollover Safety for Passenger Vehicles was carried out under the European Commission 5th Framework. In its final report (Gugler et al, 2005), the study found that rollover comprised 5-10% of all crashes and 10-20% of the fatalities, depending on the country that was reporting the statistics. These numbers indicate a higher overall incidence of rollover in Europe compared to US (2% of crashes as described above), but a much smaller percentage of overall fatalities compared to the United States (about ½ as much). Some of these differences could be due to more passenger vehicles (as a percent of total vehicles) in the European compared to US fleet which continues to have about $^{2}/_{3}$ of all vehicle sales being SUVs and light trucks. Other factors that could explain US and European rollover crash rate differences may be due to crash reporting differences among EU countries, differences in crash location (urban vs. rural) and differences in road design (more roundabouts in EU), i.e. lower speed rollovers versus single vehicle loss of control crashes in US on limited access roads.

A large amount of research has been done to analyze the reasons for rollover fatalities and injuries based on actual field data analysis. A large body of literature describes the incidence and severity of rollover injuries in the field. Huelke (1973) reported on 377 front seat occupants in 266 passenger car rollovers. Thirty percent of unrestrained occupants were ejected and half of those sustained fatal injuries. No restrained occupants were ejected. Only 6% of belted occupants had serious or fatal injuries. 33% of injuries to the head resulted from contact to interior surfaces. 50% of all fatal injuries were to the head. Head injury severity was not related to roof crush. Hight et al (1972) described a highly detailed study of 139 vehicles in rollover with 225 occupants. 65% of the events were single vehicle crashes. Forty percent of 35 ejected occupants, all unrestrained, were fatally injured. Head/face/brain was injured in nearly 70% of the occupants regardless of restraint use. The roof/side rail and header regions are listed as frequently contacted areas contributing to head injury.

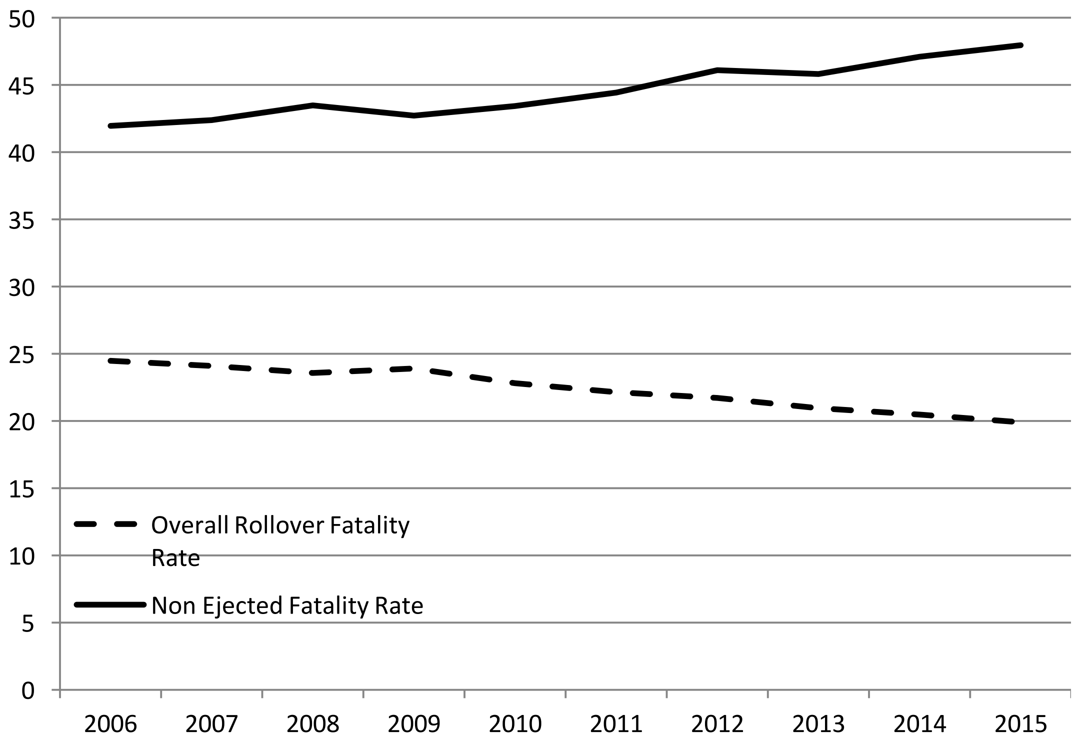

Figure 1.1. Trend in US Light Vehicle Crash Fatalities Attributable to Rollover Event as a Proportion of Total Fatalities (solid) and Non-Ejected Rollover Fatalities as a Proportion of all Light Vehicle Rollover Fatalities (dashed).

Huelke et al (1976, 1983) continued his previous analysis of rollover injury in these subsequent papers. The earlier publication discussed vehicle factors and restraints with respect to rollover injuries. Lap/shoulder belt usage nearly eliminated ejection in the cases analyzed and frequency of severe injury was greatly reduced. There is mention of the possible contribution of the B-pillar to injury potential of non-ejected occupants. Of seven belted fatalities investigated, one died from head injuries due to A-pillar contact and another from an intruding pole. The latter publication did an in-depth analysis of National Crash Severity Study (NCSS) data files. More specific vehicle sites for injury potential of non-ejected occupants were identified. The head and neck regions sustained most injury from impacts to the side rail or side window glazing area and a vast majority of those injuries were AIS (Abbreviated Injury Scale) <=2. The highest severity injuries for non-ejected occupants were in the chest and extremity areas.

In another study, Mackay et al. (1993) investigated 158 vehicle rollovers in an urban environment with respect to crash characteristics, injuries, seat belt use, and ejection. Findings included that 63% of vehicles rolled only ½ revolution (one roof inversion) or less, 80% experienced 1 roll or less and only 3 had 3 or more rolls. Sixteen of nineteen ejections were unrestrained and ten of the nineteen ejections were fatal. Minor head injuries dominated restrained drivers (AIS 1). Mackay concluded, “ejection is an indicator of a severe collision” and not in itself a predictor of injuries, i.e., injury may have occurred inside the vehicle before ejection. Also, lower urban speeds may indicate different conclusions than highway speeds.

Parenteau et al. (2001) studied pre-crash characteristics and crash injury in rollovers taken from multiple years of NASS-CDS and compared the results to similar data from the UK’s Cooperative Crash Injury Study (CCIS). They found that rollovers in the UK accounted for 13% of all crashes but accounted for 21% of all serious injury while rollovers in the US accounted for 9% of all crashes and 25% of all serious injury. They also found that 76% of rollovers in the UK occurred on roads with posted speed limits above 80kph (50mph) compared to only 51% of the rollovers in the US. For both countries, rollovers were significantly more likely to occur on higher posted speed limit roads than non-rollover crashes. Risk of serious injury by body region was similar for both countries with head, upper extremity and lower extremity the most frequently injured body regions.

Two additional studies investigated the nature of injury mechanisms. Parenteau and Shah (2000) studied drivers in single vehicle rollover crashes using 5 years of NASS-CDS data. For ejected drivers in "roll-left trip-overs" (driver side leading rollover), 60% of complete and 80% of partial ejections were through the left front non-fixed glazing. For roll-right, 33% of complete ejections were through the left front non-fixed glazing. Serious head injuries dominated the ejected driver injury pattern, especially as the number of quarter rolls increased. The results also indicate different injury patterns for restrained and unrestrained, non-ejected occupants in right side leading vs. left side (or driver side in US) leading side rollovers. Non-ejected belted drivers sustained more serious head and spinal injuries in ride side leading events, while sustaining more upper extremity and thoracic injuries in left or driver-side leading situations. Digges et al (1993) studied 4 years of NASS/CDS data with respect to AIS and HARM for ejected and non-ejected occupants in rollovers. HARM is a measure of societal cost of an injury based on maximum AIS level. It includes both medical costs to treat the injury and indirect costs such as lost income (Malliaris et al, 1982). Digges et al found that for rollover crashes, ejections are only 10% of all cases, but they contributed to 55% of all HARM. For non-ejected occupants, pillars/rail/header/upper side interior account for 18.6% of all HARM from most serious injuries. When taking into account only interior structures, the pillars/rail/header/upper interior account for 28.9% of all interior harm sources. For restrained or unrestrained occupants, these same structures account for similar levels of HARM to the head or head/spine indicating a major source of injury when occupants are not ejected. The authors suggest that interior surface padding or airbags may reduce interior contact risks. Later work by Digges and Malliaris (both 1998) concluded that improvements to belt technology could have a large benefit as belted occupants exposed to rollovers had an injury rate 4.26 times lower than unbelted occupants in rollovers.

Bedewi et al. (2003) undertook a significant analysis of the NASS database in 2003 with respect to rollover injuries and causation. He extracted 676 rollover cases from the NASS where there was a documented AIS3+ injury to a case vehicle occupant. He then analyzed the case vehicle for crash conditions such as number of rolls, roll direction, rollover initiation event, roll direction, and roof deformation for both unweighted (raw) and weighted sample sizes. In terms of injury and crash conditions, the unweighted data reflect the fatality data indicated above for vehicle type, i.e., the distribution of vehicle types is the same for injury as it is for fatality. Two thirds of the cases were 4 quarter rolls (one roof inversion) or less regardless of vehicle type. In terms of roof crush, 25% of the cases had 0 cm of roof deformation, that is, negligible roof deformation was recorded. Splitting out the minor roll severity cases (one ¼ roll) shows that 55% of those cases had no roof deformation as opposed to only 18% of the cases where there was more than one ¼ roll. Further looking at roof deformation, and considering only belted, non-ejected occupants (446 total occupants), there was an increase in tendency for more head injuries as roof deformation increased. Head injuries dominated the occupants in the data, comprising over 45% of all injuries, followed by chest (22%). Severe neck injuries occurred only in 5% of all the cases. Bedewi did not conclude a direct causal relationship between head injury and roof crush since the kinematics of the vehicle and occupant were not considered, nor is roof crush a "biomechanical metric related to injury risk". Their data is compelling to consider roof crush during the initial roll phase (first half roll or one roof inversion) with respect to occupant head injury.

This is supported by work from Otte et al. (2005) in Germany who did an in-depth investigation of 434 rollover cases. They found that over 75% of the cases were less than one vehicle roll and only had one roof contact. The belted occupants of these vehicles sustained head injuries at a greater frequency than belted frontal crash occupants, but the severity of the head injuries did not reach AIS3+ until roof deformations were over 30cm. Eighty percent of the severe injuries and 80% of the minor injuries occurred at roof deformations less than 15 cm. These were severe crashes and the report indicates that 90% of these crashes involved vehicles traveling at over 60 kph prior to the rollover event.

Atkinson et al. (2004) published a comprehensive analysis of rollover cases from the NASS-CDS from 1998-2000. Categorizing injury type, severity, and belt condition for single vehicle rollover crashes, the authors conclude that two design points are necessary to evaluate rollover injury, ideally through means of computer simulation. One design point is a 2-4 quarter turn rollover (one roof inversion) to induce roof crush and its potential effect on occupant (non-ejected) injury. A second design point is a more severe rollover event (2 roof inversions) that evaluates ejection potential, countermeasures and their effect at mitigating ejection. These 2 tests (or simulations) are based on the fact that the head injury severity of occupants is similar for belted, unejected occupants and belted ejected occupants.

NHTSA (2003) has made its own estimates of the extent of injury and death relative to roof crush through analysis of NASS cases. The flow diagram in Figure 1.2 below shows the breakdown of occupant injury with respect to the unejected occupant, that is, the occupant more likely to experience the complete roof crush event. According to the chart, NHTSA estimates that the 28% of unejected, belted occupants will have one roof related injury where there was roof intrusion present. This figure does not give the amount of roof intrusion, but the intrusion issue will be further discussed below.

In a more complete analysis, NHTSA did an assessment of roof crush and injury in a paper by Rains and Kanianthra (1995). They looked at head and neck injuries in belted, non-ejected occupants where there was at least two ¼ rolls of the vehicle. By measuring roof crush in vehicles post-crash and performing a calculation of headroom reduction (based on vehicle and occupant measurements), they found a 69% reduction in headroom for injured occupants versus a 31% reduction in headroom for uninjured occupants after controlling for rollover crash severity. In this particular comparison, the average "severity" was just over three ¼ rolls (still less than one roll).

NHTSA (2004, 2005b) extended their review of unejected, belted occupants through additional analysis of the NASS database. Comprising 7 years of NASS analysis, they found, on an annual basis, approximately 166,000 belted, unejected, vehicle occupants are involved in a rollover crash. Seventy percent of those occupants are involved in a rollover crash that has one roof inversion (basically between 2 and 5 ¼ turns of the vehicle). NHTSA shows that most severe head injuries (AIS => 3) occur in rollovers with one roof to ground impact (one roof inversion), but the rate of severe injury is much less at one roof inversion compared to 2 or more roof inversions. At higher severities (more roof to ground impacts), severe chest injuries for belted occupants become more frequent than head injuries. Digges et al. (2005) analysis of the NASS data gives similar results, but Digges broke down crashes by near and far side impacts. More severe injuries occur in far-side impacts, especially for belted occupants, thus implying a kinematic injury mechanism that can impart (or expose) head and thoracic body regions to severe impact forces.

An analysis by Padmanaban et al. (2005) looked at over 101,000 rollover crashes taken from various US state vehicle crash databases and compared a variety of vehicle variables to the likelihood of a serious or fatal injury. Of particular interest was an analysis of the effective headroom calculation (SAE International, 2005) relative to injury outcome in a rollover. This calculation is different than just measuring the head to roof height as it is based on an interior measurement from seat reference point to roof and describes how an occupant may sit in a vehicle. The analysis indicated that effective headroom had no ability to predict the amount of injury in belted occupants involved in a rollover crash.

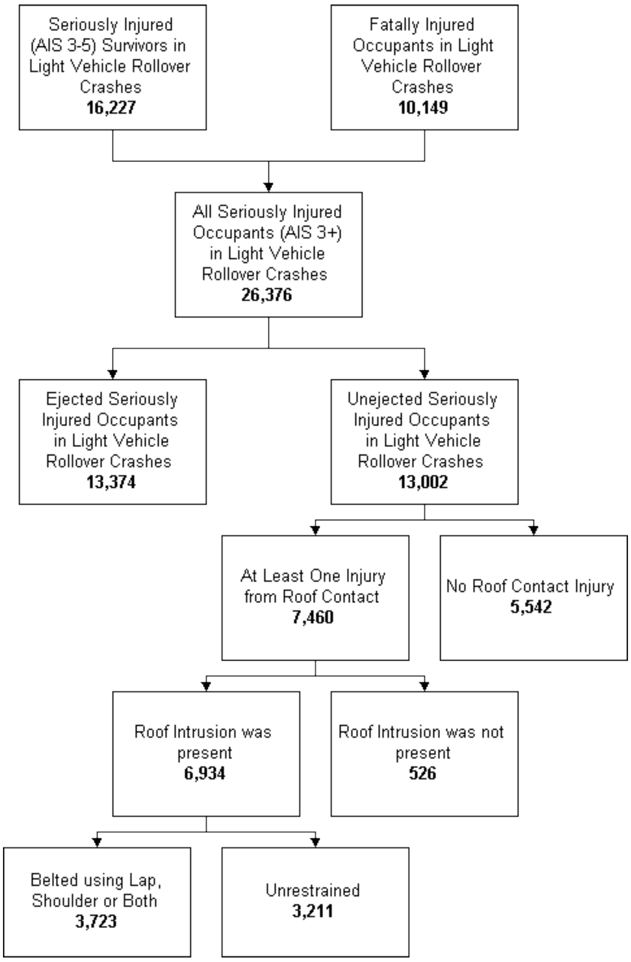

Figure 1.2. Flow Chart of Rollover Fatalities based on ejection status and restraint use (NASS-CDS year – 2005)

There has been a significant amount of analysis of the NASS-CDS data base in recent years by researchers attempting to correlate various factors of rollover crashes with the risk of injury. Mandell et al. (2010) et al analyzed NASS-CDS for association of roof crush on risk of head and spine injury as well as death for belted adults in rollover crashes after controlling for vehicle type, rollover severity (number of rolls), occupant age and occupant gender. They found that the risk of sustaining an AIS 3+ spine injury nearly doubled for as little as 8cm-15cm of roof crush compared to no roof crush, but interestingly only increased to an odds ratio of 2.69 for roof crush levels more than 30cm. However, the mortality risk at 30 cm of roof crush was 7 times the risk when little (< 3cm) of roof crush was noted. The Mandell study included cases from NASS years 1993-2006 and likely included many older vehicles designed to the previous FMVSS 226 standard that allowed roof strength-to-weight ratios (SWR) as low as 1.5.

Bambach et al. (2012) as well as Funk et al. (2012) examined multiple years of recent NASS-CDS data to determine factors associated with increased risk of injury in rollover crashes. Both papers published extensive comparisons of vehicle and occupant factors that may contribute to risk of rollover crash injury. Funk et al found a similar result regarding roof intrusion as a predictor of moderate to severe spine injury. They also found that 35% of the cases with spinal injury had little or no roof intrusion. Older occupant age (>50 vs. 16-24), higher BMI (>30 vs <25) and far side occupants (versus near side) had significantly more risk of death and spinal injury than the comparison population. Even more recently, McMurry et al (2016) reported injury patterns of belted, unejected occupants in rollover crashes taken from NASS-CDS from 1995-2013. Looking at rollover crashes where the rollover was the primary crash event, they found that these occupants were more likely to have only a single serious injury to one body region (primarily thorax, spine and head). Intrusions >15cm occurred 50% of the time in this subset of crashes and injured occupants were more likely to be older and overweight.

In summary, the rollover crash field data has been extensively analyzed over the last several decades. The data from, US, Germany and the United Kingdom all show that fatalities and serious injuries due to rollover crashes are over-represented with respect to the proportion of rollover crashes compared to all crashes. The data also shows that ejection from the vehicle is much more frequent in unbelted occupants than for belted occupants. In terms of injuries, the ejected, unbelted occupants experienced more head injuries than unejected, restrained occupants who had spine, head and thoracic injuries. More sophisticated analyses of the NASS-CDS data have revealed risk factors for occupant and crash characteristics for various serious injuries. Other studies have characterized how the occupant position and roll direction may influence injury type and severity. While providing a comprehensive portrait of the rollover injury issue, there is still missing information on injury types, frequencies and mechanisms that require a more thorough analysis of the NASS data as well as individual rollover crash data from other sources to help understand the injuries and factors that account for them.

1.2 Dynamic Rollover Testing

While the field crash databases give some ability to review the circumstances of a particular rollover crash, they lack the ability to look at how an actual rollover crash occurs. Field data takes into account all rollover cases where actual testing can look at a specific crash mode in a controlled environment. A variety of test conditions have been developed to assess vehicle and occupant motions as a result of vehicle rollover. There appears to be a consensus within the automotive safety community that by prescribing a series of rollover tests, a significant majority of the rollover field crashes can be represented (Viano and Parenteau; 2003). That may be an oversimplification of the problem since, unlike a frontal crash, rollovers can be induced through a variety of vehicle actions and collisions, be single or multiple vehicle in nature, and the vehicle can have completely different motion from a similar vehicle with just a small difference in pre-roll attitude. Regardless of the circumstances, most rollover crashes result in the roof of the vehicle contacting the ground at least once, if not several times.

The testing scenarios range from full vehicle to simulated occupant compartment, quasi-static methods that have helped demonstrate the violent nature of these events. At least 4 typical rollover modes encompass most rollovers in the field: 1.) a tripped event at a high speed like the Federal Motor Vehicle Safety Standard (FMVSS) 208 rollover test, 2.) a rollover induced by a unequal vehicle to road surface interaction (height or friction) that induces an occupant motion toward the side of the tripping before the roll event (so called curb-trip), 3.) a roll with a longitudinal component induced by a roadside object such as a guardrail (screw ramp) and 4.), a rollover induced by off-road vehicle interaction with soft soil that results in a low G, low roll-rate event.

McKibben et al. (1974) described occupant kinematics during a FMVSS 208 rollover test. For a right side (passenger rollover), the “dummies move upward and toward the right (passenger side of the interior)” and “remain pressed into the right side and upper corners of the roof/pillar junctions through most of the first and second revolutions". It is not until in the last roll that more "violent accelerations of occupants" occur. This early paper also observed the inconsistent behavior of the same vehicle make/model when subjected to the FMVSS 208 rollover method.

Sakurai et al. (1993) described testing of 12 full-vehicle screw ramp type rollovers to study roof deformation and the interaction with the crash dummy (belted). The vehicles were driven at 50 kph onto raised ramp at a prescribed angle. Ten of the twelve vehicles sustained one complete roll. The study showed that maximum neck loads occurred before maximum roof crush indicating that roof height may be better predictor of neck loads.

Johnson and Knapton (1984) ran eight staged full vehicle rollover tests of which 7 were driven into a turned down guardrail at speeds between 57 and 72 mph (91-115 kph). The eighth test was a typical FMVSS 208, 30 mph (48 kph) dolly tripped event. Dummies were either unrestrained or restrained with lap or lap/shoulder. Findings included that a significant number of rolls were achieved (1-4) unlike field data where 90.1% of vehicles have one roll or less. Occupant head and torso velocities measured at impact sites around the vehicle give a measure of energy the occupant has during the event. Occupants can strike windows and pillars at velocities as high as 20 feet/sec (6.1 m/s). This value is comparable to values seen by Ridella et al. (2001) in their work on design of rollover restraint countermeasures. Also, one lap/shoulder belted dummy "seemed to have less violent motion" than unrestrained dummies. Partial ejections were equal between restrained and unrestrained occupants, however most restrained occupants wore lap belt only.

The European ROLLOVER project (Gugler, 2005) described a unique test method to simulate a soil trip rollover. So-called "LowG" test methodology (pulse was less than 2 Gs at peak), a sled device was built to provide a series of braking inputs to a tethered vehicle on a sled platform. This induces a low roll-rate versus roll-angle profile typical of soil trip events. The project was able to demonstrate repeatability of the procedure in the lab as well as document occupant kinematics during the event. Optimization of sensor placement, response and restraint systems was identified as a key outcome of this test procedure development.

A series of papers on rollover testing was published by Orlowski et al (1985) and Bahling et al. (1990). Orlowski ran a series of eight rollover tests were using production vehicles (Chevrolet Malibu passenger cars). Four of the cars were altered to have a stiff rollcage added to the roof and pillars to prevent roof deformation during the rollover event. Unbelted, instrumented crash dummies were put into the vehicles and the vehicles were rolled off a dolly cart at 51.5 kph. The average dummy neck loads for the production vehicle was nearly the same as the neck loads for the rollcaged vehicles indicating no protection effect from a "stiffer" roof. The authors concluded that the roof deformation seen in the production vehicles had "no effect on injury mechanics". Bahling et al. repeated the Malibu tests in the early 1990's using belted dummies and determined that regardless of roof stiffness, the dummy neck injury numbers reached their peak before the vehicle roof began to crush. They also did inverted drop tests of these same vehicles using belted dummies and found similar neck loads in dummies whether or not they were in a rollcaged or production vehicle.

Friedman and Nash (2005) reanalyzed the Malibu tests and found that the dummies seated at the far side (or trailing) side of the rolling vehicle showed the highest neck loads in production (non- roof strengthened) vehicles. Friedman tried to assign a roof intrusion velocity based on film analysis of B-pillar movement. He indicates that high velocities of intrusion are present and associated with high dummy neck loads. Further work by Nash and Friedman (2007) describe a test device called the Jordan Rollover System (JRS) that simulates a near and trailing side roof impact during a rollover. The device spins a vehicle along its longitudinal axis and then lowers the vehicle to impact a moving "road". The interior of the vehicle is equipped with string potentiometers to measure deformation at the site of contact allowing for calculation of roof intrusion velocity. The system has been modified over the years and has been compared to other dynamic test systems (Mongiardini et al, 2014). Mongiardini et al indicated that when assessing the potential for head (and presumably neck) injury, a dynamic rollover test protocol must produce a roof-to-ground impact above the seating position in question.

Another particular test method that involves one roof contact that has gained recent interest is the Controlled Rollover Impact System, or CRIS, developed by the Exponent, Inc. test facility in Arizona (Cooper et al, 2001). This device uses a tractor-trailer system to carry and transport a vehicle, rotating on its longitudinal roll axis, before "releasing" the vehicle onto the ground or pavement at any part of the vehicle (roof, wheels, etc.) designated. With special camera mounts, vehicle deformations and test dummy kinematics can be videotaped in detail. CRIS may be used to evaluate a number of important parameters in a rollover event such as roll rate, drop height and impact location, lateral velocity and roof strength. CRIS tests are quite expensive to run at this time due to the vehicle preparation and the specialized rig involved. Moffatt et al. (2003) ran a series of production and roll-caged passenger cars using the CRIS fixture and measured Hybrid III neck load (belted dummy) during the rollover event. Vehicle mounted as well as fixture mounted cameras were installed to measure roof deformation. The results again indicated that the stiffer roll-caged roofs did not offer any protection from prevention of roof crush as neck loads on the dummy were similar between production and roll-caged vehicles. This was the only rollover test series run on production vehicles since the Malibu tests of the late 1980's.

Test devices simulating occupant excursion during rollover have been published frequently (Pywell (1997), Arndt (1998), Moffatt (1997)). These tests have been used to demonstrate seat belt design features and effectiveness of pretensioners on the head excursion of occupants. These test methods are useful to test belts in a one roll application, but are limited in assessing the effects belts may have during multiple rolls events where the occupant motions may be more severe in the later stages of more violent events.

Recent work at the University of Virginia has demonstrated a repeatable Dynamic Rollover Testing System (DRoTS). Kerrigan et al. (2011, 2013) have shown that they can perform a full vehicle, laboratory rollover test that has independent control of lateral velocity, drop height, roll angle and rate, and vehicle pitch angle. Seppi et al (2016) demonstrated the system was repeatable by performing multiple tests with the same vehicle and input conditions. Further work was done by Kim et al (2014) to prescribe vehicle dependent input parameters. They developed a system that could help develop field relevant touchdown conditions by suggesting "quantitative values for the change of the sled speed, tripping time, and initial deceleration value of the sled speed" of the DroTS system. Finally, Kerrigan et al (2015) demonstrated that the DroTS was capable of replicating the "injury causing portion" of an unconstrained vehicle rollover crash.

In summary, there have been many attempts to devise a repeatable dynamic test condition that could assess vehicle rollover crash as well as occupant response. These attempts have tried to determine the occupant motion in a controlled vehicle test condition that would simulate a real world rollover. The issues of test repeatability and test relevance (to one input condition) have continued regardless of the test developed. Also, the test dummies used in these were not originally developed to assess rollover crashes. Although developments continue, the future of a dynamic rollover test is still undetermined.

1.3 Regulation of Rollover Crashworthiness

Beginning over 30 years ago, roof crush resistance was instituted as a Federal Motor Vehicle Safety Standard (FMVSS) by NHTSA (last update 2009). Originally, FMVSS 216 described a test procedure that placed a large platen against the driver side roof rail of a vehicle and applied a load 1.5 times the unloaded vehicle mass up to 22,400 N. As seen in Figure 1.3, the test is performed with a vehicle pitch angle of 5 degrees and the platen placed to simulate a roll angle of 25 degrees. The regulation stated that the vehicle structure must not deform more than 127 mm (5 in.) under this load. This regulation was meant to assure that vehicles could withstand forces much more than their own mass when overturned to provide the occupant protection. A so-called "Strength-to-Weight-Ratio" (SWR) was determined from the peak force achieved in the test relative to the vehicle mass before the platen had traveled 125 mm. Some attempt has been made to correlate the deformation in the FMVSS 216 test with actual field observation. In another report, NHTSA (2004) described the field performance of 273 vehicles involved in a rollover and compared the roof damage to that seen in FMVSS 216 tests of similar vehicles. Their findings indicate that damage profiles from actual rollover crashes do not resemble those seen from the same vehicle crushed in a 216 test. Rather, the profiles look like those seen from vehicles dropped from a pre-determined height onto their roofs that NHTSA had also tested (Rains et al. 1999).

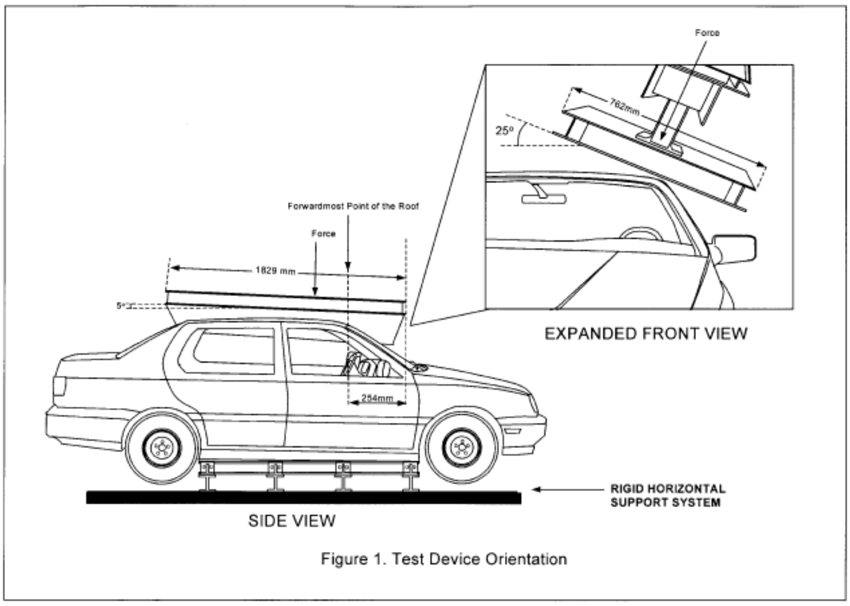

Figure 1.3. Representation of FMVSS 216 quasi-static roof crush test.

A further analysis of the data by Nash and Paskin (2005) indicated that 61% of the cases involved only one roof contact, but that most cases showed damage to the front of the roof as well as extensive windshield damage. Nash concludes that a roof test condition that involved breakage of the windshield and a platen pitch angle able to crush the front of the roof is indicated.

In 2005, NHTSA summarized their rollover testing program, which included ejection mitigation tests, and evaluation of countermeasures as well as static and dynamic roof crush evaluation (Summers et al, 2005). Looking only at the roof crush tests, quasi-static tests, similar to FMVSS 216 were carried out on several production vehicles using different platen pitch and crush angles from that used in FMVSS 216. They also crushed the roof to 254 mm to look at more severe roof deformations. The force-deflection data and the vehicle roof damage did not appear to be a function of the platen pitch or crush angle, thus NHTSA did not indicate that they would change the FMVSS 216 test with respect to these angles. The next set of tests looked at reduction of headroom relative to a point on the vehicle roof above a crash dummy's head as the roof was crushed by an FMVSS 216 platen. It was noted that each production vehicle maintained headroom for the dummy beyond the 150% of vehicle weight target set by FMVSS 216, and that most of the vehicles were able to withstand 200% or more of their vehicle weight. This was true for tests that measured a point above the dummy's head or the time at which the dummy's head was contacted by the interior "headliner", not necessarily the point initially above the dummy's head.

In 2009, NHTSA modified FMVSS 216 to include testing on both sides of the vehicle (same position of the platen as in Figure 3) and increased the requirement to a SWR of 3.0. In its Final Regulatory Impact Analysis (NHTSA 2009), NHTSA cited work by Strashny (2007) who did a comprehensive analysis of NASS-CDS data. Strashny concluded that regardless of what analysis method chosen, he was able to demonstrate a statistical correlation between vertical roof intrusion and head/neck/face injury of belted occupants involved in rollover crashes. By increasing the SWR requirements and additional side of testing, NHTSA estimated that upgraded standard would reduce fatalities by 134 and eliminate over 1000 injuries annually as manufacturers complied with standard. NHTSA's final rule phase-in required all new passenger vehicles produced after September 1, 2015 to be compliant with the new two-sided test protocol. Larger trucks and vans under 4500kg were given an extra year to be compliant (100% phase-in by September 1, 2016). The Insurance Institute for Highway Safety (IIHS) began testing roof strength in a similar manner in the early 2010s and prescribed a one-sided test, but required a minimum SWR of 4.0 to be considered "good" in their rating scheme. For current fleet vehicles, IIHS test results indicate the vehicles have SWRs exceeding 5.0 on average regardless of vehicle class (Table 1).

No similar passenger vehicle level roof strength test exists in other parts of the world. European Regulation R66 prescribes a "rollover" test for the superstructure of large passenger vehicles. This test (Figure 1.4) tilts a vehicle over a short ledge and the vehicle lands on its upper roof structure. The structure must be able to resist deformation so that an interior residual space (in both vertical and horizontal dimensions) within the vehicle is maintained to minimize occupant contact with the vehicle. This regulation has been adopted in other parts of the world as well, including Australia.

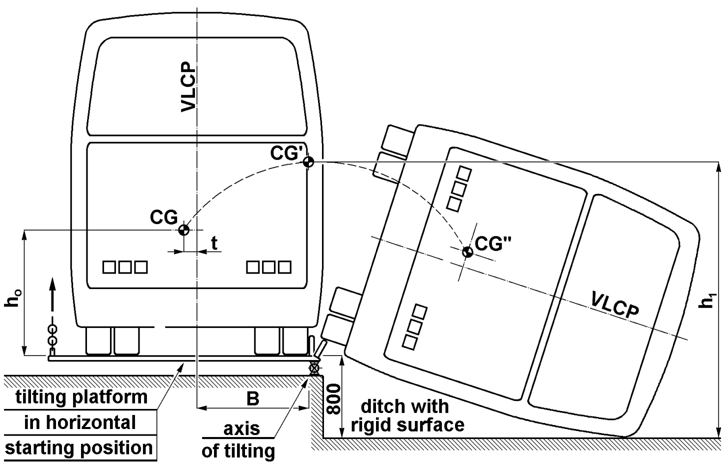

Figure 1.4. ECE Regulation 66 Test Procedure.

Table 1.3. Average Strength-to Weight Ratio reported for 5 representative 2017 MY vehicles for each vehicle class defined by IIHS and achieving a Top Safety Pick Plus rating and/or Good roof strength rating. Source: www.iihs.org

Vehicle Class	Average SWR for 5 TSP+ Vehicles
Small Cars	5.41
Medium Cars	5.07
Large Cars	5.16
Midsize SUV	5.25
Minivan/Large SUV/Pickup	5.01

1.4 Computer Simulation of Rollover

Given that each rollover is a chaotic and often unrepeatable event, computer simulation may be a more effective way to analyze the vehicle and occupant responses. Simulation of rollover events using computer methods can take many forms (Chou, 1999). Modeling allows parametric changes to be made that are prohibitively expensive to test while maintaining a consistent baseline of occupant and vehicle behavior for comparison. There are simulations that are more concerned with vehicle attitude and the effect of suspension and inertial properties on rollover as reported by Day and Garvey (2000). The model in their study included a 3-dimensional description of the vehicle including inertial properties, tire model and crush strength. Attempts to match roll kinematics of vehicle interaction with 3D terrain were made successfully. They also mention that simulation including occupants would be "time-consuming" and require more information about the vehicle accelerations as an input for the occupant model. Chace and Wielenga (1999) described a comprehensive method to build a system level model of vehicle rollover in ADAMS using component evaluation test methods. Validation of vehicle kinematics was achieved. The authors suggest that mitigating rollover potential could be evaluated through vehicle component changes and evaluated in the model.

Others tried to capture the vehicle deformation during the roll event and predict material behavior. Sakurai (1993) modeled the vehicles that were rolled as described above using the PAM-CRASH non-linear finite element software. He found that the model predicted roof deformation data well and could be used to evaluate occupant behavior in future studies. Rollover simulation to study occupant kinematics traces roots back to the original occupant models of the early 1980's. Robbins and Viano (1984) describe a rollover event using vehicle accelerometer data and high speed film analysis as inputs to a two-dimensional, linked, rigid body model of a production sedan. A linked, nine segment, rigid occupant model was placed in typical seating position. Occupant kinematics including ejection from a "pure roll" event were described. Authors promoted simulation as an inexpensive method "to study occupant and vehicle motions in the mind-boggling geometry of rollover."

More sophisticated three-dimensional rollover modeling appeared in the mid to late 1980's and continues to the present with such codes as the Articulated Total Body (ATB) and MADYMO (Mathematical Dynamic Modeling). Obergefell et al (1986) published a study simulating occupant motions during rollover using the ATB code. They modeled a vehicle undergoing a violent (60mph) rollover as a result of interaction with a turned down guardrail and also included a restrained driver. Film and data analysis helped derive 6 axis input data to drive the model. A 4.5 second simulation of the event showed good agreement of dummy kinematics (test to model) during the entire event. It also indicated that belted occupants can undergo a large amount of movement. Concern was raised over belt/body segment interactions during the entire simulation.

These authors have published other papers using this modeling method over the years. Cheng et al (1995) developed an ATB model to replicate occupant motions from one NASS case (a belted driver and unbelted passenger in a light pickup rollover crash). Occupant outputs from the modeled dummy were used to predict injury results. The belted driver had only a minor injury and model results indicate low accelerations to head/chest regions. The ejected passenger suffered fatal injuries and model data showed high injury criteria values (exceeding threshold). Ma et al. (1995) used a previously defined rollover and occupant model to look at the effect of glazing on occupant kinematics and injury. Contact force deflections for head to glazing for a variety of vehicles were evaluated. Head impact velocities in the 3-8 m/sec range (unbelted passenger) were seen for a variety of glazing tested. Predictions for head/neck injuries are given.

Simulations using linked rigid body, MADYMO (2000) modeling techniques have also appeared in the literature. Renfroe et al (1998 and 2000) have published papers attempting to model occupant motion in MADYMO during a prescribed motion to the vehicle center of gravity taken from outputs of reconstruction programs. Vehicle crush and suspension/tire modeling were done and showed good match to vehicle test data (FMVSS 208). Predicted occupant accelerations (head, chest) showed similar trends to test data, but authors did not have sufficient interior stiffness or crush data to determine occupant injury potential. They suggested the model could be used to evaluate restraints in rollover conditions. Bardini and Hiller (1999) used a combined MADYMO and vehicle dynamics prediction program approach to determine sensor fire time for rollover events. Both a curb trip type and embankment roll were modeled. No roof crush was used. Correlation of vehicle behavior to an embankment test was done qualitatively. Trajectory analysis of the head, with and without belt pretensioners, was done indicating containment of head within vehicle frame when a pretensioner was fired. (curb trip type roll). Lack of good test data and concerns over dummy lateral neck behavior were mentioned. Chou and Wu (2005) used MADYMO to develop kinematic models of rollover modes as indicated by Parenteau and Shah (2000). The authors were able to capture the response of the rigid body vehicle model to the input test conditions and compare to actual test results in terms of roll rate and angle. The model to test comparison was fairly good, but the authors indicate that more capability was needed in the model. This included better suspension and contact algorithms. The authors advocated exploring the finite element capabilities of the MADYMO software to assess structural responses as a result of the different rollover modes.

There is considerably less volume of literature that assesses dynamic roof crush through computer modeling. Initial models of vehicle roof crush did not give explicit detail (Pickett et al., 1990, NHTSA, 1996, and Friedman et al., 2001). A multi-body model of roof crush was described (Engineering Systems International, unpublished) that attempted to use kinematic joints to describe the roof deformation between various roof points (top and bottom of pillars, etc.) as described in field data studies by Lund et al (1999).

Tamborra (2003) described a finite element model of a Chevrolet S-10 pickup truck that is subjected to an FMVSS 216 test procedure. He gives significant attention to material properties and element thickness to recreate the force-deformation behavior of the vehicle during the loading cycle. A more detailed finite element analysis of FMVSS 216 roof crush behavior was published by Mao et al (2004). Using LS-DYNA software, the authors constructed a vehicle and platen model to assess the vehicle's response to a FMVSS 216-like input. They assessed roof strength and deformation through a matrix of simulations that varied the platen pitch angle and crush or roll angle finding little difference in roof strength response as a function of pitch angle. Dynamic modeling of the vehicle model (drop tests) was carried out as well. The authors were able to show the sensitivity of the model to the surface geometry on which the vehicle model had been dropped. This kind of finite element analysis to evaluate large deformations over a long period of time (seconds) is only happening now due to increased computer speeds and memory capabilities. Similar large deformation modeling was done by Jackson and

Fasanella (2005) where they assessed the structural deformation of the body and seats of a commuter airplane as a result of a drop test using LS-DYNA.

Among the European ROLLOVER project's tasks, listed in the final report (Gugler et al., 2005) was the re-creation of rollover crashes using MADYMO to assess injury prediction. The project also created finite element models of vehicles to assess structural characteristics of vehicles in rollovers. It was hoped that these models will be used to derive further restraint and structural countermeasures.

There have been significant efforts to use computer modeling to understand the interaction of occupant kinematics and vehicle characteristics during rollover to assess injury potential. Hu (2007) documented a process for simulating vehicle kinematics and occupant responses in three laboratory-based rollover tests. Occupant responses to the vehicle kinematics were described by a model of the 50th percentile male Hybrid III dummy as well as the THUMS (Total Human Model for Safety) finite element human model. He examined the sensitivity of the dummy and human model to changing test, vehicle and restraint conditions. Hu showed that even though the Hybrid III dummy was designed primarily for assessing injury in frontal impact, the dummy model showed sensitivity to certain test, vehicle and restraint conditions. For example, the dummy axial neck forces were reduced by certain seat belt parameters, however, there was no difference in neck forces when roof stiffness was changed in the vehicle model.

Parent et al (2011 a, b) published a pair of papers on an extensive parametric analysis of vehicle (roll, pitch and yaw angles, roll rate and drop height) and occupant factors (size and position) with respect to their ability to predict the vehicle and occupant responses. Using a combined finite element and rigid body model analysis, Parent showed that the drop height was a significant predictor of the vehicle roof crush and the occupant risk for injury. This is consistent with NHTSA's testing that indicated that different pitch angles did not change dramatically change vehicle response.

In more recent years, others have continued to simulate rollover crash conditions. Mongiardini et al (2014, 2016) demonstrated a validated model of the JRS rollover test system with a vehicle model and also compared and contrasted the JRS system with other systems. Friedman et al (2015) attempted to model partial ejection of belted occupants in rollover crashes. DeLima et al (2015) validated several vehicle models in a rollover crash simulation. Zhang et al (2016) attempted to validate a MADYMO multi-body model of the THOR crash dummy to be used in rollover simulations of the DRoTS system to assess occupant kinematics. Finally, Mongiardini et al (2015), modeled a vehicle and occupant (Hybrid III crash dummy model) in the JRS test fixture and demonstrated that a 50% stronger roof could reduce axial compressive loads on the dummy model's neck by 25%. They also indicated that a human model might be more suitable for modeling as the increased dummy neck stiffness may not allow for as clear a distinction in roof stiffness compared to the human.

1.5 Countermeasures

Much discussion about countermeasures for ejection and injury mitigation in rollover crashes has been offered. Digges and Malliaris (1998) suggested inflatable devices as a way to reduce a significant HARM from ejection and head protection for non-ejected occupants, but they did not elaborate on design. Roof, side window curtain or other window airbags as discussed by Mueller (1997), Ridella et al (2001), Takahashi et al (2003), and Shilladay and Mowry (2005) are nearly standard safety equipment now in the automobile industry. Originally designed for side impact protection, most side window curtain bags are now able to stay inflated for as long as 6 seconds to protect occupants in longer duration rollover events.

Methods for their design and evaluation are increasingly computer-based due to long development times and costly tests. NHSTA has developed an impactor type test to evaluate these bags in vehicles (Summers et al, 2005) that became the basis for the procedure used in FMVSS 226, Ejection Mitigation, regulation. There is evidence that manufacturers are installing larger side window curtain airbags in response to the FMVSS 226 requirements. Kahane (2014) was able to do preliminary analysis on effectiveness of rollover capable side curtain airbags in preventing fatality. Using a logistic regression approach on data from mostly larger sport utility vehicles and light trucks, he estimated that these bags reduced fatality risk by 41.3% for first-event, most-harmful event rollovers. He indicated that more years of data would be necessary to understand fleet effectiveness, but this initial analysis is promising.

Other countermeasures look at reducing injury risk for occupants that are non-ejected. This can be through protection devices or structural changes. James et al (1997) indicated that modified current production seatbelt systems can reduce vertical head excursions, but will not eliminate head contact to roof, roof rail or lateral motion of the head into open window areas. Hare et al (2002) demonstrated that pretensioning seat belts prior to a rollover test did not reduce the excursion of the dummy's head relative to production seat belt designs without pretensioning devices. Heudorfer et al (2005) demonstrated an airbag that inflates from the roof to protect the head and neck during rollover through a process that induces flexion of the head relative to the neck. Bostrom et al (2005) indicated that reversing the shoulder belt of a far side rollover occupant could reduce the head excursion during a tripped rollover event. Mattos et al (2015) recommended that advanced restraints for rollover protection could be best evaluated with a repeatable impact test (such as CRIS) or a component or inverted drop set-up. Louden (2010) created a "rollover restraint tester (RRT)" to evaluate occupant excursion in a laboratory simulated rollover event. She subjected 5th female, 50th male and 95th male Hybrid III dummies to a typical rollover roll rate for 180 degrees of roll before simulating a ground impact (Figure 1.5). The dummies were restrained with regular 3 point belts, 4 point belts, inflatable belts and a variety of pretensioners (buckle, retractor, and motorized). All advanced restraint systems reduced vertical and excursion compared to 3 point belts. Pretensioners showed reduced excursion through the impact phase as well.

Clearly, the field case analysis indicates that the prevention of head and torso translation of the unbelted occupant beyond the vehicle openings should result in a less severe injury outcome. Furthermore, prevention of head or torso contact to interior structures (rails, glazing, pillars) or intruding objects (trees, other vehicles) that an occupant in a rollover event is likely to contact should decrease risk for serious or fatal injury.

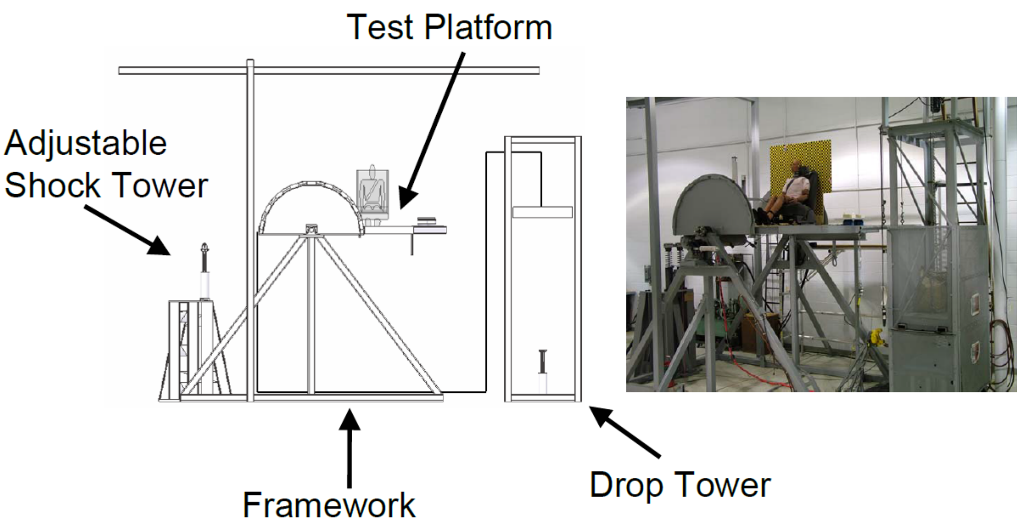

Figure 1.5. Rollover Restraint Tester set-up described by Louden (2010).

The Malibu studies by Bahling, Orlowski and Friedman have varying opinions on the ability of strengthened roofs to reduce head and neck injury. Moffatt's analysis (2005) of the CRIS and other tests showed no relation between roof strength and the potential for head injury. Hu (2007) demonstrated in a modeling study that increased roof strength and enhanced seat belt systems may not completely eliminate the risk of risk of neck injury in certain rollover crashes. While this debate continues, all new vehicles in the United States have been required to have electronic stability control since 2012. According to Kahane (2015), ESC has saved 1,362 in 2012 alone and over 6,100 lives since its introduction. This feature reduces on road tripped vehicle rollover crashes by selective, automatic and independent braking of each wheel to allow the driver to maintain control of the vehicle as a result of a sudden change in friction or movement of the vehicle. It is likely that ESC has reduced rollover incidence as a result of that technology.

1.6 Summary

The complexity of the issue of rollover vehicle performance and injury potential is very apparent given the variety and quantity of material published on the topic. There is no doubt that vehicular rollover injury is over-represented with respect to the frequency of rollovers versus all crash modes. This is seen in US crash field data that has been extensively studied, however, European data indicates that rollover crashes are also an infrequent crash type, but may imply that the risk of injury for a given crash is higher there. In terms of vehicle type, SUVs get a disproportionate amount of attention since rollovers comprise more of their overall crashes, but passenger cars also rollover. Injury occurs whether roof crush occurs or not, usually with less than one roof inversion. These injuries tend to be serious head and neck injuries, especially for belted, non-ejected occupants. Vehicle testing of rollover crashes has been limited so far and mostly has been concerned with the most severe crash types. It is expensive to do run full vehicle tests and the lack of repeatability is a major issue. The CRIS and DRoTS test methods appear to be more repeatable focusing on the single roof contact as well as able to evaluate near and far side occupants. These test methods, however, are in the research phase and are not widely used. Simulation has been an attractive alternative to testing in terms of studying occupant motion and ability to evaluate multiple occupant and vehicle parameters.

The underlying issues are the head, neck and thoracic injury mechanisms that result for belted and unbelted occupants. Piziali et al. (1998) clearly states "In field studies of rollover accidents it is difficult to determine if neck injury risk is associated with roof crush or caused by roof crush". NHTSA's analysis of field data and roof strength testing indicates there is an association between vertical intrusion of the roof and the risk for head and neck injury, however, they do not point to a definite mechanism. Strengthening roofs to reduce deformation during rollover may be an appropriate countermeasure and new regulations and consumer tests have resulted in more recent vehicles with high roof strength-to-weight ratios. More definitive analysis of field crash data is warranted to see how head and neck loading during rollover affect the potential as well as patterns of injury. A better understanding of the types of injuries seen during rollover crashes, how they occur and possible vehicle and occupant factors that may contribute to those injuries may shed more light on future countermeasures that can help to reduce the incidence and/or severity of the injuries. Finally, with the many possible combinations of occupant, vehicle and countermeasure factors possible, it appears necessary to create a computer model that can be used for parametric analysis of factors rather than expensive and time consuming testing. Models can help determine the significance of factors that lead to increased injury risk and can also help to determine if and to what extent countermeasures can be useful to reduce injury risk.

2. AIMS

The general aims of this thesis are to better understand the nature and mechanisms of injury to belted, unejected occupants due to rollover crashes and to systematically study the factors responsible for the injuries. In this way, the analysis may lead to opportunities to study protection strategies for occupants and point to future opportunities for methods to analyze countermeasure effectiveness. More specifically, the aims of this thesis are:

1) Determine if crash investigations can help deduce the role of vehicle, crash and occupant factors in rollover crash injury risk. To be addressed by Paper 1.
2) Examine distribution of injury types involving major body regions injured in rollover crashes. To be addressed by Paper 2.
3) Analyze specific cases of similarly injured rollover occupants to determine injury causation to various body regions (Papers 1 and 2). Focus on the cervical spine injuries for pure (single vehicle, single event) rollovers (Paper 2).
4) Use aggregate and case data analysis to deduce potential countermeasures and future studies for determining contributions of factors to rollover injury that can be addressed by countermeasures. To be addressed by Paper 2.
5) Determine the significance and contribution of vehicle, occupant and crash factors that may influence the risk of rollover crash injury, the following questions will attempt to be answered:
   a.) What vehicle and crash parameters are most likely to contribute to rollover injury potential? To be addressed by Paper 3.
   b.) Does vehicle design predict or affect deformation behavior? Can the restraint systems be enhanced to reduce occupant motion and prevent or minimize roof or other interior head contact? To be addressed by Paper 5.
   c.) Since testing is so expensive, can a finite element computer model be used to systematically define the interaction of vehicle and occupant in order to design safer vehicles and what tools should those be? To be addressed by Paper 4.
6) Find out if the model can answer questions about the effect of limiting deformation and the feasibility of design guidelines for vehicle structure and/or restraint systems to address the problem? What would the design need to be in terms of geometry and strength and restraint system specifications? The merits of current crash dummies and digital human models in helping these design goals will also need to be considered. To be addressed by Papers 4 and 5.

The aims form the basis for the work plan of this thesis:

1) In depth analysis of individual rollover crash investigations to determine injury types, severity and mechanism
2) Analysis of aggregate crash field data to determine national rollover injury types and frequency.
3) Creation of a computer model of dynamic vehicle rollover event that mimics actual vehicle crush and occupant compartment intrusion as well as occupant response.

4) Parametric analysis of structural and restraint components as well as occupant types (different human and dummy models) to determine the role of roof deformation and restraint system effectiveness to reduce the potential for injury through analysis of the computer model.

3. SUMMARY OF PAPERS

This chapter provides a summary of the three major areas of the thesis: understanding the injuries and their mechanisms sustained by occupants in rollover crashes, finite element modeling of specific crash conditions to determine crash, occupant and vehicle factors that are associated with the injury mechanisms, and parametric multi-body modeling analysis using vehicle and restraint system factors coupled with appropriate occupant models to determine their effect on mitigation of injury.

3.1 Epidemiology of rollover injuries and mechanisms

As stated earlier the aims of this section are to determine if crash investigations can help deduce the role of vehicle, crash and occupant factors in rollover crash injury risk. It will be necessary to first examine the distribution of injury types involving major body regions injured in rollover crashes and then analyze specific cases of similarly injured rollover occupants to determine injury causation to various body regions. Papers 1 and 2 required analysis from two well established and informative data sources. For paper 1, data was extracted from the master data repository of the Crash Injury Research and Engineering Network (CIREN). 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 vehicle rollover was characterized as either a pure rollover event or a multiple event rollover crash. For each case crash reconstruction and injury review done, a consideration of the injury ranking was undertaken and whether that 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, the Rank 1 injury was usually the highest AIS injury that occurred as a result of a rollover or a frontal or side collision.

A process called BioTab was applied to the most serious injury of each occupant meeting the inclusion criterion for this study. 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 (Schneider et al, 2011). BioTab also documents the specific “mechanisms” by which an injury is believed to have occurred.

Fifty-one rollover crashes were identified from the CIREN database. Nineteen (19) pure and 32 multi-event rollover crashes were identified. There were 55 occupants in the 51 crashed vehicles; 19 were in a single event, or pure rollover crash and 36 were in a multiple event crash with rollover. 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 by body region were different between the pure roll and multiple event roll cases (Figure 3.1). Appendices 1 and 2 in the paper (see Paper 1 below) give a complete listing of the relevant occupant and injury variables for the pure roll cases and the multiple event roll cases respectively.

It is apparent from Appendix 1 in Paper 1 below (pure roll cases) 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. The regional mechanism for all of the spinal injuries included compression combined with a flexion, extension, or lateral bending. The paper documents the other injuries that occurred and their mechanisms.

In paper 2, a two-step data analysis process was enacted. First, by combining recent years of NASS-CDS aggregate data, distributions of specific injury types in rollover crashes of belted, non-ejected occupants could be determined on a national level. Second, while mechanisms of injury for other body regions such as head and thorax body injuries can be attributed to direct impact, detailed case analysis focused only on the complex mechanisms of the identified cervical spine injuries from rollover-involved occupants and is supplemented by what vehicle and occupant factors may have played a role in the injury causation.

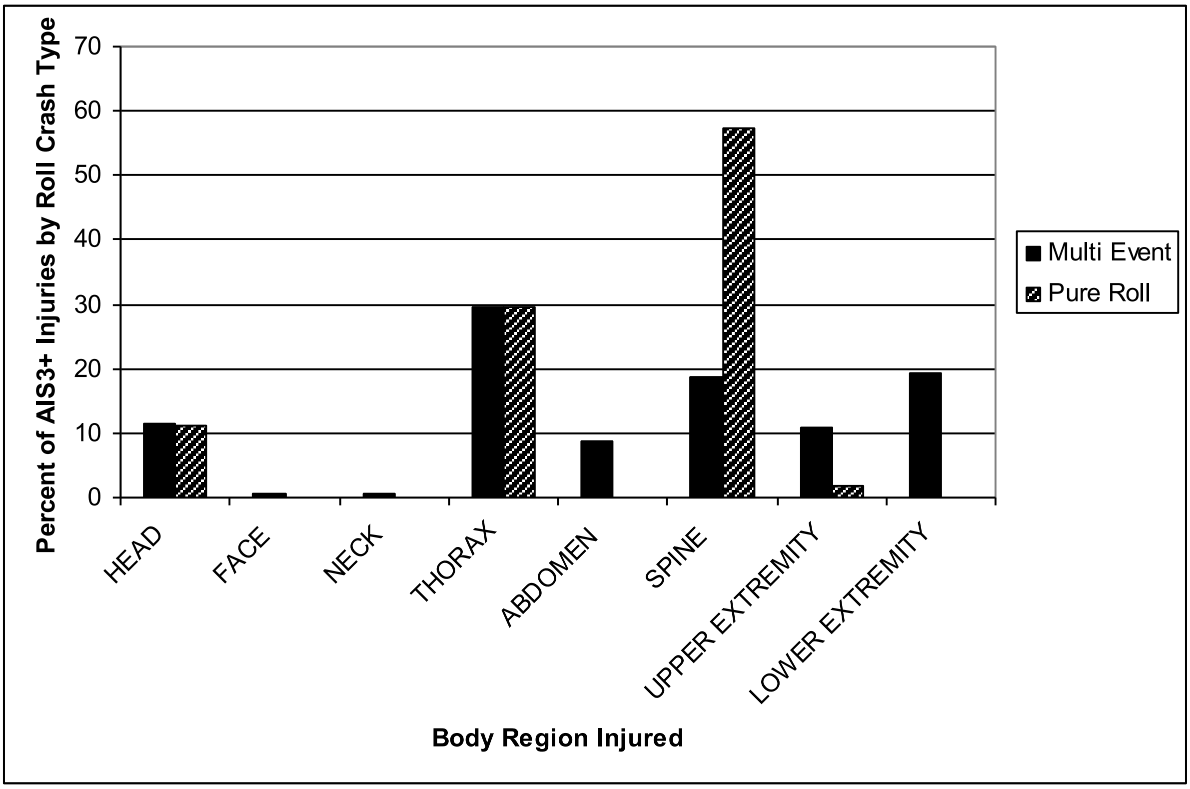

Figure 3.1. CIREN Case Distribution of 842 AIS3+ Injuries by Body Region for Occupants by Rollover Crash Type

NASS-CDS (years 2003-2011) was extracted for adult (age16 years or greater), front row, outboard, non-ejected occupants involved in rollovers of eight quarter turns (maximum of two roof inversions) or less, similar to paper 1. Rollover was defined (similar to CIREN definition) as lateral rolls about the vehicles longitudinal axis and was disaggregated by single vehicle, single event (pure rollover) and multiple event crashes of which one event, usually the most harmful, was the rollover event. The occupants must have sustained an AIS 3,4,5,6 injury for inclusion in the analysis. The injuries were selected from a pool of injuries per body region for each occupant and all serious injuries were counted in the analysis. Distributions of the weighted data by specific injury type (head, brain, neck/spine, thorax, abdomen/pelvis and extremities by AIS 90 code were prepared for these rollover-involved occupants. Injuries were studied for the top most prevalent severe (AIS 3+) injuries sustained per relevant occupant, by single or multiple event crash. Subsequently the top five injuries, by relevant body region were studied. Trends of injury type by seating position, roll direction, roof intrusion and other relevant vehicle and/or occupant factors were determined.

The second part of paper 2, the CIREN database was queried for cases that involved belted occupants in single- vehicle, single-event rollover crashes involving 8-quarter turns or less that sustained an AIS 2+ injury to the spine. One case with qualifying injuries involved a crash with 10 quarter turns was also taken for the analysis.

The vehicle kinematics were then used to identify the occupant kinematics and the certainty with which those kinematics could be determined. The case information was then used with the vehicle and occupant kinematics to identify the particular injury causation scenario for each of the AIS 3+ injuries and AIS2 fractures to the cervical spine, including the perceived loading direction, injury mechanism, rollover phase in which the injury was assumed to have occurred, and any other details associated with the injury. Once this process was completed for each case, the aggregate data was tabulated and analyzed for trends in occupant and vehicle factors that may be associated with the cervical spine injuries sustained.

As indicated in the methods, the injury distributions taken from nine years of combined NASS data were separated for occupants involved in either a pure rollover event or a multiple event rollover crash. In order of decreasing frequency, spine, thorax, and head were the dominant seriously injured (AIS => 3) body regions for the pure roll occupant group while thorax, head and lower extremities were the dominant seriously injured (AIS => 3) body regions for the multi-event rollover occupant group. This distribution is similar to the CIREN distribution in Paper 1. For the pure roll cases, the top 10 injuries (most frequent) comprise 62.6% (N=7,580 out of 12,105; weighted) of all AIS 3+ injuries in that mode while for the multi-event roll cases, the top 10 injuries comprise 42.5% (N=19016 out of 44715; weighted) of all injuries in that mode. In the multi-event rollovers, lung contusions (uni- and bilateral), pelvis and long bone fractures appeared as the most frequently coded AIS 3+ injuries. For pure rollover crashes, cervical/thoracic/lumbar spine fractures and various head/brain injuries comprised seven of the top ten injuries in this group, however, the uni- and bi-laterial lung contusions were nearly as prevalent as the combined cervical spine injuries (17.0% vs. 19.3%). See paper 2 below for more detail on specific injuries.

The query of the CIREN database to select single-event rollovers of 8 or fewer quarter turns involving only belted occupants presented 46 pure rollover cases. The database query returned a total of 28 cases involved occupants sustaining at least one AIS3+ injury and/or oneAIS2 fracture along the entire bony spine. Twenty-one of the cases involved occupants with the AIS3+ injury or AIS2 fracture specifically to the cervical spine. One of the cases did involve 10 quarter turns but was retained for relevance to the injuries. The following demographic data applies only to the 21 cervical spine injured cases.

Table 3.1. Mean Demographic and Rollover Crash Data for Selected Serious Cervical Spine Cases in the CIREN Database. BMI: Body Mass Index, Far/Near (occupant seating position relative to roll direction), Inversions (number of roof inversions: number of row occupants experiencing that number of inversions)

Sex (n)	Age	Height (cm)	Weight (kg)	BMI	# Far/# Near	Inversions
Female (8)	39 +/- 10	161 +/- 8	72 +/- 19	28+/- 8	5/3	1:1 , 2:7
Male (13)	46 +/- 20	179 +/- 6	86 +/- 18	27 +/- 5	9/4	1:8 , 2:5

The vehicle attributes and responses and attributes of the CIREN cases were analyzed first to deduce trends in crash performance. Figures 3.2 shows the relationship of maximum vertical and lateral intrusion at the injured occupant's location versus the vehicle's strength-to-weight ratio (SWR) as reported by NHTSA in their quasi-static roof strength test, Federal Motor Vehicle Safety Standard (FMVSS) 216. Moderate inverse correlations are evident in Figure 3.2a for less vertical intrusion with increasing SWR for both one and two roof inversions, but these trend lines were not significant when subjected to a t-test ($p > 0.05$ for all trend lines). Figure 3.2b indicates a fairly strong inverse relationship between lateral roof crush and SWR for 2 roof inversions, but this relationship did not achieve statistical significance ($P > 0.05$).

Figures 3.3a and 3.3b display the anatomic level of the most severe cervical spine injury as a function of the vertical and lateral intrusions for one and two roof inversions. Figure 3.3a indicates no trend in the level of cervical injury as function of vertical intrusion. Figure 3.3b shows a mild trend for more lateral intrusion being associated with increased (lower) anatomic level of cervical spine injury for two roof inversion cases only, however, this trend line was not staticictly significant ($p > 0.05$). When considering only levels C4-C7 in Figure 3.3b, the trend line (not shown) for increasing lateral intrusion associated with lower cervical spine injuries achieves statitstical significance with a t-test ($p = 0.011$).

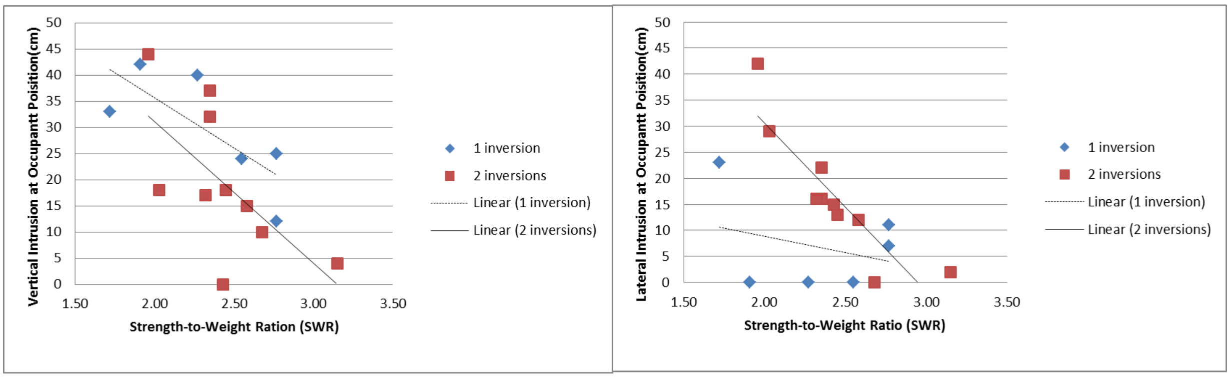

Figure 3.2. Vehicle SWR versus vertical (a) and lateral (b) intrusions at injured occupant location for the selected CIREN cases.

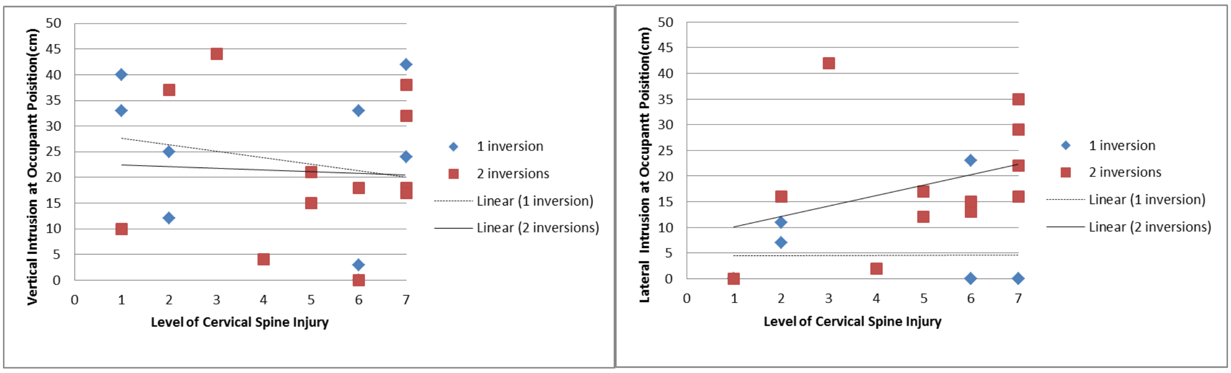

Figure 3.3. Level of most most severe cervical spine injury versus maximum vertical (a) and lateral (b) intrusion at injured occupant location.

These 2 papers provided significant information towards satisfying the aims of this project. First, the NASS analysis indicated the most serious injuries by body region. Breaking into pure roll and multi-event roll scenarios, the pure roll analysis showed that cervical spine fractures were consistently among the top injuries for that rollover crash mode. The CIREN case analysis was required to take this analysis further and found 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. Further analysis of vehicle factors found that low cervical spine trauma was associated with more lateral intrusion of the vehicle roof at the occupant seating position. All the occupants in this study were belted and not ejected, yet sustained a serious neck or other body region injury. Improved seat belt design to minimize occupant excursion could result in less opportunity for the head to strike these regions.

3.2 Parametric Finite Element Analysis of Vehicle and Occupant

The purpose for papers 3 and 4 was to demonstrate the validity and effective use of a computer model of a crash test dummy, vehicle and test procedure called the Controlled Rollover Test System (CRIS). Previous modeling studies described in Section 1 above have focused on specific rollover conditions and have not systematically studied the interactions of crash, vehicle, occupant and restraint parameters on the potential for injury that has been well documented in rollover crash data studies. These papers intend to address some of those concerns by subjecting a vehicle model, previously validated for roof strength performance, to a dynamic test to determine sensitivity of occupant and vehicle response through an analysis of vehicle crash and structural parameters. In addition, the response variation of several dummy models was evaluated to determine the most suitable occupant model to use in future analysis.

3.2.1 Vehicle Finite Element and CRIS Test Model

A 50^{th} percentile male Hybrid III dummy model was placed in the driver's seat, wearing the production three-point continuous-loop, sliding latch plate restraint system. The seat back was in an upright position at an angle of 29 degrees measured on the front surface of the seat back 10 inches above the seat cushion. The seat belt was placed on the dummy with proper routing and no slack in either the lap or shoulder belt. The CRIS is a machine that is designed to release a translating vehicle, rotating about its principal longitudinal axis, at a controlled orientation and from a desired drop height. A diagram of the CRIS, its primary components and initial test conditions are shown in Figure 3.4 as the vehicle is impacting the ground.

Physical testing was conducted using a 1999 Ford Crown Victoria with a body-on-frame construction, but the numerical simulations were performed using a finite element model for a 2001 Ford Taurus. The reason for this is that the Taurus finite element model was the closest available FE model to the Crown Victoria. A 2001 Ford Taurus finite element model (FEM - version 4) developed by the National Crash Analysis Center (NCAC) at George Washington University was obtained directly from the NCAC [13]. The model contains 921,793 nodes and 973,351 elements describing 802 individual parts. The FEM model was developed in LS-DYNA version 970 and extensively validated for frontal and side crash conditions as well as FMVSS No. 216, the quasi-static roof crush regulation prescribed by NHTSA.

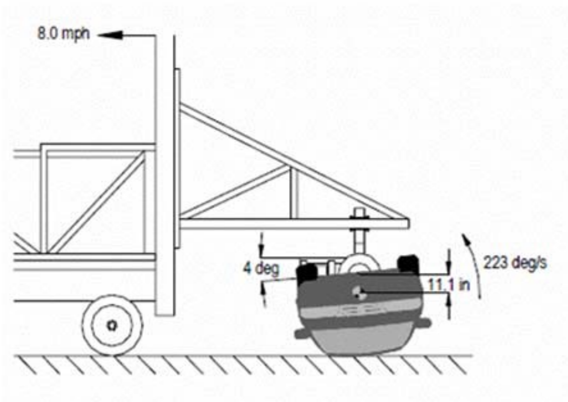

Fig. 3.4. Schematic of the Controlled Rollover Impact System (CRIS) and initial impact conditions.

To capture the same vehicle to ground impact parameters in the computer simulation model as in the test, a series of simulations were run using the Ford Taurus FEM where inertial properties of the Taurus model were modified to match the Crown Victoria properties. The initial CRIS Taurus FEM vehicle orientation is shown in Figure 3.5.

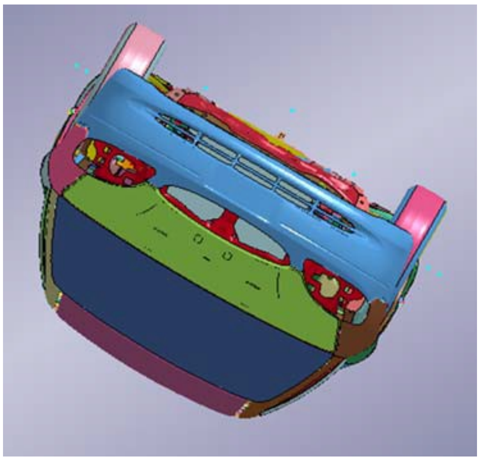

Fig. 3.5. Front View of 2001 Ford Taurus FEM Just Prior to Release from CRIS System

3.2.2 Parametric Analysis of the CRIS Model

Nine independent vehicle and crash parameters were incorporated into the model. The parameters are given in Table 3.2. Seven of these parameters were simple substitution of values (t1-t7) from the baseline parameter value. Pillar thickness variation was done for both pillars and roof rail thickness variations were done across both sides and the header (Figure 3.6) and done in increasing thickness only to approximate increased roof strength without adding significant mass to the vehicle. The material variation (showing increasing stiffness was taken from estimated material parameters adapted from previously published data. The roof morphing and seat back angle variations required separate models (9 combinations) to account for possible interaction of roof to seat during simulations. The drop height, roll and pitch angles are varied around the parameters of the original CRIS test for the Crown Victoria. LS-OPT was used to control model parameter combinations. A total of over 90 variations were analyzed.

Dummy output parameters were taken as follows: Peak head CG resultant acceleration, Head Injury Criterion (HIC), upper neck axial force (Fz), upper neck bending moment (My), and Combined Neck Injury Criteria (Nij). Vehicle output parameters taken were as follows: peak intrusion of occupant compartment in three measurements. Two diagonals across first row occupant compartment indicate intrusion at driver or passenger sides. Vertical intrusion through vehicle centerline was also measured as well as vertical acceleration of vehicle CG. Analysis of variance (ANOVA) and Global Sensitivity Analysis (GSA) was performed to assess the contribution of each input variable variation to the variance in occupant and vehicle response.

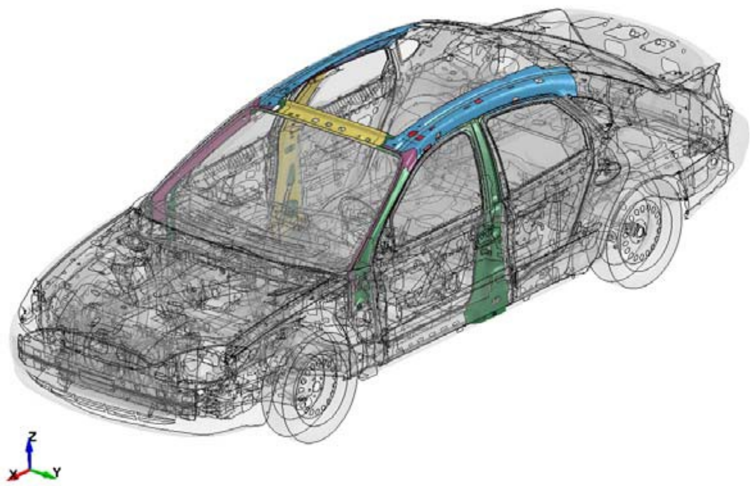

Fig. 3.6. Taurus Model Showing Locations of Pillar and Roof Rail Variations

Table 3.2. Vehicle and Test Parameters Used in Simulations

Parameter	Variation
A Pillar Thickness (t1)	Baseline, +25%, +50%
B-Pillar Thickness (t2)	Baseline, +25%,, +50%
Roof Rail Thickness- Driver Side (t3)	Baseline, +25%,+50%
Material Change Parameter (t4)	Baseline steel, intermediate steel, boron steel
Drop Height (t5)	28.2 cm, 33.3 cm, 38.4 cm
Roll Angle (t6)	46, 49, 52 degrees (to horiz plane)
Pitch Angle (t7)	+3 degrees(fwd), 0 degrees,-3 degrees (rear)
Seat Position (t9)	29, 26.5, 24 degrees
Full Roof Morphing Parameter (t12)	No morph, +1.25cm, +2.54 cm

The CRIS test series had a limited set of data collected relative to the vehicle and the dummy thus the validation of the model has some limitations. Figure 3.7 shows the residual crushed profile (plastic deformation) from two different views. No external crush or internal intrusion measurements were taken in the test, however, several important observations may be noted. The driver side A-pillar is severely crushed both vertically and laterally in both test and model. Buckling of the roof as the B and C-pillars have collapsed is also noted in both and appears quite similar.

Fig.3.7. Qualitative crush comparison of production Crown Victoria (top) from test 51502 and modified Taurus model (bottom) subjected to same input conditions adjusted for same touchdown location.

3.2.3 Parameter Analysis Results

As the simulations were carried out, it became clear that the vehicle and occupant responses were highly non-linear as parameters were varied. This makes the use of a linear analysis of variance (ANOVA) a less reliable analysis tool. Hence, all parametric variance results will be reported for the Global Sensitivity Analysis since GSA allows for non-linearity in the responses. The parameters were varied using design of experiments approach and D-Optimal point selection. It assures good coverage of multidimensional space of parameters and minimizes errors of fitting surfaces into the responses. For brevity, a vehicle response and an occupant response analysis will be shown followed by an overall parameter analysis summary. Figure 3.8 shows a GSA output graph for the driver side roof crush response as the parameters were varied. Referring back to Table 3.2, the t7 parameter, vehicle pitch angle, accounted for almost half of the roof crush response followed by roof stiffness and roll angle.

Seat position accounts for 27% of the neck response, pitch angle accounts for 26% while, roll angle roof rail thickness and drop height account for the majority of the remaining response. A similar chart is observed for the neck moment results also (Figure 3.9). Figure 3.10 shows the entire parameter variation and GSA results as a cumulative plot and the composition of influence each parameter has on a given vehicle or dummy response. The longer the bar for the variable (lower plot), the greater influence it has on the response. It can be seen that vehicle pitch angle (t7), vehicle roll angle (t6), seat position (t9) and drop height (t5) have significant influences on the responses. Overall, pitch angle accounts for about one-fourth of the overall vehicle and occupant responses, followed again by roll angle and seat position. Drop height had its largest influence on the centerline roof crush response. Pillar thicknesses (t1 and t2) each accounted for less than 5% of the total response. Material stiffness variations accounted for about 8% of the total response. The morphing variable (t12) had its largest effect on the passenger side roof crush but hardly any effect on the driver side roof crush.

Figure 3.11 contains plots presenting the dependence of the forces in the neck for three dummies on drop height. The neck force increases almost linearly when the drop height is increased. For the THOR dummy model, the changes in the drop height in the predefined range caused variation of the neck force by up to 20% from the nominal value. For HIII NCAC dummy these variations were up to 23% for the changes in the drop height. The drop height was the variable that caused the least variations in the neck forces.

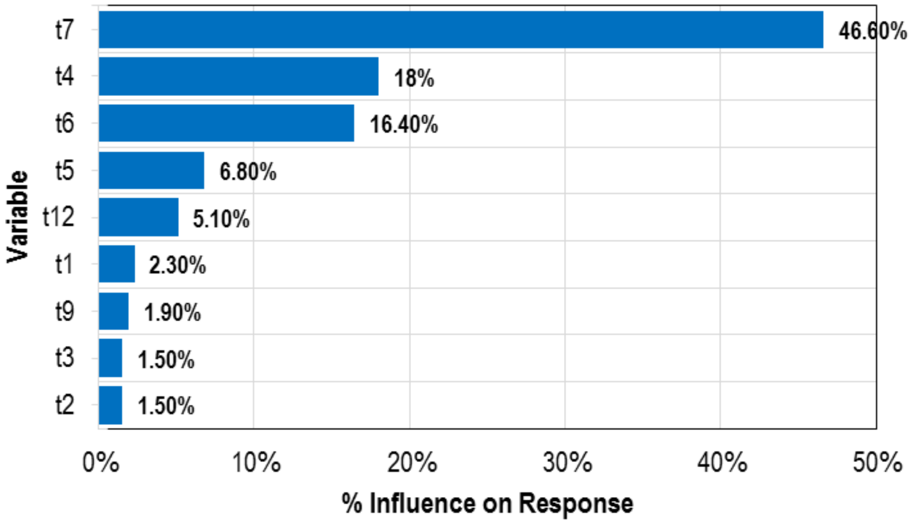

Fig. 3.8. Global sensitivity Analysis (GSA) plot of parameter contribution to the driver side roof crush response.

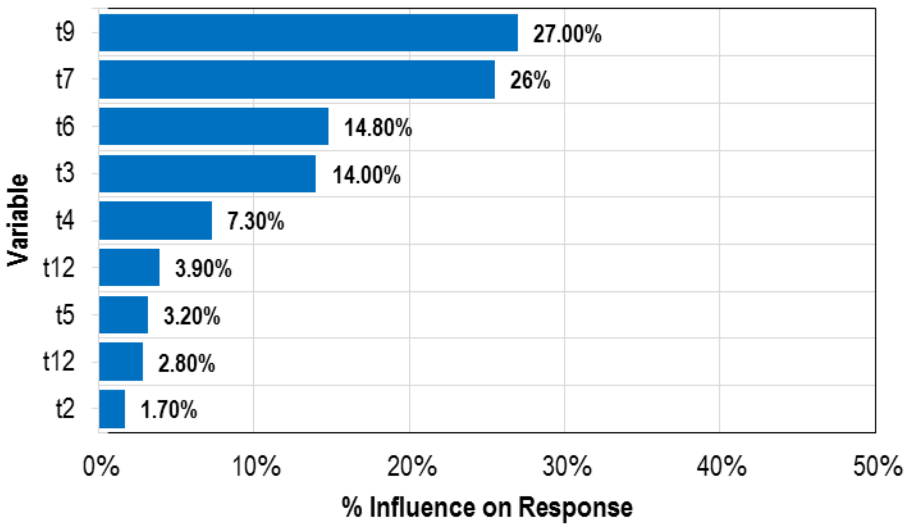

Figure 3.9. GSA plot of parameter contribution to the dummy axial neck force response.

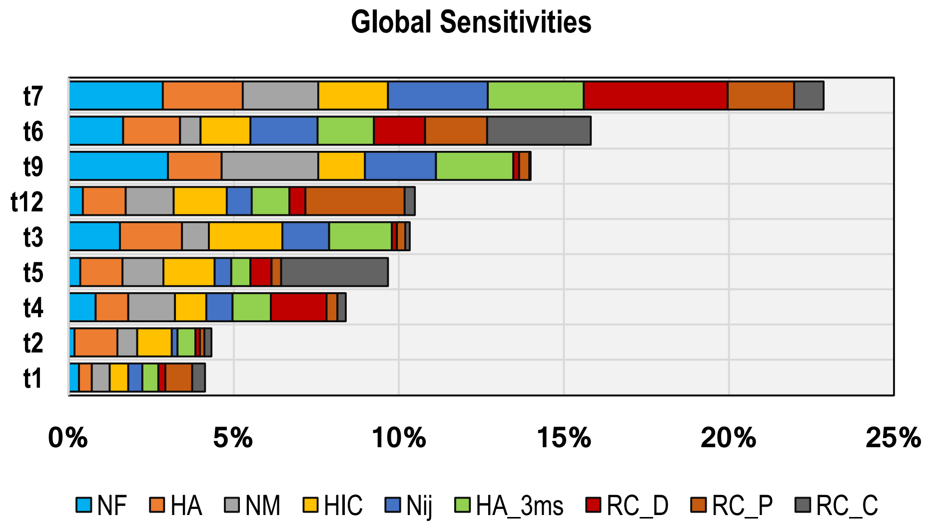

Figure 3.10. Cumulative GSA plots of parameter contribution to all dummy and vehicle responses.

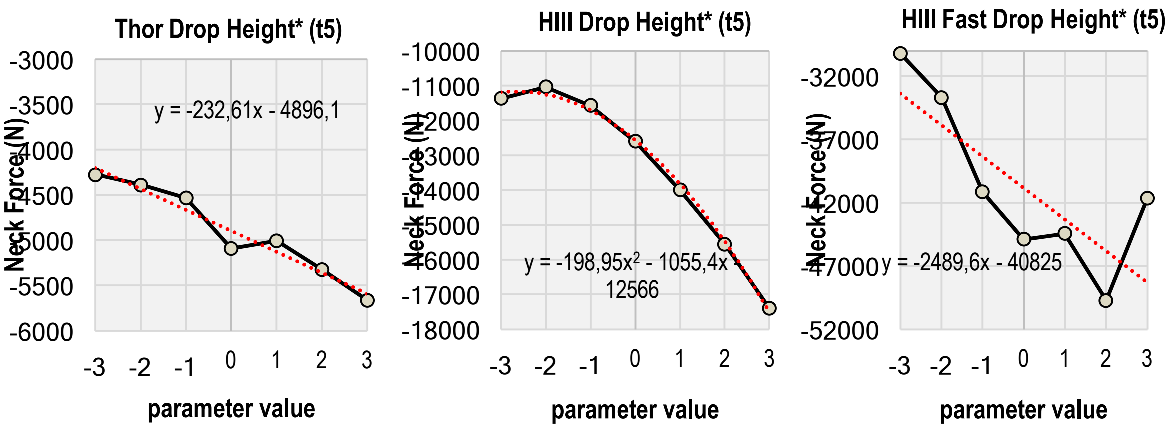

Figure 3.11. Dependence of force in the neck on (top) drop height for three models with different dummies (left) THOR (center) HIII NCAC (right) HIII FAST

In summary, computer simulation of rollover is an effective method for assessing effects of various vehicle and crash parameters on occupant response. These 2 papers represent a comprehensive effort to understand various dummy model responses to changing crash conditions that can ultimately predict human injury response in rollover crashes. Global sensitivity techniques can be useful to tease out additional interaction of parameters that can't be done with varying one parameter at a time as in the local sensitivity analysis. While vehicle response was mainly affected by individual crash conditions, the occupant responses demonstrated significant dependence on the interaction of crash parameters. This points to need to limit occupant excursion during rollover crashes as the chaotic nature of rollover crashes can lead to large effects on injury outcome. The THOR and Hybrid III (NCAC) models performed equally well, however, THOR's lower neck stiffness may be more suited to allow for understanding parameter variations in future analysis.

3.3 Determination of Factors to Reduce Injury Risk

The objective of the final paper in this thesis aim was to put everything together in terms of the factors responsible for injury risk and the potential for countermeasures to reduce that risk. The study uses a combined simulation approach to import nodal time histories derived from the vehicle (Ford Taurus) finite element model response during CRIS rollover simulations into a rigid body model simulation that adds seat belt restraints and an occupant model. The resulting simulation thus can be used to parameterize vehicle and crash conditions (previously reported in Paper 4 described above), restraint configurations (such as pretensioners and other belt routings) and occupant types (dummy and human models). The goals of the present work are threefold: 1) to investigate the effectiveness of vehicle roof strength to reduce the risk of occupant injury, 2) to evaluate the ability of vehicle restraint systems apart from and in combination with stronger roof structure to reduce injury risk and 3) to determine potential of various occupant computer models to differentiate the factors that were used in this study.

Of the ninety simulations that were run in paper 3, five of the conditions were chosen as direct inputs into this final paper's analysis. The cases were chosen based on the highest deformation of driver's side, the lowest deformation on the driver's side, the highest neck force recorded, the lowest neck force recorded, the highest Neck Injury criterion (Nij), the lowest Nij, the highest positive neck moment, and the lowest possible neck moment.

The nodal time histories of selected parts of the vehicle from those 5 LS-DYNA runs were then imported into MADYMO from the five chosen cases. These vehicle parts were based on the likelihood of contact with the occupant. The occupant models used for this parametric study were the MADYMO Facet Hybrid III 50th Percentile Dummy (HIII), the MADYMO Active Human Model (AHM with muscle activation turned off), and a newly created Facet THOR Model (THOR). The occupants were subjected to five restraint conditions composed of a passive baseline three-point belt, a three-point belt with a pre-tensioner in the buckle, a three point with a pre-tensioner in the D-ring, a three-point belt with a pre-tensioner in both the D-ring and the buckle, and finally a four-point belt with no pre-tensioner. Figure 3.12 shows the simulation with the AHM at initial drop and after 280 ms (max crush).

t = 0.0s **t = 0.280s**

Figure 3.12. Active Human Model with Three Point Belt in Deforming Vehicle

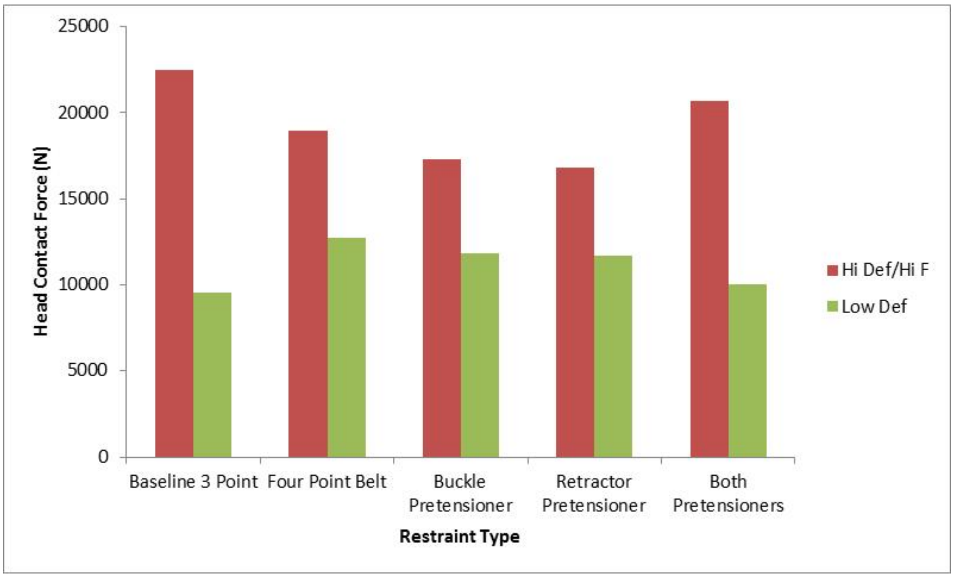

Figure 3.13. Peak Head Contact Force for THOR Occupant Model by Vehicle Strength Factors for Each Restraint System (Hi Def = weaker roof, Low Def = stronger roof).

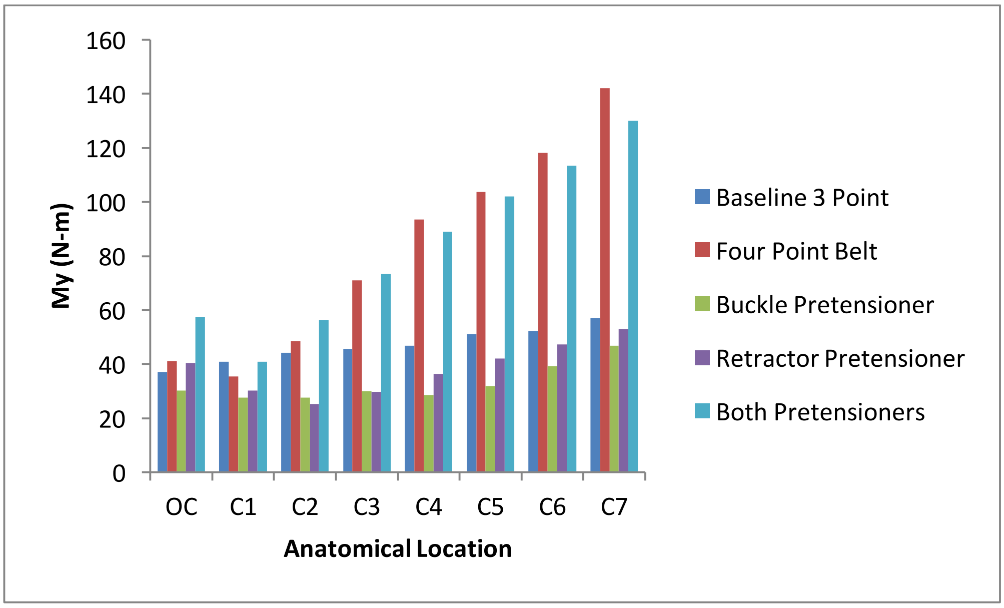

Figure 3.14. Peak resultant flexion/extension moment (My) for Each Cervical Vertebral Body Joint in Facet Human Model by restraint system for the Lowest Deformation Case.

Figure 3.14 shows the combined effect of the restraints and a stronger roof. The buckle and retractor pretensioners (individually) remain consistent moving down the cervical spine only slightly increasing at C6 and 7. The moments for those restraints remain below the moment value for the baseline restraint across the entire cervical spine and are well below the values of the highest deformation case.

The analysis in this paper revealed that vehicle roof stiffness can contribute to a reduction in injury risk. The combined strongest and highest roof parameters allowed for additional room for the occupant model to not interact as much with the intruding roof (Figure 3.13). Selection of crash dummy model to use in rollover simulations can affect the interpretation of effects. THOR neck construction results in less stiffness than Hybrid III and may be more useful to determine how to protect human occupants in rollover crashes. The THOR dummy was able to discern between restraint systems somewhat better than the Hybrid III dummy model (Figure 3.13). THOR's lower neck load cell followed the trend of reduced neck moments with advanced restraints, thus THOR may be a better dummy of choice to use in rollover testing and modeling if a dummy is used.

Figure 3.14 shows the combined effect of the restraints and a stronger roof. With either a buckle or retractor pretensioner, moments in the facet human model cervical spine remained consistent moving down the cervical spine only slightly increasing at C6 and 7. The moments for those restraints remain below the moment value for the baseline restraint across the entire cervical spine and are well below the values of the highest deformation case. This facet human model was the superior performing model in the study as it was able to determine that a combination of a stronger roof coupled with an advanced restraint system could mitigate neck loads along the entire cervical column.

4. GENERAL DISCUSSION

Injuries and fatalities in the U.S. as result of vehicle rollover have shown remarkable decreases in the past ten years. In the most recent data analyzed, NHTSA (2015a) reported that rollover fatalities in the United States have decreased from 10,442 in 2006 to 6,990 in 2015. The largest reductions in total numbers have been observed in passenger cars and pickup trucks, likely due to increased fitment of Electronic Stability Control (ESC), increased fitment of rollover deployable side curtain airbags and overall improved vehicle crashworthiness. Despite the improvements, the increasing trend of belted, unejected fatalities as a percentage of all rollover fatalities is a concern. The objective of this thesis, through systematic use of new methods of crash data analysis and computer modeling, is to determine what and how injuries are occurring in these vehicle crashes and determine factors responsible for and potential mitigation of these injuries. The following discussion summarizes the effectiveness of the methods used to achieve the stated objective.

4.1 Effectiveness of Field Data Analysis

Given the amount of literature on rollover crashes and injuries, there remains some uncertainty regarding the injuries experienced by occupants and how those injuries are caused. Most of the literature on rollover occupant injuries has focused on all the occupants in all types of rollover crashes. The papers by Heulke et al. (1973, 1976, 1983) and Mackay et al. (1993) were focused on ejections during rollover and indicated a substantial increased risk of fatality if the occupant was ejected. The papers' conclusions that belted occupants were far less likely to be ejected was obvious. Later papers by Digges (1993, 2005) focused on establishing risk of serious injury based on number of roof contacts. Bedewi (2003) was one of the first to look at individual NASS rollover cases to determine injury types and crash conditions. The finding that 2/3 of the belted non-ejected seriously injured occupants involved in a rollover crash only had one roof inversion was a compelling reason for the modeling of the CRIS test in this thesis with only one roof inversion. Also, the in-depth review of NASS cases prompted the review of CIREN cases for papers 1 and 2 since CIREN has such rich injury data descriptions.

Mandell et al. (2010), Funk et al. (2012) and Bambach et al. (2013) added substantial knowledge of the risk of injury to body regions of occupants in rollover crashes, but stopped short of providing the in-depth analysis of what specific injuries occurred and how the injuries occurred. Analysis of NASS-CDS data is excellent for providing a high level view of any crash condition and papers like Funk et al. (2012) give very good results on the risks of injury to rollover involved occupants. His and other papers detail the relationship of impact and roof crush and/or intrusion and other related occupant and vehicle factors, but a more in-depth approach was used in the first two papers of this thesis. The first paper satisfied that in-depth analysis need by utilizing both crash and injury investigations from specific rollover crashes and a new process for injury mechanism analysis. The BioTab process, along with the rich data from CIREN, provided an objective method to deduce the manner of the injuries experienced as well as any other contributing factors that may have played a role in the injury causation process.

The second paper begins with an analysis of data on rollover crash injuries experienced by belted, non-ejected occupants from a national perspective, specifically, the United States. This high level analysis is needed to determine what are the most frequent injuries, not just by body region, but specific injuries in those regions. For injuries, paper 2 showed that for the pure roll (single vehicle, single event) cases, the top 10 injuries (most frequent) comprise 62.6% (N=7,580 out of 12,105) weighted) of all AIS 3+ injuries in that mode. It also showed that spine fractures were a dominant serious injury for this population. Finally, the distribution of serious injury by body region was very similar to the CIREN analysis in paper 1, thus providing a measure of validation for both data sets. Statistical significance of this data is not readily available or required with this analysis as the raw data counts for this group are admittedly small and only trends are being reported here with no comparison to a baseline data set. Weighting factors were deemed to be appropriate (not excessive) to allow for realistic national estimates. Regardless, the aggregate data from NASS-CDS gives the high level view and a more focused injury analysis is required.

The latter part of the second paper drilled deeper into a specific injury (cervical spine fractures) in specific CIREN crashes (pure rollover or single vehicle, single event rollovers). Specific injuries were identified from injured occupants and occupant and vehicle factors were analyzed for each case to see if any patterns were observed. Comparisons of the injuries to other published work indicates that vehicle roof intrusion in both vertical and lateral direction (hence neck loading conditions) can influence injury patterns. The cervical spine facet and lamina fractures, especially in the lower c-spine regions indicate a complex off-axis loading pattern to the neck as the head interacts with intruding structures and the rest of the body loads the head and neck. Compression,lateral bending, extension alone or in any combination are possible. The CIREN data indicated older male occupants may be more at risk as well as heavier females, however no statistical significance can be done with CIREN data since all occupants are injured and there is noninjured occupants for comparison. This level of detail regarding rollover injury mechanism analysis and potential occupant and vehicle factors added significantly to the knowledge to the rollover injury causation and informed the analyses in papers 3-5. The results of papers 1 and 2 indicated next steps to determine an approach to look at injury risk in a simulated rollover crash environment where crash and occupant factors can be controlled and allowed a more thorough analysis of potential methods to to mitigate the severity of occupant rollover injury.

4.2 Effectiveness of Computer Modeling Capability/Predicatibility

When embarking on a computer modeling analysis, especially of a chaotic and random crash condition like rollover, care must be taken regarding selection of crash mode, vehicle and occupant to model. Quality of models, run times and level of validation must be considered for results to be meaningful. The modeling phase of this thesis takes an important step towards understanding how vehicle and crash parameters may influence the vehicle and occupant response in a simulation of a controlled rollover crash test condition. The repeatable and controllable CRIS test system was an ideal system to model since one can accurately prescribe initial conditions that produce consistent results while allowing for parameter variation that can provide insight into what parameters are most influential. These crash variations could be construed to be consistent with the variations seen in real world rollover crashes without going outside the bounds of reality, however, there is no way to bound the limits as the variations of a rollover crash are infinite. One limitiation of the CRIS test method is that it may be less sensitive to parameter variation as the dummy or occupant model is not allowed to rotate or translate until the vehicle is released.

In this study, a FE vehicle model was shown to be valid for overall crush response and occupant injury measures. The vehicle model chosen for the finite element studies was developed at the National Crash Analysis Center (NCAC) at George Washington University. The model, along with many others developed by NCAC have been meticulously created and rigourously evaluated for quality and performance validation. The material parameters for the roof pillar and rail variation were derived from Tamborra (2003) and provided essential, production level information. In the vehicle response evaluation section, it was shown that the roof deformation patterns between the FEM and the CRIS test are very similar. The good correlation between the test and FEM simulation of the overall roof deformation patterns, the occupant's head impact points with the roof and the similar peak neck axial force and moment indicate the confidence to use finite element models selected to simulate the CRIS test event and its variations in this study. Finally, most rollover simulation studies have used a model of a sports utility vehicle in their analysis while this study chose to use a mid-sized passenger sedan to add further challenge and to define responses in a different vehicle class. The more closed-interior, i.e., less overall interior space, would be a significant challenge as initial head-to-roof distances would be much less in a passenger vehicle than in an SUV.

The Hybrid III 50th percentile male crash test dummy model has been used in nearly all rollover modeling studies cited. Others have used human models, but this thesis used three different models to assess rollover (Hybrid III, THOR and a human model). Additional work was done to assess whether a less detailed model of the Hybrid III (HIII FAST) could be used to assess parameter variation more expediently. First, the HIII FAST dummy model gave very unsatisfactory results as far as prediction of the forces in the neck is considered. Also there was no consistency in the response of the dummy when it was used in with different versions of LS-DYNA (see Figure 4.2). The HIII NCAC model gave results quite close to the experimental values. The results obtained with it were repeatable when other versions of LS-DYNA were used up until the version 9.0.1. The Hybrid III dummy may have masked some effects of the parameters chosen. The axial stiffness of the Hybrid III neck is much higher than for humans and may have provided an unrealistic injury risk. The 12kN loads observed in the model validation study are nearly three times the threshold risk for a severe neck injury. The THOR dummy model reported significantly lower force in the neck than the HIII NCAC dummy which can be attributed to the differences in construction and the neck stiffness of the two models. The Hybrid III neck consists of alternating rubber and aluminum disks while the THOR neck has distributed stiffness representing the bony spine as well as muscles (represented as cables) resulting in a more human-like kinematic response as well as lower stiffness than the Hybrid III (Ridella, 2011). The maximum values of the moments were all much closer to the experimentally obtained value. The sensitivity analysis indicated the THOR dummy presented slightly lower variability in the neck forces and moments for almost all cases than the HIII NCAC dummy. This is consistent also with the more human-like characteristics of the THOR neck.

In order to do rapid and meaningful parameter variation, a high performance compute cluster was needed for analysis. Studies were done to establish benchmark run times and the appropriate version of LS-DYNA to use. Figure 4.1 presents the timing study for the three considered models. The same simulations were performed on one computational node (16 cores), two nodes (32 cores), and four nodes (64 cores) of a high performance cluster. The model with HIII FAST dummy runs almost 4 times faster than the model with the HIII NCAC dummy and about 7 times faster than the model where the THOR dummy was used.

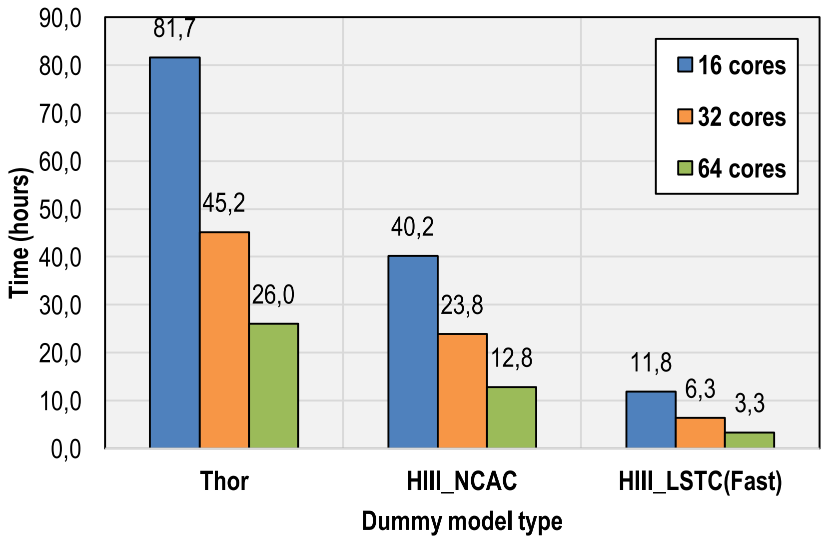

Figure 4.1. Performance of the models on different number of computational cores

In order to verify the consistency of the results, the simulations were performed with the use of different LS-DYNA versions including 7.1.1, 8.0.0 and 9.0.1 double precision solvers. The calculations conducted in versions 7 and 8 provided very close results for THOR and HIII NCAC dummy models. THOR dummy model didn't work in version 9.0.1. The results obtained for HIII NCAC dummy in version 9.0.1 were not consistent with the previous results. The model of HIII FAST dummy was giving different results in all three tested versions. THOR and HIII NCAC dummy models shouldn't be used without additional adjustments and revalidation of them in versions 9.0.1 and higher of LS-DYNA.

4.3 Parametric Analysis to Determine Effectiveness of Countermeasures

The parametric analyses of papers 3, 4 and 5 were essential to achieve the aims of the study. First, the parametric analyses of vehicle and crash factors to predict occupant response demonstrated the conditions that were most likely to maximize or minimize the occupant injury response. Global sensitivity analysis (GSA) was employed as tool to understand the variation in response.

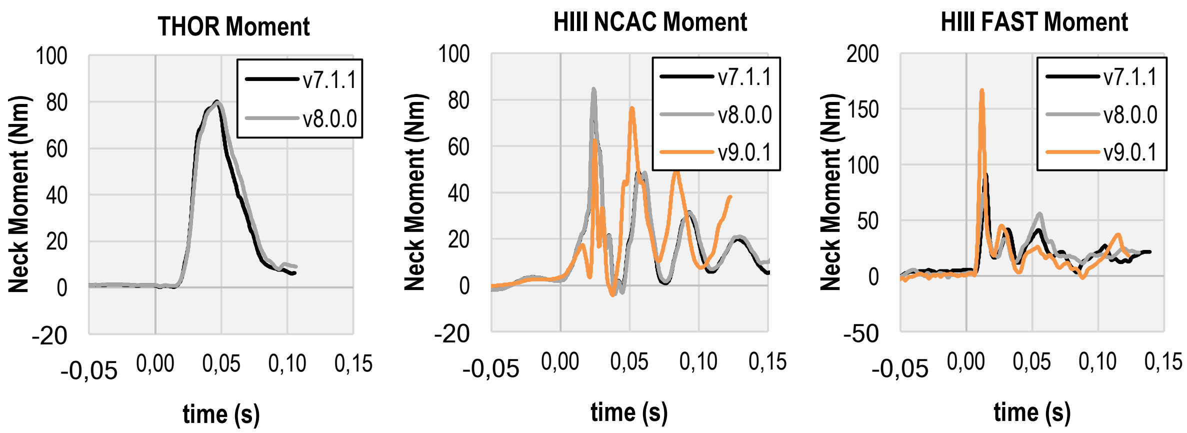

Figure 4.2. Dummy performance variation with different versions of LS-DYNA

GSA allows for simultaneous variation of all input parameters over the entire parameter space. The GSA techniques subsequently allow for evaluation of relative contributions of individual input parameters as well as the interactions between these parameters to the response of the system. One of more popular GSA techniques is Sobol's method which is also implemented in LS-OPT (Sobol, 2001), an optimization software distributed with LS-DYNA that was used in this study. In order to quantify the contribution of each parameter to the output variance, Sobol's method uses variance decomposition method. Basically, it allows for efficient estimation of the main and total effects of the parameters. With this method in place, the 90 simulations carried out in paper 3 gave excellent insights into what parameters were responsible for the variation.

Paper 5 combined all the elements needed to complete the objectives. A unique sequential modeling approach was undertaken that used vehicle model roll kinematics and deformations taken from nodal output from a previous series of finite element model simulations where crash conditions and vehicle parameters were varied to determine their effects on vehicle and occupant response (Paper 3). Five of the vehicle model results that achieved the highest and lowest vehicle deformations along with the highest and lowest Hybrid III dummy axial neck force and moment responses were imported to be combined directly with five different seat belt technologies that had been tested by Louden (2010) in her Rollover Restraint Tester. The combination of the restraint parameters and the vehicle variations (from paper 3) were run in an all MADYMO simulation with a Hybrid III model, a specially modified THOR dummy facet model (Zhang, 2016) and a facet human model. The significant amount of data generated on occupant kinematics, occupant response and injury outcome allowed determination of what restraints and roof parameters provided optimal protection. This simulation paradigm certainly cannot encompass all potential variations in the rollover crash domain for this vehicle nor can it represent the entire class of vehicle types that may rollover.

Restraint systems' effects appeared to be consistent with technology advances in some cases, but not others. The more advanced seat belt systems with single and dual pretensioners as well as 4-point belt performed better than the baseline 3-point belt in reducing the occupant displacement as well as the neck forces and head contacts. This was mostly true for the individual buckle or retractor pretensioners, but not for the 4-point belt system and the dual activated pretensioners. The 4-point belt did not have pretensioners so it may have performed similarly to the 3-point in having little effect on the occupant kinematics. The dual pretensioners may have been too effective at keeping the occupant upright an allowing the intruding roof to interact with the occupant models.

Finally, the combined roof and restraint effects need to be considered. The neck sagittal moments (mostly flexion) for the three occupants in Paper 5 indicate how cervical neck injury may be occurring (and mitigated) in rollover crashes. The roll angle, pitch angle and drop height determined the amount of vertical and lateral intrusion in the occupant compartment. This was consistent with the field cases (Ridella 2008 and paper 2) that showed high lateral intrusion associated with lower cervical spine fractures. For the human model, the progressive increase in neck moment in the highest deformation case regardless of restraint is consistent with injury mechanisms predicted by Nightingale (2016). That study indicated that "the most dangerous situation may be a combination of compression and flexion bending in the post-buckled lower cervical spine" since the compressive force and moments are maximized in the lower cervical spine.

5. CONCLUSIONS

Rollover crashes continue to occur in the field and represent a significant contribution to overall fatalities and injuries due to vehicle crashes. The nature and mechanism of the most common injuries point to the need to limit occupant excursion during rollover crashes as the chaotic nature of rollover crashes can lead to large effects on injury outcome. Determining countermeasures requires an effective method for assessing effects of various vehicle and restraint parameters on occupant response. This study represents a comprehensive effort to understand various dummy model responses to changing parameters that can ultimately predict human injury response in rollover crashes.

5.1 Field Data Analysis

The main conclusions of the first 2 papers helped to develop the path for the rest of the thesis. First, analysis of aggregate NASS data gave insight into the most frequent injuries in pure rollover crashes involving belted, unejected occupants. With cervical/thoracic/lumbar spine fractures and various head/brain injuries comprising seven of the top ten injuries in this group, this result indicates that focusing on causation of head and especially neck (spine) injuries was warranted.

Since conclusions on body region injury mechanisms cannot be drawn from large sample databases, both papers 1 and 2 took the opportunity to utilize the CIREN database coupled with objective data analysis tools to deduce specific injury mechanisms. The BioTab tool was extremely effective in understanding cervical spine injury mechanisms. Investigation of the CIREN occupant's cervical spine injury mechanism indicated that most struck the side roof rail or roof of the vehicle sometime during the rollover event. These front outboard occupants tended to go up and outboard resulting in the side or top of the head contacting these interior components and the subsequent cervical spine injury. The injury mechanism was 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. In addition to the mechanisms identified, many factors influence the risk of the neck injury, including the age and physical condition of the person; orientation of the head, neck, and torso; and location of impact and interface.

Reducing the possibility for the occupant to strike his/her head on the vehicle's interior components will reduce the risk of neck injury substantially. Limiting intrusion (both vertical and lateral) into the occupant compartment through improved roof strength would be one approach, however serious neck injury may still occur even with little or no intrusion. Stronger roofs are already being seen in more recent vehicle roof strength tests reported by NHTSA and the IIHS.

All the occupants in this study were belted and not ejected, yet sustained a serious neck or other body region injury. Improved seat belt design to minimize occupant excursion could result in less opportunity for the head to strike these regions and points to simulation studies with dummy and/or human models may be able to evaluate these devices systematically.

5.2 Simulation of rollover crashes

Computer simulation of rollover is an effective method for assessing effects of various vehicle and crash parameters on occupant response. The computer modeling phase in this thesis represents a comprehensive effort to understand various dummy model responses to changing crash conditions that can ultimately predict human injury response in rollover crashes. These studies and their results allow for the following conclusions:

Papers 3 and 4 concluded that a vehicle finite element model, representing a passenger car in a repeatable, rollover crash test condition provided insight into how vehicle and crash parameters affect response. Proper validation of the model provided confidence that the model has merit and that parameter variations give meaningful results. A variance-based global sensitivity analysis was an effective tool to determine the contribution of vehicle and crash parameters on the vehicle and occupant responses. The variables that contribute the most to the occupant and vehicle structural response (pitch angle, roll angle, and drop height) have the effect of determining where and with what force the vehicle roof impacts the ground. This information could help in identifying vulnerable areas in vehicle structures and designing countermeasures for vehicles that can mitigate intrusion and occupant contact to the roof.

Selection of a crash dummy model to use in rollover simulations can affect the interpretation of effects. When assessing occupant model quality, local sensitivity analysis allowed for comparing each dummy model's response to identical variations from initial conditions and correctly predicted occupant response to changing crash conditions. While the Hybrid III NCAC and THOR model predicted similar trends, the recently created, facet THOR dummy model presented lower variability in the neck forces and moments for almost all cases than the HIII NCAC dummy. THOR neck construction results in less stiffness than Hybrid III and may be more useful to determine how to protect human occupants in rollover crashes. Despite the advantages of reduced computation times, the HIII FAST dummy was unsuitable for this simulation regimen as it gave inconsistent results.

5.3 Value of Parametric Analysis

When assessing the vehicle and restraint parameters, an innovative modeling approach that imported vehicle kinematics and deformations combined with advanced restraint system and multiple occupant models provided an effective tool for determining what factors may help to mitigate injury risk. Vehicle roof stiffness and increased roof height can contribute to a reduction in injury risk. The combined strongest and highest roof parameters allowed for additional room for the occupant model to not interact as much with the intruding roof. It will be interesting to see how current vehicles, built with even stronger roofs than modeled in this study, perform in rollover crashes. While significant data on crashes of these vehicles is yet to be available, the analysis in this paper indicates that stronger roofs will reduce injury risk, however, restraint systems may still require improvements to reduce the potential for occupant head impact. The THOR dummy was better able to discern between restraint systems than the Hybrid III dummy model. THOR's lower neck load cell followed the trend of reduced neck moments with advanced restraints, thus THOR may be a better dummy of choice to use in rollover testing and modeling if a dummy is used.

Pretensioners had a significant effect on reduction of contact forces and neck forces, however, it was the facet human model that demonstrated that a combination of a stronger roof coupled with an advanced restraint system could mitigate neck loads along the entire cervical column.

6. FUTURE WORK

Even with the widespread introduction of rollover crash and injury mitigation technology such as ESC and rollover-capable side curtain airbags, there remains a significant amount of research and opportunity to improve on rollover crash protection. First, in-depth aggregate and case filed analysis of rollover crashes of more recent vehicles and crash conditions is warranted. The increasing trend of belted, unejected fatally injured occupants as a percent of all rollover fatalities indicates that there may be changing conditions in vehicles or crashes responsible for this trend. Higher sales of SUVs, more off-road tripped rollovers or changing occupant demographics may be occurring. The NASS has recently modernized to allow collection of more cases and from more recent vehicles. CIREN has continued its work since the papers for this thesis have been published. Current CIREN cases are drawing injured occupants in crashes from 2011 Model Year and newer vehicles that have more crash avoidance technology, stronger roofs and improved restraint systems. It would be beneficial to continue data analysis methods described in this thesis on these more recent vehicle and crash data sets.

It is clear from the computer analysis results that restraints technology has a significant effect on occupant kinematics in a rollover crash. While automobile manufacturers and their suppliers are investing in pretensioners, pre-crash pre-tensioning of belts, additional belts for far-side protection and larger curtain bags for near and far-side rollovers, these advances are usually designed for improvements in frontal and side crash protection. Adjusting algorithms for vehicle-specific rollover crashes that adjust the restraint systems for roll behavior and occupant classification may improve rollover crash performance. These systems could be tuned on laboratory test devices such as the DRoTS, CRIS or JRS systems that allow for parameterization and vehicle specific roll conditions. These test devices have shown repeatability and could prove very useful in restraint system tuning. They could also be used to look at similar restraint systems in rear seating positions to offer protection for more vehicle occupants. Finally, the THOR dummy has reached a stable design stage such that it would be a very useful tool to evaluate restraints in a rollover test environment and provide more human–like response to determine the optimal restraint design for rollover protection.

While dynamic rollover test procedures and advanced crash dummies may be used to evaluate restraints, there is limited usefulness of the testing approach. Dynamic test procedures will only review one mode and can't possibly test all scenarios cheaply. Reproducibility has yet to be demonstrated and would require considerable expense. The use of advanced human models with realistic muscle tensing and size/shape/gender is advocated for any future rollover crash performance analysis. The biofidelity of these models is improving as is the acceptance of the results of simulations using them. It is possible to create representations of any occupant size/gender/age from baseline models using available data from literature or other sources. Also, with improvements in computer CPU processing speed, throughput and inexpensive data storage, models can be exercised in any crash mode or vehicle type so that a wide range of results can be generated and used for optimizing designs.

Clearly vehicle design is changing for several reasons. Fuel economy rules have stimulated innovative changes to materials used in vehicle structure that influence crash performance. Innovative roof designs are being explored by manufacturers to allow more light into the vehicle while reducing weight. Also, more electrified vehicles are entering the market. These vehicles typically weigh more than their internal combustion engine competitors. A Tesla Model S can weigh between 2-2.2 tonnes and a Chevrolet Volt weighs 1.72 tonnes. Although the center of gravity of these vehicles is quite low, rollover crashes may still occur and challenge the roof structure. Looking to the near future, autonomous vehicles will be entering the market and provide a unique challenge for crash protection. In their Federal Automated Vehicles Policy (NHTSA, 2016), NHTSA has indicated that they expect future autonomous vehicles to be crashworthy despite the potential for significantly different occupant seating configurations and driving scenarios. Designers of these vehicles need to consider variations in exterior and interior geometry that accounts for roof stiffness, interior headroom, restraint systems and potential occupant to interior impacts that may occur in rollover situations as these vehicles travel in uncertain situations or interact with the traditional fleet during their introduction to the market.

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