Statistical Analysis and Computational Modeling of Injuries in Automobile Crashes

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(ABSTRACT)

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of less severe injuries. The purpose of this research was to investigate particular occupants and injury types in automobile crashes in order to identify national trends in injury incidence, type, and severity. A statistical analysis was performed in order to determine the effects of airbag deployment on incidence and severity of various injury and occupant types. In addition, a computational modeling study aimed to recreate actual automobile crashes that occurred in order to identify injury mechanisms and occupant kinematics during the crash. The specific studies performed were designed to investigate the effects of frontal airbags on: skin injuries, burn injuries, eye injuries, orbital fractures, severe upper extremity injuries, and pregnant occupant injuries.

The statistical analyses revealed several significant findings in injury trends related to occupant exposure to airbag deployment. In particular, occupants in frontal crashes were significantly at a higher risk to sustain a skin injury ($p=0.00$), a burn injury ($p=0.02$), a corneal abrasion ($p=0.03$), and a severe upper extremity injury ($p=0.01$) when exposed to an airbag deployment, than when not exposed to an airbag deployment. In addition, female occupants were at a statistically higher risk of sustaining an airbag induced skin injury than males ($p=0.00$). Finally, within a 95% confidence interval, older occupants were at a higher risk for sustaining both airbag induced burn injuries, and severe upper extremity injuries. While occupants in crashes with lower impact velocities were at a higher risk for airbag induced burn injuries, occupants in crashes with higher impact velocities were more likely to sustain a severe upper extremity injury. The airbag increased the incidence of eye injuries for occupants in frontal crashes, however, it also decreased the severity of the associated eye injuries. In particular, occupants who sustained an orbital fracture when exposed to airbag deployment sustained mostly closed,

less severe orbital fractures, while occupants not exposed to airbag deployment much more often sustained more severe, open, displaced, or comminuted orbital fractures.

While the airbag was shown to increase the risk of some injuries to particular occupants involved in specific crash types, the airbag appears to have provided a beneficial protective effect as it also reduced the severity of all injuries observed.

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Chapter 1:
Introduction

1.1 Introduction

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of less severe injuries (Deery, 1999). These associated minor injuries include skin contusions or lacerations (Steinmann, 1992; Walter, 1996; Weinman, 1995), eye injuries (Dubois, 1998; Duma, 1996; Gault, 1995), and upper extremity injuries (Freedman, 1995; Lundy, 1998; Richter, 2000). While these less severe injuries are not life threatening, some of the airbag induced injuries do cause residual pain and discomfort for the occupant. The purpose of this research was to investigate particular occupants and injury types in automobile crashes in order to identify national trends in injury incidence, type, and severity. The study in injury trends was designed to identify the effects of airbag deployment on various injury and occupant types. The overall goals of the study were to identify current real-world injury trends in automobile crashes, and to recreate actual crashes that occurred using computational modeling.

The research involved a two part study of automobile safety: statistical analysis of real-world trends using a national crash database, and crash recreation using computational modeling. The first 7 chapters are specific studies on occupant and injury types, while the final chapter is a computational modeling study that recreates two particular crashes that occurred involving pregnant occupants. The first 8 chapters of statistical injury analysis used the National Automotive Sampling System (NASS) database as the data source, while the computational modeling aspect of the research employed the MAthematical DYnamic MOdeling solver, called MADYMO. This chapter outlines the background and development of the NASS database, and gives a detailed explanation of the injury coding system used in the NASS cases. In addition, the statistical methods used in each study are explained. Finally, this chapter finishes with a list of objectives for chapters 2 through 9.

1.2 Methods

1.2.1 National Automotive Sampling System (NASS)

The National Automotive Sampling System (NASS) program was established in 1979 to develop a detailed database of research on motor vehicle crashes that occur in the U.S. (NHTSA, 2000). The U.S. Department of Transportation's agency, NHTSA (National Highway Traffic Safety Administration), has a branch called the National Center for Statistics and Analysis (NCSA), which operates the NASS program. The NASS CDS (Crashworthiness Data System) collects detailed data on about 5,000 crashes each year from 24 sites across the country. The specific crashes chosen for investigation are a random, representative sample of the thousands of minor, serious, and fatal crashes that occur each year on U.S. roadways.

Crashes are considered for NASS investigation if they: occur on a traffic way (driveway and parking lots excluded), are reported to police, involve a harmful event (property damage and/or personal injury), and involve at least one towed passenger car, light truck or van. Each crash is classified into categories based on type and model year of vehicle, most severe reported injury, disposition of the injured, and tow status of vehicle. Once all qualifying crashes are listed, each research team is assigned a number of crashes to investigate each week.

The crash investigators obtain data from crash sites, studying evidence such as skid marks, fluid spills, broken glass, and bent guardrails. They locate the vehicles involved, photograph them, measure the crash damage, and identify interior locations that were struck by the occupants. These researchers follow up on their on-site investigations by interviewing crash victims and reviewing medical records to determine the nature and severity of injuries resulting from the crash. The injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1999).

There are three main categories of numbers that can be discussed in reference to data in the NASS database: cases, occupants, and injuries. Cases and occupants can be discussed as either having unweighted or weighted values, and are the same number for each. So, the 'unweighted number of cases', or the 'unweighted number of occupants', refers to a count of actual people that were in crashes investigated by the NASS researchers. For example, in a single crash, there could be 5 occupants involved, with 7 injuries each. Though this is listed in the database as a single case, the convention is to count this crash as 5 cases. Therefore, cases can more appropriately be commonly referred to as the unweighted number of occupants in the crash. Each case also has a weighted value assigned to it. This 'weighted' value scales the incidence of the particular accident investigated to a number that represents actual occurrence of similar non-investigated crashes that occur in the U.S. each year. Because each crash has a unique set of crash circumstances, occupant characteristics, and resulting injuries, each case under investigation is assigned a unique weighted value. For example, 2 separate crashes could occur on the same stretch of roadway, on different days, and be assigned 2 separate weighted values. For the above example, each of the 5 occupants involved would have the same weighted value that is associated with the crash. Therefore, if the case was calculated to have a weighted value of 100, this crash would count as having 5 unweighted occupants, or 500 weighted occupants. Similarly, it would be also counted as 5 unweighted cases, or 500 weighted cases.

The third category of numbers in the NASS database is the number of injuries. This count comes from the total number of listed injuries for the crash, including the possibility of multiple injuries to the same occupant. If there were 7 injuries for each of the above occupants, this would count as 35 (unweighted) injuries in the crash, or 3,500 total weighted injuries. The unweighted numbers are the actual numbers listed in the database, whereas the weighted values are scaled from the cases investigated, intended to represent all similar injuries that occur in crashes that are not investigated.

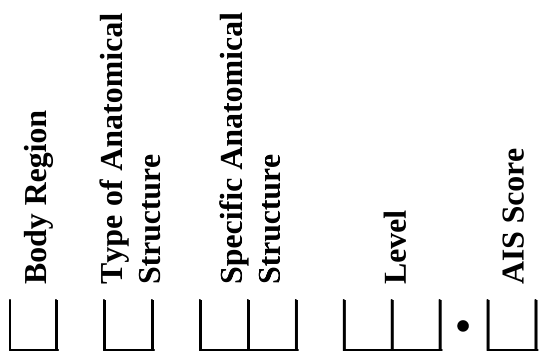
The researchers are professionally trained and conduct in-depth investigations in line with specific formal procedures and detailed scientific protocols. The NASS data are used by the government, industry, and private sector in order to assess the overall state of traffic safety, and identify existing and potential traffic safety problems. In particular, the NASS database has been used to study in an effort to establish and evaluate the relationship between occupant injury type and severity, and various crash specific characteristics (Atkinson, 2000; Deery, 1999; Duma, 1996; Farmer, 1997; Miller, 1993; Reiff, 2001; Segui-Gomez, 2000; Viano, 1990). One primary advantage of using the NASS database is that in each crash investigated, all occupants are included in the case report–not just the ones that sustained severe injuries. For this reason, the NASS database has a more accurate representation of the entire severity range of injuries that occupants sustain–with no overrepresentation for severe or fatal injuries.

1.2.2 Abbreviated Injury Scale (AIS)

The AIS injury code is a seven digit numerical account of injury that includes information on both the severity of the individual injury and the location on the body

(AAAM, 1999). The seven digit AIS injury code indicates body region, anatomical structure, and level of injury within the specific body region (Figure 1.1.a). The first number in the code indicates body region, the second represents type of anatomical structure, the third and fourth relate to the specific anatomical structure, and the fifth and sixth indicate the level of the injury within the specific anatomical structure. The last number of the injury code, after the decimal point, is the AIS score assigned to the particular injury. The current AIS scoring system assigns values to injury severity using a 6-point scale ranging from minor (AIS 1) to untreatable (AIS 6), resulting in death (Figure 1.1.b).

(a)



AIS Score	Description
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum
7	Unknown

(b)

Figure 1.1. Conventions for assigning digits of AIS injury code (a), and specific values for AIS score (b).

The AIS score is a single digit measure of the anatomical severity of an injury, not of physiological impairments or disabilities resulting from the injury. Inherent threat to life is evaluated, but the scoring includes no consideration for long-term discomfort, scarring, or disfigurement. The AIS scores are assigned for each injury sustained, and do not factor any combined effects from multiple injuries to the same patient. The conventions for assigning the first six digits for the AIS code can be found in Table 1.1.

Table 1.1. Conventions used for assigning numbers to specific injury descriptions. (NFS = Not Further Specified)

<table>
<tr>
<td>1. Body Region
1 Head
2 Face
3 Neck
4 Thorax
5 Abdomen
6 Spine
7 Upper Extremity
8 Lower Extremity
9 Unspecified</td>
<td rowspan="3">3. Specific Anatomical Structure
Whole Area
02 Skin - Abrasion
04 - Contusion
06 - Laceration
08 - Avulsion
10 Amputation
20 Burn
30 Crush
40 Degloving
50 Injury – NFS
60 Penetrating
09 Trauma, non-mechanical

Head – Loss of Consciousness (LOC)
02 Length of LOC
04 06 08 Level of Consciousness
10 Concussion

Spine
02 Cervical
04 Thoracic
06 Lumbar</td>
</tr>
<tr>
<td>2. Type of Anatomical Structure
1 Whole Area
2 Vessels
3 Nerves
4 Organs (incl. muscl/lig.)
5 Skeletal (incl. joints)
6 Head - LOC</td>
</tr>
<tr>
<td>Vessels, Nerves, Organs, Bones, Joints are assigned consecutive 2 digit numbers beginning with 02.</td>
</tr>
<tr>
<td colspan="2">4. Level
Specific injuries are assigned consecutive 2-digit numbers beginning with 02. To the extent possible, within the organizational framework of the AIS, 00 is assigned to an injury NFS as to severity or where only one injury source is given in the dictionary for that anatomic structure. 99 is assigned to an injury NFS as to lesion or severity.</td>
</tr>
</table>

1.2.3 Maximum AIS (MAIS)

The Maximum AIS (MAIS) is the highest AIS level injury for an occupant, selected from all injuries the occupant sustained in the crash. The AIS level listed in the

NASS case files is the AIS rating for the particular injury listed. The MAIS for the occupant is always either equal to or greater than the AIS value for the injury. For example, a particular occupant that has five different injuries, all rated AIS 1, with an additional major head injury (AIS 5), will have each of the five injuries listed with an AIS 1, and an overall occupant MAIS value of 5.

1.2.4 Statistical Methods

There were two methods of statistical analysis used in this study. Weighted means, standard deviations, and 95% confidence intervals were calculated for continuous random variables, such as occupant height, weight, age and crash change in velocity (Delta-V). In addition, discrete variables, such as occupant sex, seatbelt use, and seat position, were analyzed using the chi square test of independence for survey data (SUDAAN, Research Triangle Park, North Carolina). These statistical analyses were performed in order to determine if particular occupant and crash variables had a statistically significant effect in predicting injury incidence or severity for various occupant and crash types.

1.3 Research Objectives

Chapter 2. Skin Injuries

The purpose of this study is to investigate skin injuries resulting from frontal automobile crashes and to determine the effects of airbags on the incidence of skin injuries. Patterns in injury incidence are identified as well as occupants and crash types that correlate with the risk of airbag induced skin injuries for occupants exposed to airbag deployment.

Chapter 3. Burn Injuries

This study investigates burn injuries to occupants in frontal automobile crashes and determines the effects of airbags on the incidence of burn injuries. Sources and severities of burn injuries are identified and compared based on whether or not the occupant was exposed to an airbag deployment, and whether or not the airbag was the source of the burn injury.

Chapter 4. Eye Injuries

Chapter 4 investigates eye injuries to occupants in frontal automobile crashes to elucidate the effects of frontal airbags. A new four level eye injury severity scale is developed that quantifies injuries based on recovery time, need for surgery, and possible loss of sight. Using these levels, eye injury incidence and severity are investigated for occupants who were or were not exposed to frontal airbags.

Chapter 5. Orbital Fractures

Orbital fractures that occurred in frontal automobile crashes are identified and the injury incidence and severity patterns are correlated with occupant exposure to airbag deployment. The incidence of orbital fracture injury and the injury source are identified for occupants who were or were not exposed to airbag deployment.

Chapter 6. Severe Upper Extremity Injuries

The purpose of this study is to determine the overall risk and severity of upper extremity injuries in automobile crashes and to elucidate the effects of frontal airbags on these patterns.

Chapter 7. Pregnant Occupants

The purpose of this paper is to determine the overall risk and severity of injuries to pregnant occupants in automobile crashes and to outline the specific cases of maternal and fetal loss reported in the NASS database.

Chapter 8. Madymo Modeling of Pregnant Occupants

The objective of this study is to recreate actual crashes involving pregnant occupants in automobile crashes. Cases from the NASS database analysis in chapter 7 were selected to model based on primary crash and occupant characteristics found to be dominant in real world crashes.

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Chapter 2:
Skin Injuries

2.1 Introduction

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of less severe injuries (Deery, 1999). These associated minor injuries include eye injuries, upper extremity fractures, and skin injuries. In particular, skin injuries have been identified through case reports and observed primarily on the face and neck, but have also been identified on the upper extremity and chest (Antosia, 1995; Beckerman, 1995; Bhavsar, 1997; Burton, 1994; Cocke, 1992; Cooper, 1998; Dalmotas, 1995; Duma, 1996; Duma, 1998; Foley E, 2000; Foley S, 1995; Freedman, 1995; Hansen, 1999; Huelke, 1995; Klask, 2001; Lueder, 2000; Manche, 1997; Maxeiner, 1997; Molia, 1996; Morrison, 1998; Murphy, 2000; Rebel, 1996; Rozner, 1996; Scott, 1993; Smally, 1992; Smock, 1995; Steinman, 1992; Stranc, 1999; Vichnin, 1995; Weinman, 1995). A wide range of skin injuries are reported, from a minor abrasion, to a more severe laceration or avulsion. As identified in case studies, injuries to the skin can often occur due to contact with the airbag during or after deployment, and are likely caused by various combinations of normal and shear stresses.

There exists a paucity of experimental data on airbag induced skin injuries compared with the number of individual case studies with reported skin injuries. Early research done by Kikuchi et al. (1975) showed that injury severity is directly proportional to the total pressure exerted onto the skin by an airbag, though no specific injury criterion was recommended. More recently, experiments performed on human volunteers found that airbag induced skin abrasions are a function of the normal pressure applied to the skin (Reed, 1992; Reed, 1993; Sugimoto, 1994).

While studies have demonstrated experimental modeling of pressure exerted onto the skin during an airbag deployment, there are no quantitative results available on skin injury severity or frequency in real world crash situations. Although numerous case studies list skin injuries among more serious injuries that patients sustain, no study has successfully demonstrated the risk of skin injuries in crashes with and without an airbag deployment. The purpose of this study is to determine the national incidence of skin injuries in automobile crashes and to elucidate the effects of frontal airbags on these injury patterns.

2.2 Methods

In order to eliminate the inaccuracies associated with small case study projections, this study utilizes the National Automotive Sampling System (NASS) (NHTSA, 2000). The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1998). This coding allows for a consistent and accurate distinction and identification of skin injuries. The NASS database has been used for national injury projection studies to analyze injury severity and crash characteristics for such things as lower extremity injury patterns and side impact restraint effectiveness in motor vehicle crashes (Atkinson, 2000; Deery, 1999; Farmer, 1997; Miller, 1993; Reiff, 2001; Viano, 1990). Every crash investigated for the NASS database is assigned a weighted value, which scales the incidence of the particular crash investigated to a number that represents actual occurrence of similar non-investigated crashes that occur in the U.S. each year. Unweighted numbers reflect actual values counted from the cases that appear in the NASS database. The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained, and do not include combined effects from multiple injuries to the same patient.

For this study, cases in NASS were selected from the years 1995 through 2000 that include drivers and front seat occupants only, while excluding ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. These selection criteria allowed for injury mechanism analysis within similar car crashes. Skin injuries included abrasions, contusions, lacerations, and avulsions, and were identified in the NASS database using the current AIS injury codes (AAAM, 1998). Occupants with injuries and total injuries to occupants were analyzed. The study was divided into three parts.

Part 1: Skin Injury Rates

The first part of this analysis considered crashes with an airbag deployment. For all occupants who were exposed to an airbag deployment, the number of occupants that sustained a skin injury was compared with the total number of occupants who did not sustain a skin injury. Next, an analogous search was performed for crashes in which the airbag did not deploy. For all occupants who were not exposed to an airbag deployment, the number of occupants that sustained a skin injury was compared with the total number of occupants who did not sustain a skin injury. As there was no airbag deployment in these cases, sources of injury were such things as contact with the instrument panel or windshield. Occupants with injuries and total injuries to occupants were counted and compared with totals for each type of crash.

Part 2: Skin Injury Characteristics

Skin injuries to occupants were further investigated by location and type. A comparison was made between skin injury locations for occupants who sustained airbag-induced skin injuries, and occupants who sustained skin injuries from other sources, while being exposed to an airbag deployment. In addition, skin injury location and type was also investigated for occupants who were not exposed to an airbag deployment and sustained a skin injury. Resulting skin injury locations were compared as percents for total injuries in similar crashes, depending on the source of injury. Airbag and other injury sources were examined for a comparison of resulting skin injury location based on injury source.

Occupants and skin injuries were further investigated to identify trends relating skin injury source to the severity of the resulting skin injury. The skin injury AIS values were identified and compared with the injury source for occupants who sustained airbag-induced skin injuries, occupants who sustained skin injuries from other sources while being exposed to an airbag deployment, and occupants who were not exposed to an airbag deployment. Incidence of injury and percentages of occupants who received a skin injury were calculated. In other words, a comparison was made between the severity of skin injuries for occupants with an airbag as the injury source, and the severity of skin injuries for occupants who sustained skin injuries from other sources.

Part 3: Occupant and Crash Characteristics

Occupants exposed to an airbag deployment were analyzed in order to identify trends in skin injury incidence. The cases with airbag deployment were first broken down into two groups as to whether or not the occupant sustained an airbag induced skin injury. Group 1 included all occupants who received an airbag induced skin injury, while Group 2 included all of the remaining occupants. The occupants in Group 2 could have sustained a skin injury in the crash, but the source would be something other than the airbag. The groups were divided in this way in order investigate occupant characteristics that might be related to resulting incidence of airbag induced injury. Since all occupants in this analysis were exposed to an airbag deployment, risk factors could be identified that associate occupant characteristics to incidence of airbag induced skin injury.

The chi square test of independence for survey data (SUDAAN, Research Triangle Park, North Carolina) was used to investigate occupant sex, seatbelt use, and seat position, driver or passenger. Percentages and p-values were calculated for each of the variables. Average value and standard deviations were calculated for continuous variables such as occupant height, weight, age, and crash change in velocity (Delta-V).

Occupants and skin injuries in crashes with airbag deployment were further investigated to identify differences in injury trends for occupants exposed to tethered and non-tethered airbags. A tether limits the shape and size of the airbag, and both tethered and non-tethered airbags exist in the fleet of vehicles. This part aimed to investigate only crashes with airbag deployments, in order to identify a correlation between incidence of injury and airbag type. For this part, cases were also excluded that did not indicate whether the airbag was tethered or not.

2.3 Results

Part 1: Skin Injury Rates

A total of 9,687,340 weighted occupants (19,215 cases) were included in this study for the six year period from 1995 to 2000 (Figure 2.1). For crashes where the occupant was exposed to an airbag deployment, 1,350,255 weighted occupants (4,077 cases) sustained a skin injury out of 2,255,070 total weighted occupants (5,646 cases) in similar crashes (59.9%). In contrast, for crashes without an airbag deployment, 2,665,899 weighted occupants (8,029 cases) sustained a skin injury out of 7,432,270 total weighted occupants (13,569 cases) in similar crashes (35.9%). The study found that occupants were significantly more likely to sustain a skin injury when exposed to an airbag deployment, than when not exposed to an airbag deployment (p=0.00). In particular, of the occupants exposed to an airbag deployment, 893,689 of them (2,576 cases) sustained a skin injury specifically from the airbag (39.6%). In summary, occupants were much more likely to sustain a skin injury when exposed to an airbag deployment (59.9%), than when not exposed to an airbag (35.9%), a difference that was statistically significant (p=0.00).

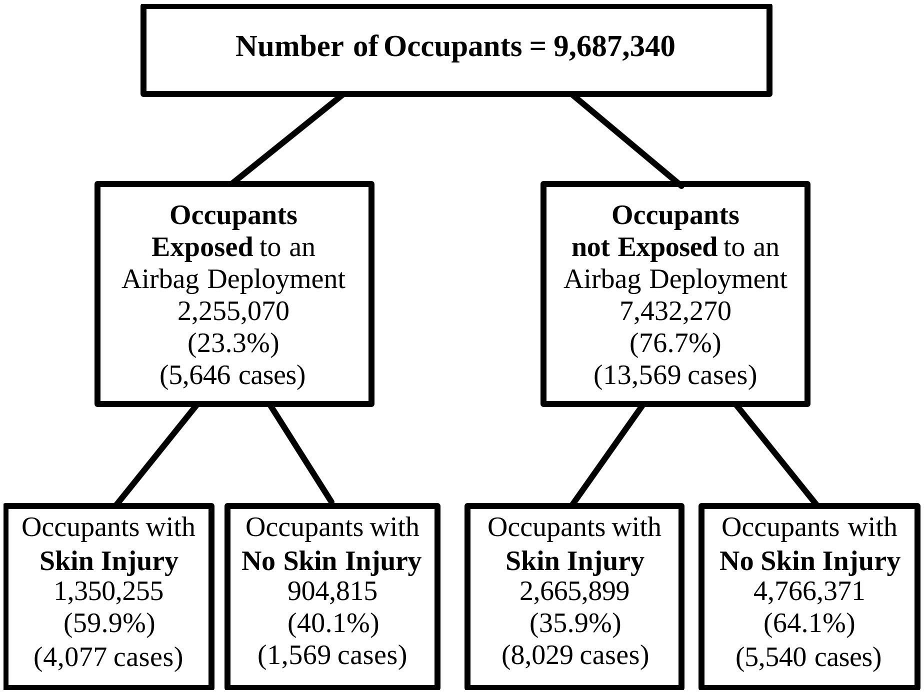

Figure 2.1. Incidence of skin injury for occupants in frontal crashes, that were or were not exposed to an airbag deployment (1995-2000).

For all the skin injuries to occupants, 34.5% occurred to occupants who were exposed to an airbag deployment, or rather, 65.5% occurred to occupants who were not exposed to an airbag deployment (Figure 22). If the occupants with a skin injury were exposed to an airbag deployment, the airbag was the source for 46.7% of the skin injuries. If an airbag did not deploy, the top two sources for skin injury were the instrument panel or glove box (30.4%), and the seatback or seatbelt (21.8%).

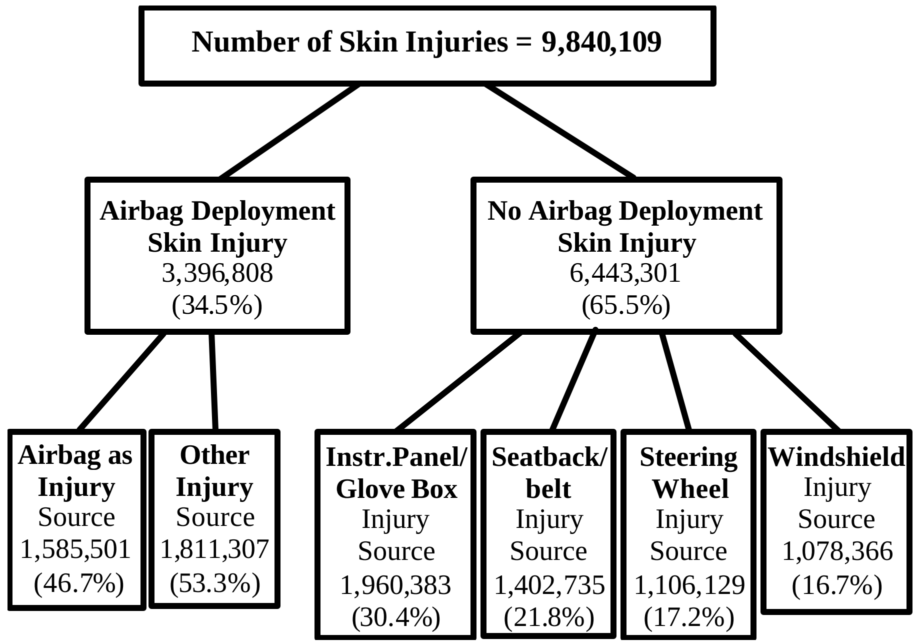

Figure 2.2. Injury sources for skin injuries that occurred to occupants in frontal crashes (1995-2000).

Part 2: Skin Injury Characteristics

There was a shift in the skin injury location depending on whether or not the occupant was exposed to an airbag deployment, and whether or not the airbag was the source of the injury (Table 2.1). For all airbag induced skin injuries, the majority occurred to the upper extremity (41.0%), and the face (41.0%). Just 2.2% of airbag-induced skin injuries occurred to the lower extremity. In contrast, occupants who were not exposed to an airbag deployment sustained skin injuries from other sources in the vehicle, and received injury most often to the face (29.4%), closely followed by the lower extremity (28.9%) and the upper extremity (20.2%).

Table 2.1. Comparison of all skin injury locations in crashes with and without airbag deployment.

	Airbag Deployment						No Airbag Deployment	
	Source: All included		Source: Airbag		Source: Other		Source: Other	
	#	%	#	%	#	%	#	%
Face	774,263	22.8%	649,625	41.0%	124,638	6.9%	1,896,567	29.4%
Neck	99,716	2.9%	67,713	4.3%	32,003	1.8%	135,401	2.1%
Chest	421,040	12.4%	152,360	9.6%	268,680	14.8%	857,604	13.3%
Abdomen	152,999	4.5%	31,130	2.0%	121,869	6.7%	289,075	4.5%
Upper Extremity	1,148,305	33.8%	650,340	41.0%	497,965	27.5%	1,300,783	20.2%
Lower Extremity	786,203	23.1%	34,333	2.2%	751,870	41.5%	1,860,682	28.9%
Back	14,282	0.4%	0	0.0%	14,282	0.8%	103,189	1.6%
Totals:	**3,396,808**	**100%**	**1,585,501**	**100%**	**1,811,307**	**100%**	**6,443,301**	**100%**

Injury types were compared for airbag induced skin injuries, and skin injuries to occupants in crashes with no airbag deployment and other injury sources (Table 2.2). There was a considerable difference in injury type depending on exposure to airbag deployment and body region with injury. If the occupant was exposed to an airbag deployment and the airbag was the source of the injury, the skin injuries were 48.6% abrasions, and 11.4% lacerations. In contrast, if an occupant was not exposed to an airbag deployment, the skin injuries were only 21.5% abrasions, while there were 57.6% contusions and 20.2% were lacerations. This indicates that nearly half of all airbag induced skin injuries were abrasions, while over half of all skin injuries to occupants who were not exposed to an airbag deployment were contusions.

Table 2.2. Comparison of skin injury types for airbag induced skin injuries and injuries in crashes with no airbag deployment and other injury sources.

	Airbag Deployment Airbag Source		No Airbag Deployment Other Sources	
	#	%	#	%
Abrasion	770,839	48.6%	1,386,280	21.5%
Contusion	624,780	39.4%	3,709,578	57.6%
Laceration	180,390	11.4%	1,300,001	20.2%
Avulsion	679	0.0%	40,769	0.6%
Unknown	8,813	0.6%	6,673	0.1%
total:	**1,585,501**	**100.0%**	**6,443,301**	**100.0%**

The airbag was the source of the skin injury for 893,689 occupants. Of these, the most severe skin injury was an AIS level 1 injury for 893,404 occupants (99.97%), and an AIS2 for 285 occupants (0.03%). There were no airbag induced skin injuries resulting in AIS severity ratings of 3 or higher. There were 2,665,899 occupants with skin injuries (8,029 cases) in crashes with no airbag deployment. All of the injuries to these occupants were from sources other than the airbag, and the highest injury severities were distributed as 2,658,845 AIS1 (99.74%), 6,596 AIS2 (0.25%), and 458 AIS3 (0.02%). In other words, regardless of the injury source or crash situation, the majority of the occupants sustained skin injuries at a severity level of AIS1.

Part 3: Occupant and Crash Characteristics

The next analysis was made by examining occupant and crash characteristics for the 2,255,070 weighted occupants who were exposed to an airbag deployment. Of the occupants with airbag induced skin injuries, 59.1% were females, while 40.9% were males. In addition, 82.2% were drivers while 17.8% were right front seat passengers. Finally, 87.2% were wearing seatbelts while 12.8% were not wearing seatbelts.

Occupant Sex. It was found that 47.3% of female occupants exposed to an airbag deployment sustained an airbag induced skin injury, compared with 32.6% of male occupants. Occupant sex was found to be a statistically significant factor in incidence of airbag induced skin injury ($p=0.00$), with females being at a higher risk than males.

Seatbelt Use. The analysis found that 40.4% of belted occupants sustained an airbag induced skin injury, while 35.7% of unbelted occupants received an airbag induced skin injury. Though this study resulted in a slightly greater incidence for the belted occupant, the difference was not statistically significant ($p=0.46$).

Seat Position. The analysis found that 38.8% of drivers exposed to an airbag deployment received an airbag induced skin injury compared with 43.9% of right front seat passengers. Though front seat passengers had a greater incidence of airbag induced skin injuries, the difference was not found to be statistically significant ($p=0.10$).

Within a 95% confidence interval, occupant weight, age, and crash Delta-V were all found to not be significant variables correlating with the risk of airbag induced skin injury (Table 2.3). However, occupant height was found to be significant, with shorter occupants being more likely to sustain an airbag induced skin injury.

Table 2.3. Comparison of Group 1 and Group 2 crash characteristics indicating correlation between incidence of airbag induced skin injury and crash variable. Mean values and standard deviations are included.

	GROUP 1: Airbag Induced Injury		GROUP 2: No Airbag Induced Injury	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation
Occupant Height (in)	65.82	0.53	67.75	0.13
Occupant Weight (lbs)	155.91	2.53	163.22	2.89
Occupant Age (yrs)	34.68	0.94	32.99	1.13
Delta-V (mph)	13.81	0.37	13.68	0.49

For the years 1995 and 2000, there were 2,137,347 weighted occupants who were exposed to an airbag deployment with a known tether type, of which, 1,298,537 sustained a skin injury. Further breakdown by airbag type revealed that 744,496 of the occupants who received injuries were exposed to a tethered airbag (57.3%), while 554,041 were exposed to a non-tethered airbag (42.7%). For the six year period from 1995-2000, there were 1,233,533 occupants exposed to a tethered airbag deployment, 744,496 of which sustained injury, a rate of 60.4%. For the same six year period, 903,814 occupants were exposed to a non-tethered deployment, while 554,041 sustained injury (61.3%).

2.4 Discussion

This chapter presents the most comprehensive skin injury study to date as it investigated 19,215 individual cases over six years to identify the effects of frontal airbags on the incidence of skin injuries. Occupants exposed to an airbag are approximately twice as likely to incur a skin injury (59.9%) as those occupants not exposed to an airbag (35.9%), a difference that was found to be statistically significant ($p=0.00$). Overall, the number of airbag induced skin injuries is increasing each year as the number of airbag equipped automobiles in the fleet increases. Although skin injuries are typically minor, the fact that nearly two out of three occupants exposed to an airbag sustained a skin injury warrants further investigation into reducing these injuries. More specifically, given that approximately one half (46.7%) of these injuries were attributed directly to the airbag, the design of the airbag itself should be considered for injury-reducing concepts.

Female occupants were found to be at a significantly higher risk of sustaining a skin injury than male occupants ($p=0.00$). Moreover, it was found that shorter occupants were also more likely to sustain an airbag induced skin injury. It appears that these two factors are significant due to the small female's increased proximity to the deploying airbag, thereby leaving the small female more likely to sustain an injurious event.

While airbags have been shown to reduce severe and fatal injuries in automobile crashes, the threat of minor injuries, such as skin abrasions, continues to increase. There are several sources of skin injuries from the airbag, included the fabric, seams, or module cover. All of these should be considered for design modification in order to minimize the risk of skin injuries for occupants exposed to an airbag deployment.

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Chapter 3:
Burn Injuries

3.1 Introduction

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have increased the risk of less severe injuries (Deery, 1999). These associated injuries include upper extremity fractures (Freedman, 1995; Kirchhoff, 1995; Lundy, 1998), eye injuries (Duma, 1996; Ghafouri, 1997; Lee, 2001), skin abrasions (Steinmann, 1992; Walter, 1996; Weinman, 1995), and skin burns. In particular, skin burns have been attributed to the high temperature gases released during deployment (Huelke, 1992; Otte, 1995; Rutan, 1997). These types of thermal burns have been identified through case reports and observed primarily on the upper extremity (Dumortier, 2001; Hallock, 1997; Heimbach, 2000; Huelke, 1995; Vitello, 1999), but have also been shown to occur on the face (Baruchin, 1999; Klask, 2001), and thigh (Pudpud, 1998; Weinman, 1995). In addition to the thermal burns, a few cases have indicated chemical burns resulting from airbag deployment (Conover, 1992; Corazza, 2000; Polk, 1994; Steinman, 1992; Ulrich, 2001). There are several potential factors that could be the direct cause of the burn. Airbags are inflated by hot gas flowing through a metal inflator housing at the rear of the bag. Immediately after the airbag reaches full deployment, the hot gas exhausts through vent ports that are typically located in the back of the airbag. An occupant could experience a burn through contact with the metal inflator housing, which stays hot up to several minutes post-deployment, or from the hot gas exiting the vent ports during and after deployment.

In order to estimate the incidence of skin burns from airbag deployments, Reinfurt et al. (1993) investigated 215 crash survivors exposed to driver side airbag deployments. This study found through occupant self-reporting that 28% of the occupants sustained an airbag induced skin abrasion, and approximately 7% of the occupants sustained an airbag induced burn. Hallock (1997) references Swanson-Biearman et al. (1993) and states that 'the Chrysler Corporation has corroborated this finding by admitting that burns occurred in 5% of all airbag deployments involving their vehicles.' However, there is no specific publication to corroborate this alleged statement by Chrysler. Other data suggests that these rates are far too high. This inflated rate is possibly due to the incorrect identification of abrasions as burns. Antosia et al. (1995) performed a retrospective review of 618 airbag-induced injuries and identified 7.8% of these as burn injuries. Given that the majority of airbag deployments result in no injury, this would imply that the incidence of burn injuries is far lower than the 7% reported by Reinfurt et al. (1993). Moreover, by considering the number of injuries rather than the number of occupants with injuries, the exposure risk may be exaggerated due to multiple injury count on a single occupant.

Although studies have demonstrated experimental and numerical modeling of heat transfer into the skin during an airbag deployment (Reed, 1994; Reed, 1999; Thomas, 1996; Thomas, 1997), no study has successfully demonstrated the national incidence of airbag induced skin burns. The purpose of this study is to elucidate the incidence and patterns of airbag induced skin burns.

3.2 Methods

In order to eliminate the inaccuracies associated with small case study projections and the confusion between skin abrasions and burns, this study uses the National Automotive Sampling System (NASS) (NHTSA, 1999). The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1998). This coding allows for a consistent and accurate distinction and identification of burn injuries. The NASS database has been used for national injury projection studies to analyze injury severity and crash characteristics for such things as lower extremity injury patterns and restraint effectiveness in motor vehicle crashes (Atkinson, 2000; Deery, 1999; Duma, 1996; Farmer, 1997; Miller, 1993; Reiff, 2001; Segui-Gomez, 2000; Viano, 1990; Zuby, 2001). Every crash investigated for the NASS database is assigned a weighted value, which scales the incidence of the particular crash investigated to a number that represents actual occurrence of similar non-investigated crashes that occur in the U.S. each year. Unweighted numbers reflect actual values counted from the cases that appear in the NASS database. The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained and do not include combined effects from multiple injuries to the same patient.

As identified in the NASS cases, burn injuries can occur to occupants as a result of an airbag deployment. For this study, cases in NASS were selected from the years 1993 through 2000 that included drivers and front seat occupants only, and excluded ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. Occupants with injuries, and total injuries to occupants were analyzed. Burn injuries in the NASS database were identified using the current AIS injury codes for burns (AAAM, 1998). This study was divided into four parts.

Part 1: Crashes With and Without Airbag Deployment

The first part of this analysis considered crashes with an airbag deployment. For all occupants who were exposed to an airbag deployment, the number of occupants that sustained a burn injury was compared with the total number of occupants who did not sustain a burn injury. Next, an analogous search was performed for crashes in which the airbag did not deploy. For all occupants who were not exposed to an airbag deployment, the number of occupants that sustained a burn injury was compared with the total number of occupants who did not sustain a burn injury. As there was no airbag deployment in these cases, sources of injury were such things as fire in the vehicle, or a fire in the instrument panel. Occupants with injuries and total injuries to occupants were counted and compared with totals for each type of crash.

Part 2: Airbag Induced Burn Injury Locations

Further investigation of injuries was made for crashes in which the occupant was exposed to an airbag deployment. Resulting burn injury locations were compared as percents of total injuries in similar crashes, depending on the source of injury. Airbag and other injury sources were compared for analysis of resulting burn injury location.

Part 3: Burn Injury Severity and Injury Source

Occupants and burn injuries were further investigated to identify trends relating burn injury source to the severity of the burn injury. The occupants exposed to an airbag deployment were sorted apart from the occupants who were not exposed to an airbag deployment. The burn injury AIS values were identified and compared with the injury source for both categories. Next, the percentage of occupants who received a burn injury was calculated. In other words, a comparison was made between the severity of burn injuries for occupants with an airbag as the injury source, and the severity of burn injuries for occupants who sustained burn injuries from other sources.

Part 4: Occupant and Crash Characteristics

Occupants that sustained burn injuries were analyzed in order to identify trends relating burn injury incidence and injury source. The occupants with burn injuries were broken down into two groups as to whether the injury source was the airbag or something else. Group 1 included all occupants who received an airbag induced burn injury, while Group 2 included all of the occupants with burns from other sources. The groups were divided in this way in order identify occupant or crash characteristics that indicated risk of injury by specific injury source.

The chi square test of independence for survey data (SUDAAN, Research Triangle Park, North Carolina) was used to investigate occupant sex, seatbelt use, and seat position. Percentages and p-values were calculated for each of the three variables. Average value and standard deviations were calculated for continuous variables such as occupant height, weight, age, and crash change in velocity (Delta-V).

3.3 Results and Discussion

Part 1: Crashes With and Without Airbag Deployment

Of the 2,421,893 occupants who were exposed to an airbag deployment, 1.54% sustained a burn injury (Figure 3.1). In contrast, for the 10,007,687 occupants not exposed to an airbag deployment, only 0.02% sustained a burn injury in the crash. It was determined that occupants were statistically at a higher risk for burn injury when exposed to an airbag deployment (p=0.02).

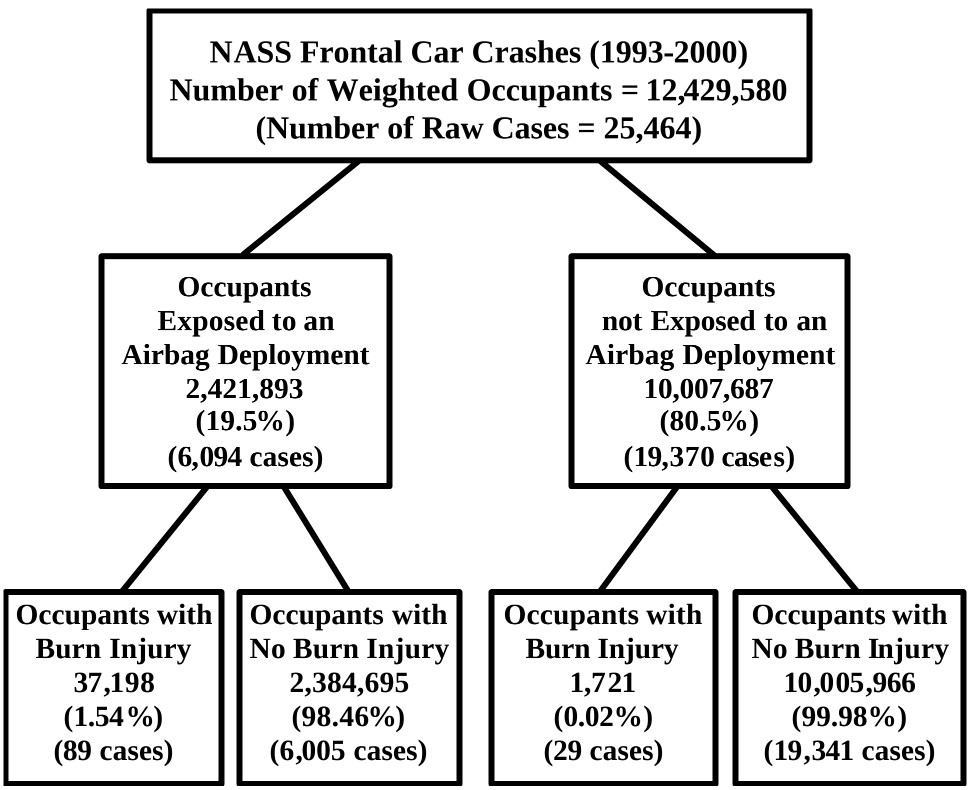

Figure 3.1. Burn injury incidence for occupants who were or were not exposed to airbag deployment (1993-2000).

Of the occupants exposed to an airbag deployment, 37,162 (85 cases) sustained a burn specifically from the airbag (1.53%). Of these occupants with airbag induced burn injury, 34,737 (74 cases) were drivers (93.5%), and 2,425 (11 cases) were passengers (6.5%). For all burn injuries to occupants, 94.8% occurred to occupants exposed to an airbag deployment (Figure 3.2). If the occupants with a burn injury were exposed to an airbag deployment, the airbag was the source of the burn injury for 99.9% of the injuries. If an airbag did not deploy, the top three sources for burn injury were a fire in the vehicle, the instrument panel, or another non-contact source.

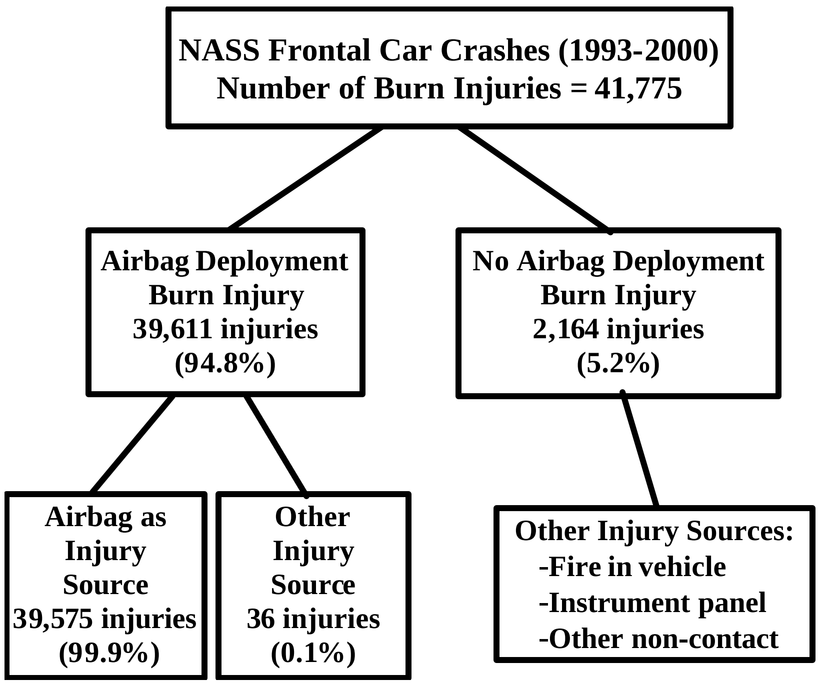

Figure 3.2. Weighted number of burn injuries that occurred to occupants in frontal crashes for the years 1993-2000.

Part 2: Airbag Induced Burn Injury Locations

Though exposure to an airbag deployment was shown to increase the incidence of burn injuries, it is also important to note the location of the resulting burn injuries (Table 3.1). The first column for each group indicates the incidence of injury to each location, while the second column is the percent of total injuries for each type. Occupants who sustained airbag induced burn injuries sustained the majority of the injuries to the upper extremity (82.5%). The next two most frequently injured regions were the face (7.7%) and the chest (2.9%). For crashes without airbag deployment, occupants sustained only 13.8% of the reported burn injuries to the upper extremity. However, this data is likely skewed because over half of the burn injuries to occupants not exposed to an airbag deployment were coded as a burn injury to an unknown body region.

Table 3.1. Locations of burn injuries in crashes with and without airbag deployment.

	Airbag Deployment						No Airbag Deployment	
	Source: All included		Source: Airbag		Source: Other		Source: Other	
	#	%	#	%	#	%	#	%
Face	3,061	7.7%	3,061	7.7%	0	0.0%	155	7.2%
Head	86	0.2%	86	0.2%	0	0.0%	0	0.0%
Neck	320	0.8%	320	0.8%	0	0.0%	0	0.0%
Chest	1,132	2.9%	1,132	2.9%	0	0.0%	0	0.0%
Abdomen	139	0.4%	139	0.4%	0	0.0%	124	5.7%
Upper Extremity	32,693	82.5%	32,663	82.5%	30	83.3%	298	13.8%
Lower Extremity	41	0.1%	41	0.1%	0	0.0%	425	19.6%
Unknown	2,139	5.4%	2,133	5.4%	6	16.7%	1,162	53.7%
Totals:	39,611	100%	39,575	100%	36	100%	2,164	100%

Part 3: Burn Injury Severity and Injury Source

The airbag was the source of the burn injury for 39,575 burn injuries to occupants exposed to an airbag deployment. Of these, 98.7% were AIS level 1 injuries, 1.3% were AIS2 burns, and only 0.04% were AIS level 3 injuries. There were no airbag induced burns resulting in AIS ratings of 4 or higher. There were 2,164 burn injuries to occupants not exposed to an airbag deployment. All of these injuries were from sources other than the airbag, and were compared by AIS injury level, to the severity of the injuries in crashes with airbag deployment, that had the airbag as injury source (Figure 3.3). The burns to occupants in crashes with no airbag deployment, were distributed as 34.1% AIS1, 10.3% AIS2, 7.8% AIS3, 18.2% AIS5, and 29.6% AIS6. In other words, if the airbag was the injury source, the injuries were mostly minor AIS1 severity; however, in cases with no airbag deployment, there were considerably fewer AIS1 burns (34.1%), and the injuries were likely to be much more serious, with nearly 30% being fatal burns rated AIS6. Although a larger proportion of occupants not exposed to an airbag deployment had a severe burn injury, the difference was not statistically significant (p=0.66).

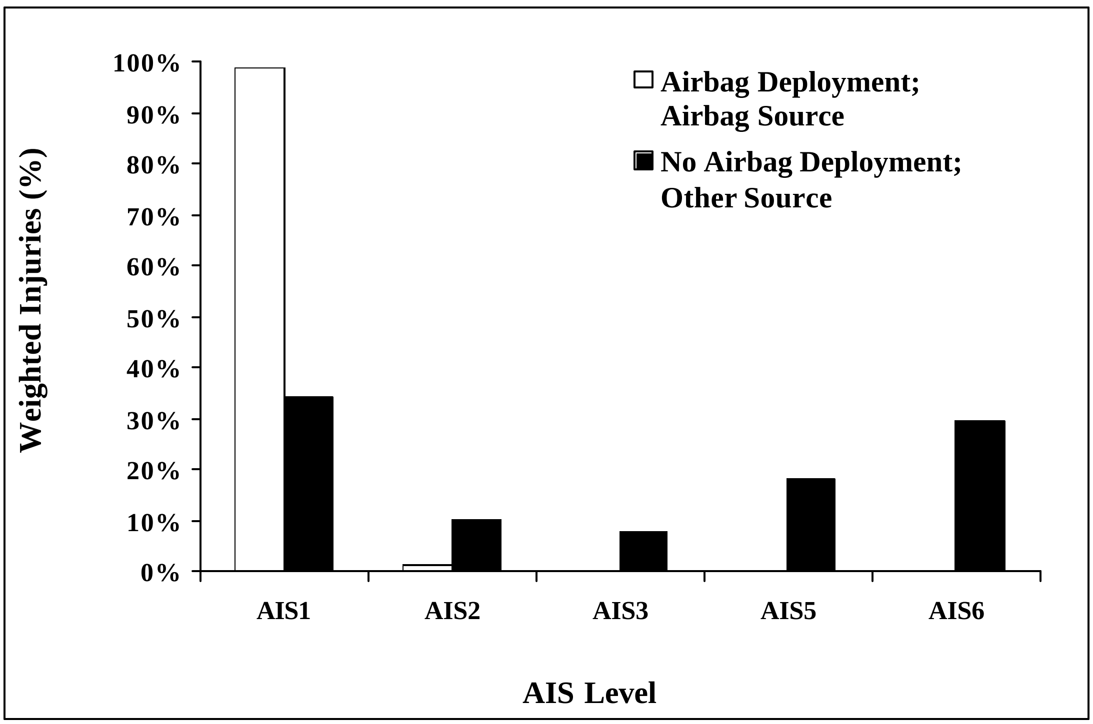

Figure 3.3. AIS injury severity comparison between airbag induced burns and burns from other sources in crashes with no airbag deployment. Note that there are no airbag induced burn injuries of severity greater than AIS3.

Part 4: Occupant and Crash Characteristics

The next analysis was made by examining occupant and crash characteristics for the 38,919 weighted occupants who sustained a burn injury from any source.

Occupant Sex. It was found that 66.1% of occupants with airbag induced burn injury were male, compared with 69.0% of occupants who sustained a burn injury from a source other than the airbag. Occupant sex was not found to be a statistically significant factor in incidence of burn injury by source (p=0.87).

Seatbelt Use. The analysis found that 84.5% of occupants with an airbag induced burn injury were wearing a seatbelt, while only 36.5% of occupants were wearing a seatbelt who sustained a burn injury from a source other than the airbag. Though this study indicated that a much greater proportion of occupants were belted who received an airbag induced burn injury, the difference was not statistically significant (p=0.16).

Seat Position. The analysis found that 93.5% of occupants with an airbag induced burn injury were drivers, compared with 90.1% of occupants that sustained a burn injury from a source other than the airbag. This difference was not found to be statistically significant (p=0.39).

Within a 95% confidence interval, occupant age, and crash Delta-V were both found to be significant variables correlating with the risk of incidence of airbag induced burn injury (Table 3.2). In particular, it was found that older occupants in crashes with a lower Delta-Vs were more likely to sustain an airbag induced burn injury. In addition, it was the younger occupants in crashes with a higher Delta-V who were more likely to sustain burn injuries from sources other than the airbag.

Table 3.2. Comparison of Group 1 and Group 2 crash characteristics indicating correlation between incidence of burn injury and crash variable.

	GROUP 1: Burn Injury; Airbag Source		GROUP 2: Burn Injury; Other Source	
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**
Occupant Height (in)	68.39	1.00	68.98	1.04
Occupant Weight (lbs)	179.40	13.91	168.45	10.62
Occupant Age (yrs)	40.34	2.63	29.29	2.65
Delta-V (mph)	11.58	1.64	50.70	8.98

3.4 Conclusions

This investigation searched the NASS database for occupants in frontal crashes for the years 1993 through 2000, and resulted in an analysis of 12,429,580 weighted front seat occupants (25,464 cases). Further investigation was done for all cases that resulted in the occupant sustaining a burn from any source. An analysis of the cases indicated that occupants exposed to an airbag deployment were statistically more likely to incur a burn injury (1.54%), than those occupants who were not exposed to an airbag deployment (0.02%) (p=0.02). In particular, 1.53% of front seat occupants exposed to an airbag deployment in a frontal collision sustained a burn injury specifically from the airbag. This rate is markedly less than the 5% or 7% estimated in previous studies. Given the large national database used to determine the risk of airbag induced burn injury found in this study, the larger rates that were previously published seem inaccurate and inflated for two reasons. First, they were based on small groups of individual case studies with no accurate national statistical weighting procedure. Second, it is likely that these studies include abrasion injuries that were misclassified as burn injuries.

Of the 39,611 burn injuries to occupants exposed to an airbag deployment, 99.9% of them were induced by the airbag. It was also shown that if the airbag was the source of the burn injuries, most occurred to the upper extremity (82.5%), and were minor with 98.7% having an AIS score of 1. In contrast, for cases with no airbag deployment, burn severities were distributed as 34.1% AIS1, 10.3% AIS2, 7.8% AIS3, 18.2% AIS5, and 29.6% AIS6. In other words, if the airbag was the injury source, the injuries were mostly minor AIS1 type; however, in cases with no airbag deployment, with sources other than the airbag, there were considerably fewer AIS1 burns (34.1%), and burn injuries were often much more serious, with nearly 30% being fatal burns rated AIS6.

An analysis of occupant and crash variables was performed to investigate particular variables correlating with risk of burn injury by injury source. Using the chi square test of independence for survey data, occupant sex (p=0.87), seatbelt use (p=0.16), and seat position (p=0.39) were all found to not be statistically significant variables in predicting injury. In addition, within a 95% confidence interval, occupant height, and weight were also found to not be significant contributors to the risk of burn injury by injury source. However, it was found that older occupants in crashes with lower Delta-Vs were at a higher risk for airbag induced burn injuries, while younger occupants in crashes with higher Delta-Vs were at a higher risk for burn injuries from sources other than the airbag.

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Chapter 4:
Eye Injuries

4.1 Introduction

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of less severe injuries (Deery, 1999). These associated minor injuries include upper extremity fractures, skin abrasions, and eye injuries. In particular, the medical literature is replete with case studies on airbag induced eye injuries (Asaria, 1999; Baker, 1996; Ball, 2001; Bhavsar, 1997; Biechl-Lautenbach, 1996; Braude, 1992; Braude, 1995; Cacciatori, 1996; Campbell, 1993; Chialant, 2000; Dalmotas, 1995; Driver, 1994; Dubois, 1998; Fukagawa, 1993; Gault, 1995; Geggel, 1996; Giguere, 1998; Goldberg, 1995; Han, 1993; Huelke, 1992; Hunt, 1995; Ingraham, 1991; Kuhn, 1995; Larkin, 1991; Lee, 2001; Lemley, 2000; Lesher, 1993; Lueder, 2000; Manche, 1997; McDermott, 1995; Michaeli-Cohen, 1996; Mishler, 1991; Molia, 1996; Morrison, 1998; Norden, 2000; O'Halloran, 1998; Onwuzuruigbo, 1996; Rimmer, 1991; Rosenblatt, 1991; Rosenblatt, 1993; Ruiz-Moreno, 1998; Sastry, 1995; Scott, 1993; Scott, 1996; Shah, 2001; Singer, 1998; Smally, 1992; Smock, 1995; Stein, 1999; Steinmann, 1992; Stranc, 1999; Swanson-Biearman, 1993; Totten, 1998; Tsuda, 1999; Vichnin, 1995; Walter, 1996; Walz, 1995; Weinman, 1995; Whitacre, 1993; White, 1995; Zabriskie, 1997; Zacovic, 1997). In addition to airbag induced eye injuries, Muller-Jensen *et al.* (1970) present a discussion on German trends of eye injuries resulting from broken windshields. Over a period of five years, 26% of windshield induced eye injury patients suffered bilateral eye injuries from broken windshield glass, and 40% of cases resulted in blindness in at least one eye.

The majority of these case studies focus on only a few occupants, however, four papers, in particular, include numerous cases of airbag induced eye injuries, offering more extensive information on occupant and collision characteristics (Duma, 1996; Ghafouri, 1997; Vichnin, 1995; Stein, 1999). Duma, *et al.* (1996), present an analysis of 25 airbag induced eye injury cases taken from the National Automotive Sampling System (NASS) database that were analyzed extensively for associated eye injuries, and occupant and crash characteristics. The majority of the occupants sustained injury from contact with the fully deployed airbag, but the most serious injuries were a result of the occupant being struck by the airbag during deployment. The Ghafouri paper (1997) includes a detailed discussion of 11 cases, along with a thorough literature review that covers 32 published cases of airbag induced eye injury. All patients were examined within 90 minutes of collision, and though patients most frequently complained of symptoms only in one eye, bilateral injury was found in 27% of the cases. Vichnin *et al.* (1995) report 14 specific cases of airbag induced eye injury and discuss occupant and crash factors that may have had an effect on the resulting ocular injury. The three most severe injuries reported were to occupants wearing eyeglasses, all of which sustained permanent ocular damage. These cases indicate that eyeglasses are a possible risk factor for severe eye injuries to occupants exposed to an airbag deployment. Stein *et al.* (1999) outline a detailed summary of the 97 published case studies on ocular injuries from airbag deployment between 1991-1998. These cases from the literature are analyzed by different variables such as: age, sex, height, eyewear, and seat position. This paper attempts to identify potential risk factors in motor vehicle crashes; however, because the statistics are based solely on reported published cases in the literature, the statistical results do not necessarily reflect national incidence, injury type or severity. For each of these papers, there was a wide range of ocular injuries reported, from a minor eyelid or corneal abrasion, to a more severe ruptured globe or dislocated lens.

There exists a paucity of experimental data on airbag induced eye injuries compared with the number of individual case study publications. Fukagawa *et al.* (1993) performed a series of experiments to examine corneal endothelial cell loss from airbag loading. By measuring the damage to the endothelial cells, the study showed that increased inflator aggressivity contributed to increased cellular damage; however, the weight of the airbag material was not found to be influential. The most recent airbag related study examined the injury potential of high-speed foam particles (Duma, 2000). Airbag deployment through a seamless module cover may release foam particles at high velocities that could result in eye injuries. The study illustrates the compounding risk of eye injuries from not only airbag contact, but also from particles released from the module during deployment.

Although previous studies have provided insight into the interaction between an airbag and the eye, the national incidence and relative risk of airbag induced eye injuries is unknown for occupants in crashes with and without an airbag deployment. The purpose of this paper is to determine the overall risk and severity of eye injuries in automobile crashes and to elucidate the effect of frontal airbags on these patterns.

4.2 Methods

In order to eliminate the inaccuracies associated with small case study projections, this study uses the NASS database. The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1998). This coding allows for a consistent and accurate distinction and identification of eye injuries. The NASS database has been used for national injury projection studies to analyze injury severity and crash characteristics for such things as lower extremity injury patterns and side impact restraint effectiveness in motor vehicle crashes (Atkinson, 2000; Deery, 1999; Farmer, 1997; Miller, 1993; Viano, 1990). Every crash investigated for the NASS database is assigned a weighted value, which scales the incidence of the particular crash investigated, to a number that reflects similar uninvestigated crashes that occur in the U.S. each year. Unweighted numbers reflect actual values counted from the cases that appear in the NASS database. The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained, and do not include combined effects from multiple injuries to the same patient. Overall injury severity for a patient is measured by the Maximum AIS (MAIS) value, which is the highest single AIS injury sustained.

For this study, cases in NASS were selected from the years 1993 through 1999 that include drivers and front seat occupants only, while excluding ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. Eye injuries were defined as damage to the periorbital skin, globe, or orbital bones. Weighted and unweighted frequencies of occupants and injuries were analyzed. Eye injuries in the NASS database were identified using the updated AIS injury codes (AAAM, 1998). The study was divided into three parts.

Part 1: Crashes With and Without Airbag Deployment

First, crashes with an airbag deployment were considered. For all occupants who were exposed to an airbag deployment, the number of occupants sustaining an eye injury was compared with the total number who did not sustain an eye injury. Next, an analogous search was performed for crashes in which an airbag did not deploy. For all occupants who were not exposed to an airbag deployment, the number of occupants that sustained an eye injury was compared with the total number of occupants who did not. As there was no airbag deployment in these cases, sources of injury were items such as the windshield and steering wheel. Statistical analysis was performed using the chi square test of independence for survey data (SUDAAN, Research Triangle Park, North Carolina). Weighted frequencies of occupants and injuries were analyzed.

Part 2: Injury Severity

A new eye injury grouping method was developed to assess the severity of eye injuries based on both the need for ocular surgery and the potential for loss of sight. The AIS system does not address both of these criteria, as it only considers the overall threat to life. Almost all eye injuries are coded as minor, level 1 AIS injuries. In consultation with ophthalmologists, eye injuries were divided into four new injury groups by level of severity. Based on these levels, the eye injuries in the NASS database were sorted according to their AIS code (Table 4.1). This new grouping method splits AIS coded eye injuries into more divisions, in order to compare the severity of eye injuries in automobile crashes from the NASS database. Level 1 includes minor injuries to the skin surrounding the eye such as an eyelid abrasion or laceration. Level 2 injuries are minor injuries to the eye such as corneal abrasions or injury to the vitreous. Level 3 includes more serious eye injuries that may require surgery and present a guarded long-term prognosis such as corneal lacerations, and orbital fractures. Finally, Level 4 injuries are the most serious eye injuries that would result in blindness, such as eye avulsion or enucleation.

Table 4.1. New AIS severity levels for eye injuries, classified by need for surgery, expected recovery time, and possible loss of sight. (NFS=Not Further Specified)

Level 1	**AIS #**	**Injury Description**
Skin: (eyelid or orbit area soft tissue)	297099.1	skin NFS
	297202.1	skin abrasion
	297402.1	skin laceration
	297602.1	skin contusion
	297802.1	skin avulsion
Level 2	**AIS #**	**Injury Description**
Eye: less severe	240499.1	eye NFS
	240416.1	conjunctiva injury
	240602.1	corneal abrasion
	240699.1	corneal injury NFS
	241499.1	uvea injury
	241699.1	vitreous injury
Level 3	**AIS #**	**Injury Description**
Eye: more severe	240408.1	tear duct laceration
	240412.1	choroid rupture
	240604.1	corneal contusion
	240604.1	corneal hyphema
	240606.1	corneal laceration
	240800.1	iris laceration
	241000.1	retinal laceration
	241200.1	scleral laceration
	251200.2	orbital fracture NFS
	251202.2	orbital fracture closed
	251204.3	orbital fracture open/displaced

Level 4	AIS #	Injury Description
Eye: most severe	230202.2	optic nerve contusion
	230204.2	optic nerve laceration
	230206.2	optic nerve avulsion
	230299.1	optic nerve injury NFS
	240402.2	eye avulsion/enucleation
	241002.2	retinal detachment
	241202.2	scleral globe rupture

Part 3: Occupant and Crash Characteristics

Occupants exposed to an airbag deployment were analyzed in order to identify trends in eye injury incidence. The cases with airbag deployment were first broken down into two groups depending on whether the occupant sustained an airbag induced eye injury. Group 1 included all occupants who received an airbag induced eye injury, while Group 2 included all of the remaining occupants. The occupants in Group 2 could have sustained an eye injury in the crash, but the source would be something other than the airbag. The groups were divided in this way in order to investigate occupant characteristics that might be related to resulting incidence of airbag induced injury. Since all occupants in this analysis were exposed to an airbag deployment, risk factors could be identified that associate occupant characteristics to incidence of airbag induced injury. The chi square test of independence for survey data was used to investigate occupant sex, corrective eyewear use, and seatbelt use. Percentages and p-values were calculated for each of the variables. Average value and standard deviations were calculated for continuous variables such as occupant height, weight, age, and crash change in velocity (Delta-V).

4.3 Results

Part 1: Crashes With and Without Airbag Deployment

A total of 10,770,828 weighted occupants (22,236 cases) were included in this study for the seven year period from 1993 to 1999. Weighted occupants that sustained eye injuries were compared based on whether or not they were exposed to an airbag deployment (Figure 4.1). Each year, there were more occupants who sustained an eye injury in a non-airbag deployment crash than in a crash with an airbag deployment. Since the proportion of airbag-equipped vehicles in the fleet is increasing, it is expected that similarly, more occupants are exposed to airbag deployments each year, and the number of occupants who sustain an eye injury in a crash with airbag deployment has also increased overall through the years 1993-1999.

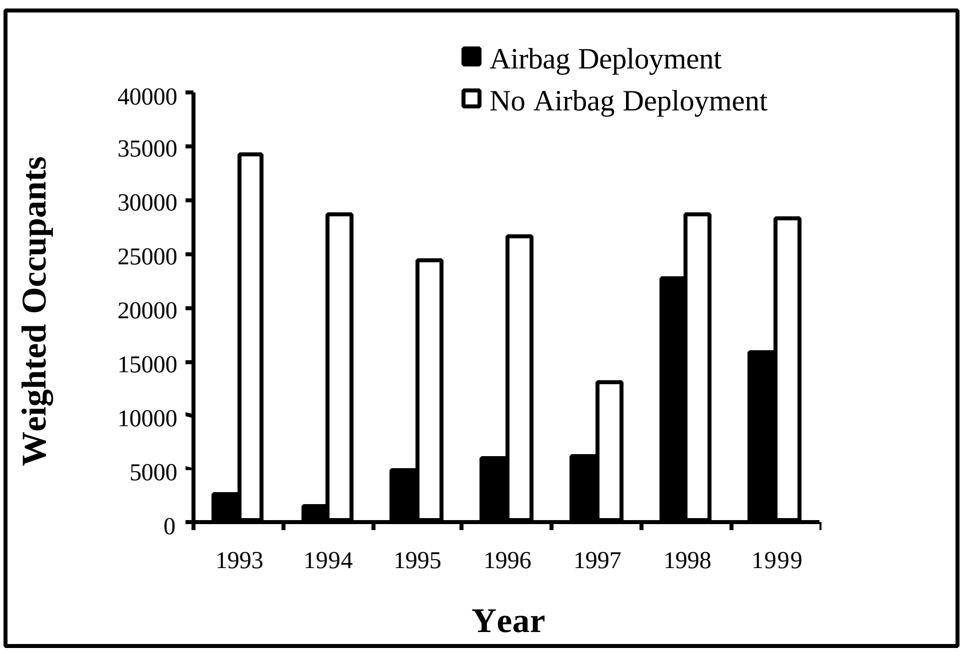

Figure 4.1. Comparison between number of weighted occupants with eye injuries in crashes with and without an airbag deployment (1993-1999).

For crashes where the occupant was exposed to an airbag deployment, 60,112 weighted occupants (241 cases) sustained an eye injury out of 1,946,924 total weighted occupants (4,789 cases) in similar crashes (3.1%) (Figure 4.2). In contrast, for crashes without an airbag deployment, 178,151 weighted occupants (1,207 cases) sustained an eye injury out of 8,823,904 total weighted occupants (17,447 cases) in similar crashes (2.0%). In summary, 3.1% of occupants who were exposed to an airbag deployment sustained an eye injury, compared with 2.0% who received an eye injury when an airbag did not deploy. Accounting for the weighted survey data, the chi square test of independence showed that this difference was not statistically significant (p=0.15).

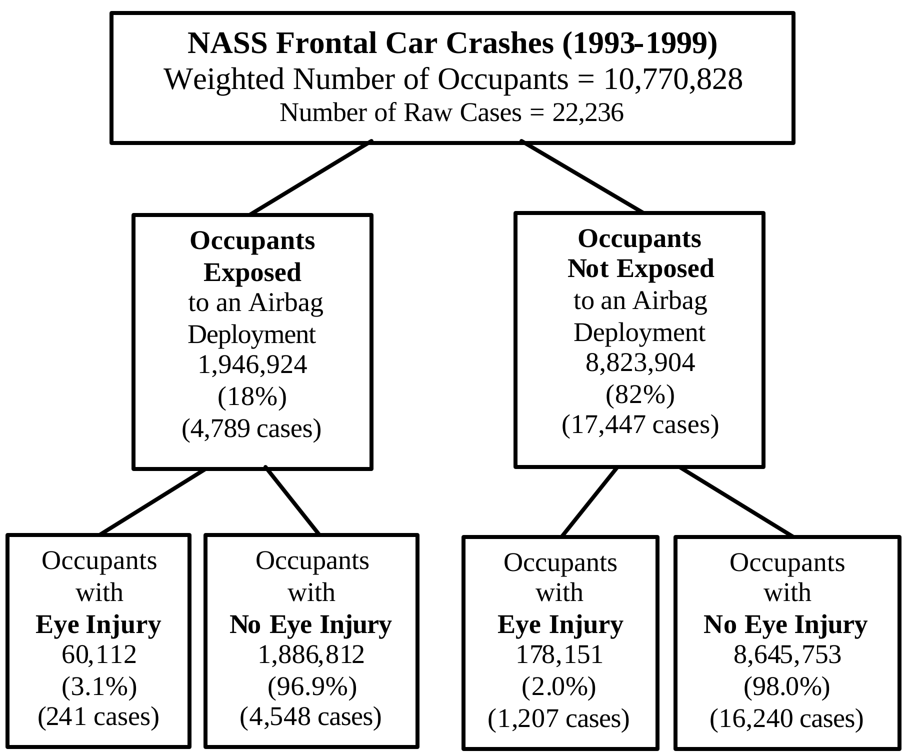

Figure 4.2. Flowchart showing incidence of eye injury for occupants in frontal crashes, depending on whether or not the occupant was exposed to an airbag deployment (1993-1999).

The next analysis used the total number of weighted injuries to occupants (Figure 4.3). These numbers differ from the previous occupant analysis in that each occupant may have had multiple eye injuries. Crashes were split first by whether or not the occupant was exposed to an airbag deployment. For all the eye injuries to occupants, 26% occurred to occupants exposed to an airbag deployment. If the occupants with an eye injury were exposed to an airbag deployment, the airbag was the source of the eye injury for 88% of the injuries. If an airbag did not deploy, the top three sources for eye injury were the windshield (34%), steering wheel (27%), and instrument panel (14%). Regardless of injury source, 76% of the occupants that incurred an eye injury were drivers and 24% were right front seat passengers.

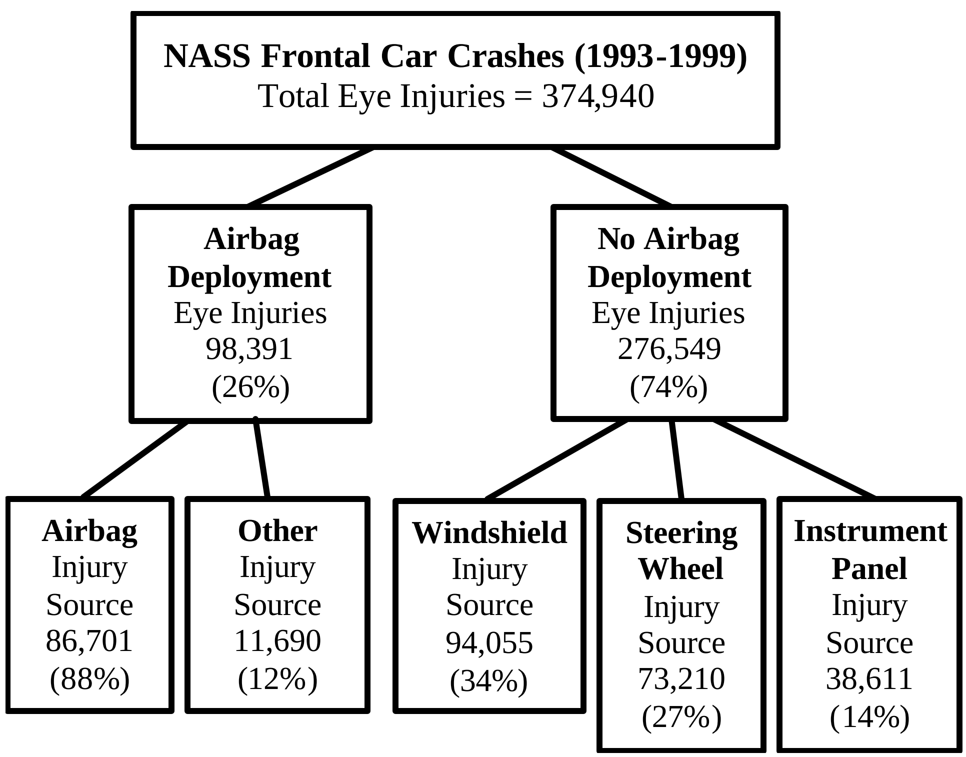

Figure 4.3. Flowchart outlining weighted eye injuries in frontal crashes for the years 1993-1999. Figure shows sources of eye injuries depending on whether or not the occupant was exposed to an airbag deployment.

Part 2: Injury Severity

Though airbag exposure was shown to increase the incidence of eye injuries, more important is the severity of the resulting eye injuries. Sorting the eye injuries into the four newly defined levels, it was shown that eye injuries from crashes without an airbag deployment were distributed as 85.0% Level 1, 4.4% Level 2, 10.1% Level 3, and 0.4% Level 4 (Figure 4.4). This was a total of 10.5% of the injuries being more serious, representing the categories of Levels 3 and 4 combined. In contrast, the eye injury distribution from crashes with an airbag deployment was 75.3% Level 1, 17.5% Level 2, 7.2% Level 3, and 0.0% Level 4. In these crashes with airbag deployments, only 7.2% of the injuries were more serious Level 3 and 4 injuries. There was a shift in the severity of eye injuries depending on whether or not the occupants were exposed to an airbag deployment, with the lower severity injuries occurring to occupants exposed to an airbag deployment.

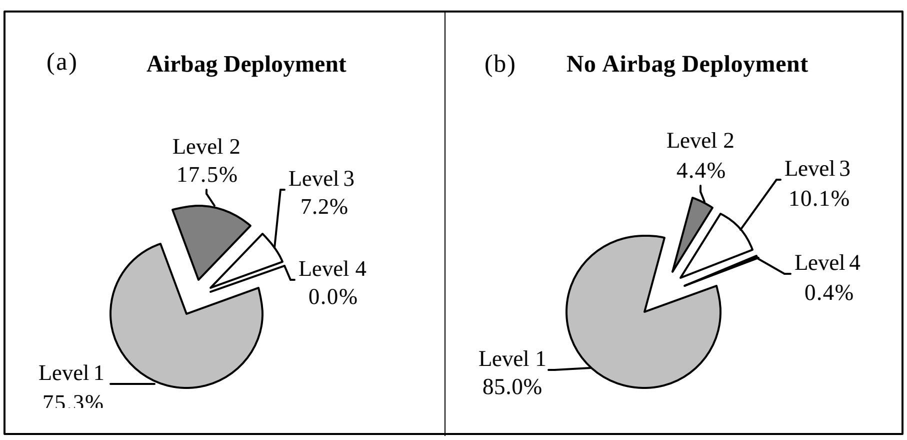

Figure 4.4: Severity levels of eye injuries sustained in crashes with an airbag deployment (a), and without an airbag deployment (b).

When examining the specific injury types, there was a statistically significant (p=0.03) increase in risk of corneal abrasions for occupants exposed to an airbag deployment. Of the occupants exposed to an airbag deployment, 0.53% sustained a corneal abrasion, compared with 0.04% of occupants not exposed to an airbag deployment.

Part 3: Occupant and Crash Characteristics

Occupant Sex. It was found that 65.4% of female occupants exposed to an airbag deployment sustained an airbag induced eye injury, compared with 47.8% of male occupants. Although female occupants sustained an airbag induced eye injury more often than males, occupant sex was not found to be a statistically significant factor in incidence of eye injury (p=0.19).

Eyeglasses Use. It was found that 28.7% of occupants who sustained an airbag induced eye injury were wearing glasses, while 25.3% of occupants were wearing glasses who did not receive an airbag induced eye injury. However, this variable was not found to be statistically significant (p=0.81) in predicting risk of airbag induced eye injury.

Contact Lens Use. It was found that 46.0% of occupants who sustained an airbag induced eye injury were wearing contact lenses, while 10.7% of occupants who did not receive an airbag induced eye injury were wearing contacts. Contact lens wear was not found to be a statistically significant (p=0.31) variable in predicting risk of airbag induced eye injury.

Use of Either Corrective Eyewear. This study examined the combined effect of airbag deployment and occupant use of glasses or contact lenses for incidence of airbag induced eye injury. The analysis found that 74.6% of occupants who sustained an airbag induced eye injury were wearing either glasses or contacts, compared with 36.0% of occupants who did not receive an airbag induced eye injury. This study revealed that more occupants who sustained injury were wearing glasses or contacts than those occupants who did not sustain injury, though the difference was not found to be statistically significant (p=0.14).

Seatbelt Use. It was found that 75.3% of occupants who sustained an airbag induced eye injury were wearing a seatbelt, compared with 85.6% of occupants who did not receive an airbag induced eye injury. This study indicated that the occupants who did not sustain an airbag induced eye injury had a slightly higher rate of seatbelt use; however, the difference was not statistically significant (p=0.45).

Next, the 1,946,924 occupants exposed to an airbag were split into two groups: Group 1 was made up of occupants who sustained an eye injury from the airbag as source, and Group 2 was the remaining set of occupants who were exposed to an airbag deployment, but that did not have an airbag induced eye injury (Table 4.2). Within a 95% confidence interval, occupant height, age, and crash Delta-V were all found to not be significant variables correlating with the risk of incidence of airbag induced eye injury. However, it was found that lighter occupants were more likely to sustain an airbag induced eye injury.

Table 4.2: Comparison of Group 1 and Group 2 crash characteristics indicating correlation between incidence of airbag induced eye injury and crash variable. Mean values and standard deviations are included.

	GROUP 1: Airbag Induced Injury		GROUP 2: No Airbag Induced Injury	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation
Occupant Height (in)	67.44	0.49	67.35	0.14
Occupant Weight (lbs)	144.06	5.21	160.56	2.84
Occupant Age (yrs)	36.31	7.07	34.09	0.70
Delta-V (mph)	11.73	1.68	13.68	0.29

4.4 Discussion

Though more occupants were injured when exposed to an airbag deployment, the airbag did provide a beneficial exchange by decreasing the severity of the associated eye injuries. A closer examination factoring in the type of eye injury showed that there was a statistically significant ($p=0.03$) increase in the risk of corneal abrasions for occupants that were exposed to an airbag deployment. Of particular interest to this study is the realization that an increasing proportion of the population will have had corrective vision procedures performed in the years to come. This, combined with the rising proportion of airbag-equipped vehicles in the fleet, warrants further investigation.

While a few studies show that there may be no increased risk of injury associated with eyes that have undergone photorefractive keratectomy (PRK), automated lamellar keratoplasty (ALK), and laser assisted in situ keratomileusis (LASIK), they are in the minority (Burnstein, 1995; Campos, 1992; Casebeer, 1994; John, 1983; Peacock, 1997). Far more studies indicate that these types of surgical procedures weaken the cornea and make it significantly more susceptible to injury (Alvi, 1995; Binder, 1988; Glasgow, 1988; Lindquist, 1992; McDonnell, 1987; Pearlstein, 1988; Rashid, 1992; Vinger, 1996; Zhaboyedov, 1990). Several studies state that the corneal flap may be susceptible to folding over or becoming dislocated after any form of blunt impact (Chaudhry, 1998; Lemley, 2000; Leung, 2000; Norden, 2000; Peacock, 1997). Moreover, a number of studies acknowledge that the mechanical integrity of the eye is reduced after vision correction procedures that involve corneal incisions, and that these negative effects persist years after the procedure (Glasgow, 1988; Lindquist, 1992; McDonnell, 1987; Pearlstein, 1988; Zhaboyedov, 1990).

In the present study, an increase in risk from corrective corneal surgery would combine with airbag deployment to shift airbag induced eye injuries to higher levels of severity. The protective effect of airbags in reducing the more serious injuries may be negated or potentially reversed. For example, a minor airbag induced corneal abrasion (Level 2) could become a corneal laceration (Level 3) or ruptured globe (Level 4), if the occupant is exposed to the airbag deployment after having undergone vision corrective surgery. Given that there was a significantly higher number of corneal abrasions for occupants exposed to an airbag deployment, patients who have undergone surgery affecting the cornea may be at a higher risk for more serious injuries. The airbag's beneficial trend of reducing eye injury severity may be short lived as the practice of corrective eye surgery becomes more prevalent. One solution may be to offer protective eyewear for patients to use while driving their car.

4.5 Conclusions

This paper presents the most comprehensive eye injury study to date as it investigates 10,770,828 weighted front seat occupants (22,236 cases) for the years 1993 through 1999 to identify the effects of frontal airbags on the incidence of eye injuries for occupants in frontal crashes. As the percentage of airbag-equipped vehicles in the fleet increased, the number of airbag induced eye injuries was also increased. An analysis of the cases indicates that 3.1% of occupants exposed to an airbag deployment sustained an eye injury, compared with 2.0% of those occupants not exposed to an airbag deployment. A chi square test of independence indicated this difference was not statistically significant ($p=0.15$). However, the risk of some eye injuries increased with occupant exposure to airbag deployment. When the occupants were exposed to an airbag deployment, 0.53% sustained a minor corneal abrasion, compared with 0.04% of occupants who sustained a corneal abrasion when not exposed to an airbag. This was a significant increase in the risk of corneal abrasion for occupants exposed to an airbag deployment ($p=0.03$).

An analysis was performed on occupant and crash variables in order to identify correlation with incidence of airbag induced eye injury. Occupants wearing either glasses or contacts sustained eye injuries more often than those occupants who were not; however, the difference was not statistically significant ($p=0.14$). In addition, it was found that within a 95% confidence interval, lighter occupants were more likely to sustain an airbag induced eye injury. Occupant height, age, sex, Delta-V, and seatbelt use were found to not be significant in predicting incidence of airbag induced injury.

Though occupants exposed to an airbag deployment sustained an eye injury more often than occupants not exposed to an airbag deployment, the airbag provided a beneficial exchange by decreasing the incidence of more severe eye injuries. Establishment of the new eye injury severity levels allowed for a more accurate estimation of eye trauma, thereby introducing a new tool to evaluate the patterns of automobile related eye injuries. Using the four new levels to group eye injury severity, it was found that the overall severity of eye injuries has decreased with exposure to airbag deployment. This was presumably accomplished because the airbag minimizes occupant contact with the windshield and steering wheel, which were the two leading sources of serious eye injuries. The current trend of increasing the number of airbags in the fleet as well as the increasing percentage of the population electing for corrective vision surgery is potentially alarming. This vulnerability allows for the current trend of reduction of more severe injuries due to the airbag exposure to be reversed, a concern that warrants the continued investigation of airbag design, eye correction procedures, and eyewear protection.

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Chapter 5:
Orbital Fractures

5.1 Introduction

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of less severe injuries (Deery, 1999). These associated minor injuries include skin contusions or lacerations, upper extremity injuries, and eye injuries (Duma, 1996; Duma, 2000; Freedman, 1995; Gault, 1995; Richter, 2000). In particular, orbital fractures have been reported in the literature occurring in sporting and other accidents, as well as in vehicle crashes, (al-Qurainy, 1991; Cacciatori, 1997; Cumberworth, 1997; Donahue, 1997; Egbert, 2000; Gault, 1995; Ghafouri, 1997; Guerra, 2000; Hartzell, 1996; Hatton, 2001; Heine, 1990; Huber, 1993; Hussain, 1994; Keane, 1993; Laine, 1993; Martello, 1997; Muraoka, 1995; Peltomaa, 2000; Poon, 1999; Richard, 1999; Rubinstein, 1991; Scott, 1993; Spring, 1996; Stewart, 1993; Williams, 2001; Wittram, 1997; Yoshioka, 1999).

There exists a paucity of experimental data on orbital fractures compared with the number of individual case study publications. Several experimental studies have aimed to elucidate mechanism of injury, to estimate fracture tolerance, or to reproduce fractures similar to those observed in real world case studies (Bullock, 1999; Fujino, 1974a; Fujino, 1974b; Fujino, 1980; Green, 1990; Hudson, 1997; Iliff, 1999; Jin, 2000; Kasrai, 1999; Smith, 1957; Tajima, 1974; Warwar, 2000; Waterhouse, 1999). Although experimental studies provide insight into the mechanism of injury, the national rate of orbital fracture incidence, type, and severity are unknown for occupants in crashes with and without an airbag deployment. The purpose of this paper is to determine the overall risk and severity of orbital fractures in automobile crashes and to elucidate the effects of frontal airbags.

5.2 Methods

In order to eliminate the inaccuracies associated with small case study projections, this study uses the National Automotive Sampling System (NASS) (NHTSA, 2000). The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1998). This coding allows for a consistent and accurate distinction and identification of facial fractures, and in particular, orbital fractures. The NASS database has been used for national injury projection studies to analyze injury severity and crash characteristics for such things as lower extremity injury patterns and side impact restraint effectiveness in motor vehicle crashes (Atkinson, 2000; Deery, 1999; Farmer, 1997; Miller, 1993; Reiff, 2001; Viano, 1990). Every crash investigated for the NASS database is assigned a weighted value, which scales the incidence of the particular crash investigated, to a number that reflects similar uninvestigated crashes that occur in the U.S. each year. Unweighted numbers reflect actual values counted from the cases that appear in the NASS database. The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained, and do not include combined effects from multiple injuries to the same patient.

For this study, cases in NASS were selected from the years 1993 through 2000 that include drivers and front seat occupants only, while excluding ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. Orbital fractures included: blow-in or blow-out fractures, as well as orbital roof or floor fractures. Fractures could be closed, open, displaced, or any combination of these, and were identified in the NASS database using the current AIS injury codes (AAAM, 1998). The study was divided into three parts.

Part 1: Crashes With and Without Airbag Deployment

The first part of this analysis considered crashes with an airbag deployment. For all occupants who were exposed to an airbag deployment, the number of occupants that sustained an orbital fracture was compared with the total number who did not sustain an orbital fracture. Next, an analogous search was performed for crashes in which the airbag did not deploy. For all occupants who were not exposed to an airbag deployment, the number of occupants that sustained an orbital fracture was compared with the total number of occupants who did not. As there was no airbag deployment in these cases, sources of injury were items such as the windshield and steering wheel. Occupants with injuries and total injuries were counted and analyzed.

Part 2: Orbital Fracture Type and Severity

Orbital fractures were further examined to compare injury types and severities, depending on whether or not the occupant was exposed to an airbag deployment. Specific orbital fracture types were compared as percents of total injuries in similar crashes, depending on airbag deployment exposure. To further analyze orbital fractures, the injuries were broken down by AIS severity level to compare fracture severity levels by airbag deployment exposure.

Part 3: Occupant and Crash Characteristics

Occupants exposed to an airbag deployment were analyzed in order to identify trends in orbital fracture incidence. The cases with airbag deployment were first broken down into two groups depending on whether the occupant sustained an orbital fracture. Group 1 included all occupants who received an orbital fracture, while Group 2 included all of the remaining occupants, who did not sustain an orbital fracture. The groups were divided in this way in order to investigate occupant characteristics that might be related to resulting incidence of injury. The chi square test of independence for survey data (SUDAAN, Research Triangle Park, North Carolina) was used to investigate occupant sex, seatbelt use, and seat position. Percentages and p-values were calculated for each of the variables. Average value and standard deviations were calculated for continuous variables such as occupant height, weight, age, and crash change in velocity (Delta-V).

5.3 Results

Part 1: Crashes With and Without Airbag Deployment

A total of 12,429,580 weighted occupants (25,464 cases) were included in this study for the eight year period from 1993 to 2000. Each year, there were more occupants who sustained an orbital fracture when not exposed to an airbag deployment than there were occupants with orbital fracture when exposed to an airbag deployment (Figure 5.1). Since the proportion of airbag-equipped vehicles in the fleet is increasing, the number of occupants in crashes who are exposed to airbag deployments each year is also increasing. In addition, it was expected that the number of occupants who sustained an orbital fracture in a crash with airbag deployment also increased overall through the years 1993-2000.

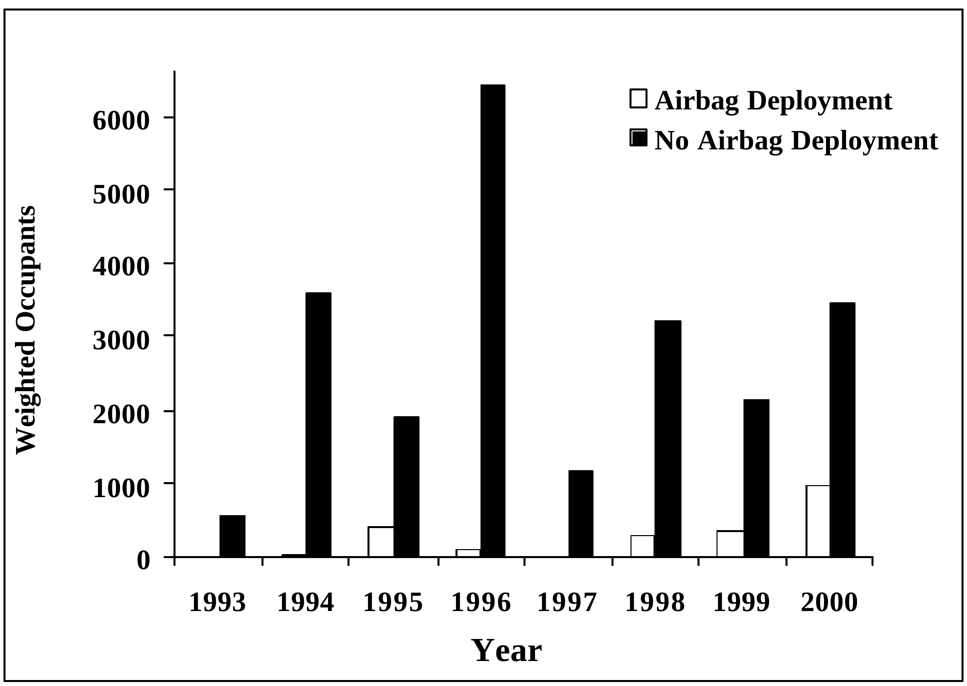

Figure 5.1. Weighted occupants with orbital fractures in frontal crashes that were or were not exposed to an airbag deployment by crash year.

For crashes where the occupant was exposed to an airbag deployment, 2,156 weighted occupants (18 cases) sustained an orbital fracture out of 2,421,893 total weighted occupants (6,094 cases) in similar crashes (0.09%) (Figure 5.2). In contrast, for crashes without an airbag deployment, 22,449 weighted occupants (216 cases) sustained an orbital fracture out of 10,007,687 total weighted occupants (19,370 cases) in similar crashes (0.22%). Although occupants who were not exposed to an airbag deployment sustained orbital fractures more than twice as often as occupants who were exposed to an airbag deployment, the chi square test of independence showed that this difference was not statistically significant (p=0.10).

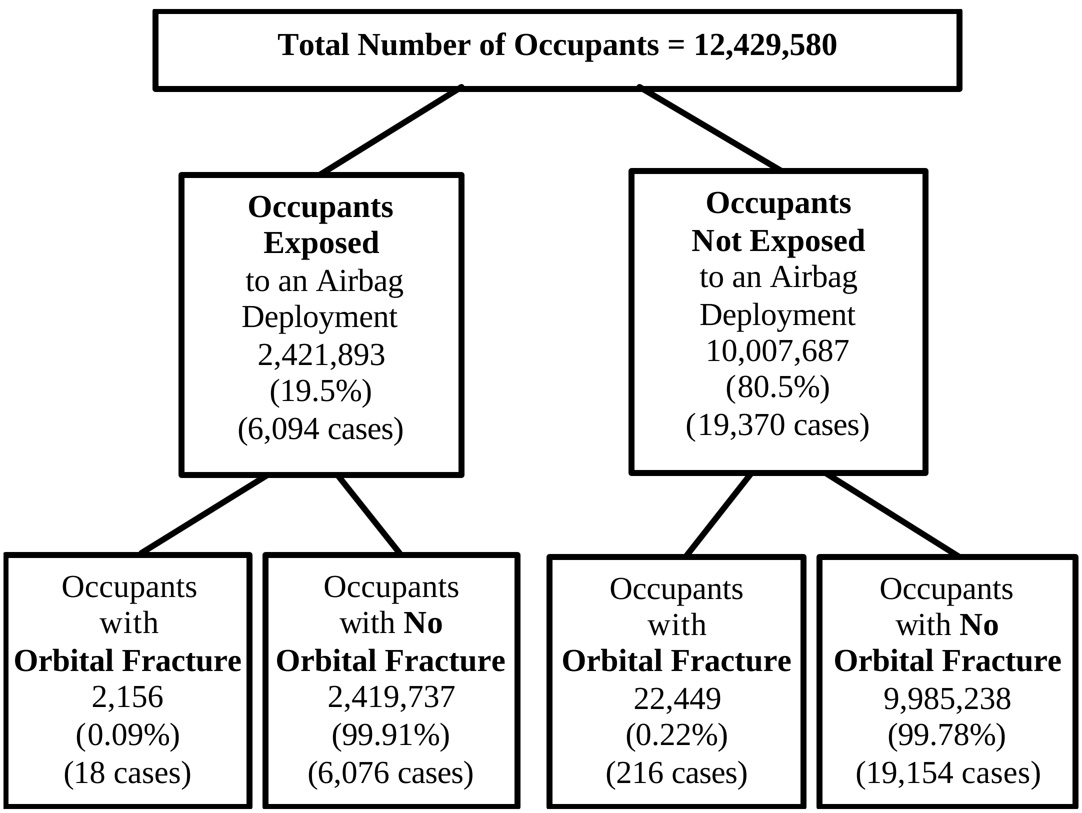

Figure 5.2. Incidence of orbital fracture for occupants in frontal crashes that were or were not exposed to an airbag deployment for the years 1993 through 2000.

For the total number of orbital fractures that occupants sustained, 26% were to occupants who were exposed to an airbag deployment, while the rest were sustained by occupants who were not exposed to an airbag deployment (74%) (Figure 5.3). For the orbital fractures to occupants who were exposed to an airbag deployment, the majority of the injuries were induced by contact with the vehicle interior (36.6%), followed by the steering wheel (30.7%). Only 11 orbital fractures were induced by the airbag as source (0.05%). In contrast, the occupants who were not exposed to an airbag deployment sustained the majority of the orbital fractures from the steering wheel (34.3%), followed by the windshield (32.4%), and the side pillar or other side interior components (15.6%).

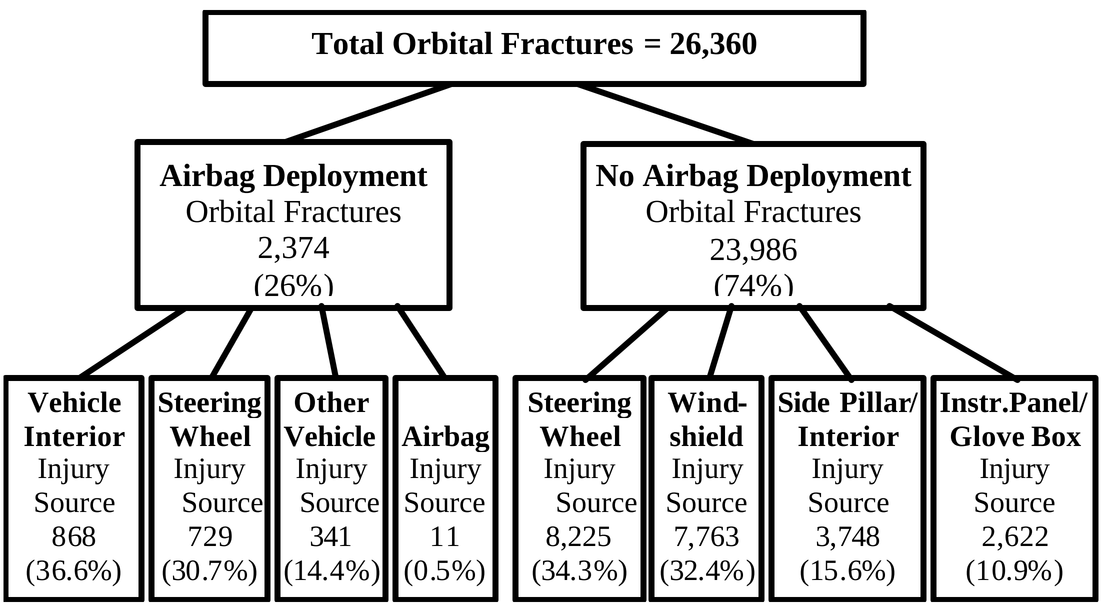

Figure 5.3. Weighted number of orbital fractures to occupants in frontal crashes for the years 1993 through 2000.

Part 2: Orbital Fracture Type and Severity

There was a shift in the fracture type depending on whether or not the occupant was exposed to an airbag deployment (Table 5.1). Occupants that were exposed to an airbag deployment sustained a closed orbital fracture most often (61.9%). In contrast, occupants who were not exposed to an airbag deployment most often received an orbital fracture that was open, displaced, comminuted, or any combination of these (61.3%).

Table 5.1. Comparison of orbital fracture types for occupants who were or were not exposed to an airbag deployment. (NFS=Not Further Specified)

	Airbag Deployment		No Airbag Deployment	
	#	%	#	%
orbital fracture closed	1,470	61.9%	5,986	25.0%
orbital fracture open/displaced/ comminuted or any combination	627	26.4%	14,715	61.3%
orbital fracture NFS	277	11.7%	3,285	13.7%
totals:	**2,374**	**100.0%**	**23,986**	**100.0%**

The difference in fracture patterns also corresponded to a difference in injury severity. Occupants who were exposed to an airbag deployment sustained the majority as AIS2 orbital fractures (73.6%), while 26.4% were AIS3 fractures (Table 5.2). In contrast, occupants who were not exposed to an airbag deployment sustained fewer AIS2 orbital fractures (38.7%), while 61.3% were AIS3 fractures.

Table 5.2. Comparison of orbital fracture severity for occupants who were or were not exposed to airbag deployment.

	Airbag Deployment		No Airbag Deployment	
	#	%	#	%
AIS2	1,747	73.6%	9,271	38.7%
AIS3	627	26.4%	14,715	61.3%
totals:	**2,374**	**100.0%**	**23,986**	**100.0%**

Part 3: Occupant and Crash Characteristics

For all occupants exposed to an airbag deployment, 84.7% of the occupants with orbital fracture were drivers, while 15.3% were right front seat passengers. When exposed to an airbag deployment, 0.06% of drivers sustained an orbital fracture, compared with 0.24% of passengers. While passengers had an incidence of orbital fracture nearly four times that of drivers, this difference was not statistically significant ($p=0.43$).

In addition, 83.0% of the occupants exposed to an airbag deployment with orbital fracture were male, while 17.0% were female. Of all the males who were exposed to an airbag deployment, 0.15% sustained an orbital fracture, compared with 0.03% of female occupants. Although male occupants sustained an orbital fracture more often than females, occupant sex was not found to be a statistically significant factor in incidence of orbital fracture ($p=0.12$).

Of all the occupants exposed to an airbag deployment with orbital fractures, 87.5% were wearing a seatbelt, while the rest (12.5%) were not wearing a seatbelt. In addition, it was found that 0.09% of belted occupants sustained an orbital fracture, compared with 0.08% of occupants not wearing a seatbelt. This study indicated that the rate of seatbelt use was independent of injury incidence ($p=0.86$).

Within a 95% confidence interval, occupant height, weight, age, and crash Delta-V were all found to not be significant variables correlating with the risk of incidence of orbital fracture (Table 5.3).

Table 5.3. Comparison of occupants exposed to an airbag deployment. Group 1 was exposed to an airbag and sustained an orbital fracture, while Group 2 was exposed to an airbag deployment, but did not sustain an orbital fracture. Mean values and standard deviations are included.

	GROUP 1: Orbital Fracture Injury		GROUP 2: No Orbital Fracture Injury	
	Mean	Standard Deviation	Mean	Standard Deviation
Occupant Height (in)	60.47	5.62	67.01	0.26
Occupant Weight (lbs)	138.73	20.67	160.30	2.30
Occupant Age (yrs)	25.66	7.61	33.74	0.62
Delta-V (mph)	13.73	1.36	13.74	0.27

5.4 Discussion

This paper presents the most comprehensive orbital fracture study to date as it investigated nearly 12.5 million front seat occupants in frontal crashes between the years 1993 and 2000 to identify the effects of airbags on the incidence of orbital fractures. An analysis of the cases indicated that occupants who were not exposed to an airbag deployment sustained an orbital fracture more than twice as often as occupants not exposed to an airbag deployment. While this difference was not statistically significant (p=0.10), the low p-value does indicate 90% confidence in the trend. As more airbag cases become available in accordance with the increased implementation of airbags into the automotive fleet, it is likely that this difference will become significant.

Although airbags have been shown to increase the incidence of some minor injuries, it appears that in the case of orbital fractures, the airbag has a considerable protective effect. This can be attributed to the airbag preventing the occupant's face from contacting the steering wheel or the windshield. In addition, of the nearly 2.5 million occupants exposed to an airbag deployment, only 11 orbital fractures were a result of contact with the airbag components, and in particular, these were all induced by the airbag cover.

Not only was there a decrease in incidence of orbital fractures for occupants exposed to airbags, but there was also a decrease in the severity of the orbital fractures that occupants sustained. Nearly two thirds of the orbital fractures to occupants who were exposed to an airbag deployment were of the lowest severity. In contrast, occupants who were not exposed to an airbag deployment sustained only one third of the fractures of the lowest severity, while nearly two thirds were of the highest severity level. In summary, both the incidence and the overall severity of orbital fractures decreased with exposure to airbag deployment as a result of the protective attributes of the airbag design.

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Chapter 6:
Severe Upper Extremity Injuries

6.1 Introduction

Although airbags have reduced the incidence of fatal and severe injuries in automobile collisions, they have been shown to increase the risk of other injuries (Deery, 1999). These associated minor injuries include corneal abrasions and skin injuries, (Campbell, 1993; Driver, 1994; Dubois, 1998; Duma, 1996; Gault, 1995; Ghafouri, 1997; Huelke, 1992; Larkin, 1991; Lee, 2001; Lemley, 2000; Lesher, 1993; Lueder, 2000; Mishler, 1991; Steinmann, 1992; Vichnin, 1995; Walter, 1996; Weinman, 1995; White, 1995; Zabriskie, 1997), as well as upper extremity injuries. In particular, upper extremity injuries have been identified through case reports that present a wide range of upper extremity injuries, from a minor abrasion, to a more severe avulsion or fracture (Dalmotas, 1995; Freedman, 1995; Huebner, 1998; Huelke, 1992; Huelke, 1995; Kirchhoff, 1995; Lundy, 1998; Marco, 1996; Michaeli-Cohen, 1996; Molia, 1996; Richter, 2000; Roth, 1993; Sances, 2000; Smock, 1995). Although upper extremity injuries were observed prior to airbag implementation, it is suggested that the risk of serious upper extremity injury to restrained occupants with airbags is higher when compared with those without airbags (Dalmotas, 1995; Kuppa, 1997; NHTSA, 1996). Upper extremity injuries have been estimated as nearly a quarter of all injuries to the whole body in motor vehicle crashes (Richter, 2000; Kulowski, 1956). In particular, Frampton et al. (1997) found that the forearm had the greatest incidence of severe upper extremity injuries in frontal collisions, accounting for 46% of the severe injuries to the upper extremity.

To investigate the interaction between the upper extremity and a deploying frontal airbag, experimental testing has been done using Hybrid III and Research Arm Injury Device (RAID) upper limbs (Kuppa, 1997; Johnston, 1997; Kallieris, 1997; Saul, 1996). In addition, numerous cadaver studies have aimed to estimate dynamic injury tolerance and to reproduce fractures similar to those observed in real world case studies (Bass, 1997; Duma, 1998; Duma, 1999; Hardy, 1997; Pintar, 1998). As identified in case reports, injuries to the upper extremity can occur due to contact with the airbag during or after deployment, and are likely caused by various combinations of axial and bending moments applied to the arm (Huelke, 1994).

Although experimental studies provide insight into the interaction between an airbag and the upper extremity, the national incidence of severe upper extremity injuries is unknown for occupants in crashes with and without an airbag deployment. In addition, although numerous case studies list upper extremity injuries among the more serious injuries that patients sustain, no study has correlated the occupant and crash characteristics with the incidence and severity of airbag induced upper extremity injuries. The purpose of this paper is to determine the overall risk and severity of upper extremity injuries in automobile crashes and to elucidate the effect of frontal airbags on these patterns.

6.2 Methods

To eliminate the inaccuracies associated with small case study projections, this study utilizes the National Automotive Sampling System (NASS) (NHTSA, 2000). The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1998). This coding allows for a consistent and accurate distinction and identification of upper extremity injuries. The NASS database has been used for national injury projection studies to analyze injury severity and crash characteristics for such things as lower extremity injury patterns and restraint effectiveness in motor vehicle crashes (Atkinson, 2000; Deery, 1999; Duma, 1996; Farmer, 1997; Miller, 1993; Reiff, 2001; Segui-Gomez, 2000; Viano, 1990; Zuby, 2001). Every crash investigated for the NASS database is assigned a weighted value, which scales the incidence of the particular crash investigated to a number that represents actual occurrence of similar non-investigated crashes that occur in the U.S. each year. Unweighted numbers reflect actual values counted from the cases that appear in the NASS database. The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained and do not include combined effects from multiple injuries to the same patient.

For this study, NASS cases were selected from the years 1993 through 2000 that included drivers and front seat occupants only, and excluded ejected occupants and rollovers. In addition, only frontal impacts were considered, which are defined as having a primary direction of force (PDOF) of 11, 12, or 1 o'clock. Only severe upper extremity injuries were analyzed, identified as having an AIS level 2 severity and higher. Such injuries include amputation, avulsion, burn, crush, dislocation, fracture, and laceration, and the upper extremity was defined to include the acromium, clavicle, scapula, humerus, elbow, radius, ulna, wrist, hand, and fingers. The injuries and specific body region were identified in the NASS database using the current AIS injury codes. Injuries to the fingers, hand, and wrist were all grouped together and termed hand injuries. Weighted and unweighted frequencies of occupants and injuries were analyzed. The study was divided into four parts.

Part 1: Crashes With and Without Airbag Deployment

This study first considered crashes with an airbag deployment. For all occupants who were exposed to an airbag deployment, the number of occupants that sustained a severe upper extremity injury was compared with the total number of occupants who did not sustain a severe upper extremity injury. Next, an analogous search was performed for crashes in which the did not deploy. For all occupants who were not exposed to an airbag deployment, the number of occupants that sustained a severe upper extremity injury was compared with the total number of occupants who did not sustain a severe upper extremity injury. Occupants with injuries and total injuries to occupants were analyzed.

Part 2: Severe Upper Extremity Injury Types and Locations

Severe upper extremity injuries were further examined to compare injury types and locations, for all occupants in frontal crashes. The cases were analyzed by whether or not the occupant was exposed to an airbag deployment, and what the injury source was. Specific upper extremity injury types were compared as percents of total upper extremity injuries in similar crashes, depending on the injury source. To further analyze injuries by location, upper extremity fractures were broken down by specific body region to compare resulting fracture location by exposure to airbag deployment and source of injury.

Part 3: Occupant and Crash Characteristics

Occupant and crash characteristics were examined in order to identify risk factors that associate occupant characteristics to incidence of severe upper extremity injury in motor vehicle crashes with airbag deployment. airbag were analyzed by continuous valued variables. Two separate statistical analyses were performed in order to identify trends in severe upper extremity injury incidence for occupants exposed to airbag deployment.

Group A verses Group B. The first comparison examined the entire set of occupants who were exposed to an airbag deployment. These occupants were split into two non-overlapping groups. Group A was the set of occupants exposed to airbag deployment who sustained a severe upper extremity injury from the airbag as source. Group B was the set of all remaining occupants who did not sustain an airbag induced severe upper extremity injury. The occupants in Group B could have sustained a severe upper extremity injury in the crash, but the source would be something other than the airbag. The groups were divided in this way in order investigate occupant characteristics that might be related to resulting incidence of airbag induced injury. Since all occupants in this analysis were exposed to an airbag deployment, risk factors could be identified that associate occupant characteristics to incidence of severe upper extremity injuries that were induced specifically by the airbag.

Group C verses Group D. The second statistical analysis again examined only occupants who were exposed to an airbag deployment. These occupants were split into two different groups from those above. Group C was the set of occupants who sustained a severe upper extremity injury in the crash, while Group D was the set of remaining occupants who did not sustain a severe upper extremity injury in the crash.

The statistical analysis examined the occupants exposed to airbag deployment by comparing Group A with Group B, and also by comparing Group C with Group D. The chi square test of independence for survey data (SUDAAN, Research Triangle Park, North Carolina) was used to investigate occupant sex, seatbelt use, and seat position. Percentages and p-values were calculated for each of the variables. Average value and standard deviations were calculated for continuous variables such as occupant height, weight, age, and crash change in velocity (Delta-V).

Part 4: Tethered and Non-Tethered Airbags

Occupants and severe upper extremity injuries in crashes with airbag deployment were further investigated to identify differences in injury trends for occupants exposed to tethered and non-tethered airbags. A tether limits the shape and size of the airbag, and both tethered and non-tethered airbags exist in the fleet of vehicles. This part investigated only crashes with airbag deployments, and cases were excluded that did not indicate whether or not the airbag was tethered.

6.3 Results

Part 1: Crashes With and Without Airbag Deployment

A total of 12,429,580 weighted occupants (25,464 cases) were included in this study for the eight-year period from 1993 to 2000. Since the proportion of airbag-equipped vehicles in the fleet is increasing, more occupants are exposed to airbag deployments each year. Accordingly, the number of occupants who sustain a severe upper extremity injury in a crash with airbag deployment has also increased (Figure 6.1).

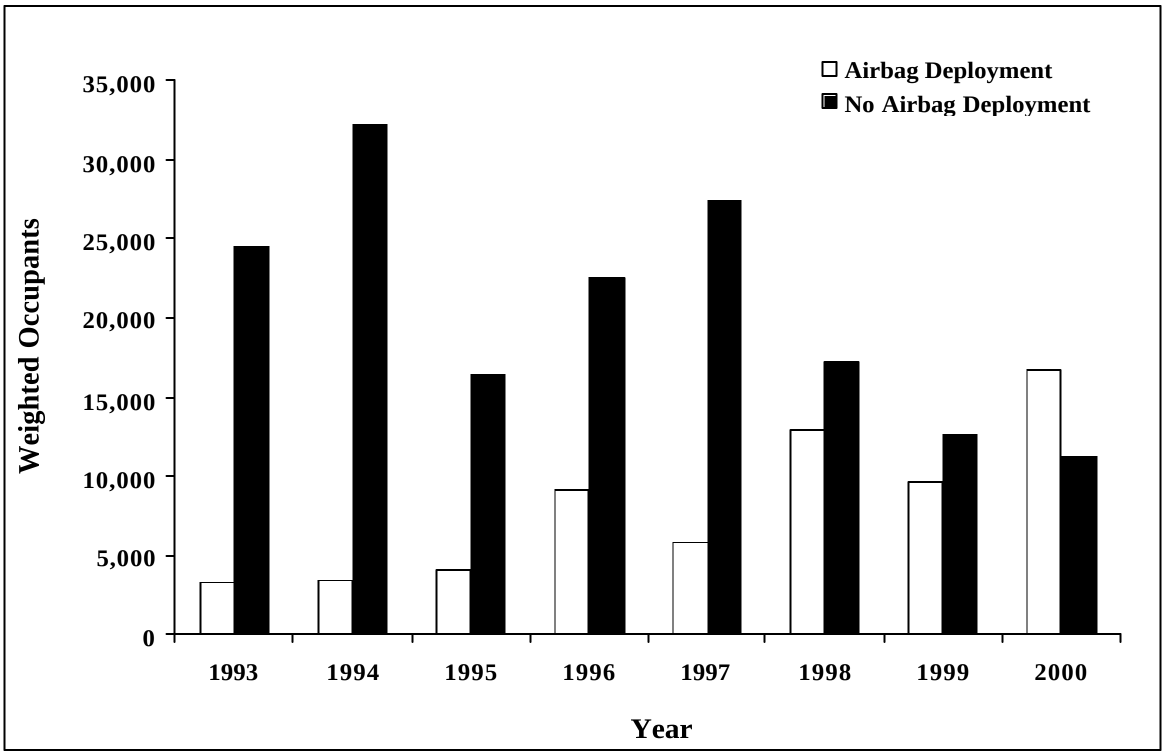

Figure 6.1. Weighted occupants with severe upper extremity injuries in frontal crashes that were or were not exposed to an airbag deployment.

For crashes where the occupant was exposed to an airbag deployment, 65,273 weighted occupants (524 cases) sustained an upper extremity injury out of 2,421,893 total weighted occupants (6,094 cases) in similar crashes (2.7%) (Figure 6.2). In contrast, for crashes without an airbag deployment, 164,339 weighted occupants (1,221 cases) sustained an upper extremity injury out of 10,007,687 total weighted occupants (19,370 cases) in similar crashes (1.6%). This difference was statistically significant, with occupants exposed to an airbag deployment being more likely to sustain a severe upper extremity injury than those occupants who were not exposed to an airbag deployment (p=0.01).

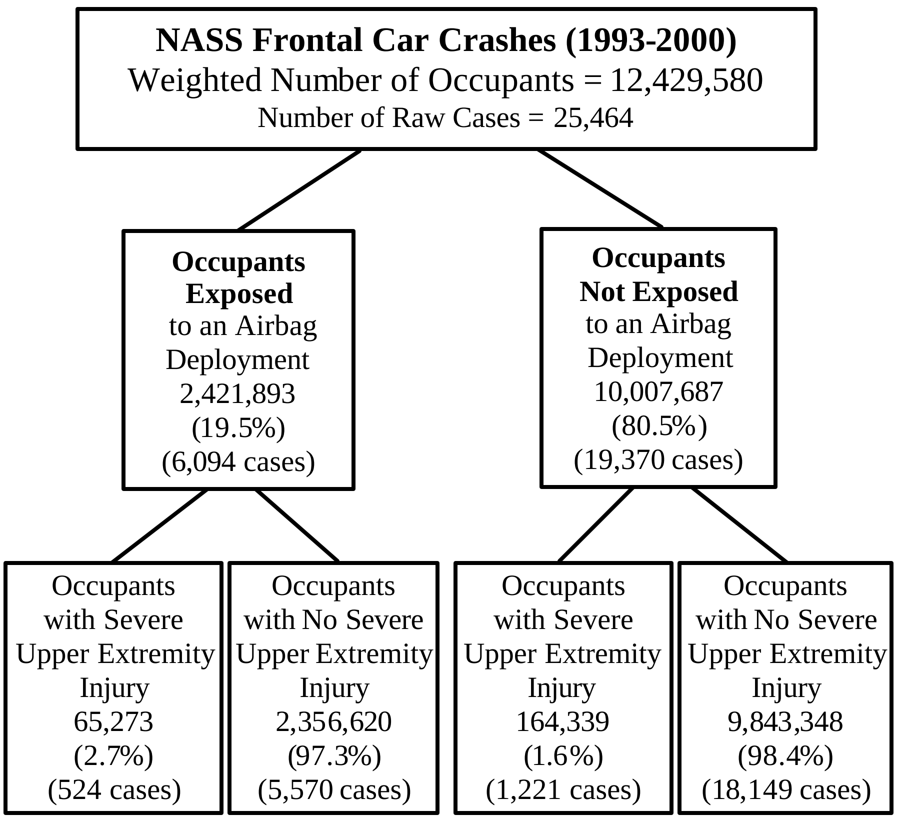

Figure 6.2. Incidence of severe upper extremity injury for occupants in frontal crashes that were or were not exposed to an airbag deployment (1993-2000).

There were 313,390 severe upper extremity injuries to occupants, of which, 88,324 were to occupants exposed to an airbag deployment (28.2%), while 225,066 occurred to occupants who were not exposed to an airbag deployment (71.8%) (Figure 6.3). The occupants who were exposed to an airbag deployment and sustained a severe upper extremity injury sustained the majority (24,455) of the injuries from the airbag as source (27.7%), followed by 17,843 from the instrument panel or glove box (20.2%), and 15,718 from the steering wheel (17.8%). If the occupants were not exposed to an airbag deployment, the majority of the injuries (100,557) were from contact with the instrument panel or glove box (44.7%), while 75,086 were from contact with the steering wheel (33.4%). In particular, of the 2,421,893 occupants exposed to an airbag, 16,145 occupants (138 cases) sustained severe upper extremity injuries specifically from the airbag (0.7%).

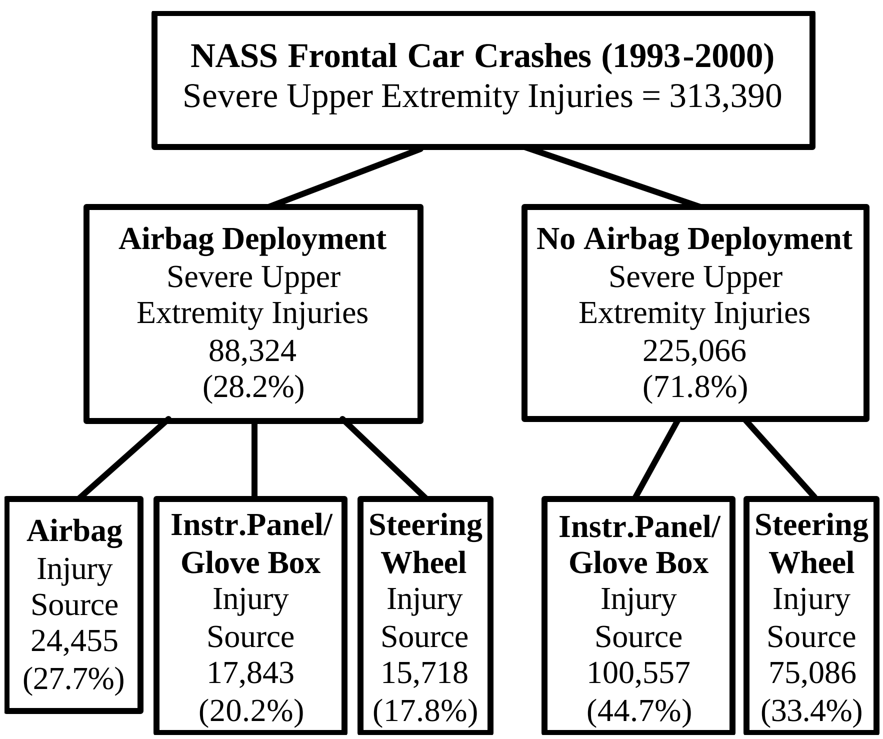

Figure 6.3. Weighted number of severe upper extremity injuries that occurred to occupants in frontal crashes (1993-2000).

Part 2: Severe Upper Extremity Injury Types and Locations

For both AIS2 and AIS3 levels, the majority of the severe injuries to the upper extremity were fractures (Table 6.1). For occupants who were exposed to an airbag deployment, 84.2% of airbag induced severe injuries were fractures, followed by 13.2% dislocations. Occupants who were exposed to an airbag deployment but sustained injuries from other sources had 89.8% fractures of all severe upper extremity injuries sustained. In addition, for occupants who were not exposed to an airbag deployment, 94.7% of severe upper extremity injuries were fractures.

Table 6.1. Comparison of severe (AIS2 and AIS3) upper extremity injury types in crashes with and without airbag deployment.

	Airbag Deployment						No Airbag Deployment	
	Source: All included		Source: Airbag		Source: Other		Source: Other	
	#	%	#	%	#	%	#	%
Amputation	675	0.8%	0	0.0%	675	1.1%	563	0.3%
Avulsion	35	0.0%	19	0.1%	16	0.0%	319	0.1%
Burn	514	0.6%	514	2.1%	0	0.0%	93	0.0%
Crush	796	0.9%	0	0.0%	796	1.2%	17	0.0%
Dislocation	6,861	7.8%	3,239	13.2%	3,622	5.7%	7,586	3.4%
Fracture	77,924	88.2%	20,593	84.2%	57,331	89.8%	213,057	94.7%
Laceration	1,051	1.2%	90	0.4%	961	1.5%	2,610	1.2%
Unknown	468	0.5%	0	0.0%	468	0.7%	821	0.4%
Totals:	88,324	100%	24,455	100%	63,869	100%	225,066	100%

There was a slight shift in the fracture location depending on whether or not the occupant was exposed to an airbag deployment, and whether or not the airbag was the source of the fracture (Table 6.2). For all airbag induced severe upper extremity fractures, the majority occurred to the radius (51.9%), followed by the ulna (34.1%). Just

7.0% of airbag-induced fractures occurred to the hand. In contrast, occupants who were exposed to an airbag deployment but sustained fractures from other sources, sustained injuries most often to the hand (23.7%), followed by the radius (21.9%), and the ulna (20.3%). In addition, occupants who were not exposed to an airbag deployment sustained injuries from other sources in the vehicle, and received injury most often to the hand (34.8%), followed by the ulna (20.3%) and the radius (17.2%).

Table 6.2. Comparison of severe (AIS2 and AIS3) upper extremity fracture locations in crashes with and without airbag deployment. (NFS=Not Further Specified).

	Airbag Deployment						No Airbag Deployment	
	Source: All included		Source: Airbag		Source: Other		Source: Other	
	#	%	#	%	#	%	#	%
Acromium	26	0.0%	0	0.0%	26	0.0%	201	0.1%
Arm NFS	7,863	10.1%	118	0.6%	7,745	13.5%	11,166	5.2%
Clavicle	7,464	9.6%	211	1.0%	7,253	12.7%	21,723	10.2%
Forearm NFS	157	0.2%	157	0.8%	0	0.0%	225	0.1%
Hand	15,002	19.3%	1,438	7.0%	13,564	23.7%	74,222	34.8%
Humerus	5,274	6.8%	941	4.6%	4,333	7.6%	23,844	11.2%
Radius	23,270	29.9%	10,696	51.9%	12,574	21.9%	36,636	17.2%
Scapula	182	0.2%	0	0.0%	182	0.3%	1,749	0.8%
Ulna	18,686	24.0%	7,032	34.1%	11,654	20.3%	43,291	20.3%
Totals:	77,924	100%	20,593	100%	57,331	100%	213,057	100%

Part 3: Occupant and Crash Characteristics

The next two analyses were made for two different groups by examining occupant and crash characteristics for the 2,421,893 weighted occupants who were exposed to an airbag deployment.

<u>Group A verses Group B.</u> It was found that 0.89% of female occupants exposed to an airbag deployment sustained a severe airbag induced upper extremity injury from the airbag, compared with 0.41% of male occupants. Although female occupants had a greater incidence of airbag induced severe upper extremity injuries, the difference was not found to be statistically significant ($p=0.28$). In addition, this analysis found that 0.65% of belted occupants sustained a severe airbag induced upper extremity injury, while 0.59% of unbelted occupants received a severe airbag induced upper extremity injury. Though this study resulted in a slightly greater incidence for the belted occupant, the difference was not statistically significant ($p=0.87$). Finally, it was determined that 1.47% of passengers exposed to an airbag deployment received a severe airbag-induced upper extremity injury, compared with 0.49% of drivers. Although front seat passengers had a greater incidence of airbag induced severe upper extremity injuries than drivers, the difference was not found to be statistically significant ($p=0.25$).

Within a 95% confidence interval, occupant height, weight, age, and crash Delta-V were all found to not be significant variables correlating with the risk of incidence of airbag induced severe upper extremity injury (Table 6.3).

Table 6.3. Comparison of Group A and Group B crash characteristics indicating correlation between incidence of airbag induced severe upper extremity injury and crash variable. Mean values and standard deviations are included.

	GROUP A: Airbag Induced Injury		GROUP B: No Airbag Induced Injury	
	Mean	Standard Deviation	Mean	Standard Deviation
Occupant Height (cm)	168.88	2.01	170.18	0.66
Occupant Weight (kg)	65.96	3.56	72.75	1.08
Occupant Age (yrs)	35.14	3.83	33.73	0.62
Delta-V (kph)	16.43	3.48	22.08	0.42

Group C verses Group D. It was found that 3.19% of female occupants exposed to an airbag deployment sustained a severe upper extremity injury from any source, compared with 2.29% of male occupants. Although female occupants had a greater incidence of severe upper extremity injuries when exposed to an airbag deployment, the difference was not found to be statistically significant (p=0.10). In addition, 2.54% of belted occupants exposed to an airbag deployment sustained a severe upper extremity injury, compared with 3.75% of unbelted occupants. Though unbelted occupants sustained injury more often, the difference was not statistically significant (p=0.26). Finally, it was determined that 2.71% of drivers exposed to an airbag deployment sustained a severe upper extremity injury, compared with 2.73% of passengers. Seat position had little contribution to risk for severe upper extremity injuries, as the difference was not statistically significant (p=0.99).

Within a 95% confidence interval, occupant height, and weight were not found to not be significant variables correlating with the risk of incidence of severe upper extremity injury (Table 6.4). However, occupant age and crash Delta-V were relevant variables in predicting injury. In particular, it was found that older occupants in crashes with higher Delta-Vs were at a higher risk for severe upper extremity injury when exposed to an airbag deployment.

Table 6.4. Comparison of Group C and Group D crash characteristics indicating correlation between incidence of severe upper extremity injury and crash variable. Mean values and standard deviations are included.

	GROUP C: Severe Upper Extremity Injury		GROUP D: No Severe Upper Extremity Injury	
	Mean	Standard Deviation	Mean	Standard Deviation
Occupant Height (cm)	170.54	0.91	170.18	0.66
Occupant Weight (kg)	74.04	2.03	72.66	1.08
Occupant Age (yrs)	40.24	2.03	33.55	0.64
Delta-V (kph)	30.69	1.74	21.85	0.43

Part 4: Tethered and Non-Tethered Airbags

Between the years 1995 and 2000, there were 2,137,347 weighted occupants who were exposed to an airbag deployment with a known tether type, of which, 1,233,533 occupants were exposed to a tethered airbag deployment (57.7%), and 903,814 occupants were exposed to a non-tethered deployment (42.3%). Of the 1,233,533 occupants exposed to tethered airbags, 37,014 sustained a severe upper extremity injury (3.0%), and 8,247 sustained a severe airbag-induced upper extremity injury (0.7%). On the other hand, of the 903,814 occupants exposed to non-tethered airbags, 20,393 sustained a severe upper extremity injury (2.3%), while 5459 sustained a severe airbag-induced upper extremity injury (0.6%).

6.4 Discussion

This paper presents the most comprehensive upper extremity injury analysis to date. This study investigated 25,464 individual cases over eight years to identify the effects of frontal airbag deployment on the incidence of severe upper extremity injuries. These cases represent 12,429,580 weighted occupants in frontal car crashes for the years 1993 through 2000. The analysis indicated that occupants exposed to an airbag were nearly twice as likely to incur an upper extremity injury (2.7%) as those occupants not exposed to an airbag (1.6%), a difference that was found to be statistically significant ($p=0.01$). In particular, 0.7% of the occupants exposed to an airbag deployment sustained a severe upper extremity injury specifically from the airbag.

The results from this study can be used to provide insight into emergency room trauma caregivers as well as to guide automotive interior and safety design decisions. In particular, the data presented in this paper indicate a larger incidence of severe upper extremity injuries in the female population. This can be explained by the weaker bone structure as well as increased proximity to the airbag due to smaller stature. In addition, the data show that the presence of a tether has no effect on the rate of airbag induced severe upper extremity injuries. This is in contrast to the popular notion that limiting the size and shape of the airbag would reduce upper limb injuries. It is anticipated that these findings and the large number of airbag induced severe upper extremity injuries will warrant further research into the design of airbags that may reduce the injury trends indicated here.

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Chapter 7:
Pregnant Occupants

7.1 Introduction

Klinich et al. (1999) estimated that each year in the United States, there are about 130,000 women involved in motor vehicle crashes while in the second half of pregnancy. Approximately 30,000 of them sustain treatable injuries, while 160 die as a result of the injuries sustained in the crash. Attico et al. (1986) reported that the largest single cause of death for pregnant females was automobile crashes. For the pregnant women who do survive, however, it was estimated that between 300 and 3,800 experience a fetal loss, most often as a result of placental abruption (Klinich, 1999).

In addition, Crosby et al. (1971) reported that the leading cause of fetal death in unrestrained mothers was death of the mother. However, if the mother survived the crash but the fetus did not, Crosby found that the leading cause of death for the fetus was placental abruption (1971). In particular, Pearlman estimated that up to 70% of all fetal losses were due to placental abruption (1997). Although maternal death may not be the primary cause of fetal death, it has a near 100% fetal fatality rate. According to Rothenberger (1978), it is a basic principle that "the best chance for fetal survival is to assure maternal survival."

Multiple studies have determined that the use of 2-point and 3-point restraints lowers the risk of fatality for the mother, and also the child (Crosby, 1968; Crosby, 1971;

Crosby, 1972; King, 1972; Pearlman, 1996b; Rupp, 2001). A recent study conducted by The University of Michigan Transportation Research Institute (UMTRI) indicated a significant increase in fetal survival with proper use of a 3-point belt (Rupp, 2001). While no specific recommendations have been made regarding the use of airbags for pregnant women, preliminary data suggests that the use of an airbag with a 3-point belt would be beneficial for the pregnant occupant in automobile crashes (Pearlman, 1996a; Rupp, 2001).

7.1.1 Fetal Loss Estimates

Several estimates of fetal loss due to motor vehicle crashes (MVCs) can be found in the literature. Pearlman et al. (1996a) estimated an annual fetal loss rate (FLR) range based on multiplying the number births that occurred each year by several factors of risk that included: the estimated overall incidence of trauma for pregnant mothers, the incidence of trauma for pregnant occupants in MVCs, and the overall estimated FLR due to placental abruption. In particular, the 4 million annual births from the year 1996 was multiplied by the 6% to 7% of women who experienced trauma during pregnancy, and by 50% to factor in the percentage of maternal trauma attributable to MVCs. Finally, this number was multiplied by a range of FLRs due to placental abruption (1% to 3%). These calculations estimated a range of annual fetal losses to be between 1,300 and 3,900.

Klinich et al. (1999) reported several alternative methods that estimated the number of fetal losses each year to be between 333 and 3,848. The number of births per year, based on 1996 CDC data, was divided by the number of females reported in the

1996 U.S. Census female population, to yield the percentage of females that were pregnant during the year. Next, the 1996 Traffic Safety Facts Sheet was used to determine the number of women in MVCs, separated into three groups: those who were uninjured, those who were injured and survived, and those who died as a result of their injuries. If the mother died in the crash, a 100% FLR was assumed. However, if the mother survived, a 1% to 3% fetal loss rate was applied to estimate the number of fetuses that died as a result of injuries that the mother was able to overcome. This yielded a range of estimated annual fetal losses to be between 462 and 3,838.

From the 1996 NASS database, Klinich et al. (1999) determined that 99.4% of women in MVCs had an Injury Severity Score (ISS) of less than 20. A fetal lose rate of 1% was associated with ISS scores less than 20, while a 20% FLR was associated with ISS scores greater than or equal to 20. This method produced an estimated 333 annual fetal losses. For the final method, Klinich et al. (1999) analyzed cases from the 1996 NASS database to identify crash severity ranges for female occupants in crashes. Crashes were divided by crash change in velocity (Delta-V) into minor (< 15 mph), moderate (15 – 30 mph), and severe crashes (> 30 mph). Klinich reported that 72% of women were involved in minor crashes, while 26% were in moderate crashes, and only 1% were in severe crashes. FLRs based on crash severity were taken from the injury risk curves developed by the second-generation pregnant dummy (Rupp, 2001). This particular method estimated between 1,490 to 3,724 annual fetal losses. Overall, Klinich's estimates of annual fetal loss ranged from 333 to 3,848.

7.1.2 Experimental and Computational Research

Previous research includes the testing of pregnant animals, the development of pregnant test dummies, and simplified modeling of a pregnant uterus. Animal testing, performed in the 1960s and 1970s, focused on restraint effectiveness using pregnant baboons subjected to sled tests (Crosby, 1968; Crosby, 1972; King, 1972; Van Kirk, 1969). In the late nineties, two prototype anthropomorphic testing devices (ATDs) were developed to investigate the ability of a crash test dummy to predict injury to a pregnant mother and fetus (Pearlman 1996b; Rupp, 2001). The first generation pregnant dummy was an adaptation of the current female dummy and was able to measure abdominal loads to evaluate the effect of restraints on the fetus (Pearlman 1996b). The second-generation dummy (MAMA-2B) was a redesign of the first generation dummy, with particular changes made to enable the new dummy to predict placental abruption (Rupp, 2001). Various restraint combinations and crash Delta-Vs were used to test both pregnant dummies. The only modeling done of the pregnant uterus in non-labor conditions was a simplified model of the uterus and its contents that aimed to examine the causes of placental abruption (Rupp, 2001).

7.1.3 Literature Review

There have been extensive groups of case reports and clinical studies published in the literature that offer insight into crash types and resulting injuries for pregnant occupants in MVCs (Aitokallio-Tallberg, 1997; Crosby, 1971; Dahmus, 1993; Elliot, 1966; Esposito, 1991; Fildes, 1992; Fort, 1970; Goodwin, 1990; Herbert, 1977; Hoff, 1991; Kissinger, 1991; Klinich, 1999; Lane J, 1977; Lane P, 1989; Pearlman, 1990a;

Pearlman, 1990b; Pearlman, 1997; Pepperell, 1977; Rothenberger, 1978; Timberlake, 1989; Williams, 1990; Wolf, 1993). However, all of the previous studies are based on local or statewide hospital medical records, and include no statistical analysis to estimate national trends in injury incidence, type or severity for pregnant occupants in MVCs. Other studies site that the NASS is not an accurate method of estimating fetal loss in MVCs, as there is no specific injury coding that details fetal outcome (Klinich, 1999). However, this study aims primarily to investigate injuries to pregnant occupants in MVCs, while a secondary goal is to report the known fetal fatalities that have occurred in the cases in the NASS database.

Although previous studies have reported large numbers of crashes that detail pregnant occupant injuries and crash types, the national incidence and relative risk of pregnant occupant injury type, severity and location is unknown for occupants in crashes with and without an airbag deployment. The purpose of this paper is to determine the overall risk and severity of injuries to pregnant occupants in automobile crashes and to outline the specific cases of maternal death and fetal loss reported in the NASS database.

7.2 Methods

To eliminate the inaccuracies associated with small case study projections, this study uses the National Automotive Sampling System (NASS) (NHTSA, 2000). The two primary advantages of using the NASS are that the database includes an analysis of approximately 5000 cases per year, and the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS) (AAAM, 1999). This coding allows for a consistent and accurate distinction and identification of occupant injuries. The NASS database has been used for national injury projection studies to analyze injury severity and crash characteristics for such things as lower extremity injury patterns, and restraint effectiveness in motor vehicle crashes (Atkinson, 2000; Deery, 1999; Duma, 1996; Farmer, 1997; Miller, 1993; Reiff, 2001; Segui-Gomez, 2000; Viano, 1990; Zuby, 2001). Every crash investigated for the NASS database is assigned a weighted value, which scales the incidence of the particular crash investigated, to a number that represents actual occurrence of similar non-investigated crashes that occur in the U.S. each year. Unweighted numbers reflect actual values counted from the cases that appear in the NASS database. The AIS scale classifies injuries by body region on a 6-point scale ranging from low severity (AIS1) to fatal (AIS6). The AIS values are assigned for each injury sustained, and do not include combined effects from multiple injuries to the same patient. The Maximum AIS (MAIS) value is the highest AIS single injury value the occupant sustained.

For this study, NASS cases were selected from the years 1995 through 2000 that included pregnant occupants in any seat position and any crash type, excluding those ejected or in rollover crashes. All pregnant occupants in crashes were included in the study, including both those with and without injuries. The injuries and specific body region were identified in the NASS database using the current AIS injury codes (AAAM, 1999). Weighted numbers of occupants in crashes and resulting injuries were analyzed. The study was divided into four parts: all pregnant occupants in crashes, pregnant occupants in frontal crashes, crashes with maternal death, and crashes with fetal loss.

Part 1: All Pregnant Occupants in Crashes

All crashes with a pregnant occupant between the years 1995 and 2000 were examined for overall details of the occupant, injury, and crash types. Pregnant occupants were examined by seat position, age, height, weight, trimester, and seatbelt use. Injuries to pregnant occupants were investigated by type, location, and severity, using MAIS values. Crashes were analyzed by Delta-V, primary direction of force (PDOF), and airbag deployment. If a particular detail was unknown about the occupant, injury, or crash, it was left out of the total count for each analysis, unless indicated otherwise.

Part 2: Pregnant Occupants in Frontal Crashes

All frontal crashes with pregnant occupants were analyzed by trimester, seatbelt use and resulting incidence of moderate injury. Moderate injury was defined as an AIS2 or greater injury. Pregnant occupants were split by trimester and seatbelt use to compare incidence of injury, and rate of seatbelt use by trimester.

Part 3: Crashes with Maternal Death

Crashes were analyzed that had severe injury to the pregnant occupant leading to maternal, and fetal death. Occupant variables were compared that included trimester, seat position, age, height, weight, and seatbelt use. Crash characteristics were identified and compared, such as: crash year, vehicle model year, crash direction, airbag deployment, and crash Delta-V. In addition, the most severe injuries to the pregnant females were identified and discussed, as well as the notable injury sources for the fatal injuries.

Part 4: Crashes with Fetal Loss

Crashes with fetal loss were identified and discussed. These cases included only those cases in which the mother survived the injuries from the crash, but the fetus did not. Specific injuries were identified, and occupant and crash details were analyzed. Occupant variables studied included: pregnant occupant trimester, seat position, age, height, weight, and seatbelt use. Crash characteristics were identified and compared, such as: crash year, vehicle model year, crash direction, airbag deployment, and crash Delta-V. Injury sources were identified for the specific injuries that led to fetal loss.

7.3 Results

A total of 230,477 pregnant occupants (482 cases) were in motor vehicle crashes between 1995 and 2000. In other words, an average of 38,412 pregnant females were in crashes every year, for the past six years.

Part 1: All Pregnant Occupants in Crashes

Of the 230,477 pregnant occupants in crashes, nearly 78% were drivers, while 20% were front seat passengers, and just over 2% were seated in the rear of the vehicle (Table 7.1). In addition, nearly 43% were in the first trimester of pregnancy, while 28.4% were in the second trimester, and 29.1% were in the third trimester. Pregnant occupants appear to be wearing their seatbelts (83.6%) at a similar rate as the overall population, which is estimated to be between 75% and 90%.

Table 7.1. Occupant characteristics for pregnant females in crashes between 1995 and 2000.

Seat Position	Total:	230,477	100.0%
	Front-Driver	179,159	77.7%
	Front-Pass	46,328	20.0%
	Rear-Center	27	0.0%
	Rear-Outboard	4,963	2.2%
Stage of Pregnancy	**Total:**	**203,521**	**100.0%**
	1st Trimester	86,536	42.5%
	2nd Trimester	57,791	28.4%
	3rd Trimester	59,194	29.1%
Belt Use	**Total:**	**149,938**	**100.0%**
	Belted	125,341	83.6%
	Unbelted	24,597	16.4%

The seat positions found in this NASS study are similar to those reported in the UMTRI pregnancy crash investigations (Klinich, 1999). They found that 60% of the pregnant occupants in crashes were drivers, while 33% were front passengers and 7% were rear passengers. However, the seatbelt use rate appeared to be higher in this study as compared with the UMTRI study. They found that only 76% of the pregnant occupants investigated were restrained by seatbelts.

All pregnant occupants in crashes were analyzed and split by trimester, and whether or not they sustained an injury in the crash (Figure 7.1). Most of the pregnant occupants in crashes were in the first trimester of pregnancy (42.5%), and these were also the occupants who were injured most often (91.5%). Second and third trimester occupants were in crashes at a similar frequency, and also had a similar rate of injury.

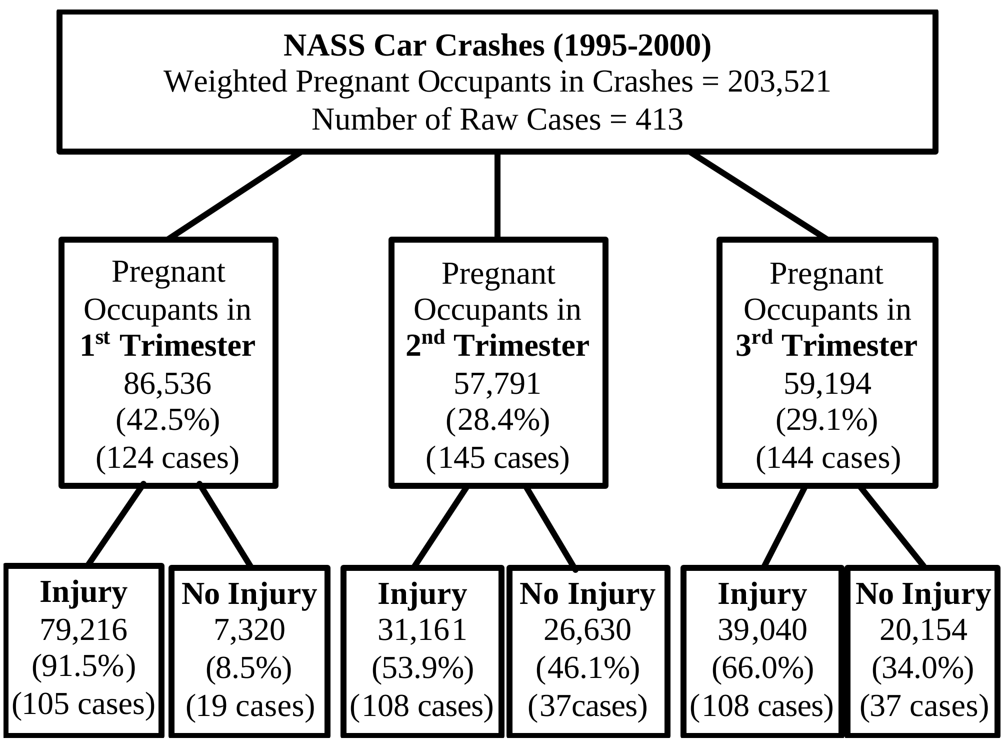

Figure 7.1. Flowchart showing incidence of injury for pregnant occupants in crashes, depending on the stage of pregnancy.

The pregnant females in crashes were split into groups and compared by height (Figure 7.2). The shortest pregnant female was 4’7”, while the tallest was 6’1”. However, the majority of the pregnant females in crashes were between 5’3” and 5’6”.

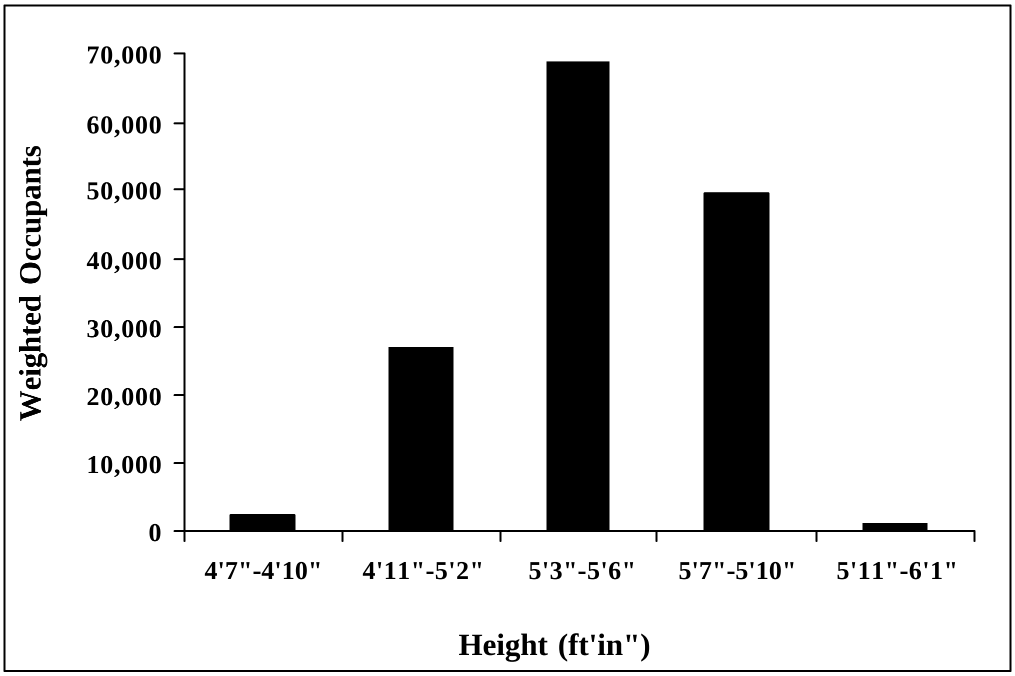

Figure 7.2. Pregnant females in crashes between 1995 and 2000, divided into groups by height.

In addition, the pregnant occupants in crashes were grouped together to identify trends in occupant size (Figure 7.3). The lightest occupant was 95 lbs, while the heaviest was 324 lbs. However, the majority of the pregnant females weighed between 126 and 150 pounds.

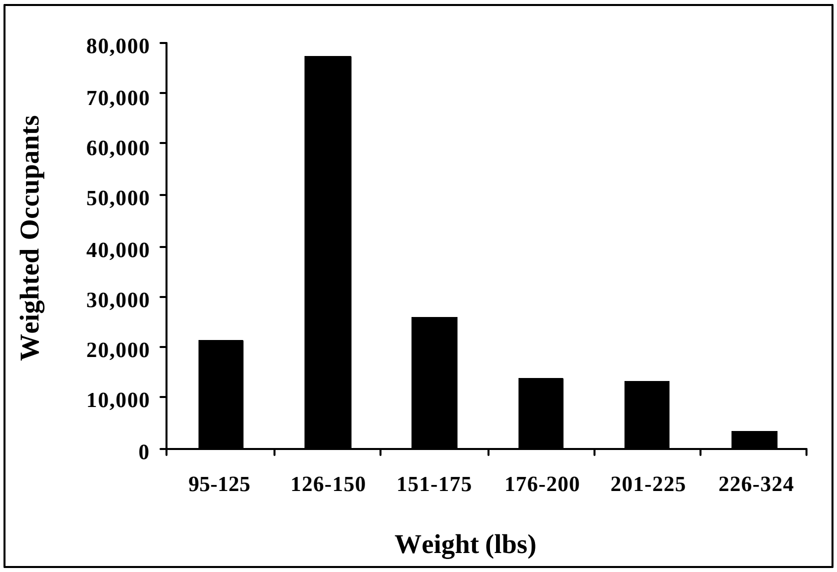

Figure 7.3. Pregnant occupants in crashes, split by weight (1995-2000).

The oldest pregnant occupant in a crash was 58 years old, while the youngest was 15. Occupants were split into groups to identify trends in age for pregnant females in crashes (Figure 7.4). Most of the pregnant females in crashes were between the ages of 26 and 30.

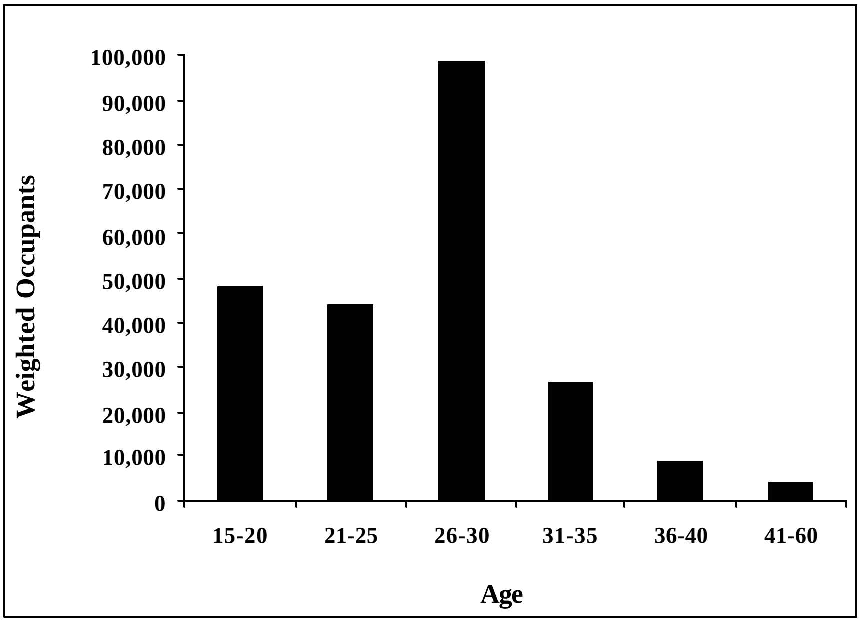

Figure 7.4. Pregnant females in crashes between the years 1995 and 2000, split by age groups.

The lowest crash Delta-V was 2.5mph, while the highest Delta-V was 53.4mph. Occupants were grouped by crash Delta-V to investigate trends in crash severity for pregnant females in crashes (Figure 7.5). The majority of the crashes had a Delta-V between 7.6 mph and 12.5 mph. The estimates of FLR by Klinich et al. (1999), found that of all women of childbearing age, 72% were in crashes of Delta-V under 15mph, while 26% were in crashes with Delta-V between 15mph and 30mph, and 1% were in crashes with Delta-V over 30mph. Based on the severity groups by Klinich et al., the cases in this NASS study indicated that 83,457 weighted pregnant occupants were in the low severity crashes under 15mph (79.9%), while 20,522 were in the mid-range severity crashes (19.7%), and just 455 were in the most severe crashes 0.4%.

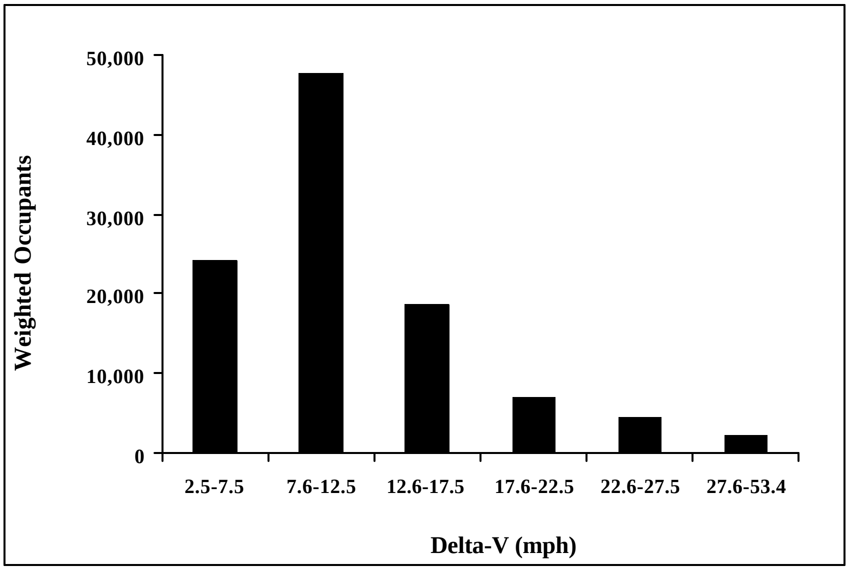

Figure 7.5. Pregnant females in crashes between 1995 and 2000. Crashes were split by Delta-V.

Of all the pregnant occupants in crashes, only 13.1% were exposed to an airbag deployment (Table 7.2). In addition, it was found that nearly half of all crashes involving a pregnant occupant were frontal crashes, followed by 40% from the side, and 11% from the rear.

Table 7.2. Crash characteristics for pregnant occupants in crashes between the years 1995 and 2000.

Airbag Exposure	**Total:**	**226,399**	**100.0%**
	Airbag Exposure	29,732	13.1%
	No Airbag Exposure	196,667	86.9%
Crash Direction	**Total:**	**120,731**	**100.0%**
	Frontal	58,995	48.9%
	Side	48,010	39.8%
	Rear	13,726	11.4%

These crash directions are similar to those found by the UMTRI pregnancy crash investigations (Klinich, 1999). They found that 62% of the pregnant occupants investigated were in frontal crashes, while 24% were in side-impacts, and 14% were rear-ended.

Injuries were broken down by type in order to identify trends for pregnant occupants in crashes (Table 7.3). The majority of the injuries were contusions (48.2%), followed by fractures (15.6%), and abrasions (14.6%). Pregnant occupants sustained only 1.7% of their injuries as concussions.

Table 7.3. Types of injuries sustained by pregnant occupants in crashes between the years 1995 and 2000.

	#	%
Contusion	197,070	48.2%
Fracture	63,637	15.6%
Abrasion	59,649	14.6%
Strain	33,283	8.1%
Laceration	32,945	8.1%
Sprain	6,749	2.6%
Concussion	4,768	1.7%
Other/Unknown	10,669	1.2%
Totals:	**408,770**	**100.0%**

Injuries to pregnant occupants were broken down by body region to identify the most commonly injured region of the body (Table 7.4). The majority of the injuries sustained by pregnant females were to the upper extremity (27.9%), followed by the chest (19.8%), and the lower extremity (18.6%). Only 8.8% of injuries to the pregnant occupant were to the abdominal region.

Table 7.4. Types of injuries sustained by pregnant occupants in crashes between the years 1995 and 2000.

	#	%
Upper Extremity	113,961	27.9%
Chest	80,837	19.8%
Lower Extremity	76,103	18.6%
Face	45,316	11.1%
Abdomen	35,831	8.8%
Neck	25,796	6.3%
Head/Skull	20,522	5.0%
Back	10,238	2.5%
Other/Unknown	166	0.0%
Totals:	**408,770**	**100.0%**

Injuries were compared by severity to identify the worst injuries that occupants sustained in the crash (Table 7.5). It was found that of all the pregnant females injured in crashes, the majority of them sustained at worst, only minor AIS1 injuries (89.3%). On the other hand, 0.3% of pregnant occupants in crashes died as a result of the injuries sustained in the crash.

Table 7.5. Maximum AIS (MAIS) values for each pregnant occupant in a crash between the years 1995 and 2000.

	#	%
MAIS1	142,511	89.3%
MAIS2	8,665	5.4%
MAIS3	4,154	2.6%
MAIS4	67	0.0%
MAIS5	52	0.0%
MAIS6 or died	509	0.3%
Injured; Unknown Severity	3,625	2.3%
Total:	**159,583**	**100.0%**

Part 2: Pregnant Occupants in Frontal Crashes

The first trimester pregnant occupants in frontal crashes had a 60.4% rate of seatbelt use. In addition, of those using seatbelts, only 3.4% sustained an injury of AIS2 or higher severity (Figure 7.6). In contrast, of those pregnant occupants not wearing their seatbelt, 13.8% sustained a moderate (AIS2+) injury.

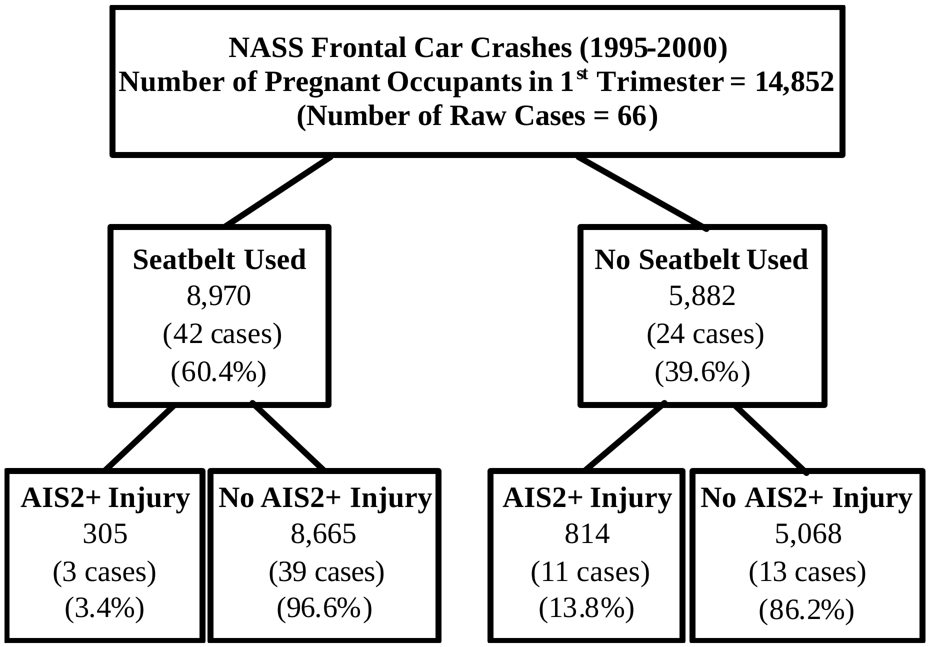

Figure 7.6. First trimester occupants in frontal crashes, in any seat position, during the years 1995-2000. Occupants were split by seatbelt use and resulting incidence of moderate (AIS2+) injury.

The second trimester pregnant occupants had the highest rate of seatbelt use in frontal crashes, at 92.5% (Figure 7.7). However, they also had the highest incidence of moderate injury for those wearing seatbelts (10.4%). In addition, the second trimester occupants also had the largest rate of moderate injury when not wearing a seatbelt (21.7%).

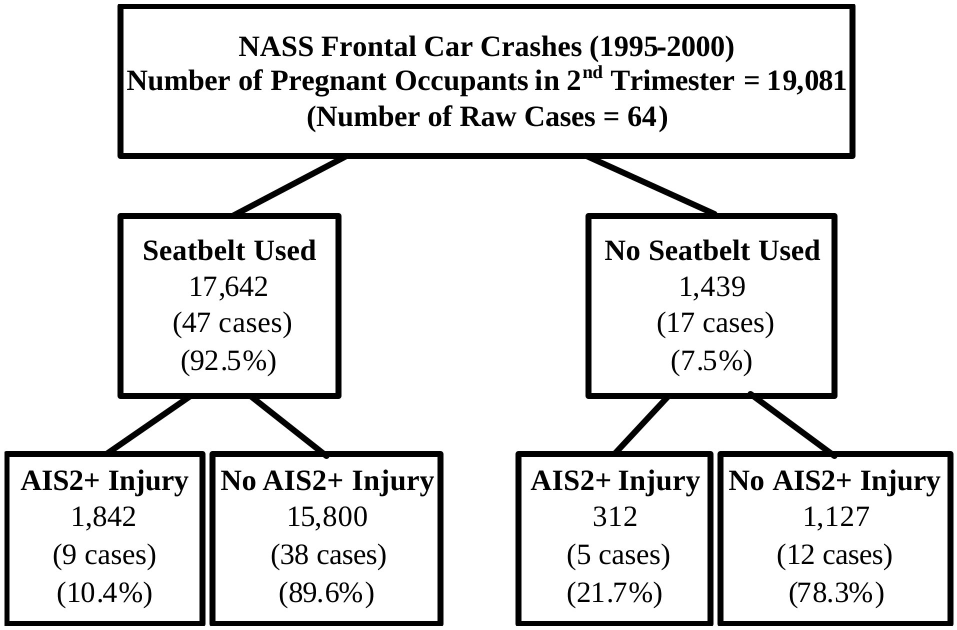

Figure 7.7. Second trimester occupants in frontal crashes, in any seat position, during the years 1995-2000. Occupants were split by seatbelt use and resulting incidence of moderate (AIS2+) injury.

Pregnant occupants in the third trimester of pregnancy had a seatbelt use rate of 85.4% (Figure 7.8). The seatbelt appears to have provided the greatest protective effect for third trimester occupants in frontal crashes, as only 0.1% of them sustained a moderate injury in the crash.

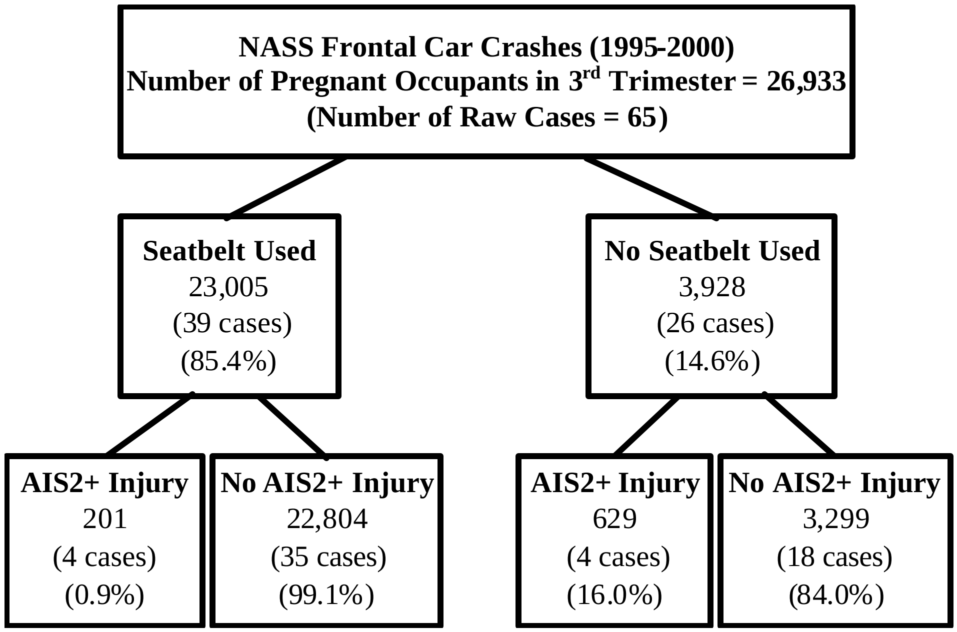

Figure 7.8. Third trimester occupants in frontal crashes, in any seat position, during the years 1995-2000. Occupants were split by seatbelt use and resulting incidence of moderate (AIS2+) injury.

Part 3: Crashes with Maternal Death

There were 509 weighted female occupants (10 cases) who died directly as a result of the injuries sustained in their crash. Of these, 25% were in the first trimester of pregnancy, 24% in the second trimester, and 18% in the third trimester. There were another 169 who died who's stage of pregnancy was unknown (33%). Of these occupants, the majority were drivers (60%), while 38% were front seat passengers, and only 2% were rear passengers. In addition, the majority of the deaths involved pregnant occupants who were not wearing a seatbelt (68%), and who were not exposed to an airbag deployment (80%). The exact details of these occupants are shown in Table 7.6. The first column is the occupant number, while the second column indicates the proportion of the data set that each weighted occupant represents.

Table 7.6. Weighted pregnant occupants who died in crashes between 1995 and 2000.

Occupant Number	% of Data Set	Trimester	Crash Year	Vehicle Year	Seat Position	Crash Direction	Age	Height (ft/in)	Weight (lbs)	Belt Used?	Airbag?	Crash Delta-V
1	3.5%	U	1995	1994	driver	U	25	5'6"	216	U	U	U
2	9.2%	3rd	1995	1994	driver	frontal	33	5'7"	170	Y	N	42.3
3	2.2%	3rd	1995	1983	rear	rear	24	5'5"	185	Y	N	24.2
4	16.1%	2nd	1996	1992	driver	frontal	33	5'8"	141	N	Y	U
5	5.5%	3rd	1997	1984	passenger	right side	20	5'4"	141	N	N	27.3
6	12.4%	U	1997	1984	driver	frontal	36	5'3"	130	N	N	39.1
7	24.4%	1st	1999	1985	passenger	frontal	26	5'4"	154	N	N	U
8	17.3%	U	2000	1999	driver	rear	26	U	U	N	N	49.7
9	8.1%	2nd	2000	1989	passenger	frontal	26	5'5"	141	N	N	22.4
10	1.4%	3rd	2000	1997	driver	right side	40	5'6"	179	N	N	U

Occupant 1 sustained a complete spinal cord laceration and was left with no sensation or motor function. She also had subarachnoid hemorrhaging to the cerebellum, and multiple lacerations to the heart, lungs, and spleen. In addition, she also fractured more than three ribs on both sides of her chest.

Occupant 2 had multiple rib fractures on both sides of her chest, along with a ruptured spleen and a full thickness bladder perforation. All of these injuries were due to contact with the steering wheel. In addition, she also fractured her foot from floor pan intrusion.

The third occupant had an atlanto-occipital dislocation, without laceration to the spinal cord. She also had a minor thyroid injury, and lacerations to the diaphragm. In addition, she sustained a complex open basilar fracture with torn and exposed brain tissue. She had subarachnoid hemorrhaging and multiple contusions to the cerebrum. Her neck injury and lung lacerations were from the seatbelt, while all her other injuries were from contact with the seat back support.

Occupant number 4 sustained a major skull fracture due to contact with the side b-pillar. She had a vault fracture that was diastatic, involving the occipital, parietal and sphenoid bones.

Occupant 5 sustained a major liver laceration with parenchymal disruption of the hepatic lobe. She fractured more than three ribs on the right side of her chest, which related to the multiple unilateral lung contusions and lacerations, and included a pleural laceration and more than 20% blood loss by volume. She was seated on the right side of the vehicle, which was hit on the right, and she sustained all of her injuries from the b-pillars and side interior of her vehicle.

The sixth occupant only had one major injury. She was the driver in a frontal crash, and was not wearing a seatbelt. She hit the steering wheel and suffered a major trachea and main stem bronchus injury.

Occupant number 7 was a passenger in a frontal crash who was not wearing her seatbelt and suffered all of her injuries from contact with the instrument panel. She had a femoral shaft fracture and a major head injury that included massive destruction of both the cranium and brain.

Occupant 8 sustained both epidural and subdural cerebral hematomas as well as basilar fracture. She had multiple rib fractures and hemo/pneumothorax along with arterial lacerations, and lung contusions. She also had a complete spinal cord transection and crush with vertebral fracture and dislocation. All of these serious injuries were induced by the seat back support and head restraint.

The ninth occupant had a pelvic fracture, an open femur fracture, and multiple rib fractures from contact with the instrument panel. She suffered a hemo/pneumothorax as well as bilateral lung contusions. Her head hit the hood of the other vehicle involved in the crash, and she sustained a basilar fracture with extra-axial hematoma.

Occupant number 10 had major iliac arterial laceration due to contact with the steering wheel. She also had a vertebral body burst fracture, disk dislocation and atlanto-occipital dislocation. These injuries all came from either the steering wheel or windshield.

All of these pregnant occupants died as a result of the injuries they sustained in their crashes, as did their unborn children.

Part 4: Crashes with Fetal Loss

There were 434 weighted pregnant occupants (8 cases) who survived the crash, but sustained injuries that led to fetal loss. These injuries included placental abruption, and major uterial laceration. None of the occupants who had fetal loss were exposed to an airbag deployment, and all of the injuries were induced by either the seatbelt, the instrument panel, or the steering wheel. The occupant and crash characteristics are shown in Table 7.7.

Table 7.7. Occupant and crash characteristics for pregnant females who survived their crash but lost their fetuses.

Occupant Number	% of Data Set	Trimester	Crash Year	Vehicle Year	Seat Position	Crash Direction	Age	Height (ft/in)	Weight (lbs)	Belt Used?	Airbag?	Crash Delta-V
1	0.2%	U	1996	1987	driver	U	27	5'8"	181	U	N	U
2	69.8%	3rd	1997	1988	driver	Frontal	17	U	U	N	N	29.2
3	1.2%	3rd	1997	1989	passenger	Left	20	5'7"	170	Y	N	24.9
4	1.2%	3rd	1998	1986	driver	U	34	U	U	U	N	U
5	3.0%	3rd	1998	1988	passenger	Frontal	19	5'6"	154	N	N	53.4
6	11.8%	3rd	1999	1994	driver	Frontal	29	5'2"	148	Y	N	18.6
7	1.4%	3rd	1999	1985	driver	Right	40	5'5"	165	Y	N	29.2
8	11.5%	3rd	2000	2000	passenger	Rear	31	5'2"	236	N	N	34.2

7.4 Discussion

This study found that about 35,000 pregnant occupants were involved in motor vehicle crashes each year, for the past six years. This rate is markedly less than the numbers estimated in previous studies. In particular, Klinich et al. (1999) estimated that each year in the United States, there are about 130,000 women involved in motor vehicle crashes while in the second half of pregnancy. Their estimate is high and potentially inaccurate for several reasons. First, their estimates are based on national averages of trauma to women in motor vehicle crashes, assuming that the same rate would apply for trauma to pregnant women in motor vehicle crashes. In addition, they identify the crash severities for all females in NASS crashes that were of childbearing age, and apply the same crash severity groupings to the number of pregnant females, estimated to be in crashes. However, it is not necessarily accurate to assume that pregnant females are in crashes of similar severities as all other female occupants.

The trends in crash direction, pregnant occupant seat position, and overall seatbelt use rate found in this study are similar to those found in the literature (Klinich, 1999). In particular, this study found that for pregnant occupants in frontal crashes, the rate of seatbelt use was different for pregnant occupants in the first (60.4%), second (92.5%), and third (85.4%) trimester of pregnancy. The seatbelt appears to have provided the greatest protective effect for third trimester occupants in frontal crashes, as only 0.1% of them sustained a moderate injury in the crash.

Of the pregnant occupants who were injured, 509 died directly from the injuries sustained in the crash (10 cases). In addition, there were 434 severe placental and urogenital injuries that resulted in an obvious fetal loss. In total, there were 943 known fetal losses as a result of the trauma sustained to pregnant women in motor vehicle crashes. For the six year period from 1995-2000, this is an average of 157 each year. However, because NASS has no specific injury coding for fetal outcome, these estimates are low, and only reflect those cases with such severe injury as to be confident of fetal fatality as an outcome.

The estimates of FLR by Klinich et al. (1999), used the 1996 NASS files to determine that of all women of childbearing age, 72% were in crashes of Delta-V under 15mph, while 26% were in crashes with Delta-V between 15mph and 30mph, and 1% were in crashes with Delta-V over 30mph. These crash severities were used to calculate FLR, assuming that 17% to 42.5% of pregnant women lose their fetuses in the most severe crash category, while 12.4% to 31% lose their fetuses in the middle Delta-V range and 2.2% to 5.5% sustain fetal loss in the low severity categories. This led to an annual fetal loss rate calculation between 1490 and 3724. Based on the known Delta-V values from this NASS study, it was determined that 83,457 weighted pregnant occupants were in the lowest severity crashes (79.9%), while 20,522 were in the mid-range severity crashes (19.7%), and just 455 were in the most severe crashes (0.4%). Based on their estimates of fetal loss percentages for various crash Delta-V categories, our study would result in 1,836 to 4,590 fetal losses for low severity crashes, 2,545 to 6,362 for mid-range severity crashes, and 77 to 193 fetal losses in the highest severity crashes. Over the six years of cases analyzed for this study, this would indicate an annual FLR between 743 and 1,858.

Previous studies have had to base their national FLR calculations on several assumptions that have led to less accurate estimations of annual FLR than those used here. One assumption made previously is that pregnant females are involved in motor vehicle crash at the same rate as all females in crashes, and another is that the crash Delta-V for all females in crashes matches the Delta-V range for crashes involving pregnant females. Because this study used six years of actual cases with pregnant occupants from a national database, the FLR found here seems to be a better estimate of annual FLR compared with those estimated in previous studies.

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Chapter 8:
Madymo Modeling of Pregnant Occupants

8.1 Introduction

Computational modeling of occupants in automobile crashes is done extensively both in academic and industrial settings. Primary advantages of computational modeling include the ability to reduce both time and cost through the ease of producing many different simulations with varying parameters. This chapter first identifies the major crash and pregnant occupant characteristics to be modeled, then models two different actual crashes that involved pregnant occupants as identified in the NASS pregnant occupant study in chapter 7.

8.2 Methods

This research involved a three part modeling study to further examine pregnant occupants in automobile crashes (Figure 8.1).

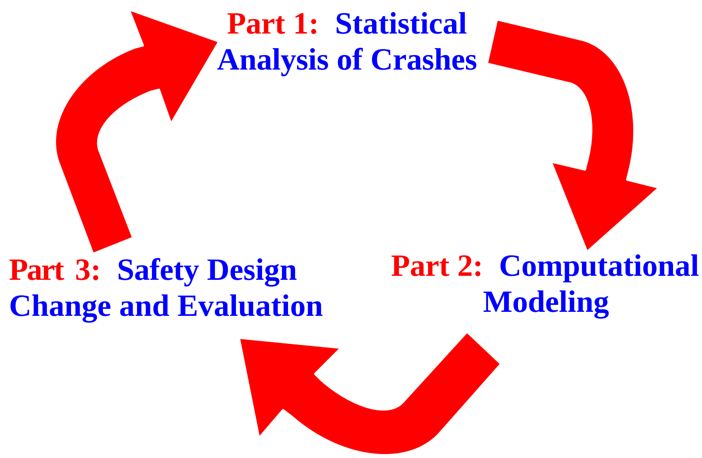

Figure 8.1. Diagram of three-part safety design paradigm for occupant protection studies.

Part 1. Statistical Analysis of Crashes

The first part of this study identifies the major pregnant occupant and crash characteristics that are prevalent in real world crashes. In order to eliminate the inaccuracies associated with small case study projections, this study uses the National Automotive Sampling System (NASS) database (NHTSA, 1999). The NASS data are used by research groups in the government, industry, and the private sector to assess the overall state of traffic safety, and identify existing and potential traffic safety problems (Farmer, 1997). The two primary advantages of using the NASS are that the database includes cases that represent all crashes that occur on U.S. roadways each year, and that the injuries are coded by trained nurses using the Abbreviated Injury Scale (AIS)

(AAAM, 1998). The AIS injury code is a seven digit numerical label of injury that includes information on both the severity of the individual injury, as well as the specific location on the body. This coding allows for a consistent and accurate distinction and identification of occupant injuries.

Part 2. Computational Modeling

The modeling part of this research involved computational modeling using a MAthematical DYnamic MOdeling software, called Madymo (Figure 8.2). Madymo enables the user to input vehicle and occupant information in order to assess the resulting moments and accelerations sustained by an occupant in crashes. Madymo allows the user to utilize both multibody and finite element systems in the same model, which can drastically reduce the time it takes to run the model solver. A full finite element model can take days to solve, whereas a mixed model with multibody sections can take as little time as several minutes.

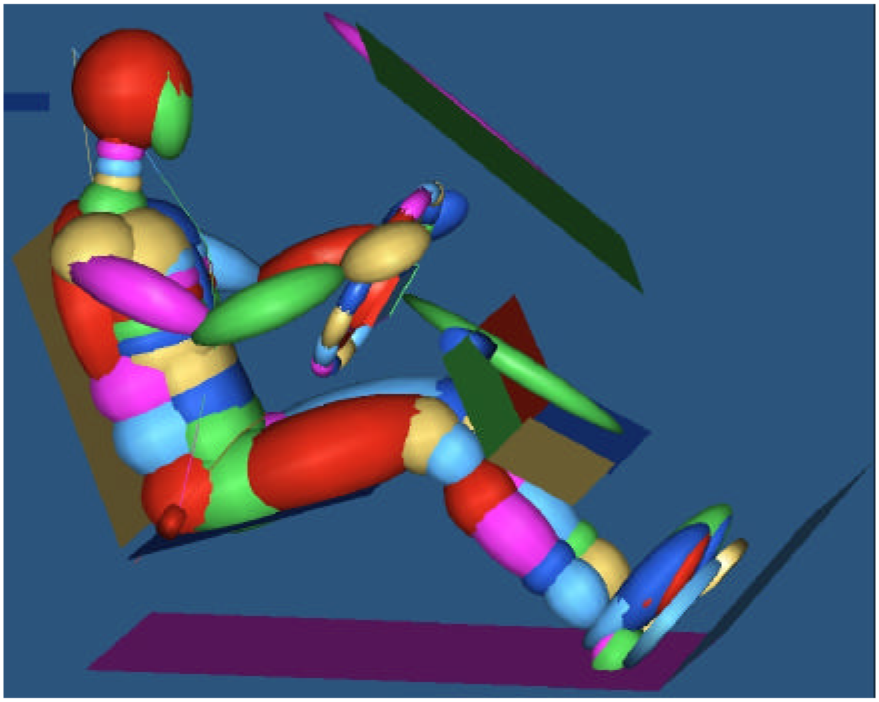

Figure 8.2. Madymo multi-body dummy model used for dynamic motor vehicle crash simulations.

Elipsoid dummy models, facet surface dummies, and full finite element human models can be used for modeling. In addition, of each of these types, a 3 year old child, 6 year old child, 5th percentile female, 50th percentile male, or 95th percentile male can be used for occupant analysis. Madymo has a function called the "Madymizer", which enables the user to scale the height and weight of any of the standard sized dummy or human models, to match an actual occupant's characteristics for more precise crash recreation.

Based on the results found in chapter 7, an actual crash was chosen that involved a pregnant occupant. This part shows how the actual crash was recreated in the madymo dynamic modeling software. The actual crash that occurred was modeled in order to analyze the injury mechanisms and occupant kinematics that occurred during the crash.

Part 3. Safety Design Change and Evaluation

The third part of this study involved making changes in safety restraint devices or interior characteristics in order to improve occupant safety. Another actual crash was modeled, using Madymo, to analyze the effects of the modifications in safety device use.

8.3 Results

Part 1. Statistical Analysis of Crashes

The first part of this study was to identify the most prevalent trends in pregnant occupant seat position, crash direction, and trimester. From the statistical analysis of crash data and occupant characteristics drawn from chapter 7, it was determined that in particular, every year for the last six years, over 35,000 pregnant females were in crashes each year (Table 8.1). Of these, the majority did sustain an injury in the crash (69%), though the use of seatbelts was high (84%). Only 13% of all pregnant occupants in crashes were exposed to an airbag deployment. However, because all crash directions and seat positions were included in this study, many pregnant occupants were not in a frontal crash which would induce airbag deployment. In addition, many of the pregnant occupants were seated in the rear compartment of the vehicle, and would not be exposed to an airbag deployment even in a high velocity frontal impact crash. However, when just examining pregnant females who were front seat occupants in frontal crashes, over 31% were exposed to an airbag deployment. In addition, it was determined that nearly half of all pregnant females in motor vehicle crashes were in the first trimester of pregnancy.

Table 8.1. Statistical results from NASS database on pregnant occupants in crashes during the years 1995-2000.

		%
Pregnant Occupants in Crashes		**230,477**
	No Injury	31%
	Injury	69%
Belt Use		
	Belted	84%
	Unbelted	16%
Airbag Exposure		
	Airbag Deployed	13%
	No Airbag Deployed	87%
Stage of Pregnancy		
	1st Trimester	43%
	2nd Trimester	28%
	3rd Trimester	29%

In addition, it was found that the majority of the pregnant occupants in crashes were drivers (78%), and nearly half were in frontal crashes (Figure 8.3).

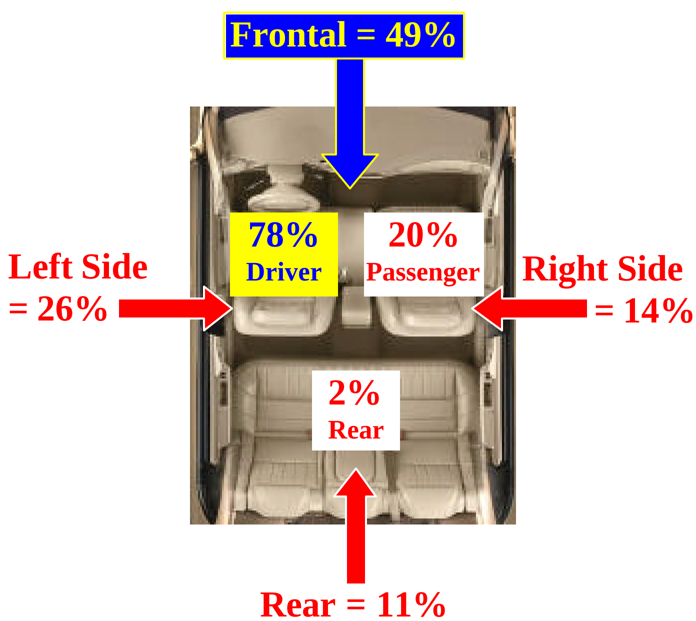

Figure 8.3. Crash types and pregnant occupant seat positions identified from a statistical analysis of the crash files in the NASS database.

Based on the results found above, several factors were identified that were a priority in the case selection for the modeling performed in part 2 and part 3. In summary, only pregnant drivers were considered who were in frontal impacts in their first trimester of pregnancy. Both belted and non-belted pregnant occupants were considered, as well as those who were or were not exposed to an airbag deployment.

Part 2. Computational Modeling

In this part, an actual crash was modeled from the NASS database, of a pregnant female driver in a frontal crash (Figure 8.4). The pregnant female was not wearing a seatbelt, and the airbag did not deploy in the crash. She sustained multiple facial, lower extremity, chest, and abdominal skin injuries, as well as a fracture to her patella. Injuries and injury sources were identified in the modeling simulation, which were consistent with the data in the actual NASS case report.

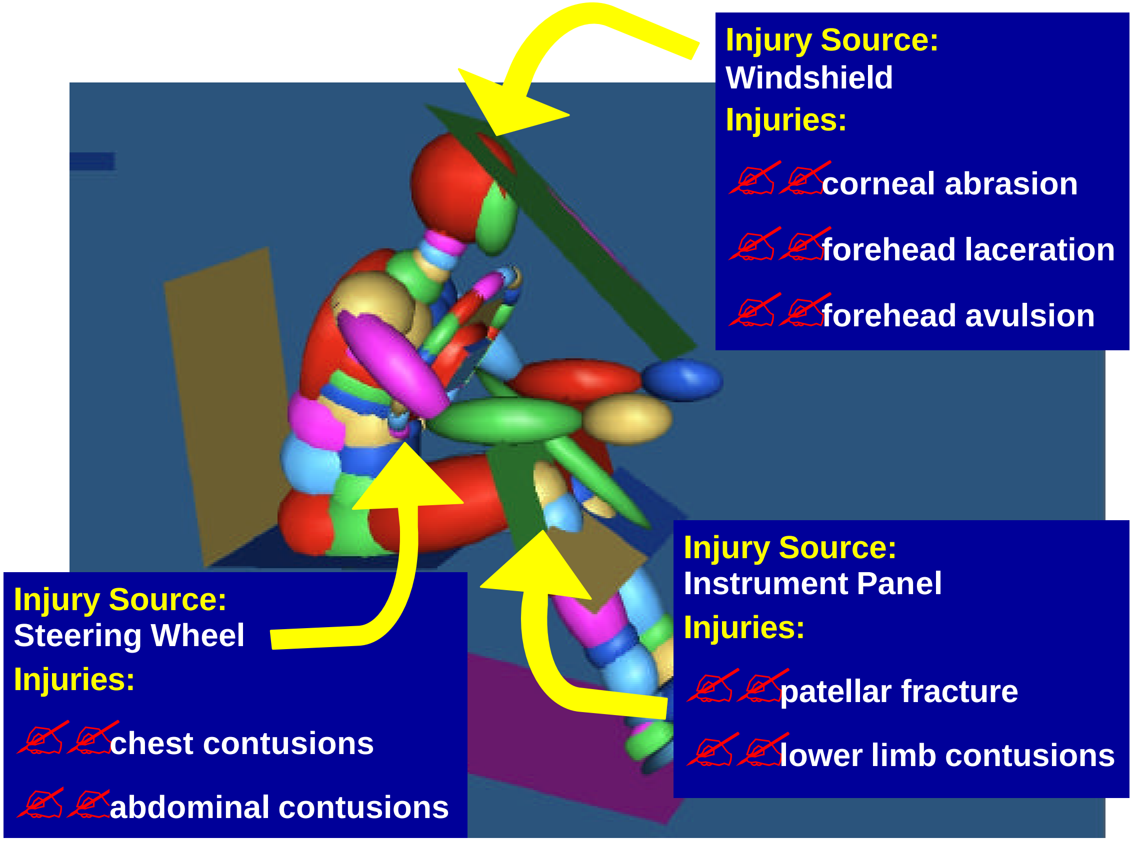

Figure 8.4. First trimester pregnant female driver in a frontal crash. She sustained multiple injuries from contact with the windshield, steering wheel, and instrument panel.

Part 3. Safety Design Change and Evaluation

A change in restraint system use was targeted for the second simulation, and another crash was chosen. This crash involved a different pregnant female driver in another frontal crash. She was wearing a seatbelt, and the airbag did deploy in the crash. The occupant sustained no injuries in the crash, which was indicated in both the simulation and actual crash report (Figure 8.5). This occupant's crash exemplifies the improvements made in occupant restraint systems.

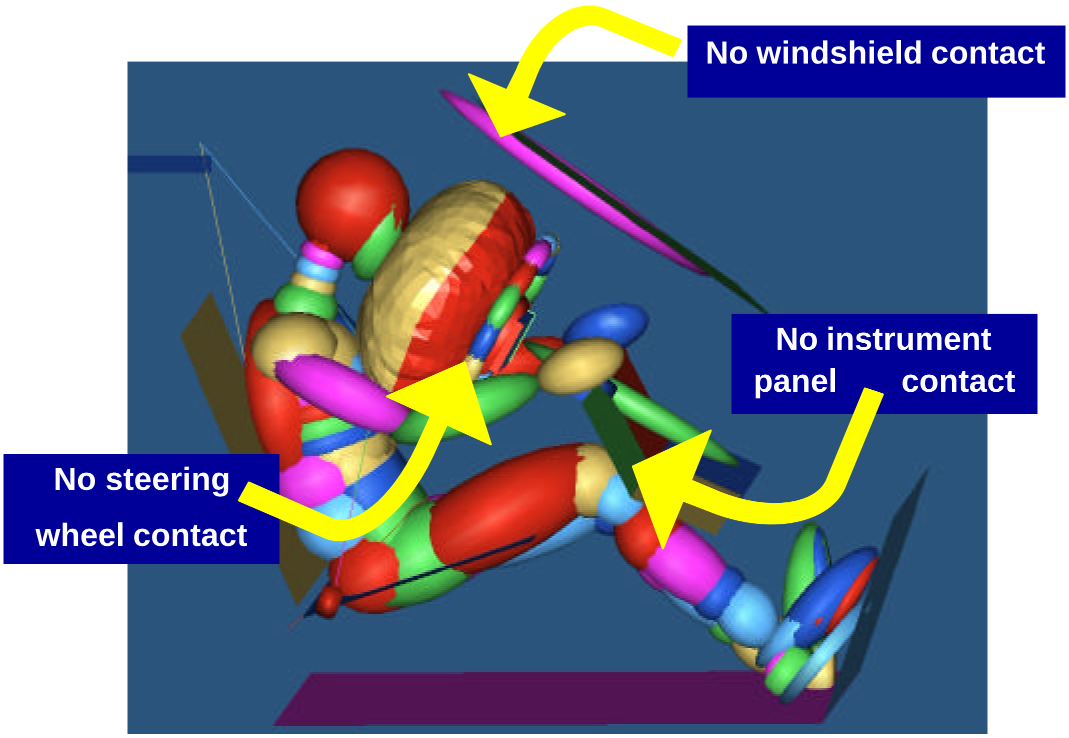

Figure 8.5. First trimester pregnant female driver in a frontal crash. She was wearing a seatbelt, and was exposed to an airbag deployment, and sustained no injuries in the crash.

8.4 Conclusions

In particular, this safety design process was used effectively in a detailed analysis of pregnant occupants in automobile crashes. The NASS database indicated that the majority of pregnant females in crashes were in the first trimester of their pregnancy, and were the drivers in frontal automobile crashes. These results indicated the priority for specific crash types to be further analyzed using computational modeling. Both occupants that were modeled were first trimester drivers, in frontal crashes. Cases were modeled both with and without seatbelt use, and with and without airbag deployment. The modeling simulations gave matching results of injuries and contact surfaces, with those reported in the NASS crash data files. By reproducing actual crashes using computational modeling, safety design changes could be made and analyzed without the associated costs and time required for full-sized sled testing. This safety design paradigm was shown to be an effective process for analyzing pregnant occupants in car crashes, but is also applicable for analyses of specific injury, or occupant types such as: eye injuries, orbital fractures, skin injuries, skin burns, severe upper extremity injuries, pregnant occupant injuries, and rear seat occupant injuries.

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Vita

Mary Virginia Jernigan

Ginny Jernigan was born in Baton Rouge, Louisiana on May 16, 1978. She later attended Dr. Phillips High School in Orlando, Florida, where she graduated in 1996, as valedictorian of her 850-member class. While at Dr. Phillips H.S., she was a 12-time varsity letter-winner, 4 years each in volleyball, soccer, and softball. She was also a 7-time captain, earning all-conference and all-county honors in all three sports, as well as all-state honors in volleyball. She was named the FHSAA Florida Female Academic Athlete of the year, and was inducted into the Metro Conference Hall of Fame. She then attended Washington & Lee University, where she was an 8-time varsity letter-winner in soccer and lacrosse. She received a Bachelors of Science degree with a double major in Math and Physics-Engineering in May of 2000, with *Magna Cum Laude* honors. At Virginia Tech, she was admitted to the department of Mechanical Engineering and was awarded fellowships from both the department of mechanical engineering and the center for biomedical engineering. After completing much of her research, she was named a finalist for the Paul E. Torgersen Graduate Student Research Excellence Awards. Remaining at Virginia Tech for her Masters of Science degree in mechanical engineering with a biomedical option, she completed her thesis studying injuries in automobile crashes. She has published articles in engineering and medical journals and conferences. In the summer of 2002, she will enter the industry, working in the safety design group at General Motors. Ginny enjoys playing sports, running, mountain-biking, sailing, camping, hiking and many other outdoor activities.

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