Characteristics of Thoracic Organ Injuries in Frontal Crashes

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(ABSTRACT)

The introduction of airbags has not reduced serious thoracic injury for belted occupants in frontal crashes. Questions have been raised regarding the ability to advance this technology with respect to its effectiveness at protecting belted occupants. This thesis investigated the effectiveness of airbags and the characteristics of residual thoracic organ injury incurred by belted occupants in vehicles equipped with airbags. Belted front seat occupants in frontal collisions from NASS/CDS case years 1993-2007 were analyzed. The use of odds ratios for comparing the effect of airbags on the occurrence of injury has shown that airbags do not significantly increase protection against head and chest injuries. Overall, the lower extremity and the upper extremity were shown to be the most adversely affected by airbags. The face was the only body region that was shown to benefit from the combination of seat belts and airbags as compared to seat belts alone. An investigation into the characteristics and distributions associated with thoracic organ injuries showed the heart and great vessels are the only thoracic organs that showed a significant reduction in the rate of injury with the inclusion of airbags. In vehicles with airbags, the thoracic organs are injured more than the ribs. Also, the average delta-V associated with serious thoracic organ injury was not different with and without an airbag available. The odds of serious injury to the lungs and spleen are higher for occupants in vehicles with airbags as compared to those in vehicles without airbags. Rib fracture is a poor predictor of moderate to fatal thoracic organ injury. Only 31-61% of thoracic organ injuries occur with an associated rib fracture.

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Chapter 1. Current State of Thoracic Protection

1.1 Occupant Protection in Frontal Impacts

Occupant crash protection in frontal impacts is a prime concern for the National Highway Traffic Safety Administration (NHTSA), the automakers, and the driving population. Protection of the head and chest, the most vital body regions, has been a priority. In the past, these body regions have accounted for the majority of fatalities and seriously injured body regions (Malliaris et al 1982; Nahum et al 2002). Safety features, such as seat belts and airbags, have been designed and tuned to protect these and other body regions. Much of the effort devoted to occupant protection has utilized these technologies to couple the occupant to the vehicle and minimize interactions with interior components of the vehicle. Figure 1 shows the overall rate of fatalities based on the number of miles driven is being reduced each year for all occupants, which can at least be partially attributed to the advancement of safety countermeasures in later model vehicles.

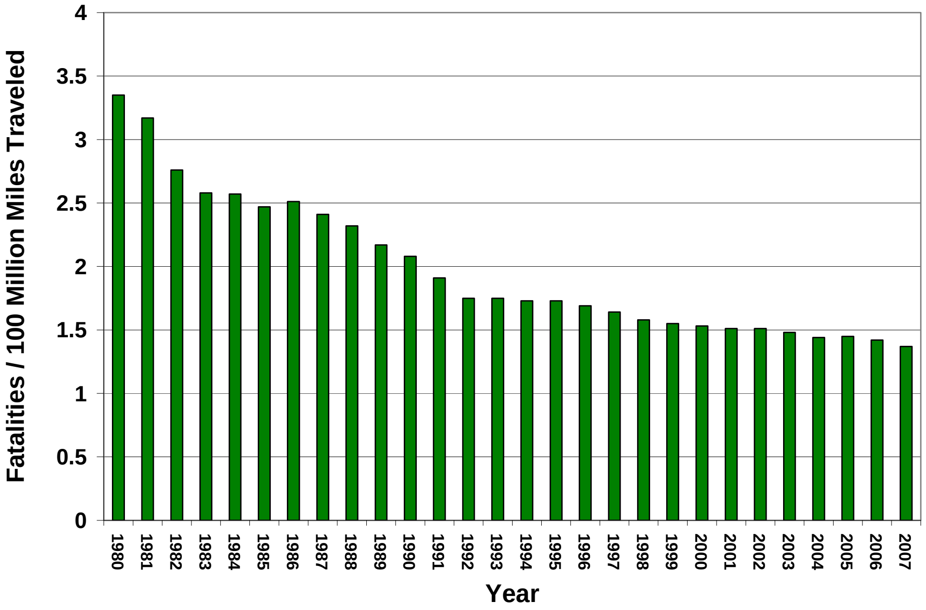

Figure 1. Rate of fatalities for every 100 million miles traveled for all occupants (NHTSA 2007).

1.1.1 Seat Belt Purpose and Effectiveness

By the early 1950s, seat belts were beginning to be included in a small portion of production vehicles in the form of lap belts. Following the creation of The National Highway Traffic Safety Administration (NHTSA) in 1967, one of the original Federal Motor Vehicle Safety Standards (FMVSS) implemented was FMVSS 208, which required lap and shoulder seat belts for all front seat occupants beginning for vehicles produced in or after 1968. Steadily, seat belt usage has increased from 14% in the early 1980's to 82% in 2007 (Kent et al 2003; NHTSA 2007; Nichols et al 2008). Seat belts are widely believed to be a highly effective tool in reducing serious injury and fatalities. NHTSA has estimated that over 210,000 deaths have been prevented from the use of seat belts alone in the United States between 1975-2005 (NHTSA 2005).

The seat belt serves to couple the occupant to the seat and transfer loads to sturdy skeletal structures such as the clavicle (shoulder belt) and the pelvis (lap belt). However, the belts also load the ribs in the event of a crash and can cause injury. As a result, energy management systems (Load Limiters) have become common in many vehicles. Load limiters are devices within the belt system that absorb energy from the crash and limit the axial load that is transferred through the belt. They are often in the form of a torsion bar, housed within the belt retractor and are engineered to limit the axial belt force to a pre-determined load of 2kN – 7kN. Load limiters have been shown to successfully reduce the number and severity of serious rib fractures (Crandall et al 1997; J.Y. Foret-Bruno et al 1998; Kent et al 2001). However, it has also been reported that load limiters may also contribute to a higher head injury risk due to increased occupant excursion (Brumbelow et al 2007).

Pretensioners have also become a common supplement to existing belt technologies and are used in many later model vehicles. Pretensioners are usually pyrotechnic devices that serve to remove slack from the belts and allow the seat belts to tightly couple the occupant to the seat. Pretensioners have been shown to reduce the Head Injury Criteria, 3ms Clip chest acceleration, and chest displacement injury criteria in crash tests, suggesting improved occupant protection. It has also been shown that the use of pretensioners and load limiters in combination can lower these dummy parameters even more than either technology by itself (Walz 2004).

1.1.2 Airbag Purpose and Effectiveness

As a result of low seat belt usage in the 1960's and 1970's, NHTSA set out to increase belt use while concurrently protecting those occupants who did not wear seat belts. NHTSA established two strategies for increasing occupant safety. It was decided it would be necessary to protect occupants with both active (seat belts) and passive restraints. The passive strategy was originally presented as an attempt to protect occupants who were not using active restraints, not necessarily in combination with active restraints. NHTSA first sought to require passive restraints in 1969. Technologies designed to satisfy a passive restraint requirement included both airbags and automatic seat belts. Following the original discussion of passive restraints and the formal announcement that the federal government would begin to peruse these technologies under FMVSS 208, the progression of a passive restraint requirement began to follow a tortuous path of litigation, regulation, and deregulation. In the early 1980's, under the Secretary of Transportation, Elizabeth Dole, the passive restraint requirement had not completed its complicated path, but it had successfully gained traction and by 1987, the phase-in of passive restraints began, with an emphasis on airbags as the preferred technology. In 1991 the Intermodal

Surface Transportation Efficiency Act (ISTEA) was enacted, which required that all passenger cars have frontal airbags for both the driver and right front passenger by model year 1998 and model year 1999 for light trucks and vans. However, the long postponement of a passive restraint requirement, designed to protect unbelted occupants was met by an increase in belt use throughout the general population. This increase was spurred by new mandatory belt use laws (MUL) instated by individual states. The implementation of MULs was given as an alternative to passive restraint requirements by the Federal government. However, the original intent of airbags, to protect those who were not utilizing an active restraint, was becoming less relevant as more occupants wore their seat belts. Ironically, more occupants were wearing their seatbelts as an alternative to passive restraint implementation. Thus, when the eventual passive restraint mandate was enacted, the necessity of such a rule had been diminished, at least with respect to its original intent of protecting unrestrained occupants. As a result, a debate has continued over the necessity and effectiveness of airbags, and is a discussion is particularly important for belted occupants. The belt use in the United States had climbed to roughly 82% in 2007. This has reduced the need for a restraint system that protects unbelted occupants and thus, the necessity of airbags continues to be an area of question (Kent et al 2003; NHTSA 2007)`.

Following many regulations and mandates, the strongest support for airbags was repeatedly shown in the occupant safety literature, noting that the inclusion of frontal airbags reduces the risk of fatalities for both belted and unbelted drivers. In field studies, the greatest reduction in fatality risk has been shown for occupants who are belted and restrained by an airbag (HLDI 1991; Kahane 1994; Lund et al 1994; Werner et al 1994a; Ferguson et al 1995; NHTSA 1996; Segui-Gomez 2000a). NHTSA has estimated that almost 20,000 lives have been saved between the years 1975-2005 because of the presence of airbags, with or without seat belts (NHTSA 2005).

More recent questioning about the effectiveness of airbags has been fueled by a few key issues. Most notably, a series of child and out-of-position (OOP) occupant fatalities were attributed to the deployment of frontal airbags. NHTSA responded by temporarily offering the option of a 30mph sled test, as opposed to a rigid barries 30 mph crash test. This gave the engineers of the airbag systems more time to fully deploy the bag, and thereby an opportunity to reduce the aggressiveness of the airbag. These vehicles with new airbags became known as sled certified vehicles. These depowered airbags were intended to combat the issue of fatalities of smaller occupants and children attributed to airbag deployment. It has sense been found that the inclusion of depowered bags, coupled with increased public awareness has been successful at reducing the number of child and infant fatalities (Ferguson et al 2008). Also, Braver et al (2005; 2008) showed that sled certified vehicles with depowered airbags offered a reduction in the risk of fatality for front seat occupants exposed to purely frontal collisions. The sled option was given as part of a federal mandate, via an updated version of the FMVSS 208.

The threat of serious injuries or fatality to front seat child occupants has also been reduced due to advancements, including occupant sensors that turn off passenger airbags based on occupant weight, passenger airbag switches, as well as public awareness programs that have encouraged parents to seat children in the back seat (Kent et al 2003). The new advances in airbag technology are referred to as “Advanced Airbags”. These are systems capable of detecting the crash severity and the presence of an adult occupant. By monitoring these variables, the force and timing with which the airbag will be deployed can be optimized to provide maximum protection for the given crash situation. Advanced airbags began to be phased in 2003 and are required in all passenger vehicles as of model year 2006 as part of the latest revisions to the FMVSS 208 (NHTSA 2008). However, despite these continued advances in the implementation and design of airbag systems, the debate over the role of frontal airbags in protecting against serious injury to the majority of belted occupants has not been resolved.

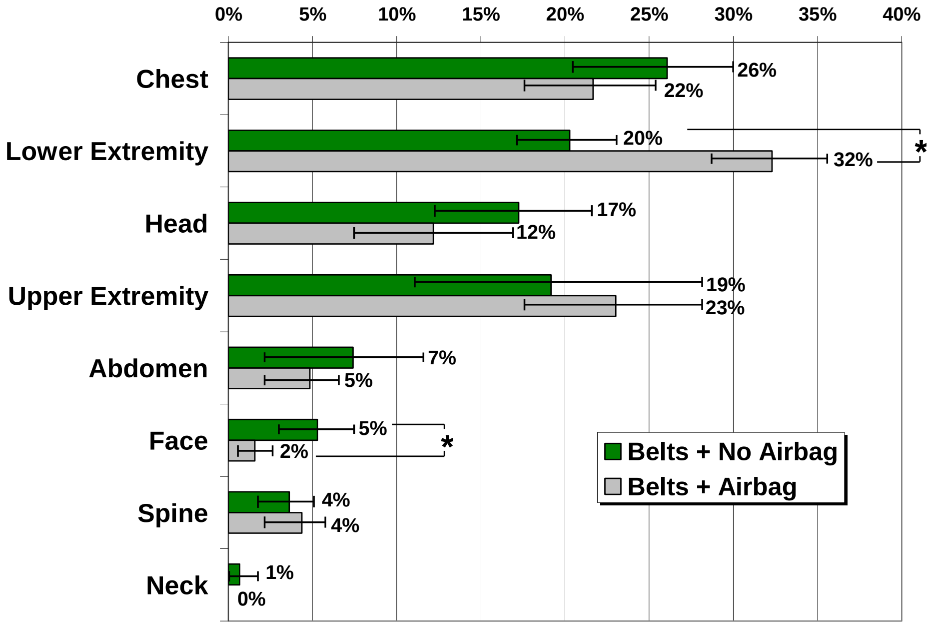

Figure 2. Distribution of MAIS3+ by body region for belted front seat adult occupants in frontal collisions for vehicles with and without frontal airbags (weighted).

The threat of serious injury in frontal crashes still remains an issue, despite the inclusion of many technologies designed to protect occupants in frontal collisions and NHTSA regulations that mandate occupant protection in 30mph crashes. Specifically, as shown in Figure 2, thoracic injuries still account for a large portion of all seriously injured body regions despite the most advanced safety systems that are often designed to help protect the thorax.

1.2 References

Braver, E. R., J. A. Kufera, M. T. Alexander, M. Scerbo, K. Volpini and J. P. Lloyd (2008). "Using head-on collisions to compare risk of driver death by frontal air bag generation: a matched-pair cohort study." Am J Epidemiol 167(5)**:** 546-52.

Braver, E. R., S. Y. Kyrychenko and S. A. Ferguson (2005). "Driver mortality in frontal crashes: comparison of newer and older airbag designs." Traffic Inj Prev 6(1)**:** 24-30.

Brumbelow, M. L., B. C. Baker and J. M. Nolan (2007). Effects of Seat Belt Load Limiters on Driver Fatalities in Frontal Vehicle Crashes of Passenger Cars. Enhanced Safety of Vehicles, Lyon, France.

Crandall, J. R., C. Bass, W. Pilkey, R. Morgan, R. Eppinger, H. Miller and J. Sikorski (1997). "Thoracic Response and Injury with Belt, Driver Side Airbag, and Force Limited Belt Restraint Systems." International Journal of Crashworthiness 2**:** 119-32.

Ferguson, S. A., A. K. Lund and M. A. Greene (1995) "Driver Fatalities in 1985-1994 Air Bag Cars." Insurance Institute For Highway Safety.

Ferguson, S. A. and L. W. Schneider (2008). "An overview of frontal air bag performance with changes in frontal crash-test requirements: findings of the Blue Ribbon Panel for the evaluation of advanced technology air bags." Traffic Inj Prev 9(5)**:** 421-31.

HLDI (1991). Highway loss data: driver injury experience in 1990 models equipped with air bags or automatic belts. Arlington, VA.

J.Y. Foret-Bruno, X. Trosseille, J. Y. L. Coz, F. Bendjellal, C. Steyer, T. Phalempin, D. Villeforceix, P. Dandres and C. Got (1998). Thoracic Injury Risk in Frontal Car Crashes with Occupant Restrained with Belt Load Limiter. Stapp Car Crash Journal, Tempe, AZ, SAE 983166.

Kahane, C. J. (1994). Fatality Reduction by Automatic Occupant Protection in the United States. The 14th International Technical Conference on Enhanced Safety of Vehicles, Munich, Germany.

Kent, R. W., J. R. Crandall, J. Bolton, P. Prasad, G. Nusholtz and H. Mertz (2001). The Influence of Superficial Soft Tissues and Restraint Condition on Thoracic Skeletal Injury Prediction. Stapp Car Crash Journal, San Antonio, TX, SAE 2001-22-0008.

Kent, R. W., C. Strother, J. R. Crandall, H. Mellander and C. Griswold (2003). Air Bag Development and Performance: New Perspectives from Industry, Government and Academia. Warrendale, PA, SAE.

Lund, A. K. and S. A. Ferguson (1994). "Driver Fatalities in 1985-1993 Cars with Airbags." The Journal of Trauma Injury, Infection, and Critical Care 38(4).

Malliaris, A. C., R. Hitchcock and J. Hedlund (1982). A Search for Priorities in Crash Protection. Society of Automotive Engineers 820242.

Nahum, A. M. and A. M. Melvin (2002). Accidental Injury: Biomechanics and Prevention 2nd. New York, Springer-Verlag.

NHTSA (1996) "Third Report to Congress: Effectiveness of Occupant Protection Systems and Their Use." U.S. Department of Transportation.

NHTSA (2005). Traffic Safety Facts 2005 DOT HS 810 631.

NHTSA (2007). Traffic Safety Facts 2007 DOT HS 811034.

NHTSA. (2008). "Advanced Frontal Airbags." from http://www.safercar.gov/portal/site/safercar/menuitem.13dd5c887c7e1358fefe0a2f35a67789/?vgnextoid=7ffae66aeee35110VgnVCM1000002fd17898RCRD#1.

Nichols, J. L. and K. A. Ledingham (2008) "The Impact of Legislation, Enforcement, and Sanctions on Safety Belt Use." National Cooperative Highway Research Program. Transportation Research Board.

Segui-Gomez, M. (2000). "Driver Air Bag Effectiveness by Severity of Crash." American Journal of Public Health 90(10): 1575-81.

Walz, M. (2004). "NCAP test improvements with pretensioners and load limiters." Traffic Inj Prev 5(1): 18-25.

Werner, J. S. and W. W. Sorenson (1994). Survey of Airbag Involved Accidents. An Analysis of Collision Characteristics, System Effectiveness and Injuries. Society of Automotive Engineers 940802.

Chapter 2. Research Approach

2.1 Data Collection

The injury and crash data used in this analysis was compiled from the NHTSA supported National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) database for case years 1993-2007. NASS/CDS is a database of expertly investigated crashes which occurred in the United States. For each case, the database includes crash characteristics, occupant injury information, and crash specific weights that are assigned to each case with respect to their relative representation of all crashes in the United States. The crash statistics presented in this thesis are based on weighted data. All injuries are categorized using the Abbreviated Injury Scale (AIS). AIS ranks injury severity by threat to life using a six-level scale where 0 = no injury and 6=fatal injury (AAAM 1998). All data were compiled using SAS statistical software (SAS, Cary, N.C.). This thesis will utilize a number of approaches to analyze the characteristics of serious thoracic organ injuries in an attempt to shed light on how to better protect all aspects of the thorax.

2.2 Sample Population Comparison

The data for this study was extracted from the NASS/CDS database for case years 1993-2007. The data set was restricted using the following filters:

- Belted occupants in vehicles with or without frontal airbags
- Cars, light trucks, and vans
- Drivers and right front passengers only
- Frontal crashes with a principle direction of force between 11- and 1-o'clock

- Minimum occupant age of 12 years
- Rollover events and ejected occupants were excluded

As of 1998, all passenger vehicles sold in the United States were required to have depowered frontal airbags for increased occupant (NHTSA 1999a). The most common seating position for occupants on U.S. highways is in the driver's seat and the right front passenger locations. These front seat occupants, in more recent model year vehicles, are protected by advanced belt systems and airbags. These countermeasures are designed to protect occupants involved in frontal crashes. The objective of this analysis is to investigate any differences in thoracic injury for those who are belted without an airbag as compared to those with an airbag. Furthermore, portions of this research investigate the effectiveness of frontal airbags. In order to properly assess these technologies, it is important that they be investigated in cases for which they are designed to provide the most protection. Rollover crashes were excluded because frontal airbags are not designed to protect occupants in this crash mode. Similarly, ejected occupants are exposed to complex injurious situations and therefore they also were excluded. The principal direction of force (PDOF) range was chosen to include only collisions where the primary force direction is head on, along the long axis of the vehicle. This is the crash mode in which frontal airbags are designed to provide the most benefit. Also, only 12 year-old occupants and older were included because younger occupants tend to be restrained differently by the belts because of their smaller size or they are in a booster or child seat, thus making the crash environment different than it would be for an older occupant. The distribution of the resulting cases is given in Table 1.

Table 1. The distribution of deployment, occupant gender and age, vehicle delta-V and injury levels are shown for the populations of occupants with and without airbags available used in this thesis. Only belted front seat occupants over the age of 12 from NASS/CDS 1993-2007 are included.

	No Airbag Available			Airbag Available		
	Unweighted	Weighted	%	Unweighted	Weighted	%
No Deployment	9,169	5,032,350	100%	5,132	4,102,152	42%
Deployment	-	-	0%	14,417	5,544,478	58%
Missing	*0*	*0*	*0%*	*20*	*4,897*	*0%*
Total	**9,169**	**5,032,350**	**100%**	**19,569**	**9,651,527**	**100%**
Driver	6,999	3,889,297	77%	16,054	8,030,257	83%
Right Front Passenger	2,170	1,143,053	23%	3,515	1,621,270	17%
Missing	*0*	*0*	*0%*	*0*	*0*	*0%*
Male	5,556	2,989,308	60%	9,868	4,745,469	49%
Female	3,605	2,001,697	40%	9,685	4,896,229	51%
Missing	*8*	*41,345*	*0%*	*16*	*9,827*	*0%*
Detla-V						
<15 kph	967	898,184	18%	3,058	2,031,101	21%
16-30 kph	3,441	1,897,764	38%	7,691	3,727,590	39%
31-45 kph	1,409	361,770	7%	2,451	648,477	7%
>46 kph	683	83,250	2%	1,029	105,658	1%
Missing	*2669*	*1,791,382*	*35%*	*5,340*	*3,138,701*	*32%*
Age						
12-20 yrs	1,985	1,322,835	41%	3,545	2,264,672	35%
21-35 yrs	3,105	1,653,606	51%	6,766	3,220,089	49%
36-50 yrs	2,170	1,150,558	36%	4,799	2,230,179	34%
51-65 yrs	1,071	471,782	15%	2,620	1,169,904	18%
> 66 yrs	838	433,569	13%	1,839	766,683	12%
Missing	*0*	*0*	*0%*	*0*	*0*	*0%*
MAIS2+	1,819	254,361	-	3,551	573,601	-
MAIS3+	862	69,939	-	1,687	141,995	-
Chest AIS3+	356	23,004	24%	548	39,190	22%
Head AIS3+	248	16,993	18%	301	22,019	12%
Lower Extremity AIS3+	332	20,016	21%	840	58,416	32%
Upper Extremity AIS3+	159	18,687	20%	431	41,621	23%
Abdomen AIS3+	92	7,087	7%	145	8,751	5%
Face AIS3+	79	5,287	6%	39	2,849	2%
Spine AIS3+	60	3,114	3%	126	7,893	4%
Neck AIS3+	5	679	1%	3	26	0%
Other AIS3+	1	15	0%	-	-	0%
Unknown AIS3+	5	220	0%	4	75	0%
Total AIS3+	**1,337**	**95,102**	**100%**	**2,437**	**180,840**	**100%**

2.2.1 Statistical Analysis

The NASS/CDS survey design includes stratification and clustering. There are 10 strata in which the cases are placed based on vehicle type, vehicle model year, crash circumstances, and injury type. The clusters are randomly selected police jurisdictions from around the country and within each of these primary sampling units, any crash has equal chance of being selected within the appropriate strata. Weights are applied to each incident based on the information related to the crash type, occupant characteristics, and the strata in which it falls.

Odds ratios are used throughout this thesis to evaluate the effectiveness of airbags from a number of different perspectives. The results are presented in bar-graph form where a point estimate of one represents equal odds with or without the restraint condition of interest. A point estimate of less than one represents an increase in odds of injury with the reference restraint condition, and a point estimate of greater than one represents a decrease in the odds of injury with the reference restraint condition. Instances where the range of the confidence intervals includes a value of one indicate a statistically insignificant relationship. The basic odds ratio formula is given in Equation 1 where p_x is the probability of injury for a given restraint scenario (i.e. x = airbag deployment):

$$OddsRatio = \frac{\left[p_{No\_x} \big/ \left(1 - p_{No\_x}\right) \right]}{\left[p_x \big/ \left(1 - p_x\right) \right]} \qquad \textbf{Equation 1}$$

The odds ratios are computed using a logistic regression model. The SAS statistical software was used to compute the point estimates for the odds ratios and the 95th percentile confidence limits (SAS, Cary, N.C.). Occupant age and delta-V are included as continuous variables and vehicle type (defined as light truck, car, or mini-van) as a categorical variable in the logistic regression model along with the restraint condition in question for the computation of the odds ratio. The restraint conditions that are investigated include: (1) comparing occupants in vehicles with and without frontal airbags available, (2) occupants exposed and not exposed to a deployed frontal airbag, and (3) occupants exposed and not exposed to a deployed, depowered frontal airbag. The stratified and cluster sample design that has been specified by the NASS/CDS database literature was used to compute all point estimates and confidence intervals with the SURVEYLOGISTIC Procedure in SAS. Both the Taylor series linearization and jackknife methods were used to compute variances used in the calculation of the confidence intervals. The jackknife method is known to provide larger confidence intervals as a result of the population variance calculation and as a result, all graphical results presented are given with the confidence limits calculated with the jackknife method due to its conservative nature. The significance of each restraint condition included in the model is given based on the jackknife confidence limits however, all reported significances are in agreement with a chi-square analysis when corrected for the weighted data based on the stratification and clustering. Statistical comparisons made between distributions and means for different airbag implementation conditions were all reported using the same variance calculation methods for a stratified and clustered sample design and a two sample t-test was used for significance reporting.

Many Comparisons will be made between populations with and without airbags. Figure 3 shows that the average age and delta-V for both of these populations is not different for vehicles with and without airbags. The distribution of cars vs. light trucks involved in crashes with no airbags is significantly different than for vehicles with airbags. The distribution by seating position is significantly different when comparing occupants in vehicles with and without airbags. Also, the distribution of occupants by gender is different in vehicles with and without airbags. Figure 3 - Figure 6 show that there is no difference in the cumulative distribution of occupant age, height, or weight, nor is there a difference in the delta-V of the vehicle for either the no airbag or airbag equipped populations.

2.2.2 Airbag Inclusion

The benefits of using the availability of airbags in the discussion of airbag effectiveness are two-fold. First, it is appropriate to assume that the crash severity distribution of both populations is the similar, as is shown in Figure 4. Also, it provides perspective on the regulatory side of airbag implementation. In other words, it is allows for a discussion about the effectiveness of airbag mandates on the major public health issue of crash injury. The major drawback to discussing airbag effectiveness with airbag implementation is the inability to directly apply an association between injury and the presence of an airbag to the actual deployment of an airbag. In fact, as shown in Table 2, 42% of belted front seat occupants with an available airbag are not exposed to a deployment. However, the majority of all injuries and specifically thoracic injuries occur in crashes severe enough to result in airbag deployment. Also, it is important to acknowledge that when comparing vehicles based on the inclusion of airbags, the comparison is also essentially comparing older and newer vehicles. Other improvements in occupant safety, including advances in seat belt design have been simultaneously introduced along with airbags into newer vehicles. This presumably would offer further protection to the occupant separately from the airbag.

Table 2. Distribution of airbag deployment, MAIS3+ injuries, and AIS3+ thoracic injuries for belted front seat occupants with an available airbag.

	Airbag Available	MAIS3+	AIS3+ Thoracic Injury
No Deployment	42%	19%	6%
Deployment	58%	81%	94%

Figure 4 shows that crash severity distribution, as determined by the vehicle delta-V, is essentially the same for occupants in vehicles with and without airbags available. Delta-V is calculated based on the WinSMASH program based on the static crush of the vehicle. WinSMASH is known to underestimate the actual vehicle delta-V by 23% (Niehoff et al 2006). It is assumed in this research that the accuracy issues associated with WinSMASH of both sample populations are offsetting and thus do not greatly influence a crash severity bias toward either of the sample populations.

Table 3. Average age and delta-V and the proportions of occupant gender, occupants in cars vs. light trucks, and occupants in the right front passenger seat for vehicles with and without airbags (weighted). *- indicates a significantly different result.

	No Airbag	Airbag	Significance
Population Size	**4,991,005**	**9,641,699**	*
Age	34.1	35.0	
Delta-V	21.8	20.5	
% Male	59.8	49.2	*
% Car	71.7	81.0	*
% Right Front Passenger	22.7	16.8	*

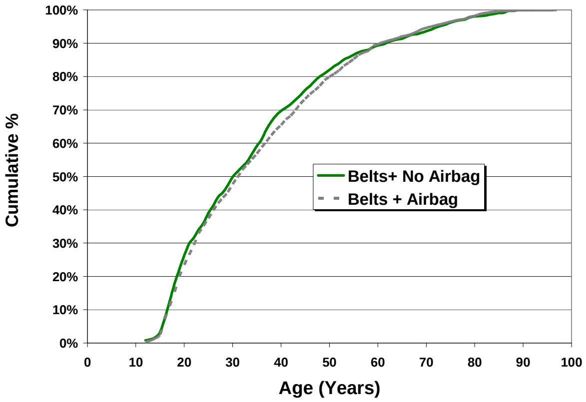

Figure 3.Cumulative percentage distribution of occupant age with and without airbags (weighted).

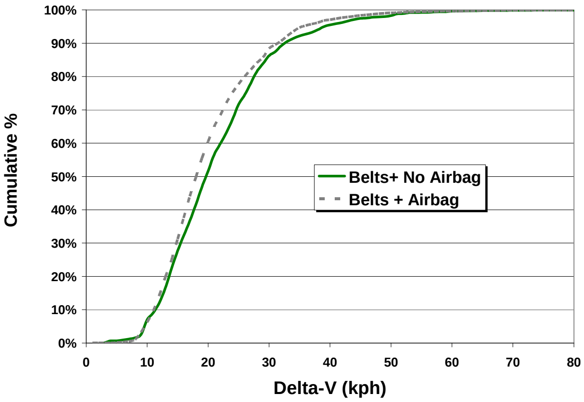

Figure 4.Cumulative percentage distribution of vehicle delta-V with and without airbags (weighted).

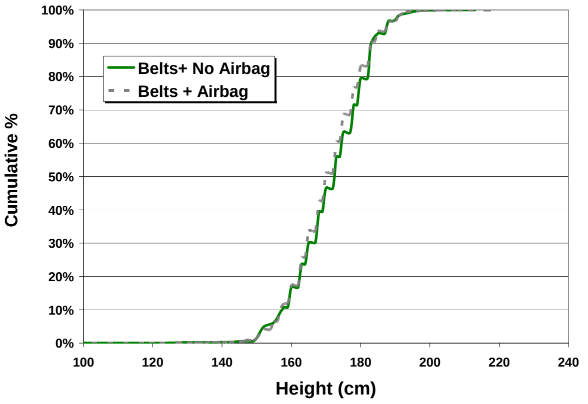

Figure 5.Cumulative percentage distribution of occupant height with and without airbags (weighted).

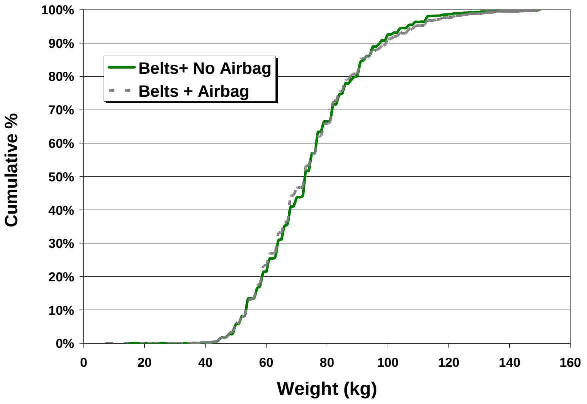

Figure 6.Cumulative percentage distribution of occupant weight with and without airbags (weighted).

2.2.3 Airbag Deployment

Another approach for comparing the effects of airbags is by investigation occupants exposed to airbag deployment as opposed to those not exposed to airbag deployment. The obvious benefit from this perspective is that it offers a more direct comparison of the effects of airbags than is seen when comparing based on the inclusion of airbags. However, as shown in Figure 7, the distribution of crash speeds for occupants in vehicles with a deployed airbag is going to be higher than for occupants who are not exposed to a deployed airbag due to the crash severity threshold required to deploy the airbag. As a result, a significant bias towards injury exists for occupants exposed to a deployed airbag. A method used to account for this bias has been to use a delta-V cutoff speed, which includes only cases over a certain crash speed, usually 15 kph. This is the speed at which airbags are generally supposed to deploy in a rigid barrier type crash. By applying a cut-off, the crash severity distributions of the two populations are essentially similar. However, this method of sectioning the data also eliminates all cases where the airbag deployed in a lower severity crash. In fact Figure 7 shows that 20% of all occupants exposed to a deployed airbag are in vehicles with a delta-V of less than 15kph. Additionally, Segui-Gomez (2000b) showed that there is a significant relationship between airbag deployment in lower severity crashes and the risk of injury. This was shown to be particularly true for females which we reported to not see any protective effects from airbags unless the crash severity is over 27kph. As a result, if all of the lower severity crashes in which an airbag deploys are removed from the study, a large portion the population who are possibly most affected by the deployment of an airbag are not included.

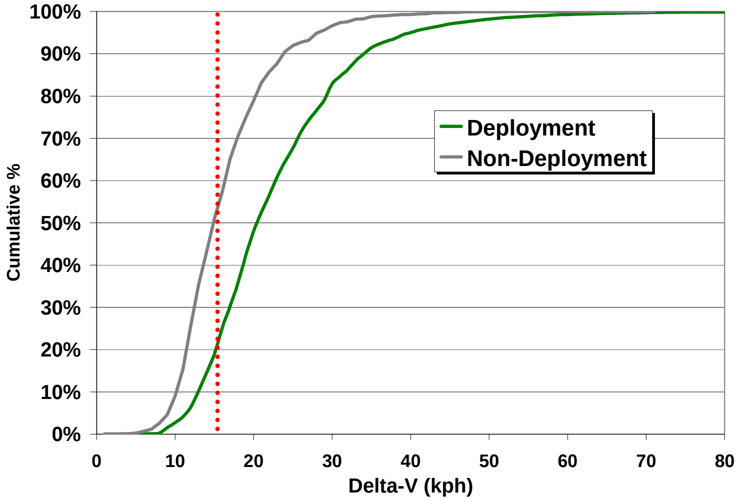

Figure 7.Cumulative percentage distribution of occupant weight with and without airbags (weighted).

2.3 Research Objectives

The question that we wish to answer from this research is why serious injuries to the thorax still occur frequently, despite the implementation of the latest occupant protection technologies designed to prevent thoracic injuries. The effectiveness of seat belts and airbags at protecting occupants will be computed for each body region. Our results will be compared with previous literature on restraint effectiveness to help provide perspective on the remaining serious thoracic injuries, which occur despite the presence of the latest countermeasures. The occupant and crash characteristics that surround serious thoracic injury will be explored. The thoracic organs will be analyzed separately from the ribs in order to note their significance in issues associated with thoracic injury. This will serve to show the manner in which thoracic organ injuries occur with respect to the crash environment, occupant characteristics, and injury type.

Beyond exploring the injury and crash characteristics associated with thoracic injury, the relationship between thoracic organ injury and rib fracture will be analyzed to understand the statistical association between rib fractures and thoracic organ injuries. A discussion will focus on the attention given to rib fracture as the predominant thoracic injury type and thoracic injury predictor in cadaver testing and the subsequent crash test injury metrics derived from them.

These individual research goals should help to better define the injury characteristics associated with serious thoracic injury, specifically thoracic organ injury, in frontal vehicle crashes. A clear perspective and discussion of the persistent issue of serious thoracic injury, the characteristics surrounding these injuries, and the role of rib fractures in all thoracic injuries will be given.

2.4 References

AAAM (1998). Association for the Advancement of Automotive Medicine. The Abbreviated Injury Scale, 1990 Revision, Update 98 (1998).

Niehoff, P. and H. C. Gabler (2006). "The accuracy of WinSmash delta-V estimates: the influence of vehicle type, stiffness, and impact mode." Annu Proc Assoc Adv Automot Med 50**:** 73-89.

Segui-Gomez, M. (2000). "Driver air bag effectiveness by severity of the crash." Am J Public Health 90(10)**:** 1575-81.

Chapter 3 Comparison of Injury for Belted Occupants With and Without Airbags

3.1 Previous Research into Airbag Effectiveness

Previous research has reported that airbags have been effective at reducing the overall number of fatalities for occupants in frontal crashes. Airbags are especially effective for unbelted occupants in frontal collisions (Zador et al 1993; Lund et al 1994; Braver et al 1997). However, with the national seat belt usage rate around 82% (NHTSA 2007), it is the occupants who are restrained by both seat belts and airbags that are of the most concern because they represent the greatest proportion of all front seat occupants on American roads.

Multiple studies have estimated that the combination of seat belts and airbags prevent 4-7% more fatalities than seat belts alone (NHTSA 1984; Viano 1988; Viano 1991; NHTSA 2001). A number of studies have also looked at the relative risk associated with different injury levels and injury types associated with seat belt and airbag use. In an early investigation into airbag effectiveness, Mallairis et al (1982) showed that there is a significant reduction of Maximum AIS (MAIS) levels for MAIS2+ and MAIS5+ levels with the presence of an airbag as compared to no restraint. Also, belts alone were shown to have a significantly improved relative risk for all MAIS injury levels, except MAIS5+ (only a small number of MAIS5+ cases lead to wide confidence intervals), as compared to those with no restraints.

Later, studies began to look at the effectiveness of airbags for reducing injury to belted occupants by focusing on specific body regions. As part of the Intermodal Surface Transportation

Efficiency Act (ISTEA), a series of reports were given to Congress to exhibit the effects that the airbag mandates were having on the driving population. In the first report to Congress, based on NASS/CDS data from 1988-1996, NHTSA reported there was a significant increase in protection for the head for belted occupants with the presence of an airbag as opposed to those with only seat belts for both AIS2+ (moderate and greater) and AIS3+ (serious and greater) injury levels. There was also an increase in effectiveness for protecting the thorax with an airbag and seat belts as compared to seat belts only for the AIS2+ levels, but not for the AIS3+ injury levels. The presence of an airbag showed a decrease in effectiveness for both injury levels with respect to the upper extremity. Notably, the effectiveness for protecting against AIS3+ upper extremity injury for seat belts was reduced from 58% to 20% with the inclusion of airbags. The lower extremity had a lower risk of AIS2+ injury with airbags, but a higher risk for AIS3+ injury levels (NHTSA 1999b). Later, NHTSA followed up with their efforts in their fifth and sixth reports to Congress in 2001 and presented that there was no significant reduction for all AIS2+ or AIS3+ injury occurrence rates for those protected by both airbags and seat belts as compared to those who were restrained only by belts when considering all body regions combined. This was once again based on a NASS/CDS study, this time conducted for case years 1988-1997. The head, however, showed an increase in protection at both injury levels with the inclusion of an airbag. Also, the newer report suggested that airbags actually reduced the effectiveness of protecting the chest for AIS3+ injuries, but still showed increased effectiveness for AIS2+ chest injuries, although this result was not shown to be significant (NHTSA 2001).

A NASS/CDS study for case years 1995-2000 by McGwin et al (2003) investigated the relative risk of AIS2+ injuries for airbags and seat belts vs. seat belts only. The relative risk values were corrected for confounding factors including gender, seat track position, occupant location, delta-V, age, and vehicle curb weight. The results showed no significant increase in effectiveness for head or chest protection with the presence of an airbag. It was noted that the data suggested a relationship between airbag deployment and injury to these body regions would be a beneficial one; however, the injurious data sample size may not have been sufficient to provide significant results. The data did not show a significant increase in effectiveness for the upper extremity with the presence of an airbag either. It was suggested that airbags may be associated with a decrease in effectiveness for protecting against lower extremity injuries; however this result was not significant. Overall, the data suggests that airbag deployment in conjunction with a belted occupant does not provide an increased protection against AIS2+ injuries, although none of the results showed significance.

Each of these studies showed that injuries to the different body regions, with the possible exception of head injuries, are not necessarily reduced with the presence or deployment of airbags for belted occupants. However, a few points need to be stressed so this is not interpreted as a call for the removal of airbags. First, and most importantly, there is still evidence cited here that shows the inclusion of airbags, with the use of seat belts, is still the most effective combination of restraints for reducing the fatality risk of front seat occupants in frontal collisions. It should also be noted that airbags were originally designed to protect unbelted occupants, and they have been shown to reduce both injuries and fatalities for occupants in this group, which still account for roughly 18% of the driving population (Kent et al 2003; NHTSA 2007). Also, much of the data may make suggestions as to the benefits or, conversely, the adverse effects of airbags, but due to a lack of injurious cases, there is a lack of significance.

Beyond these issues, it is important to note that these studies only include a small number of cases with depowered or advanced airbags, both of which may have far-reaching effects on the effectiveness of airbags with respect to moderate and serious injuries. Depowered airbags were required in 1998 and advanced airbags began to be phased in 2003 per regulation.

This study will serve to offer a comprehensive perspective on the protections associated with airbags for all body regions. The results will provide further insight and help clear up conflicting reports from the previously mentioned research by including a larger sample population and by combining investigations concerning different injury thresholds, airbag implementation effects, airbag deployment effects, and the influence of depowered airbags. The novelty of this report exists in its ability to combine all of the injurious cases from the most recent data available along with its comparison of belted only occupants to belted occupants in differing airbag exposure environments and its consideration of two different injury thresholds.

Objective

The objective is to estimate the effectiveness of airbags in reducing moderate and serious injuries for belted occupants exposed to frontal crashes. The study will be limited to adults in the front row seating positions.

3.2 Methods

The research presented here is based on the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) based study. Case years 1993-2007 will be analyzed in this investigation. Thus, this analysis will include a large number of cases that will be largely affected by any effects from the depowering of airbags or the inclusion of advanced airbags. All results pertaining to depowered airbag effects do not include vehicles with advanced airbags; all other results include advanced airbags.

The results are presented in bar-graph form where a point estimate of one represents equal odds with or without the restraint condition of interest. A point estimate of less than one represents an increase in odds of injury with the reference restraint condition, and a point estimate of greater than one represents a decrease in the odds of injury with the reference restraint condition. Instances where the range of the confidence intervals includes a value of one indicate a statistically insignificant relationship. The basic odds ratio formula is given where p_x is the probability of injury for a given restraint scenario (i.e. x = airbag deployment):

$$OddsRatio = \frac{\left[p_{No\_x} \big/ \left(1 - p_{No\_x}\right) \right]}{\left[p_x \big/ \left(1 - p_x\right) \right]} \qquad \textbf{Equation 2}$$

The odds ratios are computed using a logistic regression model. The SAS statistical software was used to compute the point estimates for the odds ratios and the 95th percentile confidence limits (SAS, Cary, N.C.). Occupant age and delta-V are included as continuous variables and vehicle type (defined as light truck, car, or mini-van) as a categorical variable in the logistic regression model along with the restraint condition in question for the computation of the odds ratio. The restraint conditions that are investigated include comparing occupants in vehicles with and without frontal airbags available, occupants exposed and not exposed to a deployed frontal airbag, and occupants exposed and not exposed to a deployed, depowered frontal airbag. The stratified and cluster sample design that has been specified by the NASS/CDS database literature was used to compute all point estimates and confidence intervals with the SURVEYLOGISTIC Procedure in SAS. Both the Taylor series linearization and jackknife methods were used to compute variances used in the calculation of the confidence intervals. All graphical results presented are given with the confidence limits calculated with the jackknife method due to its conservative nature. The significance of each restraint condition included in the model is given based on the jackknife confidence limits however, all reported significances are in agreement with a chi-square analysis when corrected for the weighted data based on the stratification and clustering.

3.3 Results

It is apparent that the distribution of occupants with a maximum AIS (MAIS) value to any body region for the MAIS2+ and MAIS3+ thresholds has not significantly changed with newer vehicles as shown in Figure 8.

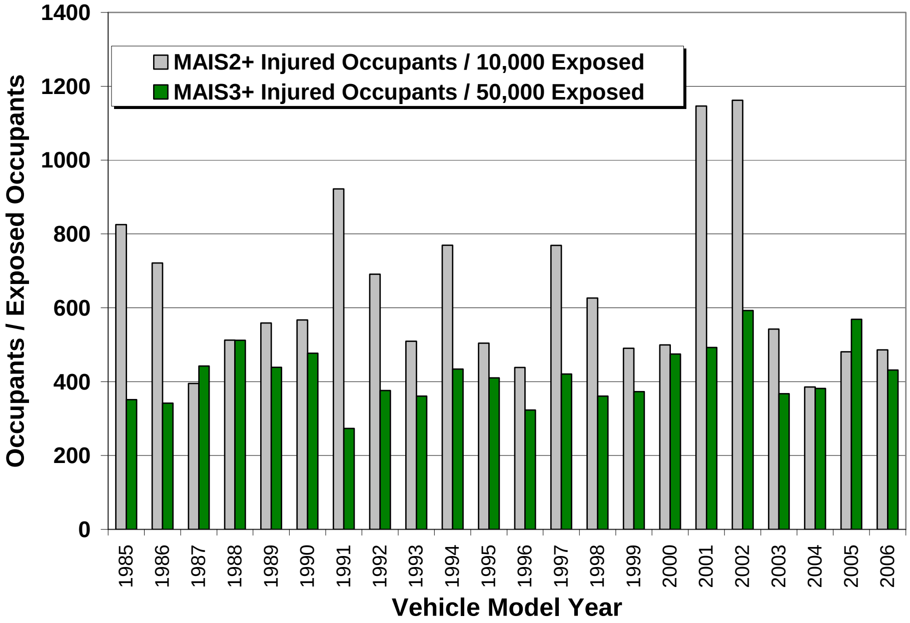

Figure 8. Distribution of MAIS2+ and MASI3+ injured occupants by vehicle model year when belted.

The distributions in Table 4 and Table 5 show the number of injuries for each body region based on the restraint types available with weights applied. These tables include only cases with a given delta-V and occupant age for use in the logistic regression model. The subsequent odds ratios are based on this data.

Table 4. Number of AIS2+ injuries by body region for belted front seat occupants with and without the presence of an airbag.

	Seat Belts Only		Seat Belts & Airbags	
	Un-weighted	**Weighted**	**Un-weighted**	**Weighted**
Head	314	26,033	425	52,815
Chest	338	32,885	491	49,864
Lower Extremity	434	49,175	1,227	199,526
Upper Extremity	303	43,537	764	106,793
Abdomen	122	5,759	192	14,567
Face	179	13,595	80	11,294
Spine	96	6,243	213	23,015
Exposure	5,271	2,662,390	12,562	5,774,866

Table 5. Number of AIS3+ injuries by body region for belted front seat occupants with and without the presence of an airbag.

	Seat Belts Only		Seat Belts & Airbags	
	Un-weighted	**Weighted**	**Un-**	**Weighted**
Head	139	10,056	136	15,045
Chest	211	12,864	308	21,269
Lower Extremity	182	10,085	489	33,953
Upper Extremity	90	7,302	283	29,838
Abdomen	48	1,623	75	5,421
Face	45	3,398	14	991
Spine	33	1,627	66	3,283
Exposure	5,271	2,662,390	12,562	5,774,866

3.3.1 Serious Injury for Occupants with Airbag Availability

The results for belted occupants in vehicles where airbags are available are given in Figure 9 - Figure 11. For all belted front seat occupants, the only body region that showed a reduction in serious injury risk, was the face. The lower extremity was the only body region that showed an increase in risk with at least 4.6x higher odds of injury with the presence of an airbag. There is no significant difference between the available restraints for protecting against serious injury to the head, chest, upper extremity, abdomen, or the spine. These results hold true when considering the driver as well. Interestingly, the results are different for the right front passenger. For this seating position, the upper extremity has 1.7-9.7x higher odds of injury with the inclusion of airbags. The airbag is not significantly more effective at protecting the abdomen, lower extremity, spine, face, chest, or the head from serious injury for the right front passenger.

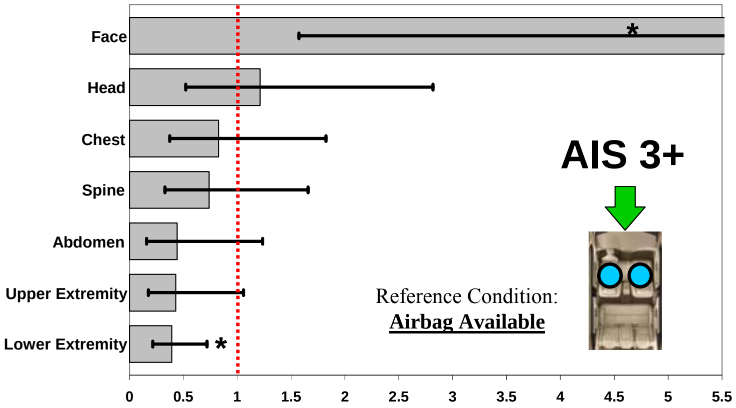

Figure 9. Odds ratios comparing the odds of AIS3+ injuries for belted front seat occupants in vehicles with airbags and vehicles without airbags (weighted).

Table 6. Odds ratio of AIS3+ injuries for front seat occupants in vehicles with airbags and vehicles without airbags and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.395**	0.217	0.720	*	0.230	0.677	*
Spine	**0.739**	0.330	1.658		0.353	1.545	
Upper Extremity	**0.431**	0.175	1.059		0.194	0.954	*
Chest	**0.828**	0.375	1.825		0.437	1.565	
Head	**1.213**	0.522	2.817		0.568	2.589	
Abdomen	**0.444**	0.159	1.238		0.173	1.141	
Face	**6.160**	1.574	24.107	*	1.831	20.732	*

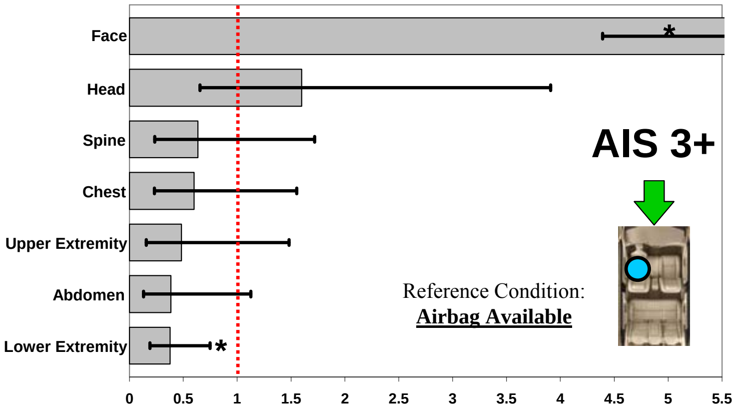

Figure 10. Odds ratios comparing the odds of AIS3+ injuries for belted drivers in vehicles with airbags and vehicles without airbags (weighted).

Table 7. Odds ratio of AIS3+ injuries for drivers in vehicles with airbags and vehicles without airbags and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.378**	0.191	0.749	*	0.206	0.698	*
Spine	**0.636**	0.235	1.720		0.262	1.544	
Upper Extremity	**0.483**	0.157	1.482		0.185	1.256	
Chest	**0.600**	0.232	1.553		0.286	1.260	
Head	**1.600**	0.655	3.909		0.729	3.511	
Abdomen	**0.384**	0.131	1.127		0.141	1.049	
Face	**17.213**	4.391	67.481	*	4.924	60.168	*

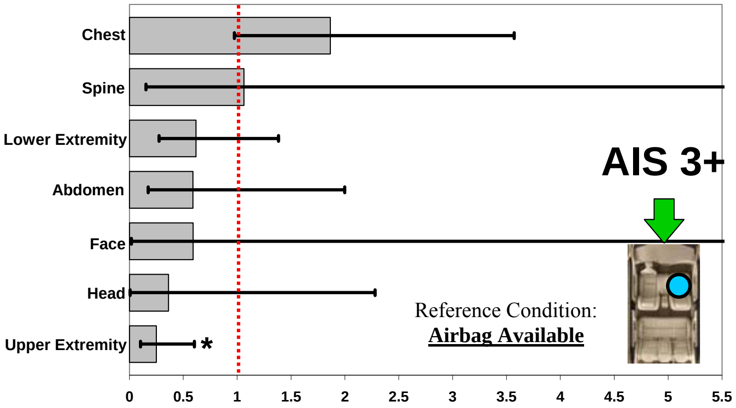

Figure 11. Odds ratios comparing the odds of AIS3+ injuries for belted right front passengers in vehicles with airbags and vehicles without airbags (weighted).

Table 8. Odds ratio of AIS3+ injuries for right front passengers in vehicles with airbags and vehicles without airbags and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.618**	0.276	1.384		0.290	1.316	
Spine	**1.063**	0.153	7.38		0.254	4.456	
Upper Extremity	**0.249**	0.103	0.602	*	0.111	0.561	*
Chest	**1.865**	0.974	3.571		1.007	3.456	*
Head	**0.363**	0.006	2.28		0.059	2.234	
Abdomen	**0.590**	0.174	1.998		0.196	1.775	
Face	**0.591**	0.019	18.567		0.072	4.836	

3.3.2 Serious Injury for Occupants with Airbag Deployment

The results for belted occupants exposed to airbag deployment are given in Figure 12 - Figure 14. For a combined analysis of both front seat positions, there is no significant reduction in odds of serious injury for any of the body regions when exposed to an airbag deployment. There are higher odds of injury for the abdomen (1.1-6.9x), lower extremity (1.6-5.0x), and upper extremity (1.7-7.4x). For the driver's seating position, these results are similar, with exceptions for the chest, which has higher odds of injury (1.02-5.8x), and the face, which has at least 3.6x lower odds of injury with airbag deployment. For the right front passenger, the only body region with a significant result was upper extremity. The upper extremity shows 2.2-16.7x higher odds of serious injury with a deployed airbag.

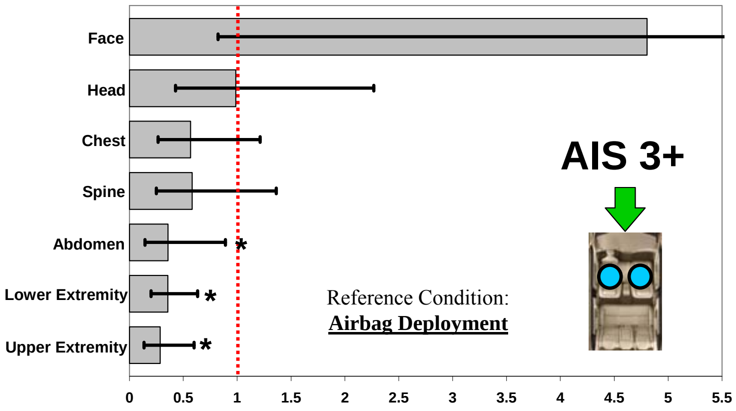

Figure 12. Odds ratios comparing the odds of AIS3+ injuries for belted front seat occupants in vehicles with airbag deployment and vehicles without airbag deployment (weighted).

Table 9. Odds ratio of AIS3+ for front seat occupants exposed to airbag deployment and those without airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.357**	0.201	0.632	*	0.211	0.602	*
Spine	**0.583**	0.249	1.363		0.266	1.276	
Upper Extremity	**0.285**	0.135	0.600	*	0.144	0.562	*
Chest	**0.567**	0.265	1.214		0.301	1.069	
Head	**0.987**	0.429	2.269		0.476	2.047	
Abdomen	**0.358**	0.144	0.891	*	0.156	0.824	*
Face	**4.805**	0.823	28.070		1.036	22.296	*

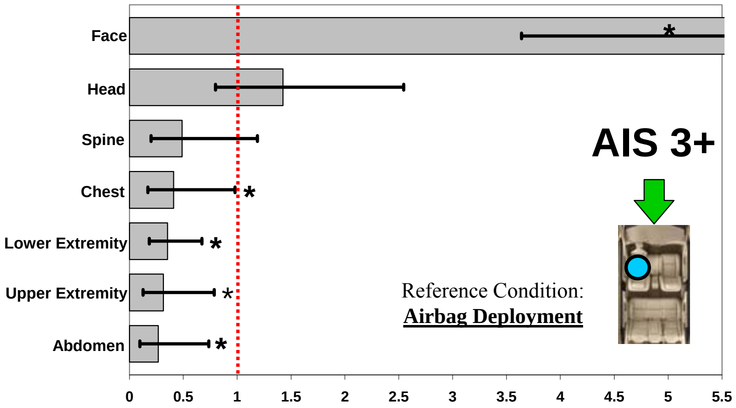

Figure 13. Odds ratios comparing the odds of AIS3+ injuries for belted drivers in vehicles with airbag deployment and vehicles without airbag deployment (weighted)

Table 10. Odds ratio of AIS3+ injuries for drivers exposed to airbag deployment and those without airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

		Jackknife			Taylor Linearization		
Body Region	**Odds Ratio**	Lower	Upper		Lower	Upper	
Lower Extremity	**0.353**	0.186	0.672	*	0.198	0.632	*
Spine	**0.488**	0.200	1.188		0.215	1.106	
Upper Extremity	**0.316**	0.127	0.787	*	0.141	0.706	*
Chest	**0.410**	0.172	0.979	*	0.204	0.827	*
Head	**1.426**	0.799	2.546		0.832	2.446	
Abdomen	**0.268**	0.098	0.736	*	0.104	0.689	*
Face	**20.582**	3.640	116.390	*	4.064	104.229	*

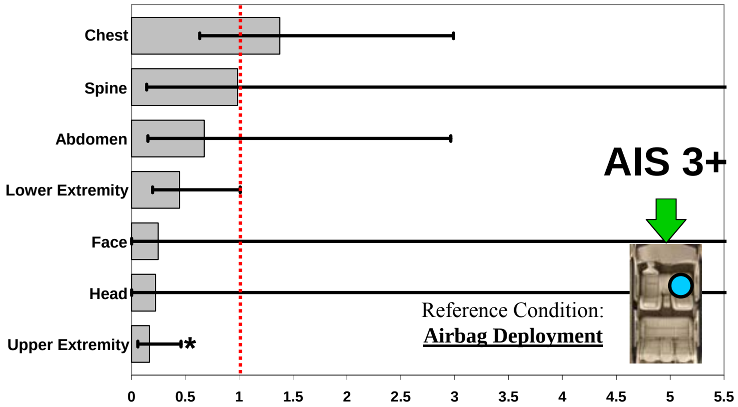

Figure 14. Odds ratios comparing the odds of AIS3+ injuries for belted right front passengers in vehicles with airbag deployment and vehicles without airbag deployment (weighted)

Table 11. Odds ratio for AIS3+ for right front passengers exposed to airbag deployment and those without airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

		Jackknife			Taylor Linearization		
Body Region	**Odds Ratio**	Lower	Upper		Lower	Upper	
Lower Extremity	**0.446**	0.197	1.010		0.210	0.948	*
Spine	**0.984**	0.141	6.875		0.209	4.635	
Upper Extremity	**0.166**	0.060	0.461	*	0.065	0.426	*
Chest	**1.378**	0.635	2.990		0.666	2.852	
Head	**0.223**	0.002	19.930		0.033	1.505	
Abdomen	**0.677**	0.154	2.965		0.186	2.464	
Face	**0.248**	0.003	18.388		0.021	2.989	

3.3.3 Moderate Injury for Occupants with Airbag Availability

Similar results were shown for moderate and greater (AIS2+) injuries as shown in Figure 15-Figure 17, when compared to AIS3+ injuries. For all belted front seat occupants, no body region showed a reduction in odds of AIS2+ injury. The lower extremity (1.03-5.0x) and the spine (1.4-4.4x) both show significant increases in injury risk. For belted drivers only, there is 2.5-9.9x less risk of an AIS2+ face injury for those who have airbags available. There is no significant difference for the head, thorax, abdomen, or lower extremity with the presence of an airbag for a belted driver. The upper extremity (1.2-3.5x) and spine (1.4-8.0x) are more susceptible to moderate injury for drivers when an airbag is available. For the right front passenger, the results are slightly different. None of the body regions are protected significantly better with the presence of an airbag as shown in Figure 17. The lower extremity is the only body region that has a significantly higher (1.7-13.0x) risk of AIS2+ injury.

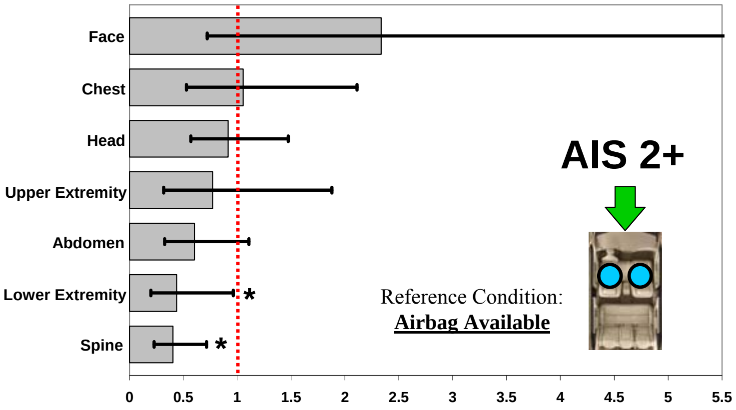

Figure 15. Odds ratios comparing the odds of AIS2+ injuries for belted front seat occupants in vehicles with airbags and vehicles without airbags (weighted).

Table 12. Odds ratio of AIS2+ injuries for front seat occupants in vehicles with airbags and vehicles without airbags and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.438**	0.199	0.963	*	0.214	0.897	*
Spine	**0.405**	0.229	0.715	*	0.237	0.692	*
Upper Extremity	**0.773**	0.318	1.880		0.358	1.669	
Chest	**1.056**	0.528	2.113		0.588	1.898	
Head	**0.917**	0.570	1.474		0.583	1.441	
Abdomen	**0.602**	0.327	1.109		0.340	1.065	
Face	**2.336**	0.722	7.561		0.910	5.997	

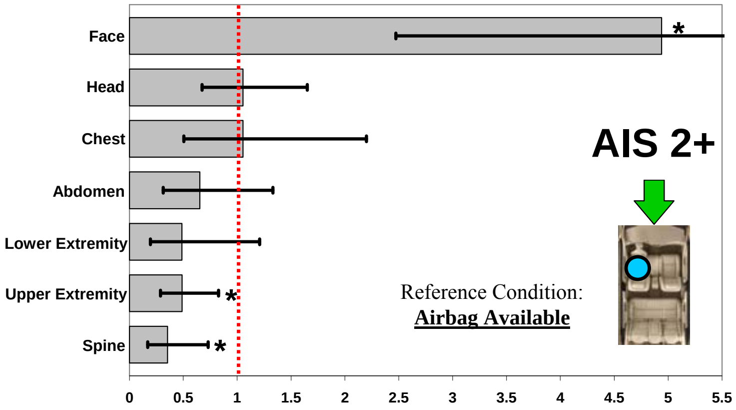

Figure 16. Odds ratios comparing the odds of AIS2+ injuries for belted drivers in vehicles with airbags and vehicles without airbags (weighted).

Table 13. Odds ratio of AIS2+ injuries for drivers in vehicles with airbags and vehicles without airbags and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.487**	0.196	1.209		0.215	1.105	
Spine	**0.353**	0.170	0.732	*	0.181	0.691	*
Upper Extremity	**0.488**	0.288	0.828	*	0.294	0.809	*
Chest	**1.055**	0.505	2.201		0.571	1.947	
Head	**1.055**	0.674	1.651		0.690	1.614	
Abdomen	**0.654**	0.313	1.332		0.332	1.253	
Face	**4.940**	2.473	9.868	*	2.617	9.326	*

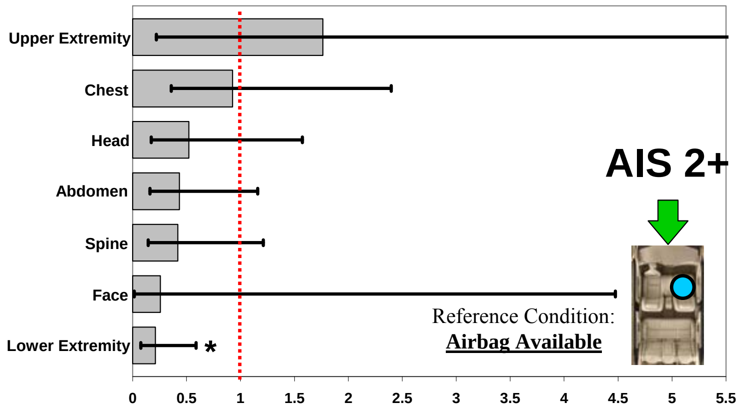

Figure 17. Odds ratios comparing the odds of AIS2+ injuries for belted right front passengers in vehicles with airbags and vehicles without airbags (weighted)

Table 14. Odds ratio of AIS2+ injuries for right front passengers in vehicles with airbags and vehicles without airbags and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.212**	0.077	0.589	*	0.090	0.499	*
Spine	**0.419**	0.145	1.211		0.165	1.066	
Upper Extremity	**1.764**	0.220	14.153		0.440	7.068	
Chest	**0.927**	0.358	2.397		0.392	2.188	
Head	**0.521**	0.173	1.573		0.194	1.401	
Abdomen	**0.434**	0.162	1.160		0.182	1.034	
Face	**0.257**	0.015	4.475		0.042	1.567	

3.3.4 Moderate Injury for Occupants with Airbag Deployment

For belted front seat occupants exposed to an airbag deployment, there are significantly higher odds of moderate or greater injuries to the spine (1.2-3.2x) and abdomen (1.2-4.2x) as compared to those who are not exposed to an airbag deployment as shown in Figure 18. No body region has lower odds of injury in the event of an airbag deployment. Figure 19 shows that the driver has significantly greater odds of injury with airbag deployment for the upper extremity (2.0-5.3x), along with the spine (1.1-4.0x), and abdomen (1.1-4.2x); however, the face (1.9-8.0x) has significantly lower odds. For right front passengers, the deployment of an airbag contributes to significantly higher odds of injury to the head (2.6-11.2x) and lower extremity (2.6-24.4x). No body region has lower odds of injury in this seat position as shown in Figure 20.

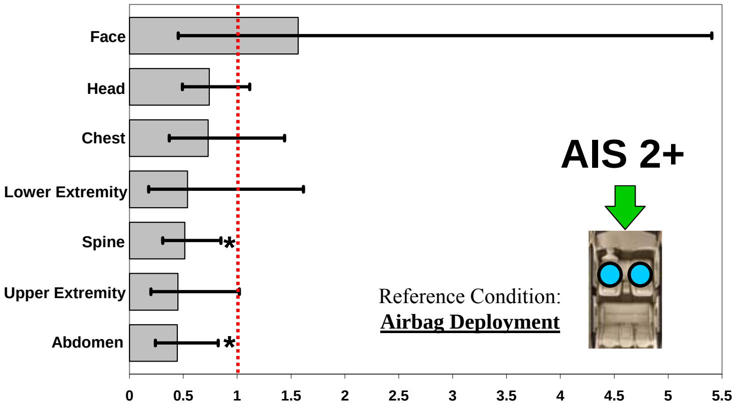

Figure 18. Odds ratios comparing the odds of AIS2+ injuries for belted front seat occupants in vehicles with airbag deployment and vehicles without airbag deployment (weighted).

Table 15. Odds ratio for AIS2+ for front seat occupants exposed to airbag deployment and those without airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.538**	0.179	1.616		0.220	1.317	
Spine	**0.513**	0.310	0.849	*	0.318	0.826	*
Upper Extremity	**0.450**	0.199	1.020		0.218	0.930	*
Chest	**0.730**	0.370	1.440		0.412	1.294	
Head	**0.741**	0.492	1.117		0.500	1.098	
Abdomen	**0.445**	0.240	0.824	*	0.249	0.793	*
Face	**1.567**	0.454	5.406		0.591	4.157	

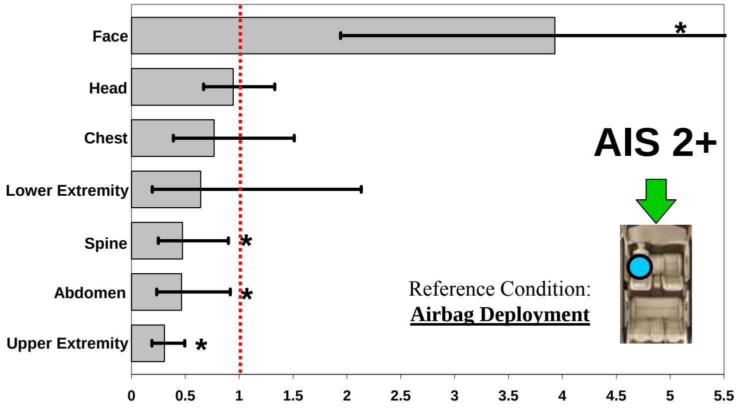

Figure 19. Odds ratios comparing the odds of AIS2+ injuries for belted drivers in vehicles with airbag deployment and vehicles without airbag deployment (weighted).

Table 16. Odds ratio for AIS2+ for drivers exposed to airbag deployment and those without airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.644**	0.194	2.133		0.246	1.684	
Spine	**0.475**	0.250	0.900	*	0.262	0.861	*
Upper Extremity	**0.306**	0.190	0.495	*	0.193	0.487	*
Chest	**0.768**	0.390	1.512		0.437	1.349	
Head	**0.944**	0.670	1.330		0.680	1.312	
Abdomen	**0.465**	0.236	0.918	*	0.248	0.873	*
Face	**3.931**	1.941	7.962		2.049	7.545	

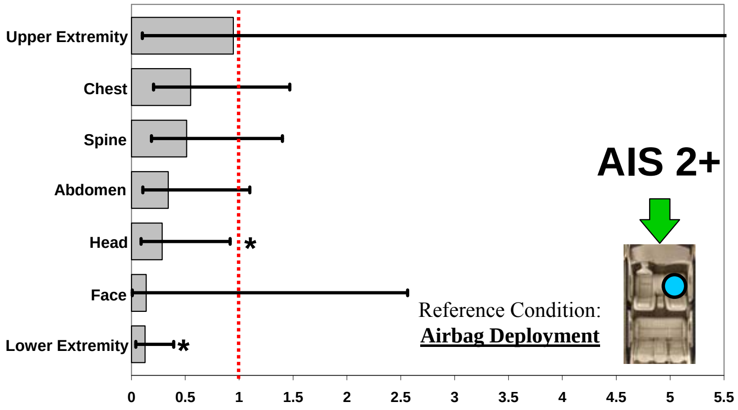

Figure 20. Odds ratios comparing the odds of AIS2+ injuries for belted right front passengers in vehicles with airbag deployment and vehicles without airbag deployment (weighted)

Table 17. Odds ratio for AIS2+ for right front passengers exposed to airbag deployment and those without airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

Body Region	Odds Ratio	Jackknife			Taylor Linearization		
		Lower	Upper		Lower	Upper	
Lower Extremity	**0.127**	0.041	0.392	*	0.049	0.326	*
Spine	**0.512**	0.187	1.402		0.216	1.213	
Upper Extremity	**0.946**	0.101	8.842		0.203	4.410	
Chest	**0.550**	0.206	1.469		0.230	1.314	
Head	**0.286**	0.089	0.917	*	0.101	0.808	*
Abdomen	**0.342**	0.106	1.099		0.127	0.923	*
Face	**0.137**	0.007	2.564		0.022	0.864	*

3.3.5 Serious and Moderate Injury for Occupants with Depowered Airbags

The results shown in Figure 21 and Figure 22 show the injury odds ratios for those who are exposed to first generation airbag deployment vs. those exposed to depowered airbag deployment. None of the body regions show a significant reduction in odds based on the presence of a depowered airbag for the AIS3+ or AIS2+ injury thresholds. The lower extremity (1.03-2.7x), spine (1.6-7.0x), and chest (1.1-4.1x) all had higher odds an of AIS2+ injury with a depowered airbag.

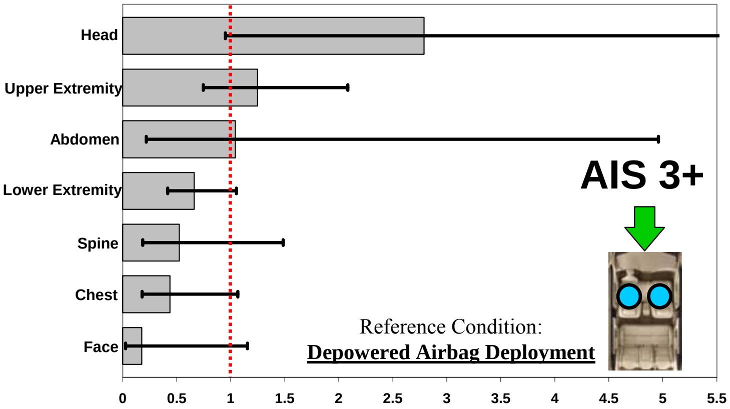

Figure 21. Odds ratios comparing the odds of AIS3+ injuries for belted front seat occupants in vehicles with first generation airbag deployment vs. those in vehicles with depowered airbag deployment (weighted).

Table 18. Odds ratio for AIS3+ for front seat occupants exposed to first generation airbag deployment and those exposed to depowered airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

		Jackknife			Taylor Linearization		
Body Region	**Odds Ratio**	Lower	Upper		Lower	Upper	
Lower Extremity	**0.662**	0.417	1.053		0.426	1.030	
Spine	**0.524**	0.185	1.486		0.208	1.319	
Upper Extremity	**1.248**	0.747	2.084		0.769	2.026	
Chest	**0.438**	0.180	1.066		0.197	0.971	*
Head	**2.789**	0.951	8.183		1.105	7.040	*
Abdomen	**1.042**	0.219	4.960		0.293	3.704	
Face	**0.176**	0.027	1.155		0.038	0.808	*

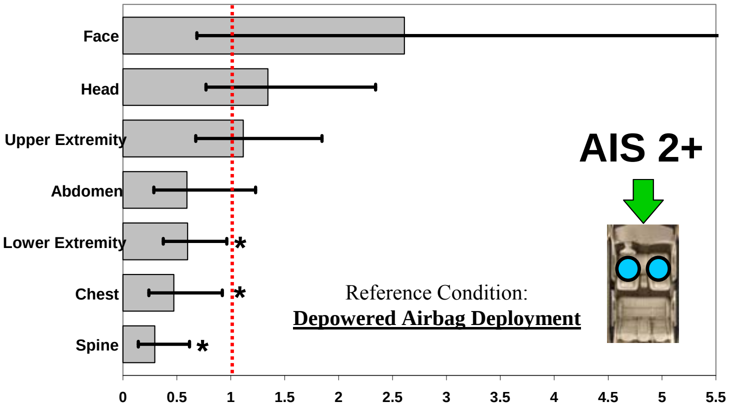

Figure 22. Odds ratios comparing the odds of AIS2+ injuries for belted front seat occupants in vehicles with first generation airbag deployment vs. those in vehicles with depowered airbag deployment (weighted).

Table 19. Odds ratio for AIS3+ for front seat occupants exposed to first generation airbag deployment and those exposed to depowered airbag deployment and confidence limits from the Jackknife and Taylor series linearization variance calculation methods (weighted).

		Jackknife			Taylor Linearization		
Body Region	**Odds Ratio**	Lower	Upper		Lower	Upper	
Lower Extremity	0.600	0.373	0.963	*	0.373	0.963	*
Spine	0.296	0.142	0.617	*	0.027	0.387	*
Upper Extremity	1.116	0.675	1.846		0.388	3.328	
Chest	0.472	0.241	0.922	*	0.272	0.888	*
Head	1.344	0.770	2.344		1.205	15.264	*
Abdomen	0.594	0.287	1.230		0.096	1.456	
Face	2.610	0.685	9.946		1.088	35.563	*

3.4 Discussion

Much of the research presented here reaffirms what has been shown previously by other studies. Like the previous studies, it has been shown that certain body regions, in particular the face, benefit from the protection of an airbag more than others. The results regarding the odds of injury with respect to the presence of a frontal airbag will provide perspective on the public benefit of frontal airbags. Specifically, what effect has the Federal government's requirement of frontal airbags had on reducing injuries? The investigation into the effect of airbag deployment is meant to include cases where there may be more of a direct relationship between injury and the deployment of the airbag. However, detailed conclusions of the nature of this relationship is beyond the scope of this research.

3.4.1 Airbag Mandate Effectiveness

Many of the previously reviewed studies investigated the effectiveness of airbags by investigating the effect of airbag deployment on injury prevention. However, it is also prudent to note any advances that have been made through regulation and policy making. From this analysis, it has been shown that the implementation of airbags has reduced the odds of AIS3+ facial injuries for all front seat occupants. Also, AIS2+ facial injuries have been reduced for the driver. On the other hand, airbags greatly increase the odds of AIS2+ and AIS3+ injury for the lower extremity and upper extremity. Airbags increased the odds of AIS2+ spinal injuries for occupants in the driver's seat. The other body regions generally showed no significant difference in the odds of injury.

3.4.2 Airbag Deployment Effectiveness

The deployment of an airbag for occupants in the front seat creates 1.1-6.9x greater odds of AIS3+ injury and 1.2-4.2x greater odds of AIS2+ injury to the abdomen. The upper (1.7-7.4x) and lower extremities (1.6-5.0x) have greater odds for the AIS3+ injury threshold. The spine has 1.1-3.2x greater odds for the AIS2+ threshold when an airbag deploys. For drivers, there is significantly greater chance of AIS3+ injury to the chest (1.02-5.8x), lower extremity (1.5-5.4x), upper extremity (1.3-7.9x), and abdomen (1.4-10.2x) when the airbag deploys. The face has at least 3.6x lower odds of injury when an airbag deploys for occupants in the driver's seat.

3.4.3 Body Region Analysis

Head Injury

Early studies suggested improved head protection. However, these studies were often based on small sample sizes because they were conducted at a time when airbags were just becoming commonplace (Werner et al 1994a; Dalmotas et al 1995). The NHTSA reports to Congress also suggested that the head had statistically significantly lower odds of serious and moderate injury when the occupant was belted and an airbag was available. However, the results of the NHTSA reports for belted occupants with airbags available are presented as being significantly different when compared to an unrestrained occupant. The focus of our analysis is to investigate the effectiveness of airbags when combined with manual belts. NHTSA reported that the effectiveness of airbags alone at protecting the head (57%) was greater than the protection of all body regions (29%), thus the assumption was given that airbags must be more effective at protecting the head. Also, there was an increase in effectiveness over belt-only protection (57%) as compared to the protection offered by the use of manual belts and airbags together (85%) for AIS2+ injuries; however, no significance was reported. Interestingly, the effectiveness of the airbag by itself at protecting against serious head injury was not found to be significantly greater when compared to an unrestrained occupant (NHTSA 2001). McGwin found no difference in the risk of AIS2+ injury for occupants restrained by belts alone as compared those restrained by belts and airbags. In general, the data from our study supports the conclusions of McGwin et al. In our study, the only significant result was for right front passengers in vehicles with airbag deployment, which showed higher odds of AIS2+ head injury. The McGwin et al study did not investigate AIS3+ injury risks. Our study found no significant difference in AIS3+ head injury protection for those protected with both seat belts and airbags as compared to those with just seat belts.

Facial Injury

Interestingly, the NHTSA reports to Congress and McGwin et al included the face as part of the head body region in their analyses. In the results reported here, the face is often the only body region that has lower odds of injury with the presence or deployment of an airbag. By not investigating the face independently, the general improvements with respect to facial injury were not noted in these previous analyses.

Our results, with respect to the face, have been previously observed in other research. A collection of Canadian case studies with belted front seat occupants showed no AIS2+ facial injuries with the deployment of an airbag. In this study, they noted that this was in contrast to other research, which showed that in the absence of an airbag, moderate and greater facial injuries account for 20% of all injuries (Dalmotas 1980; Dalmotas et al 1996). Injuries to the face are often contusions and abrasions of lesser severity. Even eye injuries, which have been reported to be associated with airbag deployment are coded as AIS2 or less (AAAM 1998; Duma et al 2002). However, facial fractures can be coded as high as AIS3 injuries and are often the result of impacts to the vehicle interior. Airbags can lead to more orbital blow-out fractures from contact with the airbag, however, the research presented here has shown that the overall odds of serious injury is significantly reduced (Francis et al 2006). A previous investigation into airbags and the occurrence of facial injury using the Pennsylvania Trauma Outcome Study for years 1990-1995 reported there was a significant reduction in the rate of facial fractures for drivers, yet the result was not seen with significance for passengers (Murphy et al 2000). This is reflected in our study as well. There is a reduction in the odds of serious facial injury with a deployed airbag for the driver, yet no significant result is seen for the right front passenger. There is a significant reduction in the odds of facial injury for front seat occupants in vehicles where an airbag is present and for driver's when an occupant is exposed to a deployed airbag.

Upper Extremity Injury

Airbags are often given as the source of upper extremity injuries. Often these injuries come in the form of minor abrasions and contusions but less frequently can be serious fractures of the forearm and hand, often the result of contact during the unfurling of the bag and bag door (Huelke et al 1995). The latest NHTSA report to Congress noted a reduction in effectiveness for belted occupants with airbags (46%) as compared to those without airbags (57%) with respect to serious upper extremity injury. The McGwin et al study did not show a significant difference in effectiveness for the upper extremity at the AIS2+ injury threshold. Our research reported here has shown there is an increase in the odds of AIS3+ upper extremity injury when exposed to a deployed airbag for front seat occupants. The same result was not significant for AIS2+ upper extremity injuries, however, the upper confidence limit is only slightly above the null value (upper confidence limit = 1.02), suggesting the odds of moderate or greater injury may also be higher with a deployed airbag. Our research agrees with Jernigan et al (2003a; 2003b), which found an increase in the percentage of AIS2+ upper extremity injuries for occupants exposed to a deployed airbag when normalized to occupant exposure to crashes. Interestingly, Figure 21 and Figure 22 show depowered airbags provide no significant reduction in the odds of upper extremity injury for either injury threshold as compared to earlier, first generation airbags. Studies have been published that suggest advantages and disadvantages with respect to upper extremity injuries and depowered airbags. Hardy et al (2001) found a lower risk of airbag induced forearm injury for cadavers exposed to depowered airbags by producing a lower average distal forearm speed as compared to upper extremities exposed to a first generation airbag deployment. Jernigan et al (2005) looked at upper extremity injury and depowered airbags in a NASS/CDS study for case years 1993-2000, which contained the first NASS/CDS case years after the federal mandate calling for the depowering of airbags in 1998. Their results showed that, while there is a decrease in the risk of upper extremity fracture with depowered airbags, there is an increase in the risk of dislocation, particularly at the shoulder. Overall, this contributed to a higher percentage of moderate and greater severity upper extremity injuries when compared to the overall exposure to crashes.

Lower Extremity Injury

Lower extremity injuries are often not given precedence as compared to head and chest injuries in the study of occupant protection, yet it has been reported that lower extremity injuries accounted for 40% of all treatment costs associated with crashes prior to the large scale inclusion of airbags in vehicles, and lower extremity injuries can often be disabling (States 1986; MacKenzie et al 1988). Our research showed from a NASS/CDS distribution, given in Figure 1, that with the inclusion of airbags, the lower extremity accounts for more serious injuries than any other body region (32%), almost equal to the chest and head combined (34%). The lower extremity is shown to be adversely affected for the AIS3+ threshold when an occupant is exposed to a deployed airbag. However, the result was not significant when considering the AIS2+ threshold, agreeing with the conclusions of McGwin et al. The adverse interaction with the lower extremity is also supported by previous research which has suggested lower extremity injuries are more common with the presence of a deployed airbag for both belted or unbelted front seat occupants (Burgess et al 1995; Loo et al 1996a; Karlson et al 1998). However, it has been suggested from one study that the airbags may be partially effective at protecting the lower extremity from interior contacts, but not effective at protecting from intrusion injuries (Loo et al 1996a). It is possible that the cause of the increase in odds of injury to the lower extremity may be attributed to a change in kinematics of the occupant with airbag deployment. The airbag may absorb loads from the torso and head, but as a result, induce the pelvis to submarine under the lap belt, increasing the possibility of contacting the interior components of the vehicle with the lower extremity. Estrada et al (2004) attributes this kinematic change to an increase in the number of lower extremity fractures, particularly for the tibia and fibula, however an increase in risk was shown for the femur and pelvis as well. From this research it has been shown the inclusion of depowered airbags seems to increase the odds of lower extremity injury however, the result was not significant for the AIS3+ injury threshold.

Abdominal Injury

The results shown here suggest that when the occupant is exposed to a deployed airbag, the abdomen has higher odds of serious injury for both the AIS2+ and AIS3+ injury thresholds. McGwin et al reported no significant relationship between airbag deployment and AIS2+ abdominal injury. The NHTSA reports to Congress did not investigate the relationship between bag deployment and abdominal injury. In fact, the relationship between the abdomen and airbag deployment is often not reported in the literature. This may be because of the occult nature of certain crash related abdominal injuries. Often, abdominal injuries may not be noted initially because the symptoms may have a delayed onset. It has been suggested that the airbag can be overloaded by an occupant and result in excessive loading of the abdomen by the bag or rim of the steering wheel. An occult abdominal injury may occur and because no other noticeable symptoms are presented, the occupant may not be triaged appropriately for the injury (Augenstein et al 1995b). It is also possible that the increased in risk is related to the same kinematic changes suggested in the discussion of the lower extremities (Estrada et al 2004). The submarining of the occupant, as a result of the airbag interaction, may cause the lap belt to load the abdomen, resulting in an increased risk of injury.

Spinal Injury

The spine seems to be adversely effected by the presence and deployment of an airbag for the AIS2+ injury threshold. No significant result was given for the AIS3+ threshold. This implies that the airbag is more effective at protecting against the more severe injury types, including cord lacerations, however, the airbag is less effective at protecting against moderate injuries, such as vertebral fractures and brachial plexus injuries (AAAM 1998). Spinal fractures can often be the result of dynamic axial loading to the spinal column (King 1993). If the interaction between the occupant and the airbag causes an axial load to be transmitted through the head and neck, an injury of this type may result. This is contrary to the results of Claytor et al (2004) who, using a NASS/CDS 1995-2001, concluded the cervical spine is better protected with seat belts and an airbag as opposed to seatbelts alone. However, the confidence limits of the comparison groups overlapped, indicating an insignificant result.

Thoracic Injury

Airbags are not believed to increase the risk of moderate or serious thoracic injuries. A small number of case studies have presented airbag induced injury mechanisms, yet they are not believed to contribute to any appreciable increase in the rate of thoracic injury (Morgenstern et al 1998; Almeida et al 2006). However, serious thoracic injuries continue to make up a large portion of all serious injuries, even with the inclusion of airbags into vehicles (22% of seriously injured body regions for belted front seat occupants with airbags). It has also been stated that the two body regions most associated with fatalities are the head and the thorax (Malliaris et al 1982; Nahum et al 2002). The inclusion of airbags has reduced the total percentage of all serious injuries more for the head (6%) than for the chest (2%), although neither reduction was significant when comparing belted occupants with airbags to those without airbags. The odds ratios presented here have expressed that the inclusion of airbags does not seem to reduce the odds of thoracic injury. When exposed to airbag deployment, belted occupants are not significantly more protected against serious or moderate thoracic injury. This is consistent with the results reported by McGwin for AIS2+ injuries. However, the latest NHTSA report to Congress showed an increased protection for AIS2+ injuries and a decrease in effectiveness for

AIS3+ thoracic injuries when comparing belted occupants with (35%) and without (58%) airbag deployment. These results were not significant. The results reported in this study have also suggested that the issue of thoracic injury is not going to improve with the inclusion of depowered airbags. The effectiveness of protecting the thorax with respect to the AIS2+ injury threshold for occupants exposed to a depowered airbag deployment has been significantly reduced and the AIS3+ effectiveness also appears to be less, although the results are not quite significant.

3.4.4 Differences in Variance Calculations

All confidence intervals are presented from the jackknife method for variance calculation within a stratified and clustered survey design. This method was chosen because it presents a more conservative estimate than the Taylor series linearization method. However, the Taylor linearization method is also accepted as an appropriate variance calculation method for a sample survey designed in this manner. As such, it is prudent to point out the scenarios where the Taylor linearization method produced significant results and the jackknife did not. A table is given with each odds ratio figure for each injury threshold level and restraint condition. In each of these tables, both the Jackknife and Taylor linearization confidence intervals are given as well an asterisk to denote whether the result is significant with each variance calculation method.

Significant increases in effectiveness were shown for the AIS3+ facial injuries with a deployed airbag and AIS2+ facial injuries with a deployed depowered airbag. Also, the head was shown to be significantly more protected by depowered airbags for both AIS2+ and AIS3+ injuries by applying the Taylor linearization method. The upper extremity was shown to have a significant increase in the odds of injury for the AIS2+ threshold when exposed to a deployed airbag using this method. The upper extremity was also shown to have significantly higher odds of injury when the occupant is in a vehicle with an airbag available for the AIS3+ threshold; the result was already presented as significant for the deployed bag in this condition with the jackknife method. The lower extremity has a significant reduction in protection with a deployed airbag for occupants in the right front passenger location. This result would indicate that all three seating comparisons would have a significant reduction in protection with the airbag deployment. The same can be said for the abdomen for the AIS2+ threshold when exposed to a deployed airbag. A significant result is presented for the right front passenger in this condition using the Taylor linearization method. A significant result is also given with this method for chest injuries at the AIS3+ threshold when exposed to a deployed, depowered airbag. There is an increase in the odds of injury to the chest at both injury thresholds in this deployment condition.

3.4 Conclusion

The odds of serious and moderate injuries vary by body region, seating position, and occupant restraints. The newest restraint technologies, specifically airbags, do not seem to be effectively providing better protection for the certain body regions. Specifically, the abdomen, lower extremities, and upper extremities appear to be adversely affected by airbag technologies. However, airbags have been shown to reduce fatalities, thus suggesting that they are still an integral part of occupant protection systems. Injuries to the upper extremity, lower extremity, and the abdomen should be explored further in order to properly assess the current state of occupant thoracic protection and investigate advances that can be made in these areas.

3.5 References

AAAM (1998). Association for the Advancement of Automotive Medicine. The Abbreviated Injury Scale, 1990 Revision, Update 98 (1998).

Almeida, F. A., B. V. Jr.a, T. T. V. Pechetb, P. J. Costantinic and J. L. Farberd (2006). "Lung injury after airbag deployment: Airbag lung " Injury Extra 37(5): 181-183.

Augenstein, J. S., K. H. Digges, L. V. Lombardo, E. B. Perdeck, J. E. Stratton, A. C. Malliaris, C. V. Quigley, A. K. Craythorne and P. E. Young (1995). "Occult abdominal injuries to airbag-protected crash victims: a challenge to trauma systems." The Journal of Trauma: Injury, Infection, and Critical Care 38(4): 502-8.

Braver, E. R., S. A. Ferguson, M. A. Greene and A. K. Lund (1997). "Reductions in Deaths in Frontal Cashes Among Right Front Passengers in Vehicles Equipped with Passenger Airbags." JAMA 278: 1473-1439.

Burgess, A. R., P. C. Dischinger and T. D. O'Quinn (1995). "Lower Extremity Injuries in Drivers of Airbag-Equipped Automobiles: Clinical and Crash Reconstruction Correlations." The Journal of Trauma: Injury, Infection, and Critical Care 38(4): 509-16.

Claytor, B., P. A. MacLennan, G. McGwin, Jr., L. W. Rue, 3rd and J. S. Kirkpatrick (2004). "Cervical spine injury and restraint system use in motor vehicle collisions." Spine 29(4): 386-9; discussion Z2.

Dalmotas, D. J. (1980). Mechanisms of Injury to Vehicle Occupants Restrained by Three-Point Seat Belts. Society of Automotive Engineers 801311.

Dalmotas, D. J., R. M. Hurley and A. German (1995). "Air Bag Deployments Involving Restrained Occupants." Society of Automotive Engineers 104(66): 1507-1512.

Dalmotas, D. J., R. M. Hurley and A. German (1996). Supplemental Restraint Systems: Friend or Foe to Belted Drivers? Association for the Advancement of Automotive Medicine, Vancouver, British Columbia.

Duma, S. M., M. V. Jernigan, J. D. Stitzel, I. P. Herring, J. S. Crowley, F. T. Brozoski and C. R. Bass (2002). "The effect of frontal air bags on eye injury patterns in automobile crashes." Arch Ophthalmol 120(11): 1517-22.

Estrada, L. S., J. E. Alonso, G. McGwin, Jr., J. Metzger and L. W. Rue, 3rd (2004). "Restraint use and lower extremity fractures in frontal motor vehicle collisions." The Journal of Trauma: Injury, Infection, and Critical Care 57(2): 323-8.

Francis, D. O., R. Kaufman, B. Yueh, C. Mock and A. B. Nathens (2006). "Air bag-induced orbital blow-out fractures." Laryngoscope 116(11)**:** 1966-72.

Hardy, W. N., L. W. Schneider and S. W. Rhouhana (2001). "Prediction of Airbag-Induced Forearm Fractures and Airbag Aggressivity." Stapp Car Crash Journal 22**:** 375-398.

Huelke, D. F., J. L. Moore, T. W. Compton, J. Samuels and R. S. Levine (1995). "Upper extremity injuries related to airbag deployments." The Journal of Trauma: Injury, Infection, and Critical Care 38(4)**:** 482-8.

Jernigan, M. V. and S. M. Duma (2003a). The Effects of Depowered Airbags on Severe Upper Extremity Injuries In Frontal Automobile Crashes. Association for the Advancement of Automotive Medicine.

Jernigan, M. V. and S. M. Duma (2003b). Incidence of Severe Upper Extremity Injuries and Minor Skin Injuries in Frontal Automobile Crashes. Society of Automotive Engineers, Detroit, MI 2003-01-0513.

Jernigan, M. V., A. L. Rath and S. M. Duma (2005). "Severe upper extremity injuries in frontal automobile crashes: the effects of depowered airbags." Am J Emerg Med 23(2)**:** 99-105.

Karlson, T. A., W. Bigelow and P. Beutel (1998) "Serious Lower Extremity Injuries in Motor Vehicle Crashes: Wisconsin, 1991 – 1994." USDOT.

Kent, R. W., C. Strother, J. R. Crandall, H. Mellander and C. Griswold (2003). Air Bag Development and Performance: New Perspectives from Industry, Government and Academia. Warrendale, PA, SAE.

King, A. I. (1993). Injury to the Thoracolumbar Spine and Pelvis. Accidental Injury: Biomechanics and Prevention. A. M. Nahum and J. W. Melvin. New York, NY, Springer-Verlag**:** 391-428.

Loo, G., J. Siegel, P. Dischinger, D. Rixen, A. Burgess, M. Addis, T. O'Quinn, L. McCammon, C. Schmidhauser, P. Marsh, P. Hodge and F. Bents (1996). "Airbag Protection Versus Compartment Intrusion Effect Determines the Pattern of Injuries in Multiple Trauma Motor Vehicle Crashes." The Journal of Trauma: Injury, Infection, and Critical Care 41(6)**:** 935-51.

Lund, A. K. and S. A. Ferguson (1994). "Driver Fatalities in 1985-1993 Cars with Airbags." The Journal of Trauma Injury, Infection, and Critical Care 38(4).

MacKenzie, E. J., J. Siegel, S. Shapiro, M. Moody and R. T. Smith (1988). "Functional recovery and medical costs of trauma: an analysis by type and severity of injury." The Journal of Trauma: Injury, Infection, and Critical Care 28(3)**:** 281-297.

Malliaris, A. C., R. Hitchcock and J. Hedlund (1982). A Search for Priorities in Crash Protection. Society of Automotive Engineers 820242.

McGwin, G., J. Metzger, J. Alonso and L. Rue (2003). "The Association Between Occupant Restraint Systems and Risk of Injury in Frontal Motor Vehicle Collisions." The Journal of Trauma Injury, Infection, and Critical Care 54(6)**:** 1182-1187.

Morgenstern, K., R. Talucci, M. S. Kaufman and L. E. Samuels (1998). "Bilateral pneumothorax following air bag deployment." Chest 114(2)**:** 624-6.

Murphy, R. X., Jr., K. L. Birmingham, W. J. Okunski and T. Wasser (2000). "The influence of airbag and restraining devices on the patterns of facial trauma in motor vehicle collisions." Plast Reconstr Surg 105(2)**:** 516-20.

Nahum, A. M. and A. M. Melvin (2002). Accidental Injury: Biomechanics and Prevention 2nd. New York, Springer-Verlag.

NHTSA (1984) "FMVSS 208 Regulatory Impact Analysis." National Highway Traffic Safety Administration

NHTSA (1999) "Fourth Report to Congress: Effectiveness of Occupant Protection Systems and Their Use." National Highway Traffic Safety Administration.

NHTSA (2001) "Fifth/Sixth Report to Congress: Effectiveness of Occupant Protection Systems and Their Use." National Highway Traffic Safety Administration.

NHTSA (2007). Traffic Safety Facts 2007 DOT HS 811034.

States, J. (1986). Adult Occupant Injuries of the Lower Limb. Society of Automotive Engineers 861927.

Viano, D. C. (1988). "Limits and Challenges of Crash Protection." Accident Analysis and Prevention 20(6)**:** 421-429.

Viano, D. C. (1991). Effectiveness of Safety Belts and Airbags in Preventing Fatal Injury, Warrendale, PA, Society of Automotive Engineers 910901.

Werner, J. S. and W. W. Sorenson (1994). Survey of Airbag Involved Accidents. An Analysis of Collision Characteristics, System Effectiveness and Injuries. Society of Automotive Engineers 940802.

Zador, P. L. and M. A. Ciccone (1993). "Automobile Driver Fatalities in Frontal Impacts: Air Bags Compared with Manual Belts." American Journal of Public Health 83**:** 661-666.

Chapter 4. Characteristics of Thoracic Organ Injuries

4.1 Introduction

This chapter will investigate the distribution of injuries associated with serious internal thoracic organ injury and associated characteristics with regard to the occupant, vehicle, and crash circumstances. This research will focus on injuries of the lungs, liver, spleen, and heart and great vessels. The analysis will be based on frontal crashes extracted from the NASS/CDS database for case years 1993-2007.

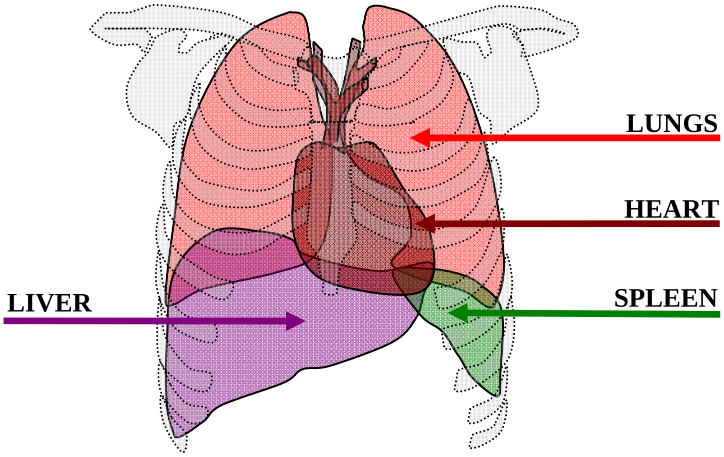

Figure 23. Diagram of thoracic and abdominal organ location with respect to each other and the rib cage.

Previous research shows that the thorax and head have been the body regions that have accounted for the most serious injuries and fatalities in the past (Malliaris et al 1982; Nahum et al 2002). Using more recent data, the previous chapter has shown the role of these body regions and the overall distribution of serious injuries has changed. However, there continues to be a very apparent issue surrounding serious thoracic injuries, which still account for 22% of all seriously injured body regions. Also, any reduction in the percentage of overall injury distributions for the head and chest as a result of airbags were not shown to be significant for belted occupants.

Much of the effort to increase thoracic protection has focused on rib fractures due to their predominance in serious thoracic injury in cadaver testing (Nahum et al 1970; Kroell et al 1971; Nahum et al 1971; Neathery et al 1973; Kroell et al 1974; Neathery 1974; Nahum et al 1975; Kleinberger et al 1998; Eppinger et al 1999). Thoracic injury criteria have been developed with the specific goal of protecting the thorax, although the distribution of injury has been weighted heavily on rib fracture. These criteria have been applied under the assumption, if the ribs are protected from serious injury, the underlying organs will consequently be protected as well (Viano 1978).

There are differences in the determination of injury for cadaver studies and field studies. The frequency of thoracic skeletal injury reporting is often lower in a clinical investigation, such as would be reported for non-fatally injured patients seen in NASS/CDS, than the actual number of fractures, such as may be seen from an autopsy of a cadaver. Early research into the deflection response of the chest noted less than half of all rib fractures in a cadaver noted via dissection were confirmed from radiology (Nahum et al 1970). Later, it was reported that only 29% of rib fractures noted from necropsy were independently identified by 5 radiologists for occupants restrained by both seat belts and airbags (Kent et al 2002). Therefore, there are significant differences in the reporting of rib fractures for cadavers and non-fatally injured occupants.

The difference in the reporting of rib fracture may help explain the difference in the ratio of serious injuries in the form of rib fractures versus thoracic organ injury that are reported to be higher in cadaver work than in field studies. However, serious injuries to the thoracic organs make up a significant fraction of all thoracic injuries as reported in NASS/CDS, as will be discussed with Figure 25. The distribution of thoracic organ injuries with respect to all serious thoracic injuries in cadaver work have been reported at 7% as compared to the 56% given in Figure 25 from a NASS/CDS investigation (Morgan et al 1994; Kleinberger et al 1998; Eppinger et al 1999). Thus, it is important to explore the contributions of thoracic organ injuries to the continuing issue of thoracic injury protection, particularly from the perspective of non-fatally injured occupants.

The relationship between rib fracture and thoracic organ injury has previously been explored. Viano (1978) showed that an overall chest compression of roughly 32% was shown to produce a significant risk of rib-cage failure, thus loosing the ability to effectively protect the underlying organs. Shorr et al (1987) and Sirmali et al (2003) presented correlations between the number of rib fractures and the probability of thoracic organ injury However, this may be only partially dependent on a cause and effect relationship. In fact, the fracture of ribs may also lead to more thoracic organ protection in certain cases. Shorr et al reported that thoracic organs can be seriously injured without rib fracture. Shorr hypothesized that the risk of organ injuries may be greater without rib fracture due to less energy absorption in the thoracic rib cage. These results, in combination with those given in Figure 25 that reflect the predominance of organ injury with respect to all serious thoracic injury, as well as reveal that it is important to understand the circumstances that lead to thoracic organ injury by itself, as opposed to investigating these injuries with respect to rib fracture. In order to investigate the role of thoracic organ injury in the overall understanding of serious thoracic injuries, it is important to understand how the organ injuries occur, the types of injuries that are seen, and the conditions in which they occur.

The most commonly injured thoracic soft tissues are the lungs, heart, and the great vessels (Cavanaugh 1993; Matthes et al 2006). The chest and the abdomen are separated by the diaphragm, which lies just superior the spleen and the liver. The liver and spleen are partially protected by the lower rib cage, as shown in Figure 23. They are the most commonly injured abdominal organs (Walt et al 1970; Lau et al 1981b; Morgan et al 1994). For the purposes of this research, the liver and spleen will be included as thoracic organs for these reasons. The liver in spleen were included as abdominal organs in the analyses from Chapter 2.

The circumstances that lead to injury of the individual thoracic organs can vary with respect to injury type, the occupant, and the circumstances of the crash. To engineer new safety measures, it is important to understand the circumstances under which thoracic injury occur. Historically, not all injury countermeasures produced large benefits and some have produced disbenefits. The previous chapter has noted that the inclusion of airbags has not produced a significant increase in frontal thoracic protection for belted occupants.

4.2 Methods

The data for this study was extracted from the NASS/CDS database for case years 1993-2007. The distribution of the resulting cases is given in Table 20. The data set, again, was restricted using the following filters:

- Belted occupants in vehicles with or without frontal airbags
- Cars, light trucks, and vans
- Drivers and right front passengers only
- Frontal crashes with a principle direction of force between 11- and 1-o'clock
- Minimum occupant age of 12 years
- No rollover events
- No ejected occupants

This analysis presents the distribution of thoracic organ injuries as a result of frontal impacts. A variety of crash scenarios and details were investigated to reveal the characteristics of crashes associated with thoracic organ injuries. NASS/CDS classifies injury severity using the Abbreviated Injury Scale (AIS). For this study, the injuries of interest are those that are categorized as serious and greater, defined as AIS3+ (AAAM 1998).

Confidence limits are reported for each distribution using the Taylor series linearization method for calculating variances within the strata and clustering of the data set. The jackknife variance calculation method was not employed for this analysis because it is not applicable for situations where a particular stratum has only one cluster, an issue which is the result of relatively small sample sizes in some comparison situations. The Taylor linearization method was used for both the SURVEYMEANS and SURVEYFREQ procedures in the SAS software (SAS, Cary, NC). The confidence limits for each proportion or average are given from these procedures as well as the standard error. The significance of the results reported is with respect to a two-sample test; comparing the overlap of confidence intervals can provide an overly conservative result. Instead, it is more appropriate to calculate significance based on the standard error of the point estimate as outlined in the literature (Schenker et al 2001; Wolfe et al 2002). All significance results are given using the α=0.05 confidence calculation method as reported by Schenker et al, 2001:

$$\left(\hat{Q}_1 - \hat{Q}_2\right) \pm 1.96\left(\hat{S}E_1 + \hat{S}E_2\right) \text{(Schenker et al, 2001)} \qquad \textbf{Equation 3}$$

This method is based on a comparison of standard errors for the respective point estimates of the two samples as given in Equation 3. $\hat{Q}_1$ and $\hat{Q}_2$ represent the mean or proportions of the two sample populations. $\hat{S}E_1$ and $\hat{S}E_2$ represent the standard errors of the two sample populations. If the range of values does not contain a value of 0 the null hypothesis is rejected at the α=0.05 level. All standard errors reported by the SAS software are based on the variance calculations using the Taylor series linearization; hence it is assumed that it is acceptable to use the weighted data from a stratified and clustered data set to determine statistical significance in this manner.

4.3 Results

The following section discusses the distribution of injuries in frontal crashes. In frontal impacts, the chest is the body region most likely to receive a serious injury for belted occupants in vehicles without airbags. The chest has the third highest percentage of serious injury for belted occupants in vehicles with airbags as expressed in Figure 24. The body region that is most frequently seriously injured was the lower extremity (lower leg and pelvis) for occupants with an airbag. The upper and lower extremities together account for over half of all AIS 3+ injuries (55%) in frontal impacts for vehicles with airbags, as shown in Figure 24.

Table 20: Distribution of AIS3+ thoracic organ injuries by restraint condition for belted front seat occupants in NASS/CDS case years 1993-2007.

Restraint Type	Occupants with Thoracic Organ AIS 3+ Injuries (Weighted)	Thoracic Organ AIS 3+ Injuries (Weighted)	Thoracic Organ AIS 3+ Injuries (Unweighted)
Belts + No Airbag	16,700	21,186	366
Belts + Airbag	26,993	32,289	541

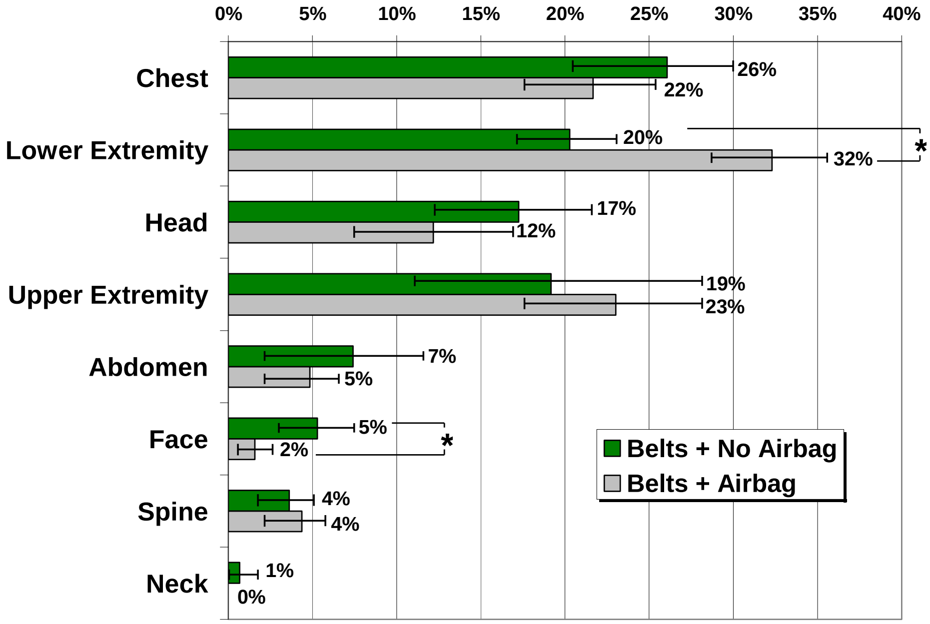

Figure 24: Distribution of occupants with MAIS3+ injury by body region.

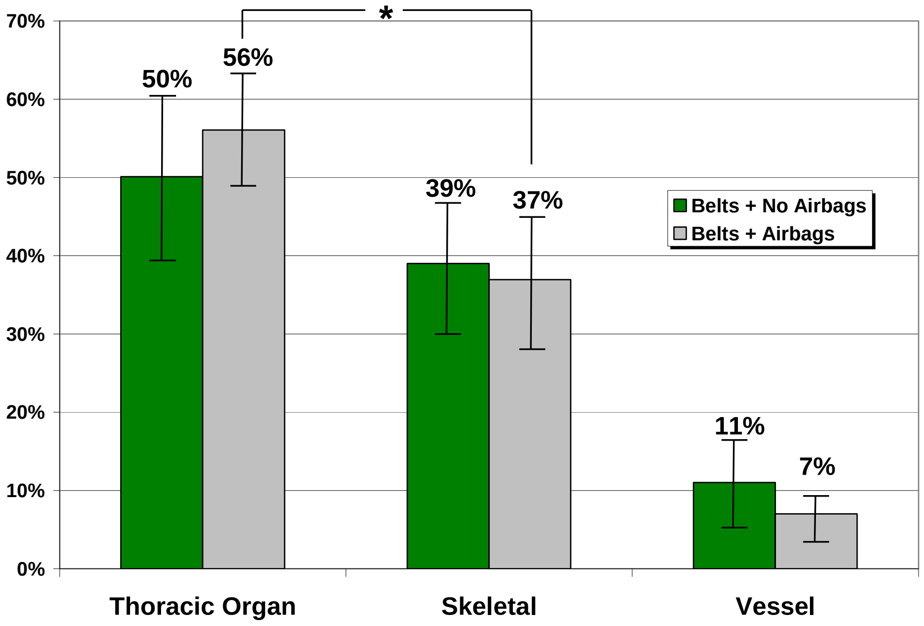

Figure 25: Distribution of AIS3+ thoracic injuries by tissue type for occupants in frontal crashes (weighted).

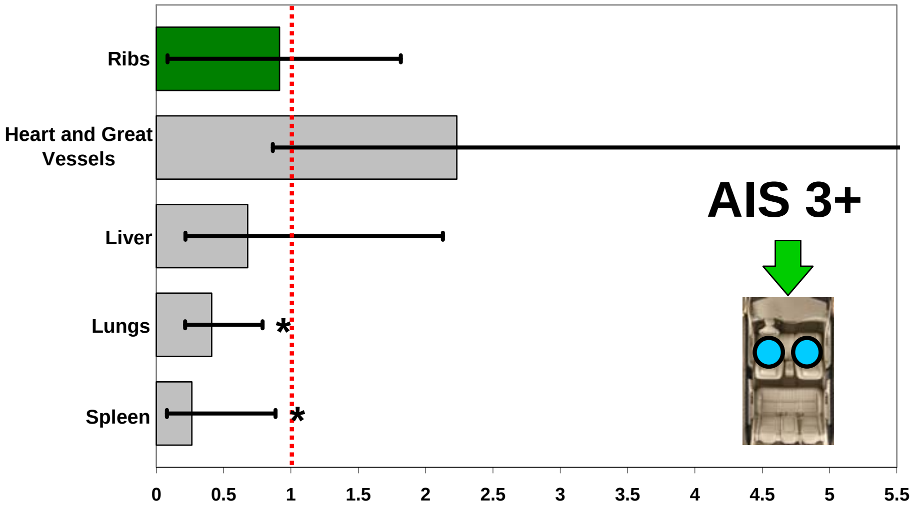

Figure 26: Odd ratio of AIS3+ thoracic injury for occupants with and without airbags presented by organ (weighted).

Figure 25 shows that, with the inclusion of frontal airbags, the thoracic organs, as opposed to the skeletal structures, comprise the most serious thoracic injuries. In fact, Figure 26 shows that there are 2.4 times (CI: 1.3-4.7x) greater odds of AIS3+ lung injuries and 3.8 times (CI: 1.1-12.7x) greater odds of AIS3+ liver injuries. It is also shown that the inclusion of airbags does not significantly reduce the odds of rib fracture. The odds ratios in Figure 26 are based on a logistic regression model adjusted for delta-V, age, and vehicle type. Figure 27 shows that lung injuries are the most injured organ type in frontal crashes, particularly in vehicles with airbags. Lung injuries and liver injuries compose a higher percentage of all thoracic organ injuries for injured occupants in vehicles with airbags, although the results are not significant for liver injuries. The percentage of serious injuries to the spleen and heart and great vessels has decreased with the changes in occupant safety technologies, although the results are also not shown to be statistically significant.

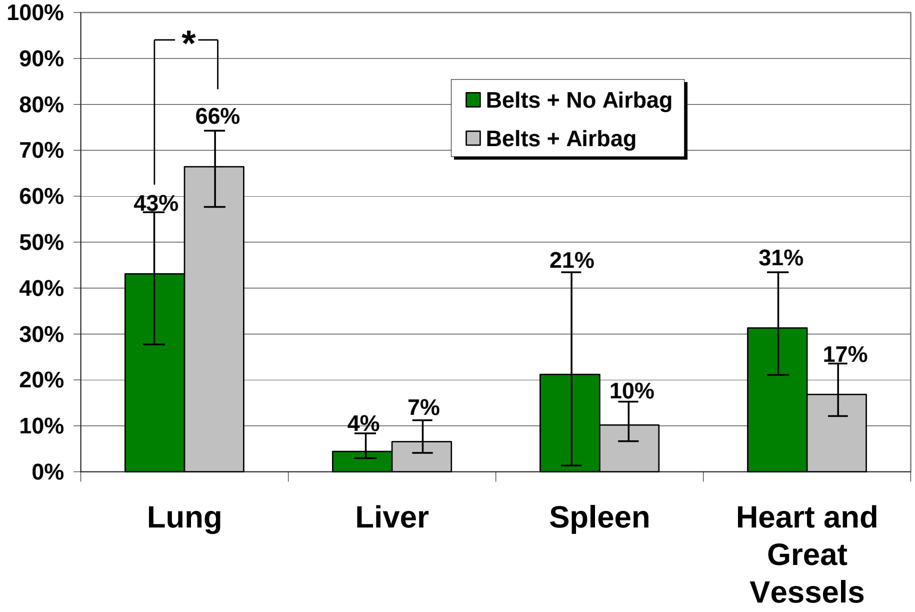

Figure 27: AIS3+ Thoracic organ injuries in frontal impacts (weighted).

4.3.1 Lung Injury Mechanisms and Distributions

AIS3+ lung injuries are mostly contusions with or without airbags. The inclusion of airbags has produced a significant reduction in injuries categorized as lacerations in frontal crashes, as shown in Figure 28. Previous research has reported that contusion is the predominant lesion for the lung ranging from 75-95% (Shorr et al 1987; Cohn 1997; Miller 2006). Lung contusions are known to be rate dependent due to the viscous response of the soft tissues (Cavanaugh 1993; King 2000; Viano et al 2000; Schmitt et al 2004). The high velocity impacts seen in MVCs are thought to create pressure waves that travel through the chest wall and cause damage to the capillaries, resulting in contusion (Cavanaugh 1993; Miller 2006). The contusion can often be found in regions where the lung tissue will have been compressed against the ribs (Miller 2006). Contusion of the lungs can lead to a greater susceptibility to pneumonia and can carry mortality rates ranging from 10-25% (Hoff et al 1994; Miller et al 2001; Schmitt et al 2004).

Often, lung lacerations are associated with rib fractures in the same region and are believed to be the result of the penetration of the broken rib into the lung tissue (King 2000; Schmitt et al 2004). Alternatively, pulmonary laceration can be the result of rapid deceleration and rupture of alveoli from high pressure wave transmission, producing shearing of the tissue (Wagner et al 1988; Cohn 1997). Lung lacerations can lead to hemothorax and pnuemothorax (Schmitt et al 2004).

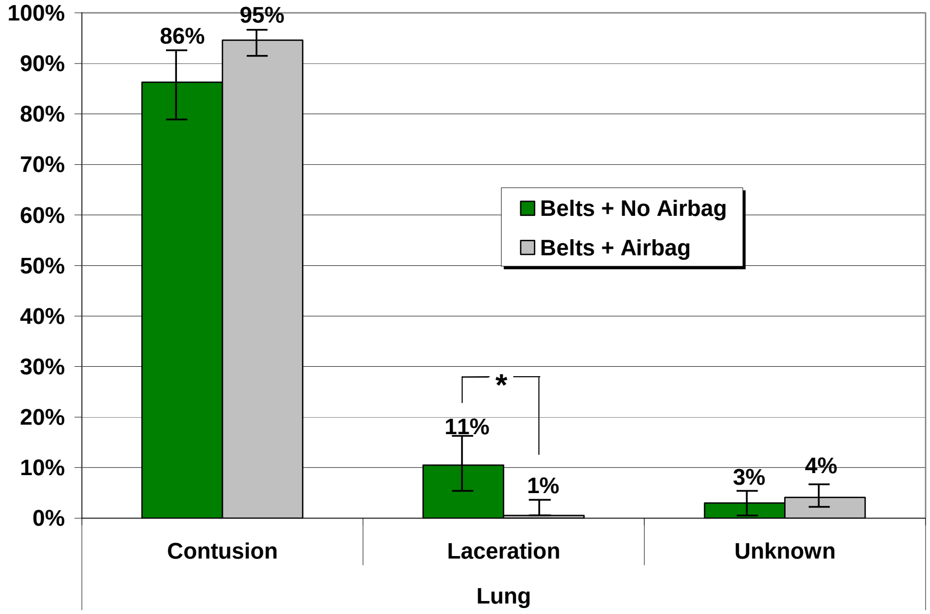

Figure 28: Distribution of AIS3+ pulmonary injuries by lesion type (weighted).

The majority of injuries to the lungs in frontal impacts were at the AIS3 level while only a quarter were of AIS4 severity. There were no AIS5-6 injuries reported in this analysis for occupants in vehicles with airbags, as shown in Figure 29. AIS3 lung injuries include unilateral pulmonary contusion in conjunction with flail chest or a unilateral laceration, with or without hemo/pnuemothorax. AIS4 lung injuries include bilateral contusions and bilateral lacerations. AIS5 injuries include complicating issues, such as >20% blood loss, the presence of bilateral lacerations, or lacerations with tension pnuemothorax; there are no codes for AIS6 lung injuries (AAAM 1998). No statistical association was shown with a Rao-Scott modified chi-square test between the presence of an airbag and serious lung injuries (p=0.2890) based on a contingency table analysis. However, there has been an increase in the number of serious lung injuries based on exposure as shown in Table 21, although the results were not significant.

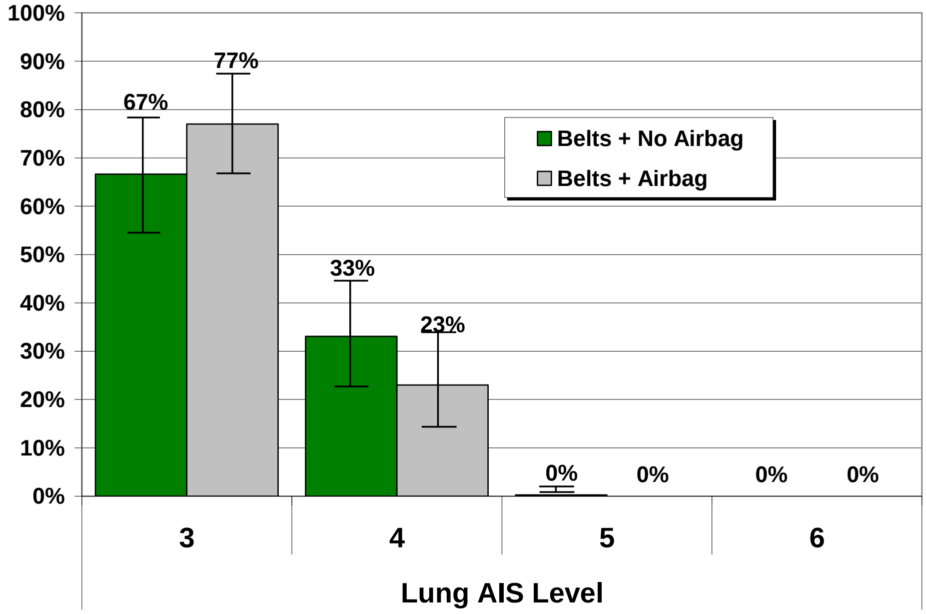

Figure 29: Distribution of pulmonary injuries by AIS level (weighted).

Table 21. Number of serious lung injuries as well as their normalized value to all exposed occupants (weighted).

	Occupants with Serious lung Injuries (Weighted)	Injuries / 10,000 Exposed Occupants (weighted)
Belts + No Airbag	9,371	**16.00**
Belts + Airbag	21,254	**22.02**

Figure 30 and Figure 31 present the distribution of contact sources associated with AIS3+ lung injuries. For belted occupants in both seating positions in vehicles with airbags, the belts are the primary source of injury and the steering assembly is the primary source for occupants in vehicles without airbags, although these results are not significant. These results may be attributed to a reduction in the potential of direct contact between the chest and the steering assembly with presence of an airbag. The airbag, when present, is shown to only account for 6% of lung injuries to the driver, but 22% for the right front passenger. The belts account for almost half of the serious driver lung injuries with an airbag present. Contusions greatly outweigh all other lesion types for serious lung injuries. Also, contusions are believed to be dependent on the compression rate of the tissue (Cavanaugh 1993; King 2000; Viano et al 2000; Schmitt et al 2004). The belt system would be the source of the initial chest compression. Thus, the seat belts may be responsible for the rate of compression as well, possibly relating to this injury mode.

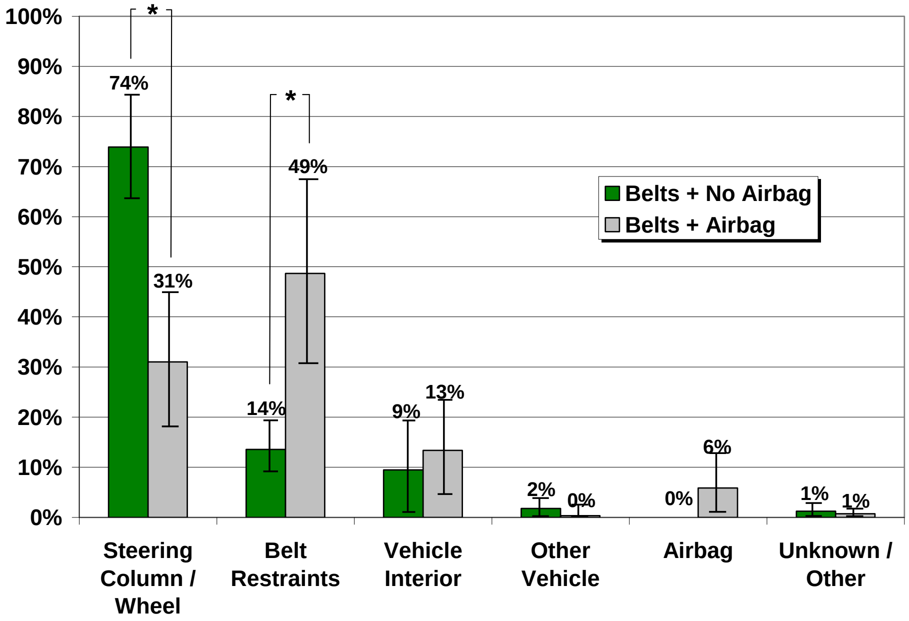

Figure 30: Distribution of serious lung injuries by injury source for drivers (weighted).

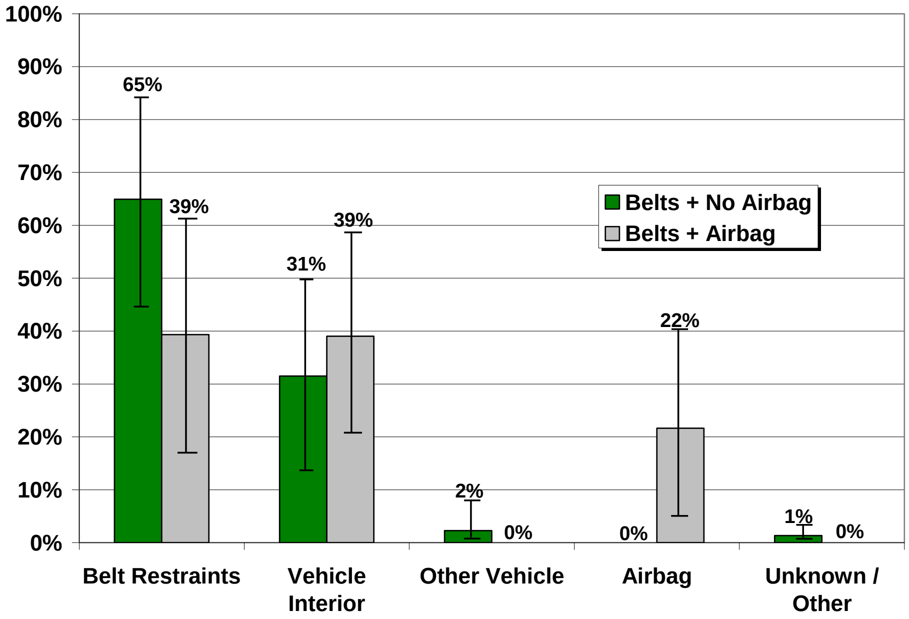

Figure 31: Distribution of serious lung injuries by injury source for right front passengers (weighted).

4.3.2 Liver Injury Mechanisms and Distributions

Rivkind et al (1989) has shown that blunt liver injuries carry higher mortality than traumatic injury of any other abdominal organ and that the majority of traumatic liver injuries are from MVCs. Unlike lung injuries, almost all AIS3+ liver injuries are lacerations for belted occupants in frontal crashes, as expressed in Figure 32. This is consistent with reports in the literature (Mays 1966; Hardy 1972; Frey et al 1973; Lau et al 1981a; Lau et al 1981b; Rivkind et al 1989; Augenstein et al 1995a; Sparks et al 2007). The liver is less protected by the rib cage than the lungs, possibly making it more susceptible to penetrating injuries and direct engagement. However, the majority of liver lacerations are not the result of penetrating trauma, but rather blunt trauma (Lau et al 1981a). Therefore, the lack of protection by the ribs from a penetrating object may not play a significant role in the distribution of lesion types The lower percentage of hepatic contusions in the overall distribution of serious liver injuries may be a reflection of the coding protocol for the liver contusion, which requires the contusion to cover 50% of the tissue surface or >20% blood loss in order to be coded as an AIS3 injury (AAAM 1998). Liver lacerations often come in the form of a stellate injury pattern, suggesting a bursting injury due to over-pressure of the organ, possibly from blunt loading (Hardy 1972; Rivkind et al 1989; Sparks et al 2007). It is believed that compression at high rates leads to excessive tensile and shear strains, resulting in the bursting of the organ.

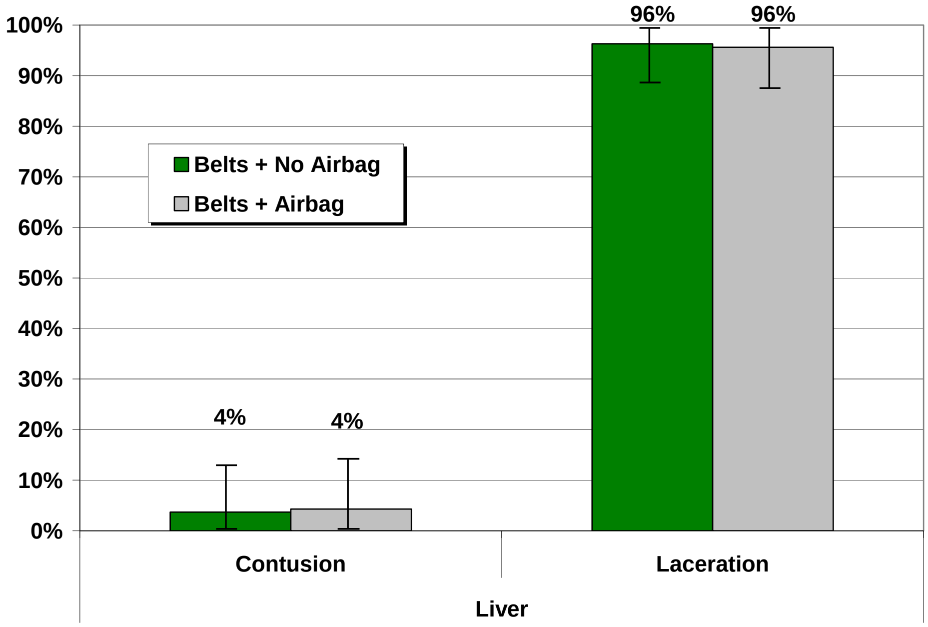

Figure 32: Distribution of AIS3+ liver injuries by lesion type (weighted).

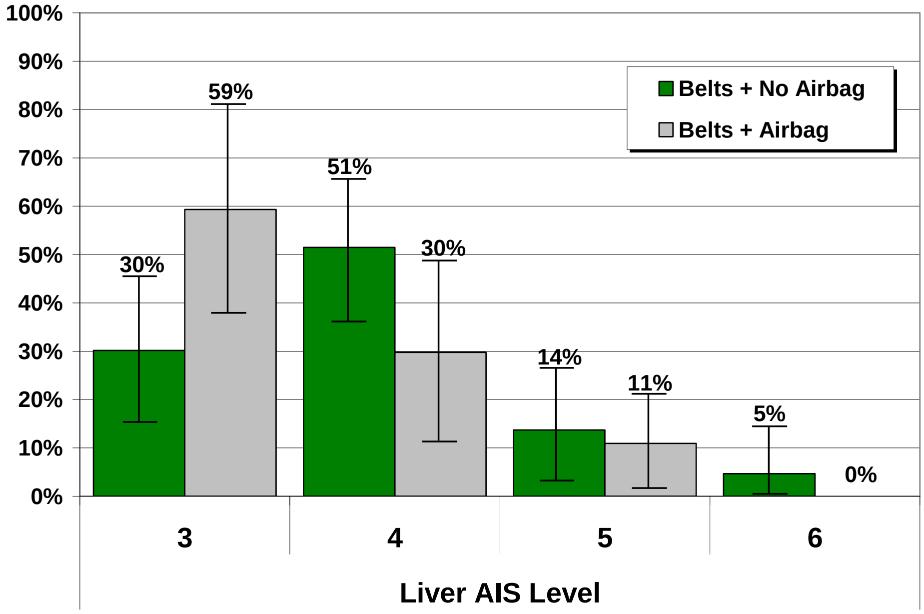

Figure 33: Distribution of liver injuries by AIS level (weighted).

Table 22. Number of serious liver injuries as well as their normalized value to all exposed occupants (weighted).

	Occupants with Serious Liver Injuries (Weighted)	Injuries / 10,000 Exposed Occupants (weighted)
Belts + No Airbag	920	**1.65**
Belts + Airbag	2,124	**2.20**

The AIS score for severity of serious liver injuries appears to be decreasing with the inclusion of airbags, as shown in Figure 33. This includes a reduction in AIS4+ injuries, which include the highly critical bursting injuries that are common in blunt hepatic trauma, although the reduction was not significant. For the occupants with an airbag present, there were no AIS6 liver injuries as opposed to 5% of those who had a serious liver injury without an airbag. An AIS6 liver injury is a complete hepatic avulsion (AAAM 1998). Also, there is no significant reduction in the number of serious liver injuries based on exposure as shown in Table 22. A modified Rao-Scott chisquared test showed that there is no statistical association between the presence of an airbag and severe liver injury (p=.5116).

There may be differences in the source of injury for the liver as shown in Figure 34 and Figure 35, although none of the results were statistically significant. For occupants in vehicles with and without airbags, the steering assembly and the seat belts are the leading sources of serious liver injury for the driver. The vehicle interior is given as the source of liver injury significantly more often for the right front passenger than for the driver. The distribution of hepatic injury sources for drivers without airbags is in agreement with previous research which has attributed 38% of serious injuries to the steering assembly. Elhagediab et al (1998) suggested that the inclusion of airbags would reduce the threat posed by the steering assembly, but our analysis did not find this decrease to be significant. However, it is possible that the decrease in injuries attributed to the vehicle interior, other than the steering assembly, may be partially the result of the airbag by limiting the ability of the body to contact these structures, although this percentage decrease is not significant. Interestingly, 89% of the components in the vehicle interior that were given as the hepatic injury source were on the right side of the occupant, corresponding to the location of the organ in the body.

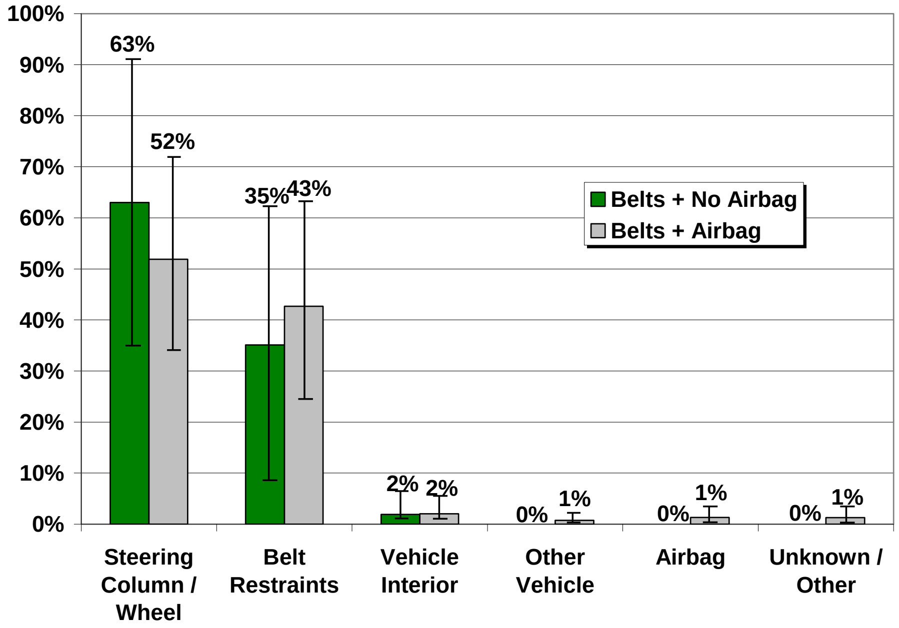

Figure 34: Distribution of serious liver injuries by injury source for drivers (weighted).

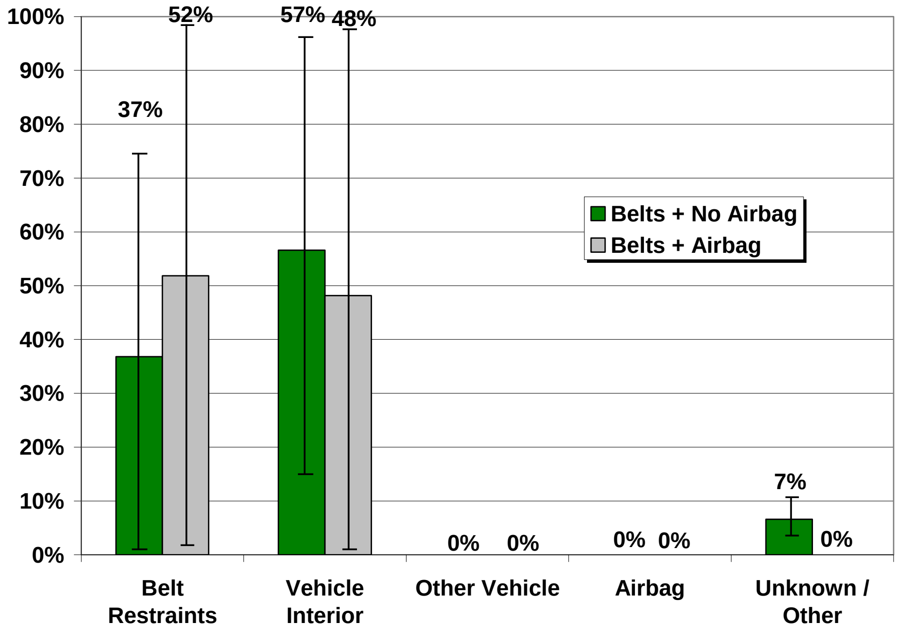

Figure 35: Distribution of serious liver injuries by injury source for right front passengers (weighted).

4.3.3 Spleen Injury Mechanisms and Distributions

Figure 36 shows that lacerations account for the largest percentage of serious injuries to the spleen. Rouhana (1993) notes that, similar to the liver, lacerations of the organ are usually not the result of penetrating trauma. Instead, usually the injury occurs as the result of a direct blow to the organ or from the rapid deceleration of the body. Both situations produce injury by placing the capsule of the spleen in tension, resulting in deep lacerations. Often, the lacerations resulting from deceleration often originate at attachment points, resulting in tears of the capsule.

There is an increase in the rate of ruptures of the spleen for airbag equipped vehicles, although this increase is not significant. There is no increase in the rate of contusions with the inclusion of airbags. According to the AIS scoring guidelines, injuries are to be coded as ruptures only if a more detailed description is not available. Ruptures are assigned an AIS value of 3. Contusions of the spleen are only coded as high as 3 if the contused tissue contains >50% of the organ surface area. However, splenic lacerations can be coded as high as 5 when total devascularization occurs or with stellate, burst-like injury patterns (AAAM 1998). Figure 37 suggests that there may be an increase in the percentage of serious injuries that are coded at the AIS5 level, although the result is not significant. The high levels of vascularization of the spleen has lead to an increased mortality rate when compared to other abdominal organs for traumatic events (Mustard et al 1984).

Interestingly, despite an increase in the average severity of serious splenic injuries, there has been a reduction in the number of injuries as compared to all exposed occupants as shown in Table 23, although neither of these patterns is statistically significant. A modified Rao-Scott chi-square test did not give a significant association between the presence of an airbag and spleen injury (p=0.3773).

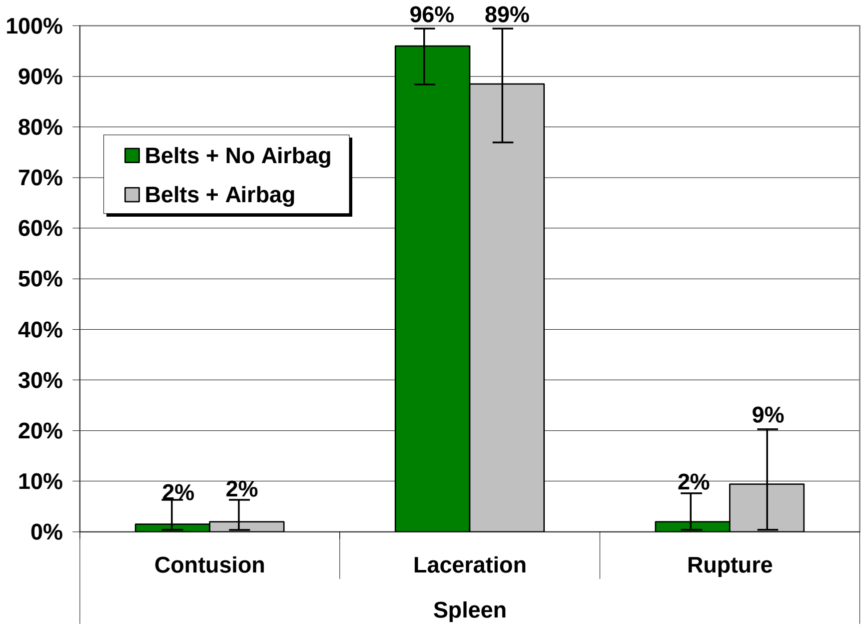

Figure 36: Distribution of AIS3+ spleen injuries by lesion type (weighted).

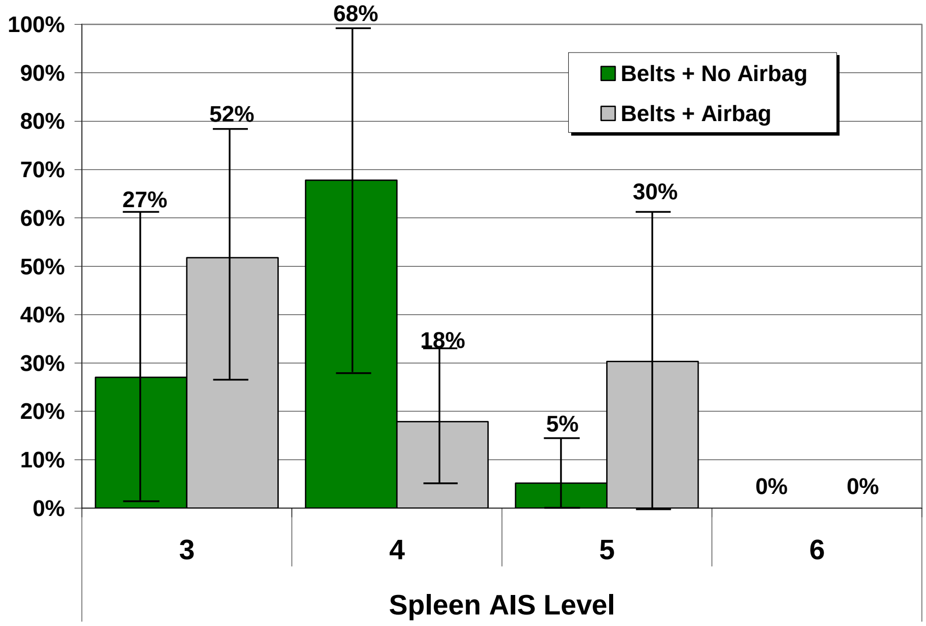

Figure 37: Distribution of spleen injuries by AIS level (weighted).

Table 23. Number of serious spleen injuries as well as their normalized value to all exposed occupants (weighted).

	Occupants with Serious Spleen Injuries (Weighted)	Injuries / 10,000 Exposed Occupants (weighted)
Belts + No Airbag	4,525	**7.86**
Belts + Airbag	3,222	**3.34**

Figure 38 and Figure 39 show there are changes in the injury sources for the spleen with the inclusion of airbags. Spleen injuries in drivers with an available airbag are significantly more likely to be attributed to the vehicle interior as compared to those without airbags. Right front passengers who have a spleen injury are more likely to suffer this injury as a result of the belts than any other source when an airbag is available. The loading path of the belts would most provide a higher likelihood of injury for the right front passenger because the shoulder belt would cross the region of the lower ribs that protect the spleen, possibly contributing to increased compression. The vehicle interior became the second largest source of serious splenic injury for drivers with the inclusion of airbags. Furthermore, 93% of the interior components that were given as the injury source for the spleen were on the left side of the occupant, corresponding to the location of the organ within the body, similar to relationship found for liver injury sources.

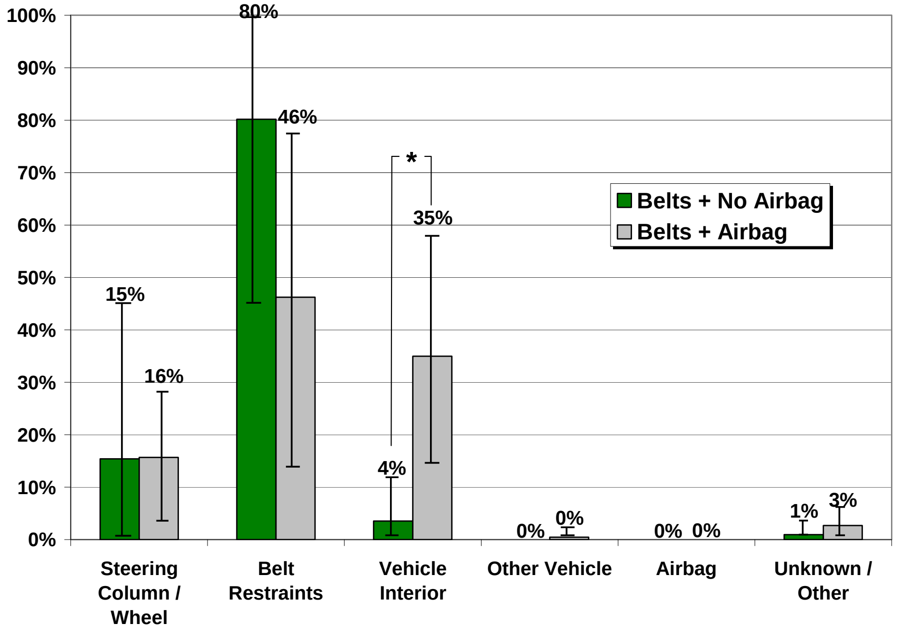

Figure 38: Distribution of serious spleen injuries by injury source for drivers (weighted).

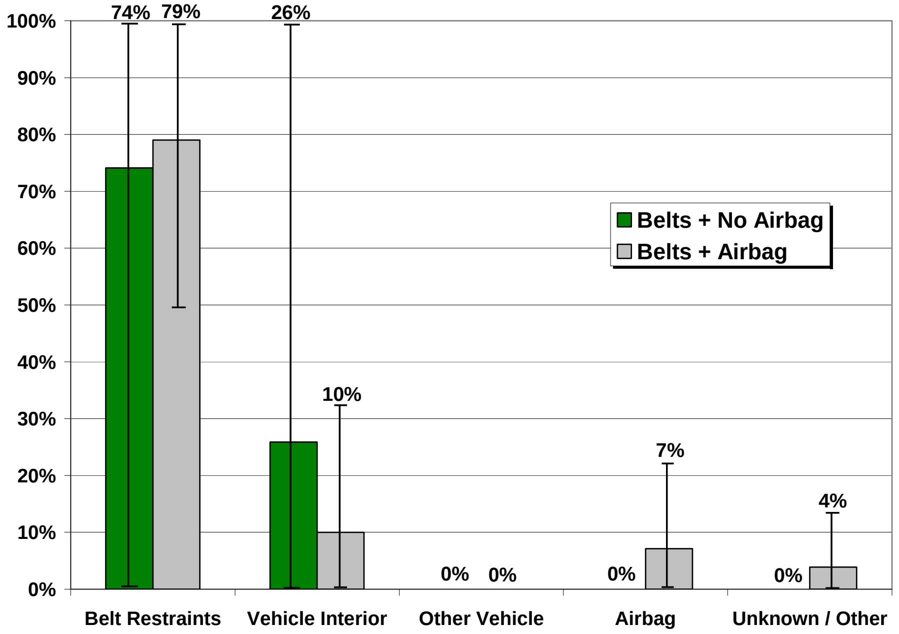

Figure 39: Distribution of serious spleen injuries by injury source for right front passengers (weighted).

4.3.4 Heart and Great Vessels Injury Mechanisms and Distributions

Injuries to the heart and great vessels can be particularly life threatening. Great vessel injuries include injuries to the thoracic aorta and vena cava. However, the NASS/CDS does not note which vessel is injured, only the level of injury and body region in which it occurs. Serious heart and great vessel injuries were primarily lacerations as expressed in Figure 40. The remainder of heart and great vessel injuries were contusions, avulsions, and ruptures. All of the contusions and ruptures for both restraint scenarios were to the heart, while 69% and 73% of the lacerations for those with and without airbags present, respectively, were to the great vessels. Shorr et al (1987) reported that contusions are the most common lesion type for the heart. Cardiac contusions are known to reduce the functionality of the heart, specifically the cardiac output (Augenstein et al 1997). Lacerations of the great vessels are known to be seriously life threatening, particularly with respect to the traumatic rupture of the aorta (TRA). TRA has been shown to account for 10-20% of all automotive fatalities (Viano 1983; Newman et al 1984).

The AIS value of serious heart and great vessel injuries appears to be increase with the inclusion of airbags. Most notably, 12% of all heart and great vessel injuries remain at the AIS6 level, as shown in Figure 41. There was no significant reduction in the percentage distribution for any of the serious injury levels. However, it was noted that there was a significant reduction in the number of heart and great vessel injuries when normalized for all belted front seat occupants exposed to frontal tow-away crashes as shown in Table 24. A modified Rao-Scott Chi-Square test revealed a significant association between the presence of an airbag and heart or great vessel injuries (p=0.0487), implying that the presence of an airbag significantly reduces the potential for serious heart or great vessel injury. Thus, while the severity heart or great vessel injury does not appear to be significantly different for occupants with and without airbags present, the rate at which the injuries occur has decreased with the implementation of airbags.

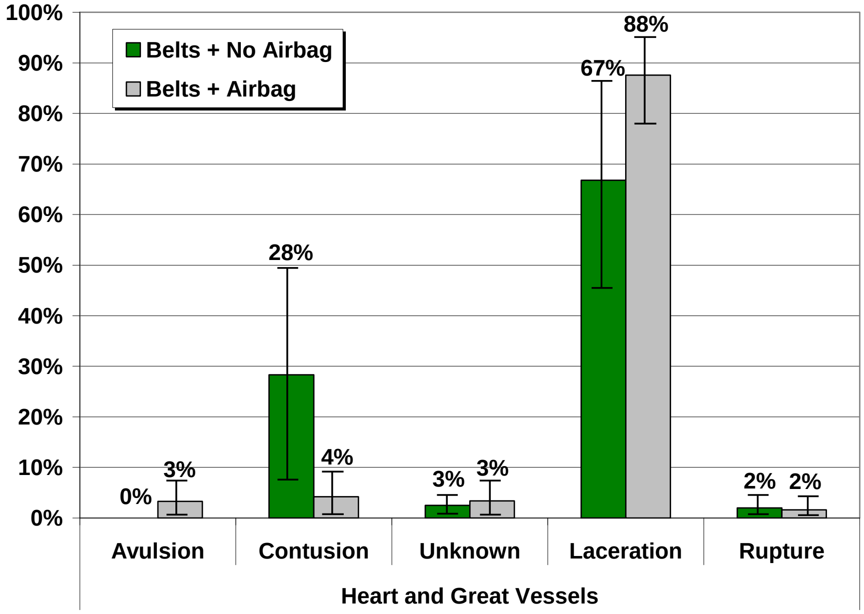

Figure 40: Distribution of AIS3+ heart and great vessel injuries by lesion type (weighted).

Table 24. Number of serious heart and great vessel injuries as well as their normalized value to all exposed occupants (weighted). (* - Indicates a significant difference in injury rate).

	Occupants with Serious Heart and Great Vessel Injuries (Weighted)	**Injuries / 10,000 Exposed Occupants (weighted)**
Belts + No Airbag	7,703	**11.61***
Belts + Airbag	3,790	**3.93***

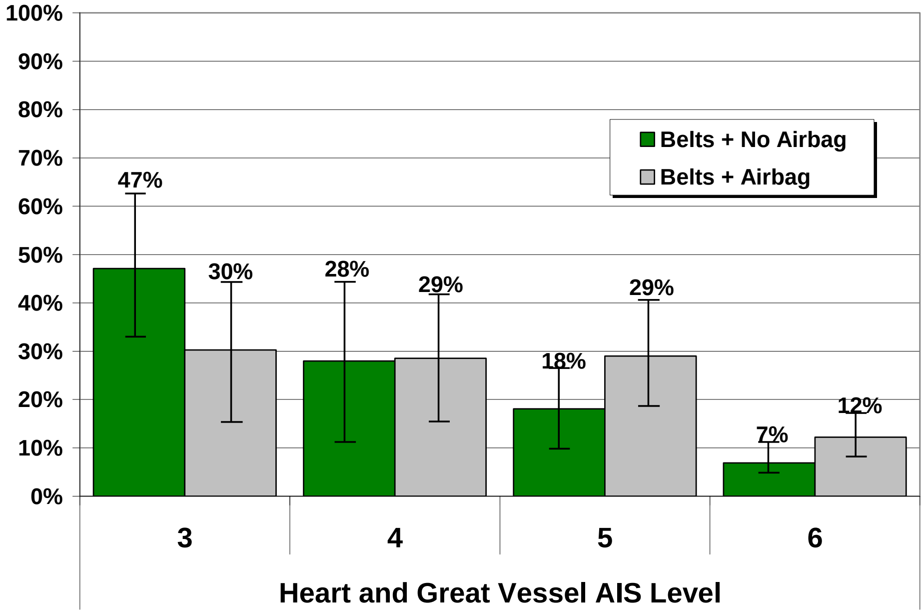

Figure 41: Distribution of heart and great vessel injuries by AIS level (weighted).

The AIS3+ heart and great vessel injury sources for drivers and right front passengers are given in Figure 42 and Figure 43. The steering assembly is the source for the most serious heart and great vessel injuries for drivers in vehicles with airbags; the vehicle interior was given as the source for the most heart and great vessel injuries to right front passengers in vehicles with airbags. The belts showed a reduction as the source of injury for occupants with an airbag present for both seating positions, but this result was only significant for the right front passengers. The vehicle interior showed a rise as the source of serious heart and great vessel injuries for both seating positions, although not statistically significant. The airbag accounts for a higher percentage (9%) of serious heart and great vessel injuries in either seating position than for any of the other organs analyzed, although it was not significantly higher than any of the other organs.

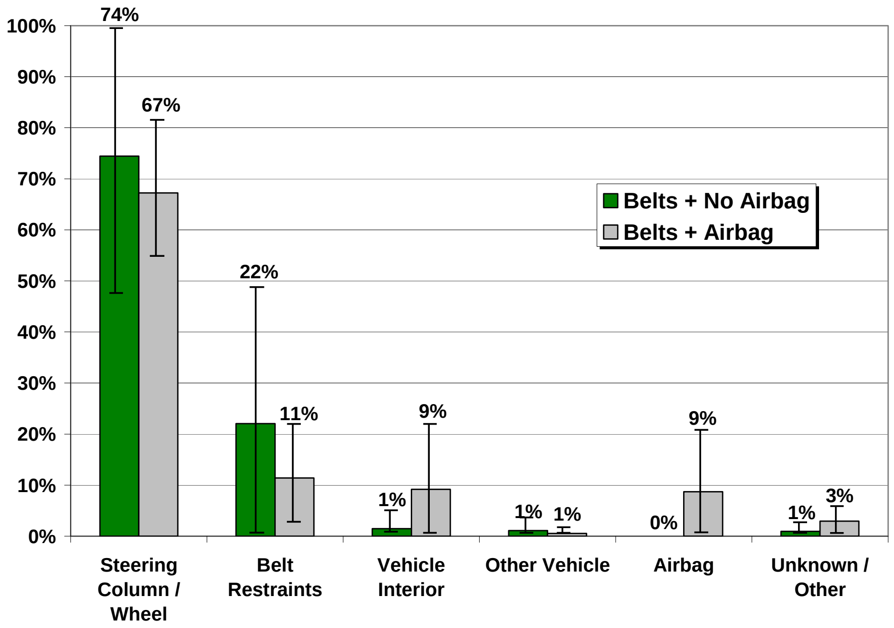

Figure 42: Distribution of serious heart and great vessel injuries by injury source for drivers (weighted).

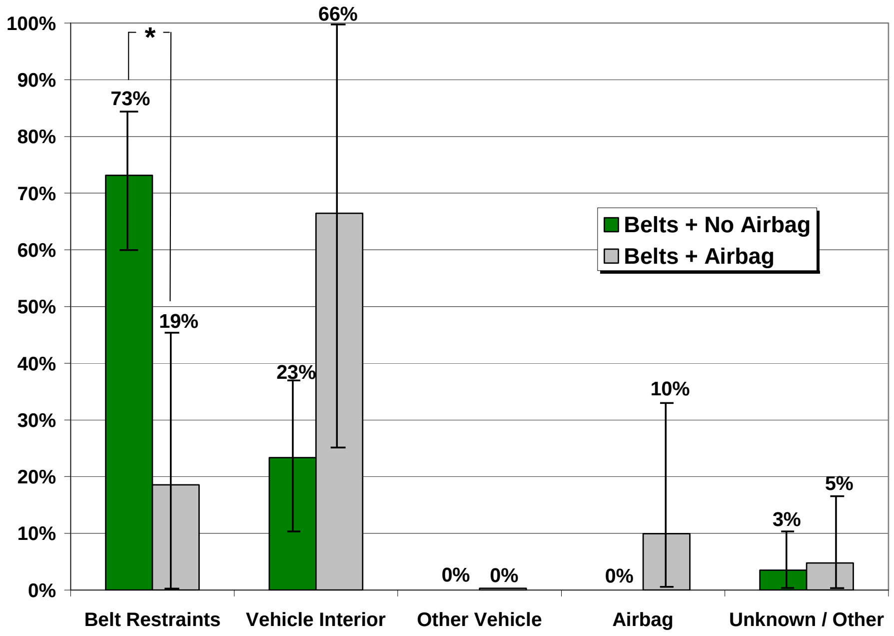

Figure 43: Distribution of serious heart and great vessel injuries by injury source for right front passengers (weighted).

4.3.5 Occupant Characteristics Associated with Injury

The previous section discussed the characteristics of the thoracic injuries with respect to the individual organs. This section will examine the characteristics of occupants who suffered thoracic organ injury. Characteristics include age, gender, weight, and stature. Significance tests were performed on all results using a two-sample paired t-test for means or a two-sample paired t-test for proportions.

Occupants with serious thoracic organ injuries were older on average (47.8 years) as compared to the average driving population, as shown in Table 25. This pattern was true for all organs; however, the results were only statistically significant for the lungs and heart and great vessels. The heart and great vessels also showed the highest average age for occupants who sustained a serious injury.

Table 26 examines whether the average age of occupants with thoracic organ injury is a function of the inclusion of airbags. Occupants with a serious spleen injury were the only group that showed a significant difference in age when comparing those with an airbag and those without. Occupants with an AIS3+ spleen injury and in a vehicle with an airbag were younger than occupants with a spleen injury in a non-airbag equipped vehicle. The spleen is at its maximum size during puberty and will reduce in size by 25-30% with time. This may be attributed to the an increased susceptibility of younger occupants to serious splenic injury.

Previous research has shown that there is an inverse bell-curve shape associated with the age of occupants in fatal crashes, where drivers between the age of 16-19 and drivers over the age of 75 had elevated fatality rates (Massie et al 1995). Similar results were shown for seriously injured occupants as well, with elevated risks associated with the 15-24 and 85-89 age groups (Tavris et al 2001). This pattern is not replicated in this data set with regard to thoracic organ injury. Higher injury rates have been reported for older occupants (>59 years), who have a 137% greater chance of sustaining a moderate or severe injury to any body region than younger occupants (Werner et al 1994b). Age thresholds for injury were not investigated on a body region or organ specific basis.

Table 25. Average age of those with an AIS3+ thoracic organ injury compared to those without.

	Organ Injury	All Occupants	Significance
All Thoracic Organs	**47.8**	**36.7**	**Significant**
Lung	**47.3**	**36.7**	**Significant**
Liver	39.4	36.7	Insignificant
Spleen	32.2	36.7	Insignificant
Heart and Great Vessels	**49.7**	**36.7**	**Significant**

Table 26. Average age of occupants who sustained an AIS3+ thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	No Airbag	Airbag	Significance
All Thoracic Organs	46.5	47.8	Insignificant
Lung	40.9	47.3	Insignificant
Liver	43.8	39.4	Insignificant
Spleen	**57.8**	**32.2**	**Significant**
Heart and Great Vessels	46.9	49.7	Insignificant

The gender ratios for serious thoracic organ injuries do not appear to be dependent on the thoracic organ of interest. Kleinberger et al (1997) reported that women may be more susceptible to injury because of lower bone strength, resulting in lower tolerance to compressive forces and more chest compression. Tavris et al (2001) noted that males are hospitalized significantly more often than females because males are more likely to be involved in a motor vehicle accident, with a male/female hospitalization ratio of 1.33:1. However, in this study, all serious or greater thoracic organ injuries, except spleen injuries, showed a higher percentage of females than exist in the general driving population. None of the gender differences were significantly higher. However, there is also no statistical difference in the distribution by gender when comparing those with an airbag as opposed to those without, although, again females accounted for a higher percentage of injuries, with the exception of those with spleen injuries.

Table 27. Statistical comparison of the gender of occupants who sustained a serious thoracic organ injury compared to those who did not.

	Gender	Percentage	Significance
All Occupants	***Female***	***49%***	**-**
	Male	***51%***	
All Thoracic Organs	Female	57%	Not Significant
	Male	43%	
Lung	Female	58%	Not Significant
	Male	42%	
Liver	Female	56%	Not Significant
	Male	44%	
Spleen	Female	47%	Not Significant
	Male	53%	
Heart and Great Vessel	Female	52%	Not Significant
	Male	48%	

Table 28. Statistical comparison of the gender of occupants who sustained a serious thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	Gender	No Airbag	Airbag	Significance
All Thoracic Organs	Female	45%	57%	Not Significant
	Male	55%	43%	
Lung	Female	32%	58%	Not Significant
	Male	68%	42%	
Liver	Female	58%	56%	Not Significant
	Male	42%	44%	
Spleen	Female	73%	47%	Not Significant
	Male	27%	53%	
Heart and Great Vessel	Female	42%	52%	Not Significant
	Male	58%	48%	

As shown in Table 29 there was no statistical difference in the height between injured occupants and the general population. With the exception of occupants with spleen injuries, there was no significant difference with injured occupants with and without an airbag. Occupants with spleen injuries and without an airbag were shorter than those with an airbag available.

These results differ from the Kleinberger hypothesis that shorter occupants are more susceptible to injury because they sit closer to the steering wheel (Kleinberger et al 1997). It was shown in a study of insurance claim cases that shorter females (<160cm) have 135% more potential of moderate or serious injury to any body region with a deployed airbag as compared to taller females (Werner et al 1994b). In particular, sitting closer to the steering wheel would make an occupant more susceptible to the "punch-out" phase of airbag deployment. This phase has been shown to be associated with thoracic and abdominal injuries (Horsch et al 1990). However, as shown previously, very few of the thoracic organ injuries are attributed to the airbag, thus the effect of occupant size may be minimized with regard to adverse airbag interaction. It is possible that this relationship may still exist for the head or other body regions, but it is not supported with respect to thoracic organ injuries by this research.

As shown in Table 31, there was no statistical difference in the weight of occupants with any serious thoracic organ injury as compared to the general population. Heart and great vessels injuries occur in occupants with a significantly higher average weight than the general driving population, as shown in Table 32. All other results showed no significance.

Table 29. Average height of occupants who sustained a serious thoracic organ injury compared to those who did not.

	Organ Injury (cm)	**All Occupants (cm)**	**Significance**
All Thoracic Organs	169.9	170.3	Insignificant
Lung	170.3	170.3	Insignificant
Liver	172.0	170.3	Insignificant
Spleen	175.3	170.3	Insignificant
Heart and Great Vessels	172.2	170.3	Insignificant

Table 30. Average height of occupants who sustained a serious thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	No Airbag (cm)	**Airbag (cm)**	**Significance**
All Thoracic Organs	171.0	169.9	Insignificant
Lung	175.3	170.3	Insignificant
Liver	168.6	172.0	Insignificant
Spleen	**163.5**	**175.3**	**Significant**
Heart and Great Vessels	171.2	172.2	Insignificant

Table 31. Average weight of occupants who sustained a serious thoracic organ injury compared to those who did not.

	Organ (kg)	**All Occupants (kg)**	**Significance**
All Thoracic Organs	76.5	75.4	Insignificant
Lung	74.4	75.4	Insignificant
Liver	78.4	75.4	Insignificant
Spleen	77.5	75.4	Insignificant
Heart and Great Vessels	**83.8**	**75.4**	**Significant**

Table 32. Average weight of occupants who sustained a serious thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	No Airbag (kg)	**Airbag (kg)**	**Significance**
All Thoracic Organs	80.6	76.5	Insignificant
Lung	87.4	74.4	Insignificant
Liver	81.2	78.4	Insignificant
Spleen	60.4	77.5	Insignificant
Heart and Great Vessels	80.5	83.8	Insignificant

4.3.6 Crash Characteristics Associated with Injury

This section will examine the characteristics which result in serious thoracic organ injury. Total delta-V is the resultant delta-V from the combination of the longitudinal and lateral delta-V calculations for the most harmful event that the vehicle was exposed to. Only vehicles with a primary direction of force between the 11- and 1-o'clock directions were included, thus the majority of force will be directed along the longitudinal axis of the vehicle. Roughly half of all vehicles did not have a reported delta-V. All cases without a reported delta-V were excluded from the comparison. The average total delta-v for vehicles where occupants suffered thoracic organ injuries was significantly higher than the average crash speed reported in NASS/CDS for frontal impacts. This was true for all thoracic organs, individually, as shown in Table 33. Table 34 shows that there is no significant difference in the average delta-v for injured occupants with and without airbags present. It may be assumed that it would require a more severe crash, i.e. a higher delta-V, to cause injury in the presence of an airbag under the assumption that the airbags are providing more protection than with belts alone. However, this hypothesis is not supported by the data presented. Loo et al (1996b) studied a population of 200 injured occupants and found speeds that lead to injury were not significantly different for belted only occupants as compared to belted occupants exposed to airbag deployment. This result was given for all occupants with an injury severity score (ISS) of 16 or higher. Interestingly, Segui-Gomez (2000b) reported that at lower speeds there may be an increase in the potential for injury associated with airbag deployment with respect to belted occupants, particularly for females. Also, it was shown that the velocity threshold where airbags showed a protective effect was much higher for females (27.5 kph) as compared to males (5.2 kph). As a result of this effectiveness threshold, it was hypothesized that it may be necessary to raise the delta-V threshold in the deployment algorithms to reduce the negative effects associated with injuries resulting from airbag deployment at lower delta-Vs. These results are based on NASS/CDS case years 1993-1996 and for drivers only. However, a similar report using NASS/CDS case years 1993-1999 by Nusholtz et al (2003) showed a net decrease in effectiveness with an increase in vehicle delta-V, with the highest effectiveness at lower speeds, and showed no difference in effectiveness for males and females.

It is important to note that only about half of all case vehicles in NASS/CDS have a specified delta-V. Many of the case vehicles are either not investigated or the damage type is out of the scope of the delta-V calculation algorithm. This presents two issues with respect to the presented results. First, approximately half of the injury cases are not included in the delta-V analysis, which will have a direct effect on the significance of the results. Second, certain types of frontal crashes are not included, specifically over-ride or under-ride crashes, which would presumably present a softer crash pulse than a more rigid impact. This loading scenario may have considerable effects on the deployment times of the airbag and thus, considerable effects on the reaction of the occupant to the deployment of the airbag.

Table 33. Average delta-v of vehicles in which an occupant sustained a serious thoracic present organ injury with an airbag compared to those who did not.

	Organ (kph)	All Occupants (kph)	Significance
All Thoracic Organs	**48.2**	**23.1**	**Significant**
Lung	**42.8**	**23.1**	**Significant**
Liver	**58.9**	**23.1**	**Significant**
Spleen	**41.6**	**23.1**	**Significant**
Heart and Great Vessels	**67.0**	**23.1**	**Significant**

Table 34. Average delta-v of vehicles in which an occupant sustained a serious thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	No Airbag (kph)	Airbag (kph)	Significance
All Thoracic Organs	49.9	48.2	Insignificant
Lung	48.4	42.8	Insignificant
Liver	57.8	58.9	Insignificant
Spleen	45.0	41.6	Insignificant
Heart and Great Vessels	52.1	67.0	Insignificant

Table 35 presents thoracic organ injuries by collision partner. Pole impacts are over represented in the number of thoracic organ injuries. Pole and tree impacts produce concentrated loading of the vehicle, which may be associated with a higher injury potential. However, the majority of thoracic organ injuries are still the result of impacts with other vehicles.

As shown in Table 36, the frequency of thoracic organ injuries by collision partner did not differ with or without airbags available. However, individually, all organs except the lungs showed a significant reduction in the percentage of injuries caused by pole impacts with the inclusion of airbags. It should be noted that there was a reduction in the total percentage of tow-away pole impacts for vehicles with airbags (11.6% without airbags, 9.1% with airbags). This may have contributed to the reduction in injuries associated with this impact type.

Table 35. Statistical comparison of struck objects for vehicles in which an occupant sustained a serious thoracic organ injury compared to those who did not.

	Object Struck	Percentage	Significance
All Crashes	***Non-Fixed***	***4%***	**-**
	Other-Fixed	***10%***	
	Pole	***10%***	
	Vehicle	***76%***	
All Thoracic Organs	**Non-Fixed**	**3%**	**Significantly More Pole**
	Other-Fixed	**7%**	
	Pole	**32%**	
	Vehicle	**58%**	
Lung	**Non-Fixed**	**3%**	**Significantly More Pole**
	Other-Fixed	**9%**	
	Pole	**36%**	
	Vehicle	**53%**	
Liver	Non-Fixed	1%	Not Significant
	Other-Fixed	5%	
	Pole	16%	
	Vehicle	79%	
Spleen	Non-Fixed	1%	Not Significant
	Other-Fixed	5%	
	Pole	14%	
	Vehicle	81%	
Heart and Great Vessel	Non-Fixed	3%	Not Significant
	Other-Fixed	2%	
	Pole	16%	
	Vehicle	80%	

Table 36. Statistical comparison of struck objects for vehicles in which an occupant sustained a serious thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	Object Struck	No Airbag	Airbag	Significance
All Thoracic Organs	Non-Fixed	2%	3%	Not Significant
	Other-Fixed	20%	7%	
	Pole	21%	32%	
	Vehicle	57%	58%	
Lung	Non-Fixed	3%	3%	Not Significant
	Other-Fixed	12%	9%	
	Pole	16%	36%	
	Vehicle	69%	53%	
Liver	Non-Fixed	0%	1%	Not Significant
	Other-Fixed	13%	5%	
	Pole	31%	16%	
	Vehicle	55%	79%	
Spleen	Non-Fixed	0%	1%	Not Significant
	Other-Fixed	60%	5%	
	Pole	21%	14%	
	Vehicle	19%	81%	
Heart and Great Vessel	Non-Fixed	3%	3%	Not Significant
	Other-Fixed	4%	2%	
	Pole	28%	16%	
	Vehicle	66%	80%	

The distribution of vehicle types that are associated with thoracic organ injuries are generally not significantly different than the general distribution of vehicle types involved in tow-away crashes as shown in Table 37. When comparing vehicles types associated with serious thoracic organ injury for those who have no airbag available as compared to those with airbags, there is a higher distribution of injuries in cars as shown in Table 38 with the exception of liver injuries. This may suggest that SUVs and trucks with airbags available provide better protection against thoracic organ injuries in frontal crashes, although the results are not significant.

Table 37. Statistical comparison of vehicle type in which an occupant sustained a serious thoracic organ injury compared to those who did not.

	Vehicle Type	Percentage	Significance
All Vehicles	***Car***	***82%***	**-**
	SUV/Truck	***18%***	
All Thoracic Organs	Car	84%	Not Significant
	SUV/Truck	16%	
Lung	Car	86%	Not Significant
	SUV/Truck	14%	
Liver	Car	80%	Not Significant
	SUV/Truck	20%	
Spleen	Car	90%	Not Significant
	SUV/Truck	10%	
Hear and Great Vessels	Car	77%	Not Significant
	SUV/Truck	23%	

Table 38. Statistical comparison of vehicle type in which an occupant sustained a serious thoracic organ injury with the presence of an airbag compared to those without an airbag present.

	Vehicle Type	No Airbag	Airbag	Significance
All Thoracic Organs	Car	72%	84%	Not Significant
	SUV/Truck	28%	16%	
Lung	Car	70%	86%	Not Significant
	SUV/Truck	30%	14%	
Liver	Car	80%	80%	Not Significant
	SUV/Truck	20%	20%	
Spleen	Car	83%	90%	Not Significant
	SUV/Truck	17%	10%	
Hear and Great Vessels	Car	66%	77%	Not Significant
	SUV/Truck	34%	23%	

4.4 Conclusion

Chest injuries make up a significant portion of the total injured body regions for belted occupants in frontal impacts. Thoracic organs account for over half of the AIS3+ chest injuries. Each thoracic organ has its own distributions of injury type and mechanism as well as characteristics associated with crash mode and occupant variability. Also, characteristics are often significantly different when comparing whether an airbag is available or not.

4.4.1 Lungs

- Lung injuries account for 66% of serious thoracic organ injuries with airbags.
- 95% of serious lung injuries are contusions with airbags present.
- The most common injury source is the steering assembly when no airbag is available for drivers; belt restraints when airbags are available. The belts and vehicle interior are each the source for 39% of injuries to the right front passenger with an airbag present.

4.4.2 Liver

- 96% of serious liver injuries were lacerations with airbags present.
- 41% of serious liver injuries are AIS4 or AIS5, which include bursting type injuries.
- The steering assembly and the belt system are listed as the source for the vast majority of AIS3+ injuries with and without airbags available for the driver. The belts and vehicle interior account for the most injuries to the right front passenger with an airbag present.
- Injuries associated with the vehicle interior were attributed to components on the right side of the occupant for 89% of the injuries.

4.4.3 Spleen

- 89% of serious spleen injuries with airbags are lacerations; 9% are ruptures.
- 4% of serious spleen injuries are attributed to the vehicle interior when no airbag is present and 30% with airbags; 92% were left side components for occupants with airbags.
- The belt system is listed as the source for the majority of splenic injuries for both airbag scenarios and for both the driver and right front passenger.

4.4.4 Heart and Great Vessels

- 88% of heart and great vessel injuries are lacerations; 73% of lacerations were to the great vessels, all contusions and ruptures were to the heart.
- The steering assembly (67%) accounts for the most serious heart and great vessel injuries for the driver and the vehicle interior (66%) for the right front passenger with an airbag available.
- The airbag was attributed to 9% of serious heart and great vessel injuries, more than any other thoracic organ.
- There is a significant association between the reduction in the number of heart and great vessel injuries and the presence of airbags.

4.4.5 Occupant Characteristics

- Occupants with serious lung and heart and great vessel injuries had a significantly higher age as compared to general driving population; occupants with serious spleen injuries were younger with an airbag, on average, as compared to those without airbags.
- The average height of occupant with serious splenic injury is higher with an available airbag than occupants in vehicles without an available airbag; the average weight of an occupant with a heart or great vessel injury is higher than the general driving population.

4.4.6 Crash Characteristics

- All thoracic organ injuries occur at a higher delta-v as compared to all tow-away crashes; there was no significant difference in delta-V for vehicles with occupants who sustained serious thoracic organ injury when comparing those with and without airbags.

4.5 References

AAAM (1998). Association for the Advancement of Automotive Medicine. The Abbreviated Injury Scale, 1990 Revision, Update 98 (1998).

Augenstein, J. S., K. Digges, L. V. Lombardo, E. B. Perdeck, J. E. Stratton, C. V. Quigley, A. C. Malliaris, P. M. Byers, D. B. Nunex, G. A. Zych, J. L. Andron, A. K. Craythorne and E. Y. Perri (1995). Chest and Abdominal Injuries Suffered by Restrained Occupants. International Congress an Exposition, Detroit, MI, SAE 950657.

Augenstein, J. S., E. B. Perdeck, J. Williamson, J. E. Stratton, M. Murtha, K. Sapnas, K. Digges, A. C. Malliaris and L. V. Lombardo (1997). Heart Injuries Among Restrained Occupants in Frontal Crashes. SAE International Congress and Exposition, Detroit, MI, SAE 970392.

Cavanaugh, J. C. (1993). The Biomechanics of Thoracic Trauma. Accidental Injury: Biomechanics and Prevention. A. M. Nahum and J. W. Melvin. New York, NY, Springer-Verlag**:** 362-390.

Cohn, S. M. (1997). "Pulmonary contusion: review of the clinical entity." The Journal of Trauma: Injury, Infection, and Critical Care 42(5)**:** 973-9.

Elhagediab, A. M. and S. W. Rhouhana (1998). Patterns of Abdominal Injury in Frontal Automotive Crashes. 16th International Technical Conference on Experimental Safety Vehicles 98-S1-W-26.

Eppinger, R., E. Sun, F. Bandak, M. Haffner, N. Khaewpong, M. Maltese, S. M. Kuppa, T. Nguyen, E. Takhounts, R. Tannous, A. Zhang and R. Saul (1999) "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems - II."

Frey, C. F., M. Trollope, W. Harpster and R. Snyder (1973). "A fifteen-year experience with automotive hepatic trauma." The Journal of Trauma: Injury, Infection, and Critical Care 13(12)**:** 1039-49.

Hardy, K. J. (1972). "Patterns of liver injury after fatal blunt trauma." Surg Gynecol Obstet 134(1)**:** 39-43.

Hoff, S. J., S. D. Shotts, V. A. Eddy and J. A. Morris, Jr. (1994). "Outcome of isolated pulmonary contusion in blunt trauma patients." Am Surg 60(2)**:** 138-42.

Horsch, J., I. V. Lau, D. Andrzejak, D. C. Viano, J. W. Melvin, J. Pearson, D. Cok and G. Miller (1990). Assessment of Air Bag Deployment Loads. Society of Automotive Engineers 902324.

Kent, R., J. Crandall, J. Patrie and J. Fertile (2002). "Radiographic Detection of Rib Fractures: A Restraint-Based Study of Occupants in Car Crashes." Traffic Inj Prev 3(1)**:** 49-57.

King, A. I. (2000). "Fundamentals of impact biomechanics: Part I--Biomechanics of the head, neck, and thorax." Annu Rev Biomed Eng 2**:** 55-81.

Kleinberger, M. and L. Summers (1997). Mechanisms of Injuries for Adults and Children Resulting from Airbag Interaction. 41st Association for the Advancement of Automotive Medicine, Orlando, FL.

Kleinberger, M., E. Sun, R. Eppinger, S. M. Kuppa and R. Saul (1998) "Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems."

Kroell, C. K., D. C. Schneider and A. M. Nahum (1971). Impact Tolerance and Response of the Human Thorax. Proceedings of the 15th Stapp Car Crash Conference, New York, Society of Automotive Engineers 710851.

Kroell, C. K., D. C. Schneider and A. M. Nahum (1974). Impact Tolerance and Response of the Human Thorax II. Proceedings of the 18th Stapp Car Crash Conference, Warrendale, PA 741187.

Lau, V. K. and D. C. Viano (1981a). "An experimental study on hepatic injury from belt-restraint loading." Aviat Space Environ Med 52(10)**:** 611-7.

Lau, V. K. and D. C. Viano (1981b). "Influence of impact velocity on the severity of nonpenetrating hepatic injury." The Journal of Trauma: Injury, Infection, and Critical Care 21(2)**:** 115-23.

Loo, G. T., J. H. Siegel, P. C. Dischinger, D. Rixen, A. R. Burgess, M. D. Addis, T. O'Quinn, L. McCammon, C. B. Schmidhauser, P. Marsh, P. A. Hodge and F. Bents (1996). "Airbag protection versus compartment intrusion effect determines the pattern of injuries in multiple trauma motor vehicle crashes." The Journal of Trauma: Injury, Infection, and Critical Care 41(6)**:** 935-51.

Malliaris, A. C., R. Hitchcock and J. Hedlund (1982). A Search for Priorities in Crash Protection. Society of Automotive Engineers 820242.

Massie, D. L., K. L. Campbell and A. F. Williams (1995). "Traffic accident involvement rates by driver age and gender." Accid Anal Prev 27(1)**:** 73-87.

Matthes, G., U. Schmucker, E. Lignitz, M. Huth, A. Ekkernkamp and J. Seifert (2006). "Does the frontal airbag avoid thoracic injury?" Arch Orthop Trauma Surg 126(8)**:** 541-4.

Mays, E. T. (1966). "Bursting injuries of the liver. A complex surgical challenge." Arch Surg 93(1)**:** 92-106.

Miller, L. A. (2006). "Chest wall, lung, and pleural space trauma." Radiol Clin North Am 44(2)**:** 213-24, viii.

Miller, P. R., M. A. Croce, T. K. Bee, W. G. Qaisi, C. P. Smith, G. L. Collins and T. C. Fabian (2001). "ARDS after pulmonary contusion: accurate measurement of contusion volume identifies high-risk patients." The Journal of Trauma: Injury, Infection, and Critical Care 51(2)**:** 223-8; discussion 229-30.

Morgan, R., R. Eppinger, M. Haffner, N. Yoganandan, F. Pintar, A. Sances, J. Crandall, W. Pilkey, G. Klopp, D. Kallieris, E. Miltner, R. Mattern, S. M. Kuppa and C. Sharpless (1994). Thoracic Trauma Assessment Formulations for Restrained Drivers in Simulated Frontal Impacts. Society of Automotive Engineers 942206.

Mustard, R. A., Jr., S. S. Hanna, G. Blair, A. W. Harrison, G. A. Taylor, H. A. Miller and R. Maggisano (1984). "Blunt splenic trauma: diagnosis and management." Can J Surg 27(4)**:** 330-3.

Nahum, A. M., C. W. Gadd, D. C. Schneider and C. K. Kroell (1970). Deflection of the Human Thorax Under Sternal Impact. International Safety Conference Compendium, New York, Society of Automotive Engineers 700400.

Nahum, A. M., C. W. Gadd, D. C. Schneider and C. K. Kroell (1971). "The Biomechanical Basis for Chest Impact Protection. I. Force-Deflection Characteristics of the Thorax." The Journal of Trauma: Injury, Infection, and Critical Care 11(10)**:** 874-82.

Nahum, A. M. and A. M. Melvin (2002). Accidental Injury: Biomechanics and Prevention 2nd. New York, Springer-Verlag.

Nahum, A. M., D. C. Schneider and C. K. Kroell (1975). Cadaver Skeletal Response to Blunt Thoracic Impact. Proceedings of the 19th Stapp Car Crash Conference 751150.

Neathery, C. K. (1974). Analysis of Chest Impact Response Data and Scaled Performance Recommendations. Proceedings of the 18th Stapp Car Crash Conference 741188.

Neathery, C. K. and T. E. Lobdell (1973). Mechanical Simulation of Human Thorax Under Impact. Proceedings of the 17th Stapp Car Crash Conference 730982.

Newman, R. J. and S. Rastogi (1984). "Rupture of the thoracic aorta and its relationship to road traffic accident characteristics." Injury 15(5)**:** 296-9.

NHTSA (1999). Federal Motor Vehicle Safety Standard DOT HS 808 878.

Nusholtz, G. S., F. Famili, L. Di Domenico, Y. Shi, Z. B. Aoun and Y. Hongsakaphadana (2003). "Air bag effectiveness as function of impact speed." Traffic Inj Prev 4(2)**:** 128-35.

Rivkind, A. I., J. H. Siegel and C. M. Dunham (1989). "Patterns of organ injury in blunt hepatic trauma and their significance for management and outcome." The Journal of Trauma: Injury, Infection, and Critical Care 29(10)**:** 1398-415.

Rouhana, S. (1993). Biomechanics of Abdominal Trauma. Accidental Injury: Biomechanics and Prevention. A. M. Nahum and J. W. Melvin. New York, NY, Springer-Verlag**:** 391-428.

Schenker, N. and J. F. Gentleman (2001). "On Judging the Significance of Differences by Examining the Overlap Between Confidence Intervals." The American Statistician 55(3)**:** 182-186.

Schmitt, K. U., P. Niederer and F. Walz (2004). Trauma Biomechanics: Introduction to Accidental Injury. New York, Springer.

Segui-Gomez, M. (2000). "Driver air bag effectiveness by severity of the crash." Am J Public Health 90(10)**:** 1575-81.

Shorr, R. M., M. Crittenden, M. Indeck, S. L. Hartunian and A. Rodriguez (1987). "Blunt thoracic trauma. Analysis of 515 patients." Ann Surg 206(2)**:** 200-5.

Sirmali, M., H. Turut, S. Topcu, E. Gulhan, U. Yazici, S. Kaya and I. Tastepe (2003). "A comprehensive analysis of traumatic rib fractures: morbidity, mortality and management." Eur J Cardiothorac Surg 24(1)**:** 133-8.

Sparks, J. L., J. H. t. Bolte, R. B. Dupaix, K. H. Jones, S. M. Steinberg, R. G. Herriott, J. A. Stammen and B. R. Donnelly (2007). "Using pressure to predict liver injury risk from blunt impact." Stapp Car Crash J 51**:** 401-32.

Tavris, D. R., E. M. Kuhn and P. M. Layde (2001). "Age and gender patterns in motor vehicle crash injuries: importance of type of crash and occupant role." Accid Anal Prev 33(2)**:** 167-72.

Viano, D. C. (1978). Thoracic Injury Potential. International Meeting on the Simulation and Reconstruction of Impacts in Collisions, Lyon, France.

Viano, D. C. (1983). Biomechanics of Non-Penetrating Aortic Trauma: A Review. 27th Stapp Car Crash Conference.

Viano, D. C. and A. I. King (2000). Biomechanics of Chest and Abdomen Impact. The Biomedical Engineering Handbook. J. D. Bronzino, CRC Press.v1**:** 24.

Wagner, R. B., W. O. Crawford, Jr. and P. P. Schimpf (1988). "Classification of Parenchymal Injuries of the Lung." Radiology 167(1)**:** 77-82.

Walt, A. J., J. G. Thomas and R. D. Williams (1970). Blunt Abdominal Injury: A Review of 307 Cases. Impact Injury and Crash Protection. E. S. Gurdjian, W. A. Lange and L. M. Thomas. Springfield, IL, Charles Thomas**:** 101-124.

Werner, J. V. and W. W. Sorenson (1994). Survey of Airbag Involved Accidents An Analysis of Collision Characteristics, System Effectiveness and Injuries. Society of Automotive Engineers 940802.

Wolfe, R. and J. Hanley (2002). "If we're so different, why do we keep overlapping? When 1 plus 1 doesn't make 2." Cmaj 166(1)**:** 65-6.

Chapter 5. Rib Fractures and Thoracic Organ Injury

5.1 Introduction

Trauma is the third leading cause of death in the United States, and the leading fatality risk for those under forty years of age (Shorr et al 1987; Ziegler et al 1994; Sirmali et al 2003). Thoracic trauma represents 10-15% of all trauma and leads to 25% of all deaths related to trauma. Blunt trauma of the chest is more common than penetrating trauma and the majority of blunt chest traumatic injuries are the result of motor vehicle crashes (MVCs) (Poole et al 1981; Shorr et al 1987; Clark et al 1988; Ziegler et al 1994; Shweiki et al 2001; Sirmali et al 2003).

Rib fractures are often associated with blunt chest trauma (70%), and the severity and number of fractures can dictate the severity and survivability of a traumatic event (Sirmali et al 2003). Sirmali et al investigated 548 cases of rib fracture due to trauma and found increasing extrathoracic complication rates with an increase in the number of rib fractures. The extrathoracic complications were often pulmonary in nature and included hemothorax, pnuemothorax, hemo-pnuemothorax, pneumonia, atelectasis, and adult respiratory distress syndrome (ARDS) (Shorr et al 1987; Sirmali et al 2003).

Associated extrathoracic injuries, other than pulmonary complications, often include abdominal organ injuries (Shorr et al 1987). The most common of these injuries include liver and spleen injuries. Sheiwki et al (2001) reported a significant correlation between any rib fractures on the right side or any lower rib fracture with liver injury. The same was reported for spleen injury with left side rib fractures. These findings supported those reported by Clark et al (1988). Lee et al (1990) computed relative risk values for liver or spleen injury for those who did and did not sustain at least 3 rib fractures as the result of trauma. Hospitalized subjects with three or more rib fractures are 3.6 times more likely to have liver injuries and 6.2 times more likely to have spleen injuries than those without rib fracture.

Automobile crashes often involve the transfer of large amounts of energy that must be dissipated by the vehicle, the restraints, and the occupants. Later model vehicles have incorporated countermeasures such as seat belts and airbags to help transfer the energy to regions of the vehicle or occupant that will reduce injury risks. These occupant restraints can produce rib fractures (Shorr et al 1987; Sirmali et al 2003). Also, extrathoracic injuries, are often associated with rib fracture, whether from the excess intrusion of the ribs or laceration from the fractured rib. However, it is difficult to determine if rib fractures cause organ injuries, or if rib fractures and organ injuries simply occur together in crashes (Flagel et al 2005).

Objective

The goal of this paper is to determine whether an association exists between rib fractures and lung, liver, and spleen injuries in MVCs for varying airbag exposures.

5.2 Methods

The data for this paper was extracted from NASS/CDS 1993-2007 real world crash investigations. The results were compiled using SAS (SAS Institute, Cary, NC). The cases for this study were restricted to belted drivers and right front seat passengers who were involved in crashes where the most harmful event was a frontal collision and the principal direction of force was between 11- and 1-o'clock. Cases with a rollover or an ejected occupant event were excluded. Three restraint conditions were considered: (1) occupants in vehicles with an airbag available, (2) occupants exposed to an airbag deployment, and (3) occupants exposed to a first generation or depowered airbag deployment. The statistical significance of the results are reported using 95% confidence intervals and two sample t-tests for comparing between organs and a modified Rao-Scott chi-square test for the contingency table analysis. The significance results were based on the Taylor series linearization method for computing variances of a stratified and clustered survey design. The relationships between thoracic organ injury and rib fracture investigated in this study are with regard to the lungs, liver, and spleen. These three organs have been listed in the literature as having the strongest association to the presence of rib fracture (Shorr et al 1987; Sirmali et al 2003). The lowest coded injury for any of these three organs according to the AIS scale is a value of 2 (moderate injury). Rib fracture injuries can be coded at the AIS1 level (minor injury) (AAAM 1998).

Based on the cases that meet the above restrictions, this analysis looks specifically at the rib fracture side and its relation to organ injury as follows:

- Lung injuries associated with any rib fracture
- Spleen injuries associated with left or bi-lateral rib fractures
- Liver injuries associated with right or bi-lateral rib fractures

NASS/CDS does not provide information regarding which rib(s) were fractured, so a more in-depth analysis of this nature was not possible. All reported injuries are categorized using the Abbreviated Injury Scale (AIS).

5.3 Results

Table 39: Distribution of occupants for each organ injury.

	Total Injury (Unweighted)	Total Injury (weighted)
Lung	442	30,666
Liver	292	17,480
Spleen	258	19,767
Skeletal	1,329	192,876

The total number of injuries for each organ is given in Table 39. Thoracic injuries make up a large fraction of all serious injuries in automobile accidents. As shown in Figure 44, chest injuries comprise 22% of serious injuries in frontal crashes for belted occupants in vehicles with a frontal airbag.

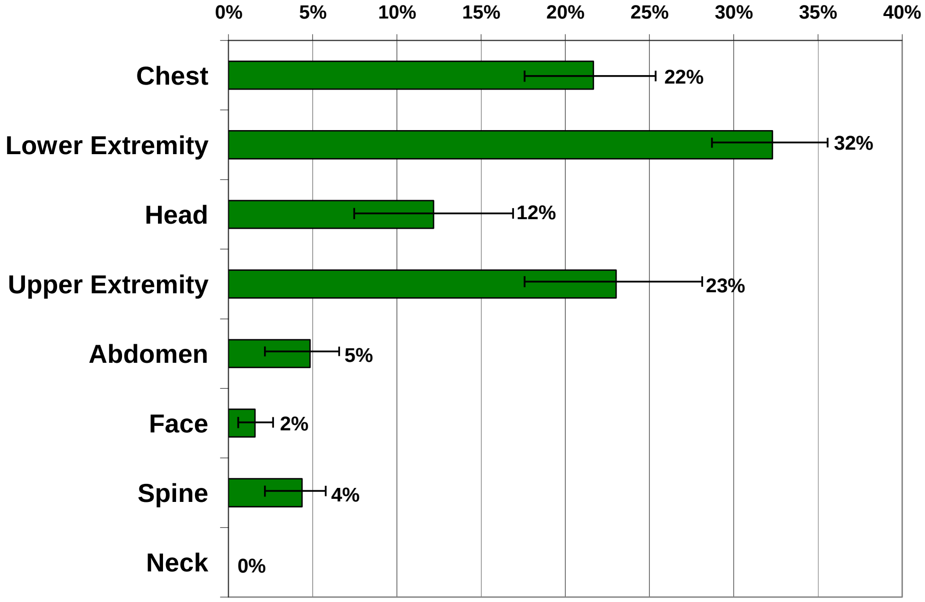

Figure 44: Distribution of AIS3+ injuries by body region for belted occupants with airbags in frontal crashes (weighted).

5.3.1 Occupants in Vehicles Equipped with Airbags

Figure 45 illustrates that lung injuries occur in 8% of rib fracture cases, liver injuries in 10% of cases and spleen injuries in 4% of cases with fracture. Thus, thoracic organ injuries are infrequently associated with rib fractures in frontal crashes for occupants with airbags. The liver had the highest percentage of injuries with the presence of an airbag, but the large confidence intervals should be noted. 17% of rib fracture cases had an associated lung, liver, or spleen injury.

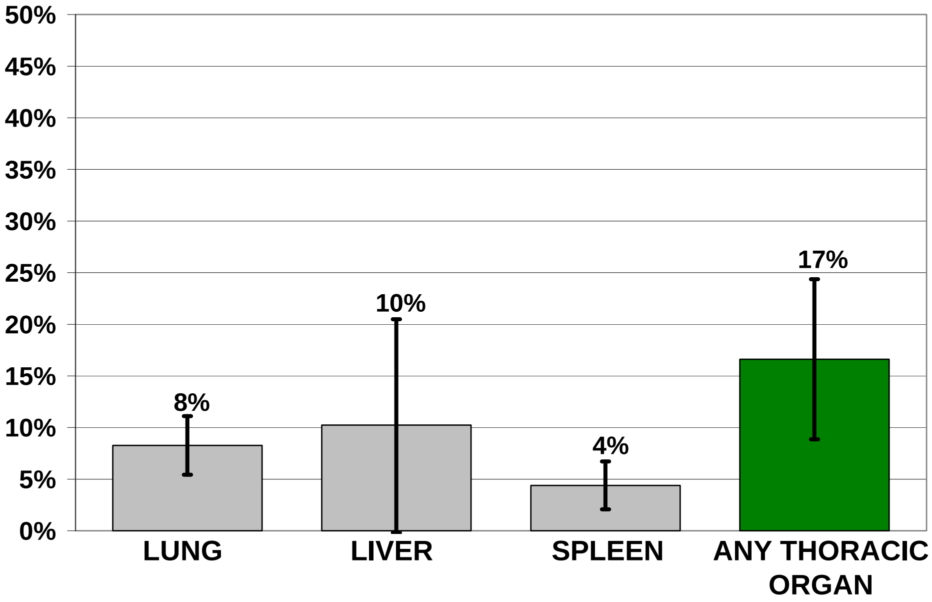

Figure 45: Risk of an AIS2+ organ injury given the presence of a rib fracture for belted occupants in vehicles with a frontal airbag (weighted).

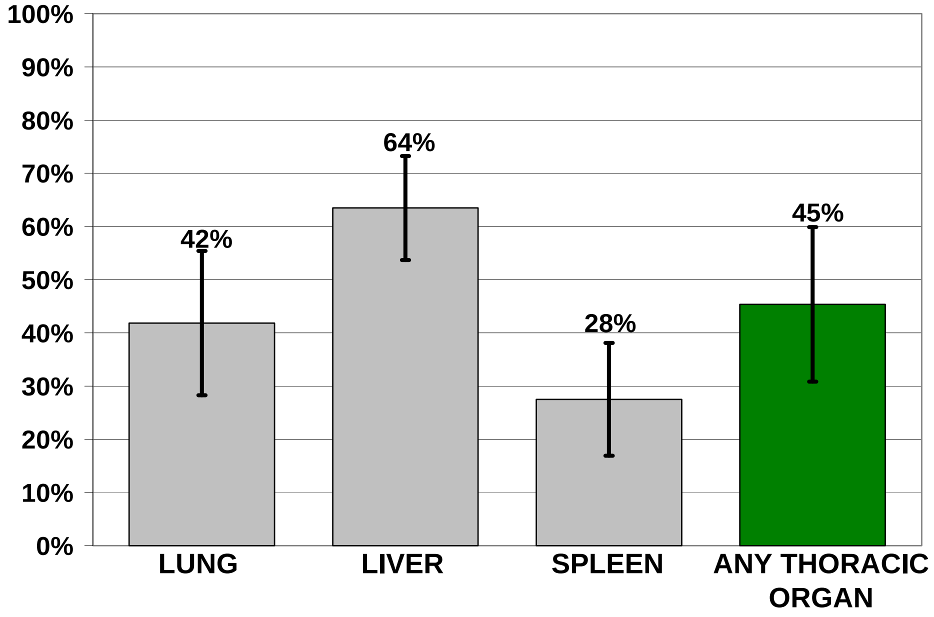

Figure 46: Risk of rib fracture given an AIS2+ organ injury for belted occupants in vehicles with a frontal airbag (weighted).

Analyzing the rate of occurrence of an associated rib fracture when an organ injury occurs provides a different perspective. Given that there was an AIS2+ lung or spleen injury, Figure 46 suggests that there are not associated rib fractures in the majority of all frontal crashes with serious thoracic organ injuries. This result is shown with a point estimate that is less than 50%, although this result is not statistically significant for occupants with lung injuries, for which the confidence interval contains the 50% value. However, when a liver injury occurs, the majority of occupants have an associated rib fracture. Combined, if any of the three organs are injured, the 40-69% of occupants do not have an associated rib fracture. The spleen shows both the lowest percentage of organ injuries associated with rib fractures as well as the lowest percentage of rib fractures associated with organ injury. This may imply that there is less of direct relationship between rib fracture and spleen injury than there is for the lung or liver with the presence of an airbag.

Table 40: 2x2 contingency test table test utilizing a modified Rao-Scott chi-square to test for independence between organ injuries and associated rib fractures for occupants in vehicles with a frontal airbag (weighted).

		No Fracture	Fracture	
Lung	**No Injury**	**9,530,612**	**99,472**	**p-value < 0.0001**
	Injury	**12,470**	**8,973**	
		0.13%	8.27%	
Liver	**No Injury**	**9,572,127**	**67,312**	**p-value < 0.0001**
	Injury	**4,407**	**7,681**	
		0.05%	10.24%	
Spleen	**No Injury**	**9,561,218**	**77,377**	**p-value < 0.0001**
	Injury	**9,374**	**3,558**	
		0.10%	4.40%	
Any Thoracic	**No Injury**	**9,521,385**	**90,433**	**p-value < 0.0001**
	Injury	**21,698**	**18,012**	
		0.23%	16.61%	

Table 41: Relative risk of thoracic organ injury with the presence of rib facture for hospitalized occupants in a vehicle with an available airbag (weighted). * - indicates a significantly greater risk with rib fracture.

	Relative Risk	Confidence Intervals		Significance
		-	+	
Lung	**3.43**	**1.81**	**6.51**	*
Liver	**13.40**	**3.41**	**52.63**	*
Spleen	**2.43**	**1.08**	**5.46**	*
Any Thoracic Organ	***4.34***	***2.40***	***7.85***	*

The Rao-Scott modified chi-square contingency test results shown in Table 40 express that there indeed is a significant association between the thoracic organ injuries with rib fractures for belted occupants in frontal crashes where an airbag is present. The chi-square test used in a 2x2 contingency table, as shown above in Table 40, compares the percentage of occupants who sustained an organ injury without an associated rib fracture to the percentage of occupants who sustained an organ injury with rib fracture. The results of the test specify if there is a significant association between the two groups (thoracic organ injury and rib fracture). The results given for each organ in Table 40 show that an association exists between the groups. These results do not tell us, however, whether the organ injuries are caused by the rib fracture or if either injury type is the direct result of increased crash severity only. The results given in Table 41 show there is an increased risk of injury to each of the thoracic organs with the presence of a rib fracture when the occupant is hospitalized following the collision in which the vehicle had an airbag available.

5.3.2 Occupants Exposed to Airbag Deployment

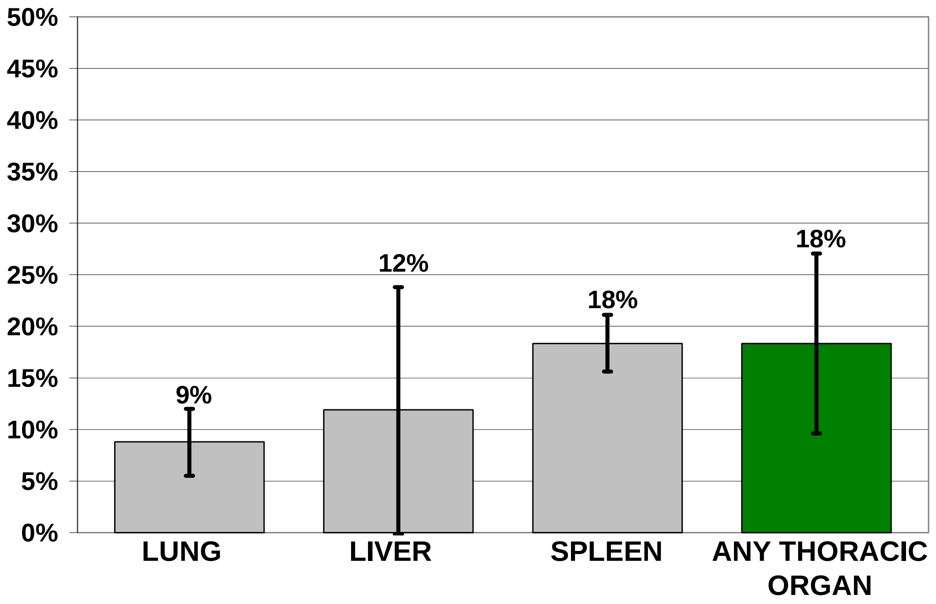

Figure 47: Risk of an AIS2+ organ injury given the presence of a rib fracture for belted occupants exposed to a deployed frontal airbag (weighted).

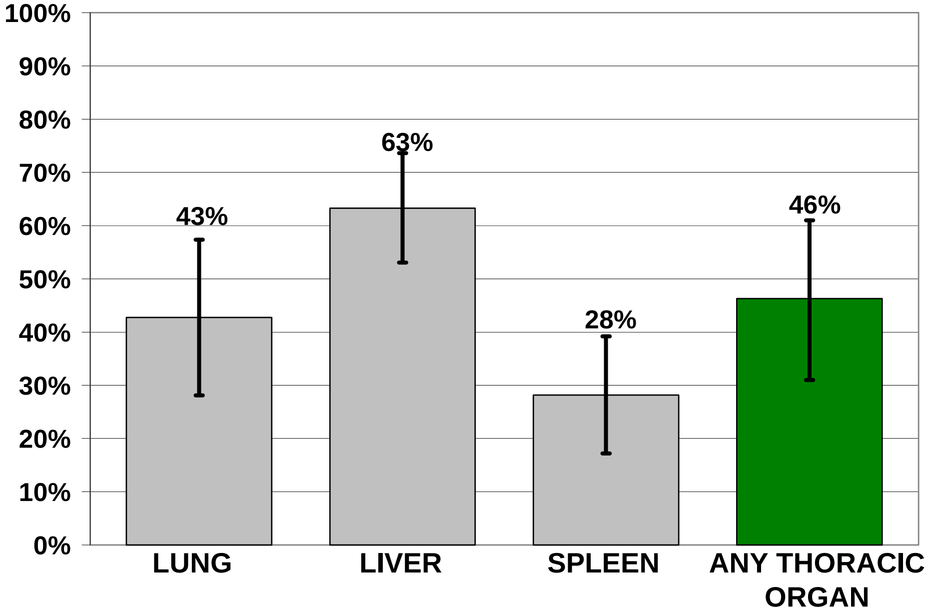

Figure 48: Risk of rib fracture given an AIS2+ organ injury for belted occupants exposed to a deployed frontal airbag (weighted).

Only 36% of occupants in vehicles with an available frontal airbag were also exposed to the deployment of an airbag. However, Figure 45 and Figure 47 show the percentage of rib fractures that have an associated thoracic organ injury are roughly equivalent for occupants in vehicles with airbags as compared to occupants who are exposed to an airbag deployment, with the exception of spleen injuries. Spleen injuries occur in a significantly higher percentage of cases with associated rib fracture when an airbag deploys (18%) as compared to occupants in vehicles with frontal airbags available (4%).

There was no appreciable difference in the percentage of combined organ injury cases that had an associated rib fracture, as shown in Figure 46 and Figure 48, for occupant in vehicles with an available airbag as compared to those exposed to an airbag deployment. Table 42 shows with airbag deployment, there is a significant association between rib fracture and each thoracic organ injury. The results given in Table 43 show there is an increased risk of injury to each of the thoracic organs with the presence of a rib fracture when the occupant exposed to a deployed airbag is hospitalized.

Table 42: 2x2 contingency test table test utilizing a modified Rao-Scott chi-square to test for independence between organ injuries and associated rib fractures for occupants exposed to a deployed frontal airbag (weighted).

		No Fracture	Fracture	
Lung	**No Injury**	**5,438,442**	**86,413**	**p-value < 0.0001**
	Injury	**11,238**	**8,385**	
		0.21%	8.85%	
Liver	**No Injury**	**5,477,068**	**55,576**	**p-value < 0.0001**
	Injury	**4,340**	**7,494**	
		0.08%	11.88%	
Spleen	**No Injury**	**5,467,085**	**64,963**	**p-value < 0.0001**
	Injury	**8,929**	**3,500**	
		0.16%	5.11%	
Any Thoracic	**No Injury**	**5,429,510**	**77,420**	**p-value < 0.0001**
	Injury	**20,170**	**17,378**	
		0.37%	18.33%	

Table 43: Relative risk of thoracic organ injury with the presence of rib facture for hospitalized occupants exposed to a deployed airbag (weighted). * - indicates a significantly greater risk with rib fracture.

	Relative Risk	Confidence Intervals		Significance
		-	+	
Lung	**3.21**	**1.56**	**6.59**	*
Liver	**11.92**	**2.91**	**48.78**	*
Spleen	**2.36**	**1.03**	**5.41**	*
Any Thoracic Organ	***4.10***	***2.19***	***7.69***	*

5.3.3 Occupants Exposed to First Generation and Depowered Airbag Deployments

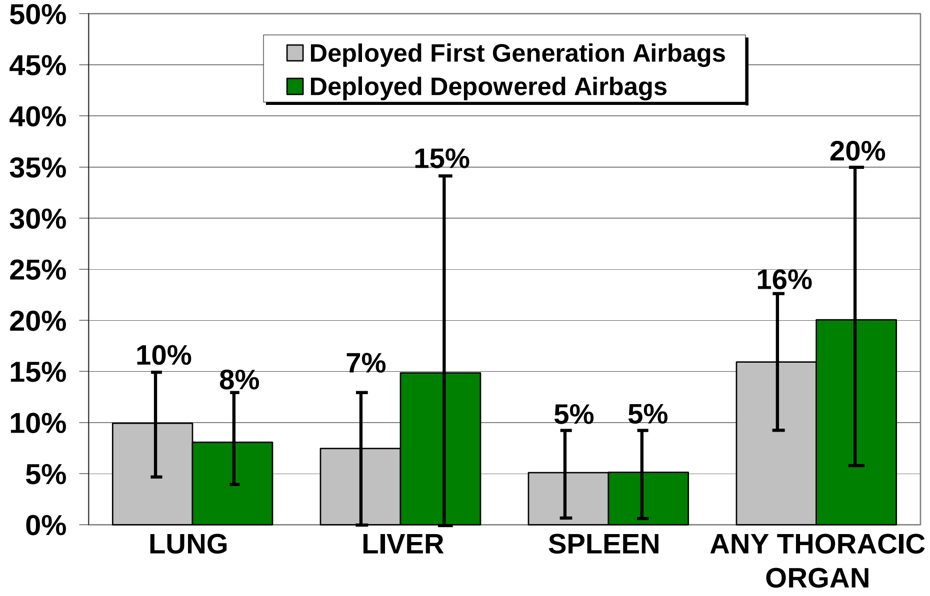

Figure 49: Risk of an AIS2+ organ injury given the presence of a rib fracture for belted occupants exposed to a deployed first generation or depowered airbag (weighted).

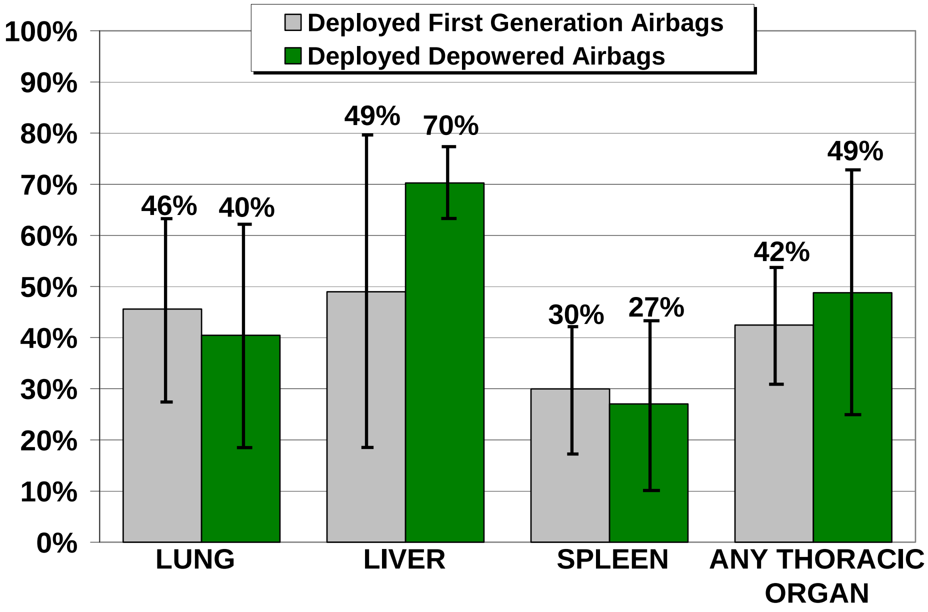

Figure 50: Risk of rib fracture given an AIS2+ organ injury for belted occupants exposed to a deployed first generation or depowered airbag (weighted).

Figure 49 shows there is no significant difference in the percentage of occupants who experienced a rib fracture and have an associated thoracic organ injury when exposed to a first generation airbag deployment, as compared to those exposed to a depowered deployment. While the result may not be statistically significant, the liver does appear to be injured more frequently when a rib fracture is present for depowered airbags as compared to first generation airbags. Figure 50 shows there is no statistically significant difference between first generation airbags and depowered airbags, with respect to the percentage of rib fractures when a liver injury is sustained. Both Table 44 and Table 46 show there is a significant association between rib fracture and thoracic organ injury for occupants exposed to either a first generation airbag deployment or a depowered airbag deployment. The results given in Table 45 show that there is an increased risk of injury to each of the thoracic organs with the presence of a rib fracture when an occupant exposed to first generation airbag deployment and is hospitalized following the collision. However, Table 47 shows that there is not a significant increase in risk of lung or spleen injury when an occupant is exposed to a deployed, depowered airbag and hospitalized following the crash.

Table 44: 2x2 contingency test table test utilizing a modified Rao-Scott chi-square to test for independence between organ injuries and associated rib fractures for occupants exposed to a deployed, first generation frontal airbag (weighted).

		No Fracture	**Fracture**	
Lung	**No Injury**	**3,013,596**	**35,622**	**p-value < 0.0001**
	Injury	**4,686**	**3,929**	
		0.16%	9.93%	
Liver	**No Injury**	**3,030,535**	**23,442**	**p-value < 0.0001**
	Injury	**1,967**	**1,889**	
		0.06%	7.46%	
Spleen	**No Injury**	**3,026,402**	**26,657**	**p-value < 0.0001**
	Injury	**1,432**	**3,343**	
		0.05%	11.14%	
Any Thoracic	**No Injury**	**3,009,750**	**33,251**	**p-value < 0.0001**
	Injury	**8,533**	**6,300**	
		0.28%	15.93%	

Table 45: Relative risk of thoracic organ injury with the presence of rib facture for hospitalized occupants exposed to a deployed, first generation airbag (weighted). * - indicates a significantly greater risk with rib fracture.

	Relative Risk	Confidence Intervals		Significance
		-	+	
Lung	**6.72**	**2.82**	**16.03**	*
Liver	**8.35**	**1.71**	**40.65**	*
Spleen	**4.12**	**1.42**	**11.96**	*
Any Thoracic Organ	***5.80***	***3.45***	***9.73***	*

Table 46: 2x2 contingency test table test utilizing a modified Rao-Scott chi-square to test for independence between organ injuries and associated rib fractures for occupants exposed to a deployed, depowered frontal airbag (weighted).

		No Fracture	Fracture	
Lung	**No Injury**	**2,424,846**	**50,791**	**p-value < 0.0001**
	Injury	**6,552**	**4,456**	
		0.27%	8.07%	
Liver	**No Injury**	**2,446,532**	**32,134**	**p-value < 0.0001**
	Injury	**2,373**	**5,605**	
		0.10%	14.85%	
Spleen	**No Injury**	**2,440,683**	**38,307**	**p-value < 0.0001**
	Injury	**5,586**	**2,068**	
		0.23%	5.12%	
Any Thoracic	**No Injury**	**2,419,760**	**44,168**	**p-value < 0.0001**
	Injury	**11,637**	**11,078**	
		0.48%	20.05%	

Table 47: Relative risk of thoracic organ injury with the presence of rib facture for hospitalized occupants exposed to a deployed, depowered airbag (weighted). * - indicates a significantly greater risk with rib fracture.

	Relative Risk	Confidence Intervals		Significance
		-	+	
Lung	2.03	0.70	5.90	
Liver	**13.66**	**2.56**	**72.99**	*
Spleen	1.73	0.53	5.62	
Any Thoracic Organ	***3.41***	***1.31***	***8.88***	*

5.3.4 Occupants with AIS3+ Rib Fractures When Exposed to Airbag Deployment

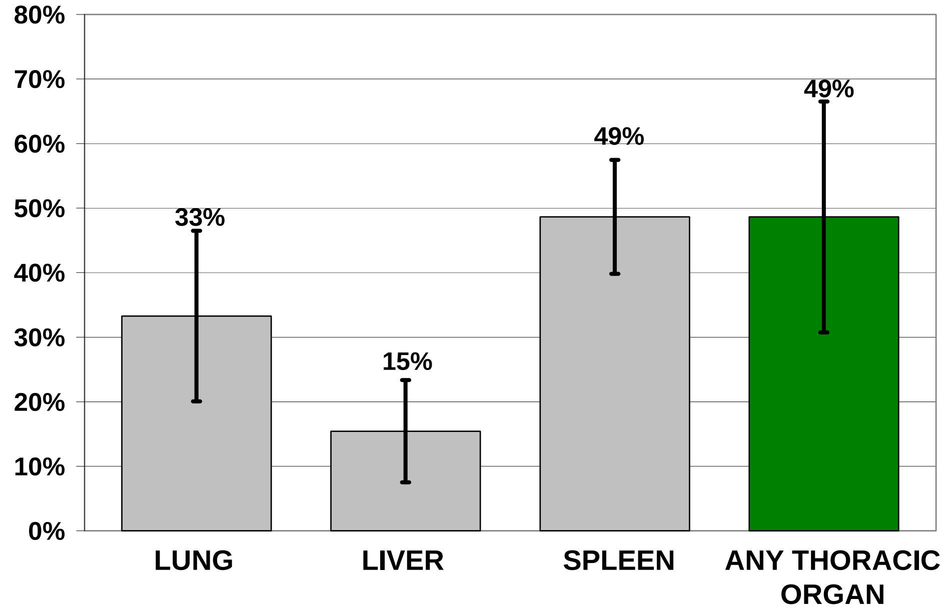

Figure 51: Risk of an AIS2+ organ injury given the presence of an AIS3+ rib fracture for belted occupants exposed to a deployed frontal airbag (weighted).

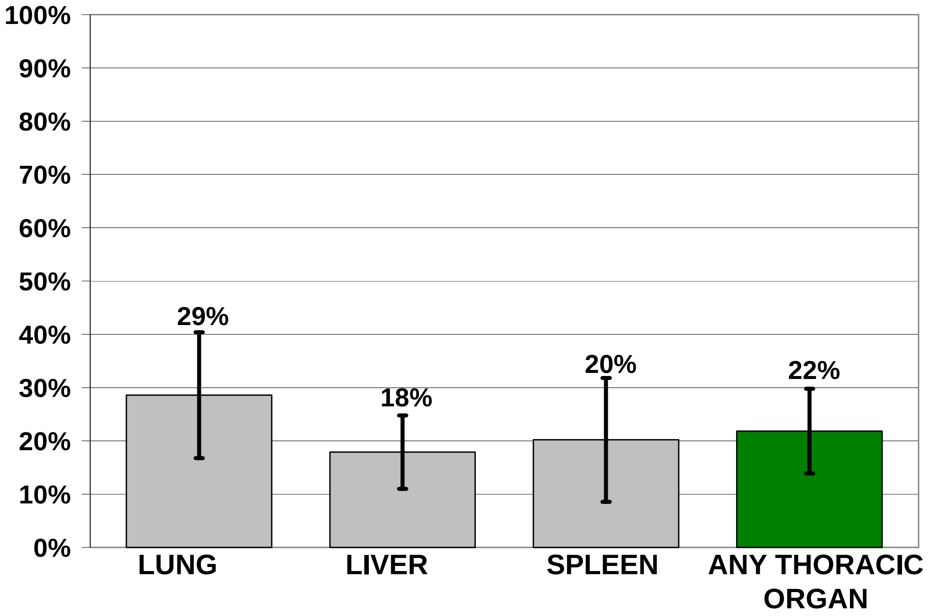

Figure 52: Risk of an AIS3+ rib fracture given an AIS2+ organ injury for belted occupants exposed to a deployed frontal airbag (weighted).

The presence of a serious (AIS3+) rib injury exhibits an increased propensity for thoracic organ injury as compared to the presence of any rib fracture (AIS1+). This is particularly true for lung and spleen injuries. There is no change in the distribution of liver injuries with an AIS3+ rib injury. 31-66% of all serious rib fracture injuries have an associated thoracic organ injury, as shown in Figure 51. The AIS scale accounts for the number of rib fractures when specifying the severity of rib injuries. However, it also accounts for associated injuries to the lungs, in particular, the presence of hemothorax, pnuemothorax, or lung contusions for AIS3+ rib injuries. Thus, the percentage of lung injuries with an AIS3+ rib injuries will be heavily dependent on the association used in the assignment of an AIS value. The determination of a rib AIS value does not account for the presence of splenic or liver injuries, thus any associations between liver or spleen injury with respect to serious rib fracture would not be influenced by the coding of the rib injury.

When a thoracic organ injury is present, only 14-30% of occupants have an associated AIS3+ rib injury, as shown in Figure 52. There is a significant reduction in this percentage for any thoracic organ or the liver alone when compared to the percentages expressed for occupants with any rib fracture. There is no significant reduction in percentage for the spleen. There is a significant increase in the percentage of AIS3+ rib injuries with the presence of a lung injury. However, this is likely to be heavily dependent on the determination of the AIS value. Table 48 shows there is a significant association between AIS3+ rib injuries and thoracic organ injury. Table 49 shows that there is a significant increase in risk for the lungs, spleen, and for any thoracic organ injury with the presence of an AIS3+ rib fracture. However, there is no statistical increase in risk for liver injuries with the presence of an AIS3+ rib fracture for hospitalized occupants.

Table 48: 2x2 contingency test table test utilizing a modified Rao-Scott chi-square to test for independence between organ injuries and associated AIS3+ rib fractures for occupants exposed to a deployed frontal airbag (weighted).

		No Fracture	Fracture	
Lung	**No Injury**	**5,513,608**	**11,247**	**p-value < 0.0001**
	Injury	**14,012**	**5,611**	
		0.25%	33.28%	
Liver	**No Injury**	**5,521,038**	**11,605**	**p-value < 0.0001**
	Injury	**9,717**	**2,117**	
		0.18%	15.43%	
Spleen	**No Injury**	**5,524,378**	**7,670**	**p-value < 0.0001**
	Injury	**9,920**	**2,509**	
		0.18%	24.65%	
Any Thoracic	**No Injury**	**5,498,269**	**8,661**	**p-value < 0.0001**
	Injury	**29,351**	**8,197**	
		0.53%	48.62%	

Table 49: Relative risk of thoracic organ injury with the presence of AIS3+ rib facture for hospitalized occupants exposed to a deployed airbag (weighted). * - indicates a significantly greater risk with AIS3+ rib fracture.

	Relative Risk	Confidence Intervals		Significance
		-	+	
Lung	**5.90**	**2.61**	**13.37**	*
Liver	1.09	0.29	4.13	
Spleen	**7.79**	**3.06**	**19.84**	*
Any Thoracic Organ	***4.15***	***2.10***	***8.19***	*

5.4 Discussion

The results of this analysis show a number of relationships between thoracic organ injury and rib fractures for belted occupants in vehicle crashes. Rib fractures in frontal crashes, regardless of airbag deployment, often do not have an associated organ injury. However, there was a significant increase in the percentage of spleen injuries for occupants with a rib fracture when comparing those in vehicles with frontal airbags and those who are exposed to airbag deployment. Neither the lungs or liver individually or the combined percentage of all thoracic organs showed any noticeable difference with respect to these airbag conditions. Only 36% of occupants in vehicles with frontal airbags were subjected to a deployment. Thus, the significant difference in the percentage of spleen injuries is particularly unique in the absence of a significant result for the other organs. This result reflects the possibility that the association between spleen injuries with rib fracture is affected to a greater degree than for liver or lung injuries with the deployment of an airbag. However, when investigating the percentage of thoracic organ injuries that have an associated rib fracture, there is no appreciable difference for occupants who are in vehicles with an available frontal airbag as compared to those exposed to a deployed frontal airbag. The association between liver injuries and rib fracture appears to be heightened for occupants exposed to depowered airbags. Liver injuries with the presence of a rib fracture and the risk of rib injury with a liver injury showed an increase in percentage for occupants with a depowered airbag deployment as opposed to those exposed to a first generation airbag deployment. However, neither of these results was statistically significant.

The contingency table analyses show a significant relationship between organ injuries and associated rib fractures in all airbag conditions investigated here. This illustrates that in cases of no rib fracture, it is a less likely an organ injury will occur. When a rib fracture does occur, there is a significantly greater chance that an associated organ injury will be present as well. With regard to this chi-square contingency table analyses, it should be noted that in the majority of crashes, occupants in vehicles equipped with frontal airbags present are not injured. Compared to all occupants in crashes, only a very small percentage of occupants have organ injuries without rib fracture.

The relative risk results given for each organ express that there is indeed a significant risk of thoracic organ injury in the presence of a rib fracture for occupants who are in crashes that are severe enough that they require hospitalization. This is true for each airbag condition except for deployed, depowered airbags. In this scenario, there is a significant increase in risk for liver injury or for any thoracic organ injury, but there is not a significant increase in risk for the lungs and spleen by themselves. There is also no significant increase in risk for liver injury in the presence of a serious rib fracture. However, there is a significant in risk of liver injury with the presence of any rib fracture. The results reported by Lee et al (1990) with regard to the liver are within our confidence bounds of our results. However, the results reported by Lee gave a significantly higher risk of spleen injury than is given from our results. It should be noted that the results from Lee were tabulated for occupants hospitalized between 1984 and 1986. This pre-dates the vast majority of airbag equipped vehicles, and this difference may account for the difference in risk reporting.

When a rib fracture occurs, there is often no thoracic organ injury. Much of the attention paid to the protection of the thorax in a crash has been with respect to rib fracture. Rib fracture has been used as a surrogate for thoracic organ injury. Injury criteria have been developed based on a number of cadaver studies that have focused primarily on the protection of the ribs due to its frequency in the distribution of all injuries based on tissue type. The theory is, by protecting the ribs, the underlying organs are protected as well (Nahum et al 1970; Kroell et al 1971; Nahum et al 1971; Neathery et al 1973; Kroell et al 1974; Neathery 1974; Nahum et al 1975; Neathery et al 1975; Viano 1978; Viano et al 1988). As discussed earlier, radiologic observations underpredict the actual number of rib fractures (Nahum et al 1970; Kent et al 2002). The underestimation would affect the development of a relationship between rib fracture and thoracic organ injury. This is particularly important for coding the AIS severity of rib fractures, which depends on the number of fractures. However, our study, which is based on field data and radiologic determination of rib fracture, shows rib fractures are not necessarily effective in predicting thoracic organ injury. Only 31-61% of thoracic organ injuries occur with any associated rib fracture in the presence of a deployed airbag. Even with the presence of an AIS3+ thoracic injury, only 31-66% of occupants had an associated organ injury.

5.5 Conclusions

This analysis has shown thoracic organ injuries possess a significant association with the occurrence of rib fractures, but it does not explain the source of this association. It is unknown how much of the relationship can be attributed to a cause and effect scenario. The correlation may be a function of crash severity alone. A crash event severe enough to cause a rib fracture may be sufficient for an organ injury to occur separately. It is also true that the presence of rib injury does not accurately predict the presence of a thoracic organ injury. Between 31-61% of thoracic organ injuries occur without the occurrence of rib fracture when an airbag deploys for belted occupants.

5.6 References

AAAM (1998). Association for the Advancement of Automotive Medicine. The Abbreviated Injury Scale, 1990 Revision, Update 98 (1998).

Clark, G. C., W. P. Schecter and D. D. Trunkey (1988). "Variables affecting outcome in blunt chest trauma: flail chest vs. pulmonary contusion." The Journal of Trauma: Injury, Infection, and Critical Care 28(3)**:** 298-304.

Flagel, B. T., F. A. Luchette, R. L. Reed, T. J. Esposito, K. A. Davis, J. M. Santaniello and R. L. Gamelli (2005). "Half-a-dozen ribs: the breakpoint for mortality." Surgery 138(4)**:** 717-23; discussion 723-5.

Kent, R., J. Crandall, J. Patrie and J. Fertile (2002). "Radiographic Detection of Rib Fractures: A Restraint-Based Study of Occupants in Car Crashes." Traffic Inj Prev 3(1)**:** 49-57.

Kroell, C. K., D. C. Schneider and A. M. Nahum (1971). Impact Tolerance and Response of the Human Thorax. Proceedings of the 15th Stapp Car Crash Conference, New York, Society of Automotive Engineers 710851.

Kroell, C. K., D. C. Schneider and A. M. Nahum (1974). Impact Tolerance and Response of the Human Thorax II. Proceedings of the 18th Stapp Car Crash Conference, Warrendale, PA 741187.

Lee, R. B., S. M. Bass, J. A. Morris, Jr. and E. J. MacKenzie (1990). "Three or more rib fractures as an indicator for transfer to a Level I trauma center: a population-based study." The Journal of Trauma: Injury, Infection, and Critical Care 30(6)**:** 689-94.

Nahum, A. M., C. W. Gadd, D. C. Schneider and C. K. Kroell (1970). Deflection of the Human Thorax Under Sternal Impact. International Safety Conference Compendium, New York, Society of Automotive Engineers 700400.

Nahum, A. M., C. W. Gadd, D. C. Schneider and C. K. Kroell (1971). "The Biomechanical Basis for Chest Impact Protection. I. Force-Deflection Characteristics of the Thorax." The Journal of Trauma: Injury, Infection, and Critical Care 11(10)**:** 874-82.

Nahum, A. M., D. C. Schneider and C. K. Kroell (1975). Cadaver Skeletal Response to Blunt Thoracic Impact. Proceedings of the 19th Stapp Car Crash Conference 751150.

Neathery, C. K. (1974). Analysis of Chest Impact Response Data and Scaled Performance Recommendations. Proceedings of the 18th Stapp Car Crash Conference 741188.

Neathery, C. K., C. K. Kroell and H. Mertz (1975). Prediction of Thoracic Injury from Dummy Responses. Proceedings of the 19th Stapp Car Crash Conference 751151.

Neathery, C. K. and T. E. Lobdell (1973). Mechanical Simulation of Human Thorax Under Impact. Proceedings of the 17th Stapp Car Crash Conference 730982.

Poole, G. V., Jr. and R. T. Myers (1981). "Morbidity and mortality rates in major blunt trauma to the upper chest." Ann Surg 193(1)**:** 70-5.

Shorr, R. M., M. Crittenden, M. Indeck, S. L. Hartunian and A. Rodriguez (1987). "Blunt thoracic trauma. Analysis of 515 patients." Ann Surg 206(2)**:** 200-5.

Shweiki, E., J. Klena, G. C. Wood and M. Indeck (2001). "Assessing the true risk of abdominal solid organ injury in hospitalized rib fracture patients." The Journal of Trauma: Injury, Infection, and Critical Care 50(4)**:** 684-8.

Sirmali, M., H. Turut, S. Topcu, E. Gulhan, U. Yazici, S. Kaya and I. Tastepe (2003). "A comprehensive analysis of traumatic rib fractures: morbidity, mortality and management." Eur J Cardiothorac Surg 24(1)**:** 133-8.

Viano, D. C. (1978). Thoracic Injury Potential. International Meeting on the Simulation and Reconstruction of Impacts in Collisions, Lyon, France.

Viano, D. C. and I. V. Lau (1988). "A viscous tolerance criterion for soft tissue injury assessment." J Biomech 21(5)**:** 387-99.

Ziegler, D. W. and N. N. Agarwal (1994). "The morbidity and mortality of rib fractures." The Journal of Trauma: Injury, Infection, and Critical Care 37(6)**:** 975-9.

Chapter 6: Conclusion

6.1 Conclusions and Contributions

The introduction of airbags has not reduced serious thoracic injury for belted occupants in frontal crashes. The most current vehicles in the United States have the most advanced safety counter measures including load limiting seat belts, pretensioners, depowered airbags, and dual-stage airbags. Despite these advances, injuries to occupants continue to occur. The original intent of airbags was to protect unbelted occupants. However, the vast majority of occupants now use their seat belts. This has raised questions regarding the ability to advance this technology with respect to its effectiveness at protecting belted occupants.

This thesis investigated the effectiveness of airbags and the characteristics of residual thoracic organ injury incurred by belted occupants in vehicles equipped with airbags. Real-world crash investigations were used from NASS/CDS case years 1993-2007. Only belted occupants were included because they represent the largest proportion of occupants in the United.

The use of odds ratios for comparing the effect of airbags on the occurrence of injury has shown that airbags do not significantly increase protection against injuries to the most vital body regions, i.e. the head and chest with respect to belted only occupants. In addition, the odds of AIS2+ chest injury are 2.1 times (CI: 1.08-4.14x) greater with a depowered airbag than with a first generation airbag.

Overall, the lower extremity and the upper extremity were shown to be the most adversely affected by airbags. The face was the only body region that was shown to benefit from the combination of seat belts and airbags as compared to seat belts alone. The lower extremity has a 2.6 times (CI: 1.3-5.2x) greater odds of AIS3+ injury for the driver with the presence of an airbag. Right front passengers also have 4.7 times (CI: 1.7-13.0x) greater odds of AIS2+ lower extremity injury when an airbag is available. The lower extremities also have 1.7 times (CI: 1.04-2.7x) greater odds of injury for all front seat occupants exposed to a depowered airbag deployment as compared to occupants exposed to first generation airbag deployments. There are 4.0 times (CI: 1.7-9.7x) greater odds for AIS3+ upper extremity injury for the right front passenger in a vehicle with an available airbag as compared to those without an available airbag. A driver has 2.0 times (CI: 1.2-3.5x) greater odds of AIS2+ upper extremity injury in a vehicle with an available airbag as compared to an occupant without an available airbag. The face has a 4.9 times (CI: 2.5-9.9x) lower odds of AIS2+ injury and 17.2 times (CI: 4.4-67.5x) lower odds of AIS3+ injury to the driver when an airbag is available, as compared to occupants without an available airbag. Depowered airbags do not provide additional protection against injury to any body region.

An investigation into the characteristics and distributions associated with thoracic organ injuries showed the heart and great vessels are the only thoracic organs that showed a significant reduction in the rate of injury with the inclusion of airbags. The rate of heart and great vessel injuries is 11.61 injured occupants for every 10,000 belted occupants exposed to a frontal crash without airbags and 3.93 injured occupants with airbags. Also, the average delta-V associated with serious thoracic organ injury was not different with and without an airbag available. This agrees with the previous findings which showed that airbags do not offer additional protection against thoracic injury for a belted occupant. If the airbags actually increased protection for the occupant, a higher severity crash would be required to cause injury. This result is shown to not be true. The odds of serious injury to the lungs was 2.4x (CI: 1.27-4.67x) higher for occupants in vehicles with airbags as compared to those in vehicles without airbags. The odds of serious spleen injury was 3.8x (CI: 1.13-12.7x) higher for occupants in vehicles with airbags as compared to those in vehicles without airbags. The odds of rib fracture were not shown to be significantly affected by the presence of an airbag. However, with the presence of an airbag, the thoracic organs account for significantly more serious injuries than the ribs with respect to all serious thoracic injuries.

There is no significant difference in the size or gender of occupants who sustain thoracic organ injuries when comparing the injured to the general driving population. There is also no difference in the size or gender of occupants who sustain thoracic organ injuries with the presence of airbags as compared to no airbags present. Also, there is no significant difference in the types of crashes or vehicles that produce thoracic organ injuries when compared to the general driving population. The lesion (e.g. contusion or laceration) and severity of thoracic organ injury for belted occupants does not vary with and without airbags. The source of injury does vary with the presence of an airbag, seat position, and organ. For the driver, the belts and steering column were given as the source for the most thoracic organ injuries. The belts and the vehicle interior were attributed to the most thoracic organ injuries for the right front passenger. The airbags were rarely listed as the source of injury for the thoracic organs.

Rib fracture is a poor predictor of moderate to fatal thoracic organ injury. Only 31-61% of thoracic organ injuries occur with an associated rib fracture. There is not necessarily a cause and effect relationship between rib fracture and organ injury. The two injuries may simply be associated with a severe crash. However, in serious crashes requiring hospitalization, there is a 4.34x (CI: 2.40-7.85x) increase in risk of thoracic organ injury in vehicles equipped with airbags as compared to those without rib fracture. Injury criteria developed based on cadaver research has been almost exclusively based on the presence of serious rib fracture because of its predominance in the coding of injuries from autopsy. Specifically, it has been assumed that the protection of the ribs against serious injury would also provide adequate protection against thoracic organ injury. This is not supported by our results which show that only 14-30% of thoracic organ injuries occur with a serious rib fracture. In addition, the results from this research show that it may not be appropriate, in a clinical setting, to assume that the lack of rib fractures necessarily suggests a lack of thoracic organ injury as well.

Overall, the introduction of airbags has not been shown by this research to provide additional protection against serious injury to any body region, with the exception of the face. Furthermore, the inclusion of airbags has increased the ratio of serious thoracic organ injuries to rib fractures. Airbags have only been shown to significantly reduce the rate of heart and great vessel injuries. No positive effects were observed for any other thoracic organs. The lesions and severity of organ injuries, the occupants who sustain thoracic organ injury, and the crashes that produce thoracic organ injury have not changed with the inclusion of airbags. The source of the injury for each organ changes with the presence or absence of an airbag. Finally, a significant association exists between thoracic organ injuries and rib fracture for occupants in vehicles with available airbags, yet rib fractures lack the ability to predict the occurrence of thoracic organ injury.