INCIDENCE AND RISK OF DIRECT STEERING WHEEL IMPACT IN VEHICLES EQUIPPED WITH ADVANCED AIR BAGS

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ABSTRACT

Despite the widespread availability of airbags and a belt use rate of over 85%, U.S. drivers involved in crashes continue to be at risk of serious thoracic injury. One hypothesis is that this risk may be due to the lack of airbag deployment or the airbag 'bottoming-out' in some cases. The objective of this study is to determine the incidence and thoracic injury risk of direct steering wheel contact due to airbag "bottoming-out".

The analysis is based upon cases extracted from the National Automotive Sampling System Crashworthiness Data System (NASS/CDS) database for case years 1997-2011. The NASS/CDS data set was restricted to vehicles of model year 1998 and later. The approach was to compare the frontal crash performance of sled-certified airbags, sometimes called depowered airbags, with advanced airbags involved in frontal crashes. NASS/CDS steering wheel deformation measurements were used to identify cases in which thoracic injuries may have been caused due to steering wheel impact and deformation. The distributions of injuries for all cases were determined by body region and injury severity. These distributions were used to compare and contrast injury outcomes for cases with frontal airbag deployment for both belted and unbelted drivers.

Among frontal crash cases with belted drivers, observable steering wheel deformation occurred in less than 4% of all cases, but accounted for 29% of all MAIS3+ belted drivers and 28% of belted drivers with serious thoracic injuries (AIS3+). Similarly, observable steering wheel deformation occurred in approximately 13% of all cases with unbelted drivers involved in frontal crashes, but accounted for 58% of MAIS3+ unbelted drivers and 66% of unbelted drivers with serious (AIS3+) thoracic injuries.

INTRODUCTION

Seatbelts and airbags are the two primary components of the safety system that helps to secure the occupant and reduce the rapid deceleration experienced by occupants in a frontal crash. However, despite the widespread availability of airbags, and seatbelt usage over 85% in the United States, drivers still may contact the steering wheel in the event of a crash, and may subsequently incur serious injury as a result of steering wheel impact.

The design of frontal airbags, one potential influence on the incidence of steering wheel deformation, has evolved through several generations since their first introduction into the U.S. fleet in selected models in the 1970s. Driver airbags first became mandatory for vehicles in the U.S. fleet in 1994. In response to changes in Federal Motor Vehicle Safety Standard No. 208 (FMVSS 208) [1], depowered frontal airbags, sometimes called sled-certified airbags, were introduced into the U.S. fleet in 1998. Depowered airbags were intended to reduce the risk of injury to front seat occupants by reducing the force with which these airbags were deployed. Advanced airbags, sometimes referred to as Certified Advanced 208 Compliant (CAC) airbags, began to be phased into the U.S. fleet in model year 2004 with complete phase in by model year 2007. A few models contained CAC-airbags as early as model year 2003. Like depowered airbags, advanced airbags sought to reduce occupant risk by employing a sophisticated system of occupant sensors and a two-stage inflator design which could tailor the force of deployment to the severity of the crash, the location of the occupant, and belt status. Some manufacturers included some of the features of advanced airbags, e.g. dual inflators, in their sled-certified airbag designs.

One concern has been whether advanced airbags may be associated with higher injury risk than earlier airbag designs. Based on an analysis of Fatality Analysis Reporting System (FARS), Braver et al [2] reported that the mortality for belted drivers was higher for advanced airbag equipped vehicles than for sled-certified vehicles. One hypothesis is that drivers may be bottoming-out airbags in which only a single stage was deployed. If the airbag was bottomed-out, the driver could directly impact and deform the steering wheel assembly which underlies the airbag. The hypothesis is that steering wheel deformation would then be correlated with greater frontal crash injury risk.

Objective

The objective of this study is to determine the factors associated with steering wheel deformation during a frontal crash and the resulting injury outcomes.

Approach

Our approach was to compare frontal crash injury risk in vehicles with and without measurable steering wheel deformation. The study was based upon real world crashes extracted from the National Automotive Sample System's (NASS) Crashworthiness Data System (CDS). NASS is a crash data collection program established by the National Highway Traffic Safety Administration (NHTSA). Each year NASS/CDS investigates approximately 5,000 cases, selected from police reported crashes at 24 sites across the United States. NASS crash investigators document vehicle damage, occupant impacts with the interior, and crash site evidence, such as skid marks, and damage to roadside objects. In addition, the nature and severity of the injuries sustained by the occupants are collected through the review of medical records and interviews with the crash victims.

The following study is based upon cases extracted from NASS/CDS 1997-2011. In order to be included in the dataset, cases were required to meet the following conditions:

- Vehicles model year 1998 and newer
- Drivers age 12 and older
- Frontal impacts with airbag deployed
- Exclude rollover cases
- Exclude cases involving driver ejection
- Belt use was known
- Steering wheel deformation was recorded

These criteria were chosen to include only the latest safety technologies. The model year 1998+ restriction was chosen to coincide with the year depowered airbags were introduced into the U.S. fleet. These countermeasures are designed to protect occupants involved in frontal crashes. Rollover crashes account for an over-representative number of serious injuries and deaths from car crashes, but the injurious circumstances are often unclear. Due to the complex nature of rollovers, they were not included in this analysis.

This study considered both the effect of belt usage, and the type of frontal airbags in the vehicle. Our dataset contained two generations of airbag designs: 1) depowered airbags introduced in 1998 and 2) Certified Advanced 208 Compliant (CAC) airbags. CAC airbags, sometimes called advanced airbags, first began to be phased into the U.S. fleet in model year 2004 with complete phase in by model year 2007. A few models contained CAC-airbags in model year 2003. The type of driver airbag was identified for each vehicle prior to the analysis [3].

NASS describes the severity of occupant injuries based on the Abbreviated Injury Scale (AIS). AIS ranks injury severity on a scale of 1-6 based on its threat to the life of the occupant [4]. AIS=1 is a minor injury, AIS=3 is a serious injury and AIS=6 is an unsurvivable injury. Our analysis classified injury severity by the maximum AIS (MAIS) level injury sustained by an occupant. For drivers who were fatally injured, MAIS was set to 6 regardless of individual injury level. The injuries were further classified by body region, i.e. the head, face, neck, chest, abdomen, spine, upper extremities, and lower extremities. The injury distribution was described by computing the highest, i.e. most severe, injury sustained in each body region. In the analysis which follows, NASS sample weights were applied in order to represent the national population.

In the analysis which follows, we seek to answer the following questions:

- How frequently does steering wheel deformation occur?
- What are the injury outcomes of steering wheel deformation?
- What causes steering wheel deformation to occur?
- What controls the magnitude of steering wheel deformation?

For the steering wheel analysis, the dataset was then further divided into those vehicles with and without steering wheel deformation. Cases with steering wheel deformation were identified with the NASS/CDS variable "rimdef", and subsequently grouped by the occupant injuries recorded by NASS/CDS. In this analysis, the comparison between vehicles with and without measurable steering wheel deformation was based upon the risk of injury. For a particular body region, the risk of injury is expressed in terms of the fraction of cases at a given severity, as shown in equation (1), where n is the number of cases at a given severity and N_{Total} is the total number of cases with known injury severity. The following analysis also presents the relative risk, or the ratio of risk of injury in vehicles with steering wheel deformation versus in vehicles without steering wheel deformation, as shown in equation (2), where $R_{with\ Deformation}$ is the risk of injury with steering wheel deformation, and $R_{without\ Deformation}$ is the risk of injury without steering wheel deformation.

$$Risk\ of\ Injury = \frac{n}{N_{Total}} \qquad (1)$$

$$Relative\ Risk = \frac{R_{With\ Deformation}}{R_{Without\ Deformation}} \qquad (2)$$

Confidence intervals were computed in our analysis using SAS routines SurveyReg, SurveyFreq, and SurveyLogistic to account for the complex sampling scheme employed by NASS/CDS. The cases collected in NASS/CDS are clustered into 24 primary sampling unit (PSU). The cases are further separated into 10 strata based on factors which include vehicle damage and the severity of the occupant injuries.

Results

Dataset Composition Table 1 presents the composition of the belted driver dataset for both unweighted and weighted values. The dataset is organized based on the steering wheel (SW) deformation, as well as the number of drivers sustaining MAIS 2+ and MAIS 3+ injuries. Likewise, the composition of the dataset for unbelted drivers is presented in Table 2 as a function of steering wheel deformation and MAIS level. Steering wheel deformation was not recorded in 426 cases, while another 171 cases involved steering wheel deformation caused by a person or object other than the driver, e.g. rescue personnel or occupant compartment collapse. These cases were omitted from the dataset.

Table 1
Dataset Composition by Steering Wheel Deformation for Belted Drivers

Driver Injury Level	Unweighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	10,429	9,604	825
MAIS 2+	2,136	1,637	499
MAIS 3+	984	643	341
Driver Injury Level	Weighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	3,290,900	3,172,037	118,863
MAIS 2+	288,036	244,481	43,555
MAIS 3+	74,588	52,780	21,808

Table 2
Dataset Composition by Steering Wheel Deformation for Unbelted Drivers

Driver Injury Level	Unweighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	2,407	1,705	702
MAIS 2+	982	505	477
MAIS 3+	599	249	350
Driver Injury Level	Weighted		
	Total	No Measurable SW Deformation	Measurable SW Deformation
Exposed	611,062	532,286	78,776
MAIS 2+	109,695	69,533	40,162
MAIS 3+	45,059	18,918	26,141

Lastly, the dataset was broken down by airbag type. Table 3 presents the unweighted and weighted values for the belted drivers. The composition of the dataset for unbelted drivers is presented as a function of airbag type in Table 4.

Table 3
Dataset Composition by Airbag Type for Belted Drivers

Driver Injury Level	Unweighted		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	10,429	7,522	2,907
MAIS 2+	2,136	1,618	518
MAIS 3+	984	762	222
Driver Injury Level	Weighted		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	3,290,900	2,550,071	740,829
MAIS 2+	288,036	229,192	58,844
MAIS 3+	74,588	55,522	19,066

Table 4
Dataset Composition by Airbag Type for Unbelted Drivers

Driver Injury Level	Unweighted		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	2,407	1,855	522
MAIS 2+	982	782	200
MAIS 3+	599	478	121
Driver Injury Level	Weighted		
	Total	Depowered Airbag Vehicles	CAC Vehicles
Exposed	611,062	487,600	123,462
MAIS 2+	109,695	86,479	23,217
MAIS 3+	45,059	35,070	9,989

Frequency of Steering Wheel Deformation

Figure 1 shows the distribution of cases with and without measurable steering wheel deformation for drivers exposed to frontal crashes, with MAIS2+ injuries and with MAIS3+ injuries. Only 4% of belted drivers were involved with a steering wheel with any measurable deformation. However, this 4% of cases was overrepresented in the injury outcomes, and was associated with 15% of MAIS2+ drivers and 29% of MAIS3+ injured drivers. Even for drivers wearing their belts with deployed airbags, steering wheel impact with measurable deformation still accounted for nearly one-third of serious to fatally injured belted drivers.

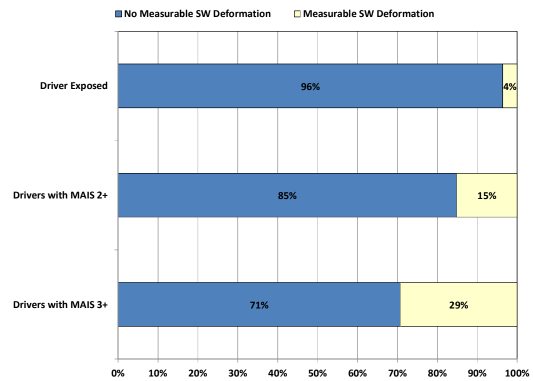

Figure 1. Distribution of Belted Drivers with and without Steering Wheel Deformation

Figure 2 shows the distribution of cases with and without measurable steering wheel deformation for unbelted drivers exposed to frontal crashes, with MAIS2+ injuries and with MAIS3+ injuries. As might be expected unbelted drivers were more likely to cause steering wheel deformation (13%) than belted drivers (4%). In most belted cases, the three point belt keeps the driver out of the steering wheel. Although a small fraction, the 13% of drivers in vehicles with steering wheel deformation is overrepresented in the injury outcomes. This small fraction is associated with 37% of MAIS2+ drivers and well over half (58%) of MAIS3+ unbelted drivers. Clearly, failure to wear a safety belt puts unbelted drivers at a higher risk of impacting the steering wheel than belted drivers. The result was a sharply elevated risk of injury.

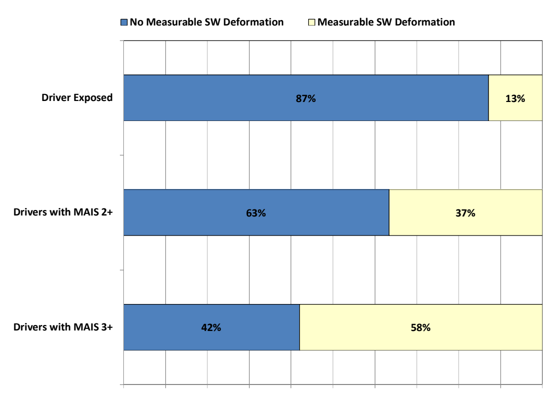

Figure 2. Distribution of Unbelted Drivers with and without Steering Wheel Deformation

Injury Consequences of Steering Wheel Deformation for Belted Drivers Figure 3 presents the distribution of total delta-V for vehicles with and without measurable steering wheel deformation. The median delta-V for crashes without measurable steering wheel deformation was 19 km/hr while the median delta-V for crashes with measurable steering wheel deformation was 30 km/hr. This figure shows that, as might be expected, steering wheel deformation is more likely to occur in higher severity crashes.

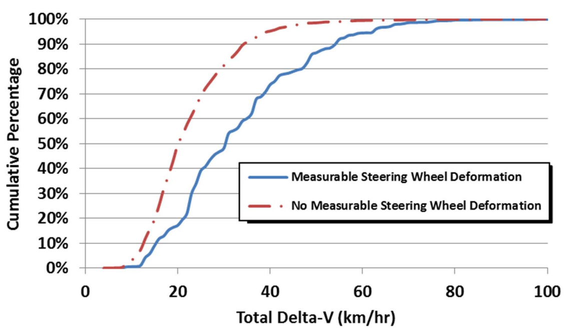

Figure 3. Total Delta-V Distribution of Vehicles With and Without Steering Wheel Deformation (Belted Drivers)

Figure 4 compares the distribution of the risk of AIS2+ injuries for cases with and without measurable steering wheel deformation. For all body regions, measurable steering wheel deformation was associated with a higher risk of AIS2+ injury. The lower extremities had the highest risk of all body regions. Head and chest were the body regions with the third and fourth highest risk of AIS2+ injury.

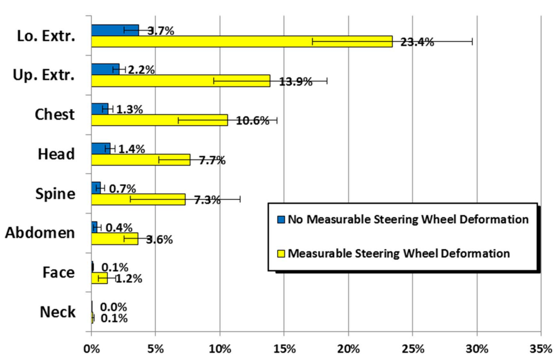

Figure 4. Risk of AIS2+ Injuries by Body Region for Belted Drivers

Figure 5 compares the risk of AIS3+, or serious injuries, for cases with and without measurable steering wheel deformation. For all body regions, measurable steering wheel deformation was associated with a higher risk of AIS3+ injury. Lower extremity carried the highest risk of AIS3+ injury. The thorax carried the second highest risk of injury from steering wheel deformation.

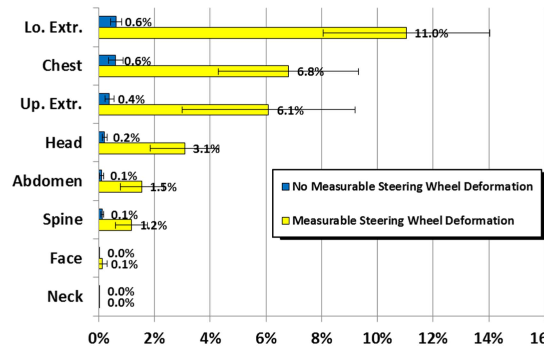

Figure 5. Risk of AIS3+ Injuries by Body Region for Belted Drivers

Figure 6 and Figure 7 shows the relative risk of AIS2+ and AIS 3 injuries in vehicles with steering wheel deformation when compared to vehicles without steering wheel deformation, respectively. The risk of AIS2+ thorax injury increases by a factor of 8 if there is steering wheel deformation. Even more worrisome is that the risk of AIS3+ thorax injury increases by a factor of 11 if there is steering wheel deformation. For AIS2+ injuries, the increase in risk was statistically significant in all body regions except the neck. For AIS3+ injuries, the increase in risk was statistically significant for all body regions except face and neck.

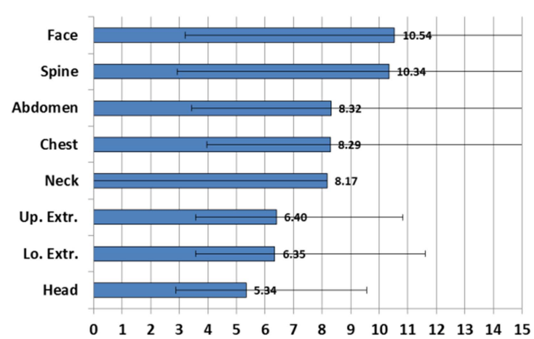

Figure 6. Relative Risk of AIS2+ Injuries by Body Region for Belted drivers with and without steering wheel deformation

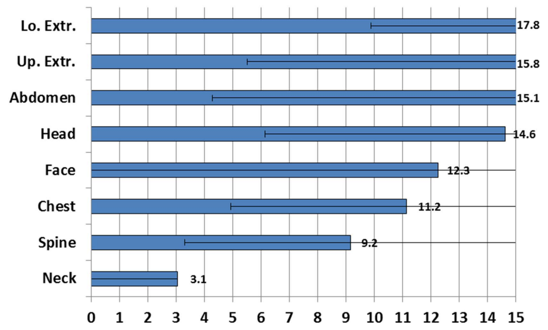

Figure 7. Relative Risk of AIS3+ Injuries by Body Region for Belted drivers with and without steering wheel deformation

Injury Consequences of Steering Wheel Deformation for Unbelted Drivers Figure 8 presents the distribution of total delta-V for vehicles with and without measurable steering wheel deformation. The median delta-V for crashes without measurable steering wheel deformation was 20 km/hr while the median delta-V for crashes with measurable steering wheel deformation was 30 km/hr. As with belted drivers, steering wheel deformation for unbelted drivers is more likely to occur in higher severity crashes.

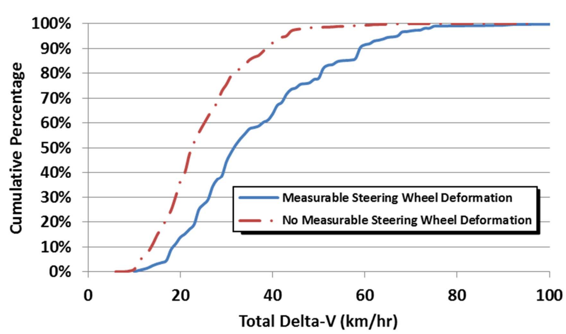

Figure 8. Total Delta-V Distribution of Vehicles With and Without Steering Wheel Deformation (Unbelted Drivers)

Figure 9 compares the distribution of the risk of AIS2+ injuries between cases with and without measurable steering wheel deformation. Likewise, Figure 10 compares the risk of AIS3+, or severe injuries, for cases with and without measurable steering wheel deformation. For all body regions, steering wheel deformation was associated with a higher risk of injury.

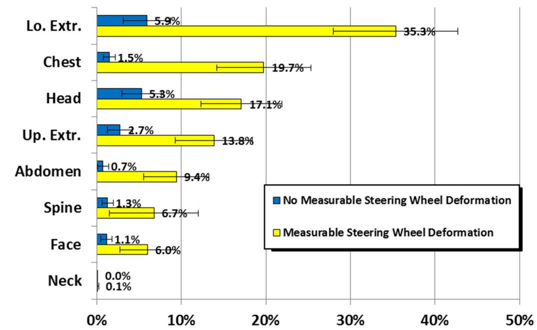

Figure 9. Risk of AIS2+ Injuries by Body Region for Unbelted Drivers

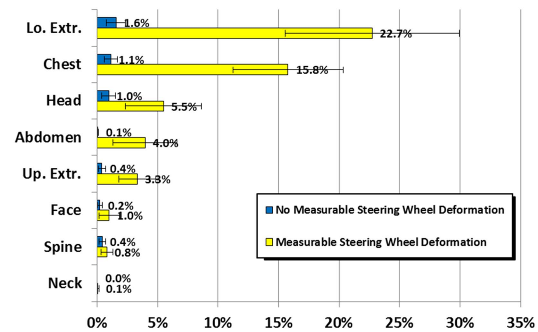

Figure 10. Risk of AIS3+ Injuries by Body Region for Unbelted Drivers

Figure 11 and Figure 12 shows the relative risk of AIS2+ and AIS 3 injuries as a ratio of risk of injury in vehicles with steering wheel deformation and those without steering wheel deformation, respectively. The risk increases by a factor of 13 for AIS2+ thoracic injury and by a factor of 14 for AIS3+ injury if there is steering wheel deformation.

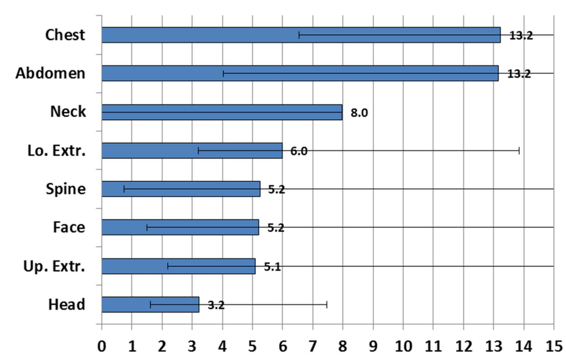

Figure 11. Relative Risk of AIS2+ Injuries by Body Region for Unbelted Drivers with and without steering wheel deformation

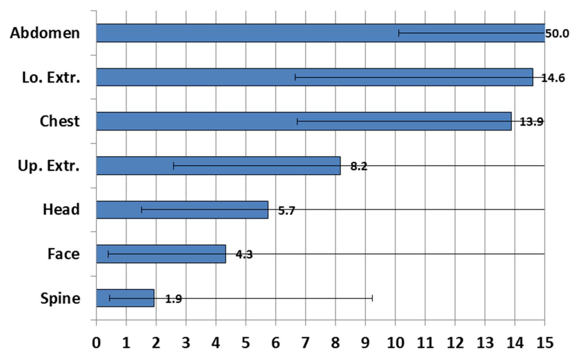

Figure 12. Relative Risk of AIS3+ Injuries by Body Region for Unbelted Drivers with and without steering wheel deformation

Factors which Influence Steering Wheel Deformation Magnitude In order to determine the potential factors that may influence the severity of steering wheel impact, we approximated the complex interaction between the driver and the vehicle's restraint system with a simple mass-spring system. For a steering wheel with a linear spring stiffness in which an occupant of mass *m* contacts the steering wheel at velocity *v*, the steering wheel-restraint deformation x can be computed as follows:

$$\frac{1}{2}mv^2 = \frac{1}{2}kx^2 \tag{3}$$

$$x = \left(\sqrt{\frac{m}{k}}\right)v \tag{4}$$

This simple model does not, of course, account for the non-linear force-deflection of the belt-airbag-steering wheel system, but is useful to identify the factors which are likely to control steering wheel deformation. As a first approximation, this qualitative analysis indicates that steering wheel deformation is likely to be influenced by the delta-V, the mass of the occupant, and the stiffness of the belt-airbag-steering wheel system.

The effect of multiple event crashes was also considered in the analysis. In 34% of the cases the vehicle experienced multiple crash events, e.g. a crash where the vehicle strikes a guardrail, and was then redirected onto the road where it collided with another vehicle. In these multiple event crashes, the airbag may inflate during the first event to protect the occupant, but after deflating does little to help the occupant when it is deflated during the subsequent events.

Test of Model Effects To account for the stratified sampling scheme used by NASS/CDS, the SurveyReg function in SAS 9.2 was used to test the effect of each of the independent variables in a Wald test. Magnitude of steering wheel deformation was used as the response. The weight of the occupant, as well as the longitudinal and lateral delta-V were included as continuous covariates. The belt status and type of airbag were included in the analysis as categorical covariates. The effect of multiple event crashes was used as a categorical variable (1 if crash involved multiple events, 0 if single event crash) and tested for its effect on steering wheel deformation. The dataset considered for the Wald test and the subsequent regression model used only cases with measurable steering deformation.

As shown in Table 5, longitudinal delta-V, occupant weight, and belt were statistically significant at the alpha=0.05 level in influencing steering deformation. However, lateral delta-V, the type of airbag, and the factor of multiple event crashes did not have a statistically significant effect on magnitude of steering wheel deformation.

Table 5
Test of Model Effect Result by SAS

Variable	F Value	Pr > F
Longitudinal Delta-V	9.89	0.002
Lateral Delta-V	0.12	0.731
Weight	10.85	0.001
Belt Status	6.87	0.010
Advanced airbag	2.51	0.115
Multiple Crash Events	1.06	0.305

The effect of multiple events can also be illustrated using the distribution of steering wheel deformation. Figure 13 and Figure 14 shows that for single and multi-event crashes, there was little difference in the magnitude of steering wheel deformation for either belted or unbelted drivers

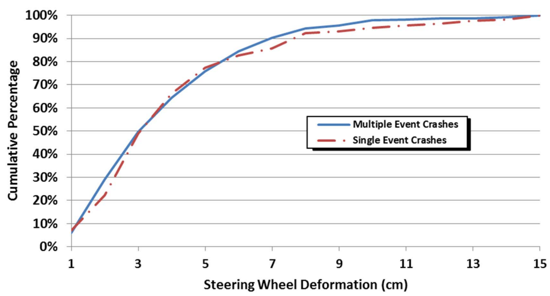

Figure 13. Belted Driver Steering Wheel Deformation Distribution for Multiple and Single Event Crashes

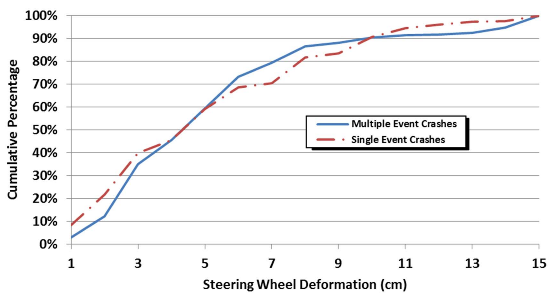

Figure 14. Unbelted Driver Steering Wheel Deformation Distribution for Multiple and Single Event Crashes

Multiple Linear Regression Model Based on the model effect test result, the following variables were used to create a linear regression model: longitudinal delta-V, weight, and belt status. The height of driver, although generally correlated with weight, was excluded in favor of weight. In this analysis, the weight of the driver serves as a better representative of the inertial loading of the driver upon the airbag. Another Wald Test of effects was performed using the three chosen variables to determine their significance. The result of the model effect test of the three variables tabulated in Table 6 suggests all three chosen variables are statistically significant to the model. However, the model intercept was not considered significant.

Table 6
Test of Model Effect Result by SAS

Variable	F Value	Pr > F
Intercept	1.63	0.2027
Longitudinal Delta-V	10.14	0.0017
Weight	10.34	0.0015
Belt Status	6.57	0.0112

Table 7 presents the estimated coefficient of each variable and its corresponding 95% confidence limits. For the categorical variables, "Belt Status", the estimated coefficient is multiplied by 1 for unbelted drivers. Otherwise, the coefficient is multiplied by zero to indicate no effect. Note that none of the coefficients, except the intercept, span zero, indicating we can reject the null hypothesis that any of the coefficients are zero.

Table 7
Multiple Linear Regression Parameter Estimates

Variable	Coefficient Estimates	95% Confidence Limits	
Intercept	0.738	-1.108	2.584
Longitudinal Delta-V	0.0454	0.0173	0.0736
Weight	0.0259	0.01	0.0418
Belt Status	0.89	0.205	1.576

Model Validation Figure 15 illustrates the linear regression model comparison for both belted and unbelted drivers. The figure compares the predicted steering wheel deformation of a 70 kg driver in a belted or unbelted scenario. The model shows that, given the same longitudinal delta-V, an unbelted driver is expected to experience larger steering wheel deformation in a frontal crash.

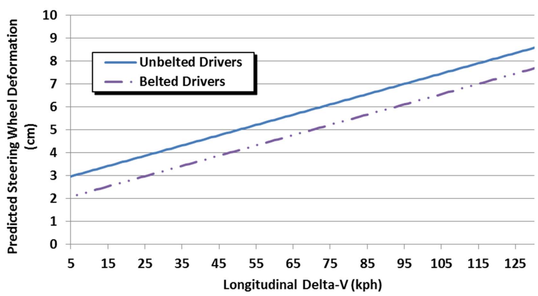

Figure 15. Linear Regression Model for Belted and Unbelted 70 kg Driver

Figure 16 and Figure 17 shows the actual versus predicted steering wheel deformation for belted and unbelted scenarios, respectively. A linear line with a slope of one has been included for comparison. For both belted and unbelted drivers, the model was able to predict steering wheel deformation for the large portion of the cases with deformation ranging from 3 to 7 cm.

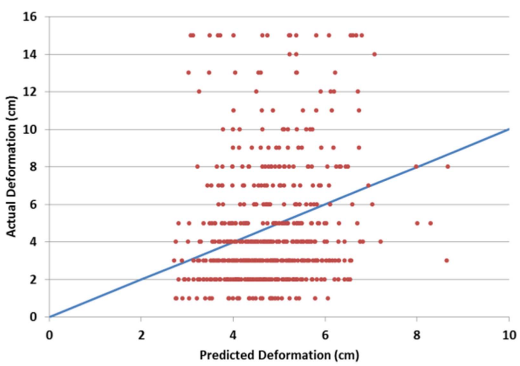

Figure 16. Model Validation – Actual Deformation against Predicted Deformation for Belted Driver

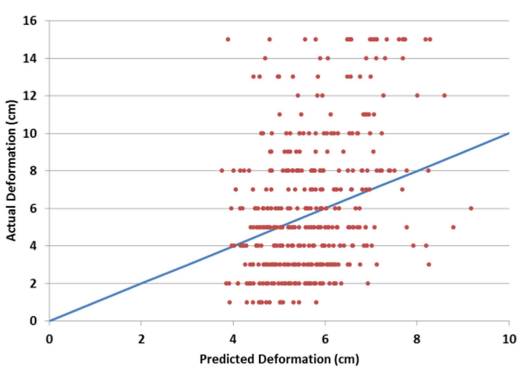

Figure 17. Model Validation – Actual Deformation against Predicted Deformation for Unbelted Driver

Factors which Influence the Incidence of Steering Wheel Deformation In addition to modeling the magnitude of steering wheel deformation, we are also interested in the delta-V threshold at which steering wheel deformation first becomes measurable. In this section, we use logistic regression to model the probability of steering wheel deformation as a function of delta-V, belt use, and occupant weight.

The probability of the discrete outcome can be estimated using a logistic regression. A logistic regression model was constructed using the SurveyLogistic function of SAS 9.2. Similar to the regression model, the logistic model also considers the stratified sampling scheme used by NASS/CDS, and contains the three variables: longitudinal delta-V, weight, and belt status.The estimated coefficient of each variable and its respective 95% confidence interval are tabulated in Table 8.

Table 8
Logistic Regression Parameter Estimates

Variable	**Coefficient Estimates**	**95% Confidence Limits**	
Intercept	-6.3029	-7.156	-5.4497
Longitudinal Delta-V	0.0683	0.0593	0.0773
Weight	0.0231	0.0153	0.0308
Belt Status	0.6693	0.4628	0.8758

Table **9** lists the result of the Chi-Square test which test against the null hypothesis that at least one of the variables' regression coefficients is equal to zero in the model. Based on the calculated Chi-Square value and the associated probability, we can reject the null hypothesis that at least one of the variables' regression coefficients is equal to zero.

Table 9
Testing Global Null Hypothesis

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	174,721	3	<.0001
Score	233,606	3	<.0001
Wald	274	3	<.0001

Using the parameter estimates in Table 8 and the logarithmic regression equation shown in equation (5), the probability of steering wheel deformation for a 70 kg belted and unbelted driver can be estimated with respect to longitudinal delta-V, as shown in a Figure 18.

$$P = \frac{e^{(Intercept+A*Delta-V+B*Weight+C*Belt)}}{1+e^{(Intercept+A*Delta-V+B*Weight+C*Belt)}} \quad (5)$$

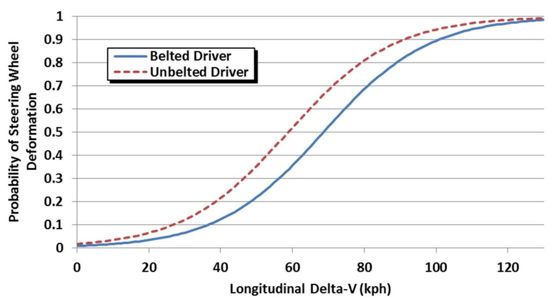

Figure 18. Probability of Measurable Steering Wheel Deformation for Belted and Unbelted 70kg Driver

Figure 19 and Figure 20 illustrate the 95% confidence limits constructed by the logistic regression analysis for a 70 kg belted and unbelted drivers.

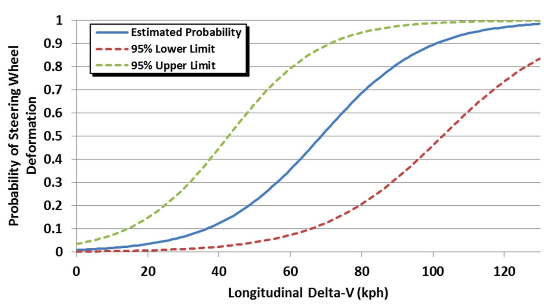

Figure 19. Probability of Measurable Steering Wheel Deformation for 70kg Belted Driver

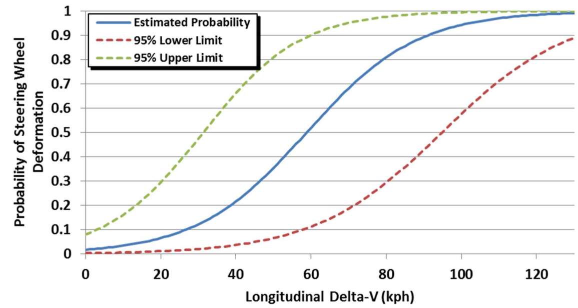

Figure 20. Probability of Measurable Steering Wheel Deformation for 70kg Unbelted Driver

Discussion

This analysis sought to characterize the factors influencing steering wheel deformation in a frontal crash. As a first step, we considered a simplified linear model to relate steering wheel deformation with delta-V. The linear regression model included longitudinal delta-V, weight, and belt status and showed statistical significance in predicting steering wheel deformation. Each of these variables constituted a significant contribution in the response variable, steering wheel deformation.

The linear regression model indicated that unbelted drivers were likely to experience larger steering wheel deformation. For two drivers of the same weight experiencing identical delta-V during a frontal crash, our model predicted that the unbelted driver would experience on average approximately 1 cm greater steering wheel deformation. The model also suggests that a driver of greater weight will experience greater steering wheel deformation. On average, the linear regression model estimates that steering wheel deformation will increase by 0.26 cm per 10 kg of weight increase. Likewise, a driver involved in a higher delta-V crash will likely experience greater steering wheel deformation. On average, the linear regression model estimates that steering wheel deformation will increase by 0.45 cm per 10 km/hr increase in delta-V. However, no statistically significant difference was observed between advanced airbags and sled-certified airbags in terms of steering wheel deformation. Multiple event crashes were also found to be statistically insignificant in affecting steering wheel deformation.

The risk of any steering wheel deformation was also a function of delta-V, belt use, and driver weight. A 70-kg driver has a 10% probability of deforming the steering wheel at 27 km/hr. By comparison, a belted driver of the same weight must be in a much more severe crash (delta-V = 36 km/hr) to have the same 10% chance of any measureable steering wheel deformation.

Our study has several limitations. The analysis did not consider the effect of load-limiting seatbelts or seat-belt pre-tensioners. These enhancements to seat belts were introduced concurrently with the transition from sled-certified airbags to CAC airbags and may have affected the stiffness of the combined seat belt-airbag-steering wheel system. Our linear model of the driver restraint system does not, of course, account for the non-linear force-deflection of the belt-airbag-steering wheel system, but was regardless useful to identify the factors which are likely to control steering wheel deformation. Follow-on studies will investigate non-linear models of this system. The initial proximity of the driver with respect to the steering wheel is not recorded in NASS/CDS. We initially considered using driver height as one indication of likely driver proximity to the airbag. However, driver weight and driver height are highly correlated. Here we chose to use driver weight rather than height in order to capture inertial loading of the airbag by the driver. It may be possible however to infer driver-airbag proximity using other methods in follow-on studies. Finally, our analysis used delta-V as a measure of crash severity. Delta-V does not capture the influence of crash pulse which may also affect driver-steering wheel interaction.

CONCLUSIONS

This study has investigated the incidence of steering wheel deformation and the associated driver injury outcome. The study was based upon the analysis of 10,429 belted drivers and 2,407 unbelted drivers of MY 1998 and later passenger vehicles. Our conclusions are as follows:

- Only 4% of belted drivers were involved with a steering wheel with any measurable deformation. However, this 4% of cases was overrepresented in the injury outcomes, and was associated with 15% of MAIS2+ drivers and 29% of MAIS3+ injured drivers.

- Unbelted drivers were more likely to be associated with steering wheel deformation (13%) than belted drivers (4%). In most belted cases, the three point belt keeps the driver out of the steering wheel. Although a small fraction, the 13% of unbelted drivers in vehicles with steering wheel deformation is overrepresented in the injury outcomes. This small fraction was associated with 37% of MAIS2+ drivers and well over half (58%) of MAIS3+ unbelted drivers. Clearly, failure to wear a safety belt puts unbelted drivers at a higher risk of impacting the steering wheel than belted drivers. The result is a sharply elevated risk of injury.

- The incidence of steering wheel contact increases as higher delta-V increases. Crashes with measurable steering wheel deformation had a median delta-V of about 19 mph, compared to a median delta-V of about 14 mph in cases without steering wheel deformation.

- The risk of both AIS2+ and AIS3+ injury was greater for crashes involving steering wheel deformation. For belted drivers in crashes with steering wheel deformation, the risk of AIS2+ thoracic injury was 13 times greater than for crashes without steering wheel deformation. The risk of AIS3+ thoracic injury was 14 times greater than for crashes without steering wheel deformation.

- The analysis of our NASS/CDS dataset indicated that longitudinal delta-V, belt usage, and occupant weight were the primary factors which influenced both the incidence and magnitude of steering wheel deformation. The proposed linear regression model estimates 1 cm greater steering wheel deformation for unbelted driver, an approximate 0.27 cm increase in steering wheel deformation per 10 kg increase in driver weight, and an approximate 0.45 cm increase in steering wheel deformation per 10 km/hr increase in delta-V. After controlling for crash severity, driver belt use, and driver weight, our analysis showed no statistically significant difference in the magnitude of steering wheel deformation between sled-certified airbags and CAC airbags.

Even in vehicles equipped with airbags, serious thoracic injury is associated with steering wheel impact and deformation. This study demonstrates that a promising path for further thoracic injury reduction lies in enhancements to airbag and belt systems which reduce steering wheel impact. The study also shows that, even for the most advanced restraint system, the importance of investigating the steering wheel as a driver load path in addition to simply the airbag and belts. Without factoring in the steering rim load path, the assessment of airbag and belts effectiveness may be incorrect in serious injury cases.

ACKNOWLEDGEMENTS

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