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AIS 3+ THORACIC INJURIES AMONG DRIVERS IN REAL-WORLD MOTOR VEHICLE FRONTAL CRASHES: THE EFFECT OF IMPACT DIRECTION, IMPACT LOCATION AND STATUS OF SEAT BELT

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Abstract: This paper, comparing seat belt usage, investigates the combined effects of specific impact directions and impact locations on the serious-to-maximum thoracic injuries of drivers in frontal impact based on the 1995-2010 data from the United States Department of Transportation (US DOT) National Automotive Sampling System-Crashworthiness Data System (NASS-CDS). The selected sample is classified by three impact locations (distributed, offset and corner) and two impact directions (pure frontal and oblique), resulting in a total of six crash configurations. The risks of thoracic injury and its anatomic structure injury for drivers, considering using seat belt or not independently, in different frontal crash configurations are evaluated. The relative risks are computed also. Overall, results of the analyses reveal that the effectiveness of thorax protection by the seat belt is significant. But for thoracic organ injuries, in frontal corner impact, using seat belt may not decrease the risk of serious-to-maximum injuries significantly, as in frontal distributed impact for skeletal injuries.

Keywords: Impact direction, Impact location, Injury risk, Thoracic Injury, Seat belt usage

1 Introduction

Vehicle crash accidents and associated occupant injuries and fatalities remain a big concern for society, though more and more vehicles receive high scores in the New Car Assessment Program (NCAP) through the enhancement of structural crashworthiness and the equipment of advanced safety technology in the past decades [1][2]. This is likely due to the randomly occurred crash configurations in real-world accidents that could not be completely covered in existing regulatory crash tests. For instance, current frontal crash tests primarily address full width (100%) rigid barrier impact (angular 30deg in FMVSS 208) and 40% offset deformable barrier impact. However, real-world frontal crashes frequently occur at different percentages of the overlay of vehicle frontal ends (corner impact and etc.), at other impact directions and especially in different combinations of impact direction and impact location. Also, the shortcomings of the dummy used for the crash test may probably help explain the differences. For instance, the ribcages of the anthropomorphic test devices (ATDs) typically do not allow for much local deformation, which may overlook the thoracic injury caused by the local loading of seat belt[3][4]. Thus, further investigation should be done to find the influential factors on the injuries in crash.

A great number of factors, like change of impact velocity, impact direction and location, seat belt usage, may have influence on the type and severity of injuries sustained by the occupants. Among the crash variables, general crash configuration (front impact, side impact, rear impact and etc.) should be emphasized. In this research, we may first select the front impact as the dominating research direction due to its high frequency in real traffic accidents, and others (side, rear or others) will be discussed in the future. In addition, we may focus on the drivers' thoracic injuries only in this research to simplify the analyses and the discussions.

The substantial influence of impact location (or vehicle damage distribution) on the driver's thoracic injury has been identified previously. For this reason, different impact locations should be selected to investigate the relationship between them. Considering that drivers should sit in the left of the vehicle in the US, we may select the corner impact and offset impact on the left of vehicles first and the locations on the right may be discussed later. In addition to impact location, impact direction has considerable influence on the drivers' thoracic injuries as well. Except for the pure frontal impact, the oblique impact is of great importance for its high proportion occurring in the real world. As the reasons stated above, we may select pure frontal impact and oblique impact at eleven o'clock in this research. To take the influence of the seat belt on the thoracic injury into account, using seat belt or not is identified when we calculate the risk of injury and the relative risk.

Hence, a total of six crash configurations combining three impact locations and two impact directions are used to classify the selected data [5]. In each category, seat belt usage is separated to calculate the thoracic risk of injury independently and the relative risk is evaluated based on the results above. Furthermore, the anatomic structure risk of injury and relative risk are calculated to investigate the influence of the impact configuration and the status of seat belt on them.

2 Method

2.1 Data sources

The data used in this research is from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) for the years of 1995-2010. Nearly 5000 crashes from across the country were randomly sampled annually by trained US DOT crash investigators to obtain relevant data. The vehicles involving in these crashes were always towed from scene for their serious damage. Thus, the NASS-CDS database is a representative, random sample of thousands of minor, serious, and fatal crashes. To make the crashes represent all motor vehicle crashes recorded by the police, the inflation factor (RATWGT) should be considered in the research. The NASS-CDS has been extensively used by researchers to promote the development of the restraint system and evaluate the occupant injuries.

The NASS-CDS database was queried using coded variables of specific interest to the authors. These coded variables are defined in the NASS-CDS Analytical User's Manual 2010[6] In addition; the cases with unknown data will be excluded to ensure the effectiveness of the statistical analyses.

2.2 Vehicle selection

In this research, only the event ranked as the most severe one will be considered, though more than one crash event may be involved in a single crash. For vehicle selection, impact direction and impact location (vehicle damage location) defined in Collision Deformation Classification (CDC), should be considered primarily. Impact direction is indicated by the principal direction of the resultant force (PDOF) resulted in the deformation on the damaged vehicle. The impact direction is represented by the clock direction (Fig.1) relative to the vehicle at the point of impact. Impact location is classified according to the projected area of the deformed vehicle based on the CDC (Fig.1). Other variables not described herein were taken into account during the database query.

According to the state above, the database is screened based on the following rules. Firstly, vehicles in crashes with a Principal Direction of Force equal to 11 and 12 o'clock, that is pure frontal impact (DOF=12) and oblique impact (DOF=11), are selected for analyses. Secondly, vehicles with damage location of distributed frontal impact (D), left offset frontal impact (Y) and left corner frontal impact (L) are concerned. Additionally, only vehicle to vehicle collisions under horizontal impacts without fire occurring, undercarriage or rollover were selected.

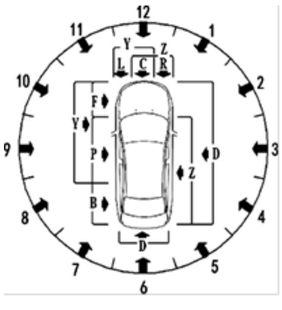

Fig.1: Definition of impact direction and damage location

2.3 Occupant selection

Occupant variables used to select the cases in this research include age, seat position and others. Only non-ejected adult drivers, who are older than 16, have been selected for the analysis. For the reason that the influence of seat belt usage on driver's thoracic injury is a key point of this research, the status of seat belt usage should be considered. In this research, ignoring the differences between failures of the seat belt and not using the seat belt, the cases have been divided into two parts: using seat belt and not using seat belt.

2.4 Injury selection

Injury body region, type and severity in this research follow the NASS Guidelines based on the abbreviated injury scale (AIS), which was developed by the Association for Advancement of Automotive Medicine (AAAM) [7]. As an anatomical injury scoring system, AIS is a numerical system of 7-digit code for injury severity description. AIS 0 represents non-injuries sustained by the drivers in this study, and AIS1 through AIS6 represent increasing severity of injuries defined by 'threat to life'. The meanings of the codes are that: AIS 1 for minor, AIS 2 for moderate, AIS 3 for serious, AIS 4 for severe, AIS 5 for critical and AIS 6 for maximum severity. In this research, we only focus on the thoracic injury, but we did not screen these cases for injuries of other types.

2.5 Statistical analyses

The database, weighted with the inflation factor (RATWGT), is edited using SPSS (IBM SPSS Statistics) for further recoding and analyses. As the statement above, the cases with missing information or with variables coded as unknown are excluded.

	D		Y		L		Total
	FRONT	OBLIQUE	FRONT	OBLIQUE	FRONT	OBLIQUE	
	Number(percent)						
Driver	418683	118302	90423	47151	69063	36878	780500
Safety belt use	282063(67.4%)	82275(69.5%)	64986(71.9%)	26194(55.6%)	44101(63.9%)	23196(62.9%)	522815(67.0%)
AIS 3+ thoracic injury	15902(3.8%)	11005(9.3%)	3530(3.9%)	885(1.9%)	1857(2.7%)	2020(5.5%)	35199(4.5%)

Table.1 Characteristics of drivers distributed by impact location and impact direction

The method of cross-tabulation (CROSSTAB) was used to analyze the data with respect to impact location and impact direction in consideration of the status of seat belt for thoracic injury and specific anatomical structures of the thorax. In this research, the risks of injuries refer to the fraction of drivers with a specific injury with respect to all drivers within our sample, including drivers with and without such injuries, in the same category. In addition, the relative risks are defined by dividing the injury risk for using seat belt by that for not using seat belt. In consideration of the accuracy of the relative risk, the ninety-five percent confidence intervals (95% CI) are calculated by the Delta method [8]. Also, Chi-square tests and Mantel-Haenszel tests are used to investigate the relationship between injury and crash related variables. Chi-square test, in order to test the association between the status of seat belt and the thoracic injury, is done at a significance level of 0.05. Mantel-Haenszel test, to examine whether impact category has significant influence on the relationship between the status of seat belt and the thoracic injury, is performed at a significance level of 0.05.

The meaning of the relative risk should be noted of its great importance in this research. If the relative risk is less than the value of one and the value of one falls outside of the confidence intervals, our findings may indicate that the injury is more likely to occur for drivers not using seat belt than for drivers using their seat belt. In other words, the effectiveness of the seat belt may be significant potentially significant. The lesser the value of the relative risk, the effectiveness of the seat belt increases. In contrast, the greater the value of relative risk, the effectiveness of the seat belt decreases, may potentially aggravate specific thoracic anatomy during a crash event.

3 Results and discussion

The national weighted estimate (RATWGT) revealed a total of 780500 drivers involved in this queried sample for analysis. In addition, nearly 4.5% (35199) of all queried drivers sustained AIS 3+ thoracic injuries. For the reason that some drivers may have more than one injury, overall 51133 AIS 3+ thoracic injuries were selected.

Table 1 shows the selected characteristics of drivers distributed by impact location and impact direction.

3.1 Thoracic injuries

Table 2 shows the AIS 3+ thoracic injuries distributed by the status of seat belt. Results of Chi-square tests show that the relationship between status of seat belt and occurrence of thoracic serious-to-maximum injury is statistically significant ($p<0.001$). This indicates that the status of seat belt may have great influence on the AIS 3+ thoracic injuries for drivers and further research may be pursued in the future to further access influencing factors.

	No AIS 3+ thoracic injury	AIS 3+ thoracic injury	Total
Using belt	511227 (97.8%)	11588 (2.2%)	522815

Not Using belt	234073 (90.8%)	23612 (9.2%)	257685
Total	745300 (95.5%)	35200 (4.5%)	780500

Table.2 Relationship between the status of seat belt and the occurrence of AIS 3+ thoracic injury. Statistically significant, p<0.001 (Chi-square tests).

Figure 2 shows the distribution of risks of AIS 3+ thoracic injury by impact location, impact direction and the status of seat belt use. Overall, there is highest risk of AIS 3+ thoracic injuries in oblique distributed impact category when seat belt is not used. The risk in this category is much greater than the other risk categories. It indicated that without protection of seat belt, nearly a quarter of drivers in an oblique distributed impact will sustain serious-to-maximum (AIS 3+) injuries for the reason that distributed impact may lead to more energy release and oblique impact may restrain the ability of energy absorption by the vehicle structure. In addition, without the protection of the seat belt, the driver may have greater opportunities to contact with the parts in vehicle and sustain much higher force; this may cause an increased opportunity for serious thoracic injury for drivers.

Results of Mantel-Haenszel tests allow us accept the assumption that the impact location and impact direction have effect on the relationship between the occurrence of serious-to-fatality injury and the status of seat belt. That verifies the method in this research that doing the analyses according to the combine of impact direction and impact location is necessary.

Figure 3 gives the relative risks of AIS 3+ thoracic injuries under using seat belt versus not using seat belt for different impact categories. The highest relative risk for thorax is in frontal corner impact category (RR 0.79, 95% CI 0.68-0.91). Also, the relative risks in frontal impact categories increase within the impact location deviating from the center of the vehicle to the corner of the vehicle. It indicates that with the frontal impact point going left, the effectiveness of the seat belt isn’t as significant as it is in center, which may probably be resulted from the rotation of the drivers. The above observations and the assumptions indicate that further investigations should be done to find the relationship between the status of seat belt and the risk of injury. Thus, further analyses based on the data of risk of injury by specific thoracic anatomic structure under the 6 impact categories are represented below.

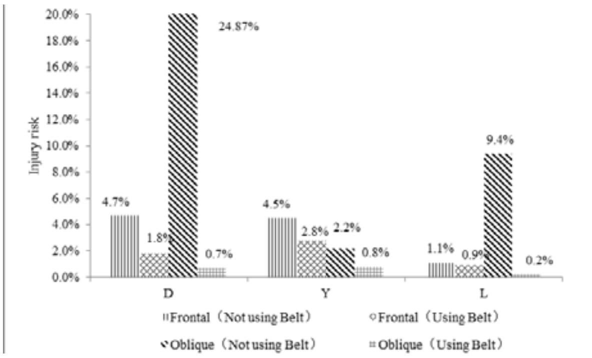

Fig.2: The risks of AIS 3+ thoracic injuries by impact location, impact direction and the status of seat belt. Statistically significant, p<0.001 (Mantel-Haenszel tests).

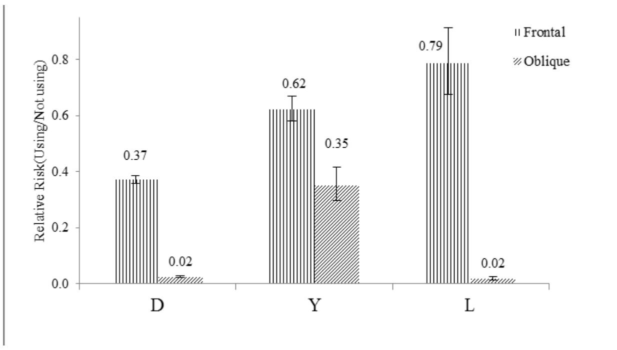

Fig.3: The relative risks of thoracic injuries under using seat belt versus not using by impact location and impact direction

3.2 Thoracic injuries by type of anatomic structure

Figure 4 and Figure 5 show the types of thoracic injury by impact category. Figure 4 represents restrained drivers and Figure 5 represents unrestrained drivers. According to the statistical results, organ, skeletal and vessel injuries are the dominating types for thoracic injuries. Additionally, the proportion of the vessel injuries decrease substantially due to seat belt use, which may surely indicate that the use of the seat belt can protect the vessels effectively. In contrast, the proportion of the skeletal and organ injuries has less obvious correlation of injury distribution due to seat belt usage under different impact categories. Thus, the research below will focus on the organ and skeletal injury to investigate the influence of seat belt on the risks of AIS 3+ thoracic injuries.

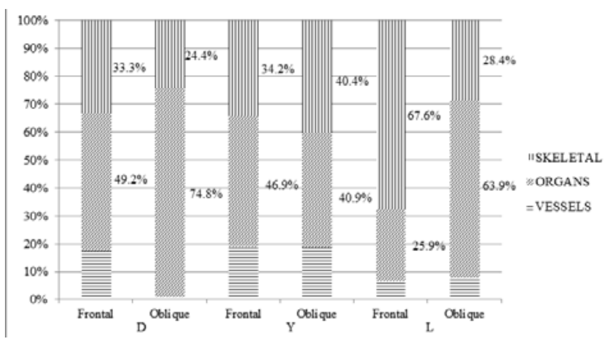

Fig.4: Type of thoracic injury of drivers using seat belt by impact location and impact direction

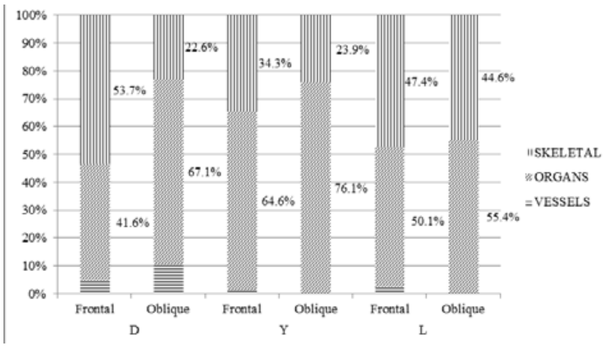

Fig.5: Type of thoracic injury of drivers not using seat belt by impact location and impact direction.

3.3 Thoracic organ injuries

Figure 6 gives the risks of AIS 3+ thoracic organ injuries by impact location, impact direction and the status of the seat belt. Figure 7 shows the relative risks for AIS 3+ thoracic organ injuries under using seat belt versus not using seat belt for different impact categories.

Comparing the Fig.6 to Fig.2, we find substantial similarity between the figures, though the two focus on different level of the risk of injury. In accord with the discussions based on Fig.2, we may emphasize that the oblique impact is much more dangerous for drivers without using the seat belt for the shortage of the structure's energy absorption resulting in a higher collision wave.

In Fig.7, the highest relative risk for thoracic organ injury is in frontal corner impact category (RR 0.79, 95% CI 0.68-0.91). This suggests that the effect of the seat belt may be not significant, which means that using the seat belt in this situation may not decrease the risk of thoracic organ injury as we hope. Also, we may find that the relative risks in frontal impact categories increase within the impact location deviating from the center of the vehicle to the corner of that. This finding may help us to understand thec reason for the statistical results above. First, assuming that the impact forces applying to the three locations have the same magnitude, the forces on the corner location may causes greater rotational inertia effect compared to that on offset location. Also, that on offset location surely causes greater rotational inertia effect than that on distributed location. Additionally, asymmetrical structure of seat belt fails to prevent relative motion of the drivers' spine with respect to their pelvises during the vehicle's relative rotation. Another reason which may be associated with this phenomenon should be noted is that the front cross member will not have contact with another vehicle to make the front rails absorb the energy efficiently. This may result in a serious impact for the vehicle and the drivers. In this situation, the first peak of the crash pulse may be too high to cause a big acceleration for the vehicle and the drivers, and the seat belt may not provide the protection for its mechanical interval. These may result in that the corner impact causes the worst effectiveness of seat belt for drivers. In consideration of the oblique impact, we may find that in the three impact locations, the effectiveness of the seat belt for drivers is all better than that for frontal impact, especially in distributed and corner locations. That may probably because the moment arm is always shorter than the frontal impact considering the same impact locations.

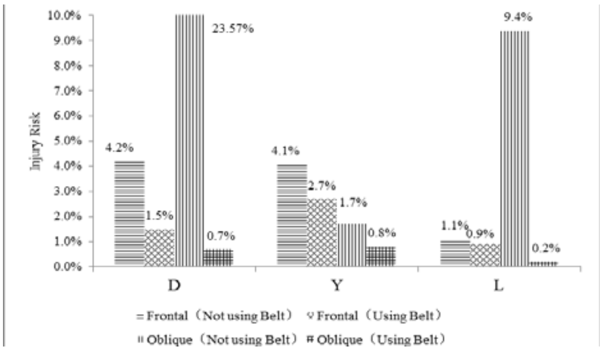

Fig.6: The risks of AIS 3+ thoracic organ injuries by impact location, impact direction and the status of seat belt.

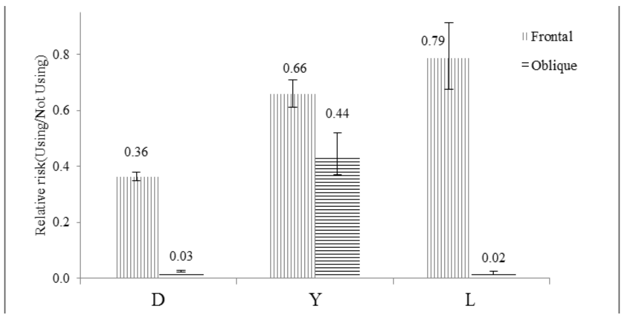

Fig.7: The relative risks of thoracic organ injuries under using seat belt versus not using by impact location and impact directio

3.4 Thoracic skeletal injuries

Figure 8 gives the risks of AIS 3+ thoracic skeletal injuries by impact location, impact direction and the status of the seat belt. Figure 9 shows the relative risks of AIS 3+ thoracic skeletal injuries under using seat belt versus not using seat belt for different impact categories.

In Fig.9, the highest relative risk for thoracic skeletal injury is in frontal distributed impact category (RR 0.64, 95% CI 0.62-0.67). This suggests that the effect of the seat belt may be not significant as the others, which means that wearing the seat belt in this situation may not decrease the risk of thoracic organ injury as they can in other situation. Also, we may find that the relative risks in frontal impact categories decrease within the impact location deviating from the center of the vehicle to the corner of that. The reasons for this may be probably complicated because of the great number of variables involving in this circumstance. We can possibly assume that the vehicles with same mass have crashes with the target vehicle in the three impact locations. As we know, the central collision may release more kinetic energy than the others. Thus, much more energy should be absorbed in distributed collision than that in offset collision, surely much more than that in corner collision. Due to this reason, the relative displacement of the drivers may be farther more which may lead to more local loading on the driver thorax by seat belt. The higher local loading and the much more compression, resulting from the local loading, may lead to the fracture of the ribcage. Thus, though the use of the seat belt can decrease the risk of the contact with the things like steering wheel, the local loading and compression resulting from the seat belt may partially hurt the drivers. This may probably reduce the effectiveness of the seat belt for drivers.

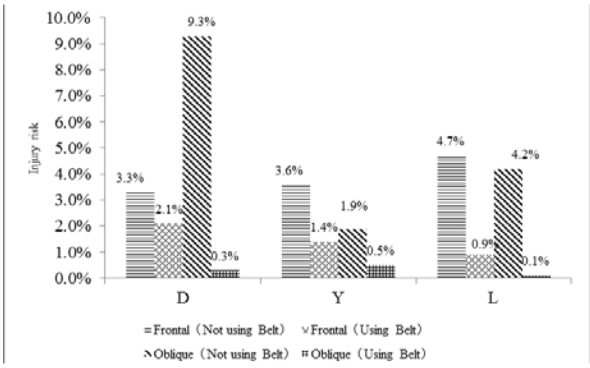

Fig.8: The risks of AIS 3+ thoracic skeletal injuries by impact location, impact direction and the status of seat belt

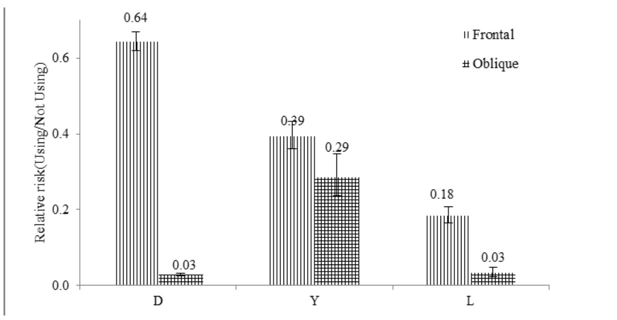

Fig.9: The relative risks of thoracic skeletal injuries under using seat belt versus not using by impact location and impact direction

4 Conclusions

This paper presents an analysis and discussion of the risk of thoracic serious-to-maximum injuries sustained by drivers considering seat belt usage and the combination of specific impact directions and impact locations. The following conclusions can be drawn from the paper.

First, the impact location and impact direction have statistical significant effect on the relationship between the occurrence of serious-to-maximum injury and the status of seat belt. In different categories, the types of the thoracic injury and the effectiveness of the seat belt are disparate. For instance, in frontal distributed impact, the effectiveness of the seat belt may be restraint for skeletal injury. The conclusion is similar for the thoracic organ injury in frontal corner impact. Additionally, the results of the Mantel-Haenszel tests verified the conclusion.

Second, the importance of some crash configurations like corner impact which may not be parts of current US FMVSS motor vehicle standards and regulatory testing should be considered. From the discussions above, we may find that in some situations, like corner impact, the risk of injuries is of such a high value and the seat belt may not provide enough protection. To take these characteristics of impact into account and try to consider them in the regulatory or the standard may promote the companies or the researchers to enhance the technology for protecting the drivers better.

Third, this paper stresses the necessity of more study on dummy with the ribcages considering the local deformation to reflect the drivers' mechanical response better.

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References

[1] Cavanaugh J M. The biomechanics of thoracic trauma in Accidental Injury: Biomechanics and Prevention Hrsg: AM Nahum[J]. JW Melvin Springer Verlag NY, 1993.

[2] Groskin S A. Selected topics in chest trauma[J]. Radiology, 1992, 183(3): 605-617.

[3] Foster J K, Kortge J O, Wolanin M J. Hybrid III-a biomechanically-based crash test dummy[R]. SAE Technical Paper, 1977.

[4] Donnelly B R, Morgan R M, Eppinger R H. Durability, repeatability and reproducibility of the NHTSA side impact dummy[R]. SAE Technical

Paper, 1983.
[5] Lai X, Ma C, Hu J, et al. Impact direction effect on serious-to-fatal injuries among drivers in near-side collisions according to impact location: Focus on thoracic injuries[J]. Accident Analysis & Prevention, 2012, 48: 442-450.
[6] NHTSA, 2010, “National Automotive Sampling System (NASS) Crashworthiness Data System Analytical User’s Manual”, U.S. Department of Transportation,
[7] AAAM, 1998, Association for the Advancement of Automotive Medicine, 1998. The Abbreviated Injury Scale, 1990 ed.(1998 Update). Association for the Advancement of Automotive Medicine, Des Plaines
[8] Gardner, M.J., Altman, D.G., 1994. Statisitics with Confidence. BMJ Publications, Reprint pp. 51–52