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The influence of vehicle damage on injury severity of drivers in head-on motor vehicle crashes

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ABSTRACT

Data from crashes investigated through the Crash Injury Research and Engineering Network (CIREN) Program were used to assess differences in injury patterns, severity, and sources for drivers, protected by safety belts and deploying steering wheel air bags, in head-on frontal impacts. We studied whether exterior vehicle damage with a different distribution (wide vs. narrow) across the front vehicle plane influenced injury characteristics. Drivers from both impact types were similar on the basis of demographic characteristics (except age), restraint use, and vehicle characteristics. There were significant differences in the type of object contacted and intrusion into the passenger compartment at the driver's seat location. The mean delta *V* (based on the kilometers per hour change in velocity during the impact) was similar for drivers in both (wide vs. narrow) impact types. There were no significant differences in injury patterns and sources except that drivers in wide impacts were almost 4 times more likely (odds ratio (OR) = 3.81, 95% confidence limits (CL) 1.26, 11.5) to have an abbreviated injury scale (AIS) 3 serious or greater severity head injury. Adjusted odds ratios showed that drivers in wide impacts were less likely (OR = 0.54, 95% CI 0.37, 0.79) to have severe injury (based on injury severity score (ISS) > 25) when controlling for intrusion, vehicle body type, vehicle curb weight, age, proper safety belt use, and delta *V*. Drivers with intrusion into their position or who were driving a passenger vehicle were almost twice more likely to have severe injury, regardless of whether the frontal plane damage distribution was wide or narrow. Our study supports that the type of damage distribution across the frontal plane may be an important crash characteristic to consider when studying drivers injured in head-on motor vehicle crashes.

1. Introduction

In spite of improvements in vehicle safety, motor vehicle crash related trauma remains a compelling public health problem and a challenge for pre-hospital medical care providers, emergency medicine physicians and trauma surgeons. Crashes are complex events and many crash parameters including delta *V* (vehicle change in velocity at the time of impact), delta *T* (crash duration), and the crash pulse (vehicle deceleration over time) may influence injury risk for occupants (Hollowell et al., 1999). Research also shows that the vehicle's stiffness, mass, and structure also may influence the impact (Varat and Husher, 2003). Crash characteristics influence injury patterns and severity and provide valuable information for the diagnosis and rapid treatment of the trauma patient (Augenstein et al., 2003).

Frontal crashes are one of the most common types of crashes, and often result in severe injuries. In addition to the frontal principal direction of force (PDOF), the external damage across the frontal plane of the vehicle (e.g., wide, narrow, corner, etc.) and intrusion into the occupant compartment may affect injury severity. During a wide frontal collision, more of the vehicle's frontal plane is involved, resulting in damage to a wider area. As previous researchers note, this collision type is similar to the Federal Motor Vehicle Safety Standards (FMVSS) 208 tests using fixed barriers (Hollowell et al., 1999). During a frontal impact with a narrow object, less of the vehicle's front plane is damaged. Because the narrow object may

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not have contacted either of the frame rails, the vehicle bumper may tear away from the frame rails without absorbing energy from the impact.

This study used the Crash Injury Research and Engineering Network (CIREN) database to study driver injuries during head-on frontal crashes. We hypothesized that exterior vehicle damage with different distributions (wide vs. narrow) across the front vehicle plane may result in different injury characteristics even when the principal direction of force is the same.

2. Methods

2.1. Data sources

Multiple centers throughout the United States conduct field investigations, under a modified National Automotive Sampling System (NASS) protocol (NHTSA CIREN Report, 2002) to obtain detailed vehicle and crash information for the CIREN Program. These crashes involve both fatally injured occupants dying at the scene and seriously injured occupants transported to Levels 1 and II trauma centers for treatment. Level 1 trauma centers provide comprehensive trauma care 24 h a day and conduct research, education, and injury prevention programs. Level II trauma centers also provide 24-h trauma care but may not have a surgery residency or research program.

Patients are identified through Trauma centers and the medical examiner offices and their inclusion in the program also is based upon the circumstances of their crash. In general, crashes involving late model year cars (less than 8 years earlier than the year of crash) and occupants with serious injury (usually abbreviated injury scale (AIS) 3 or greater) are investigated in the CIREN Program.

Medical data are obtained by personal interviews with injured occupants, medical chart reviews, and diagnostic images. A multidisciplinary team, consisting of trauma surgeons, nurses, biomechanical engineers, and crash investigators, at each CIREN center reviews each case to assign the source of each injury.

2.2. Crash and occupant selection

All available CIREN data (1997–2006) were used to identify drivers in head-on frontal crashes. In crashes with multiple impacts, the frontal impact ranked as the most severe by the crash investigator was selected for study. The collision deformation classification (CDC) (Society of Automotive Engineers, 1980) is the standard used by crash investigators to categorize motor vehicle crashes on the basis of direction of force, area of damage, and type of damage distribution. We used the CDC in the CIREN database to identify vehicles with deformation along the frontal plane that were in head-on crashes with a principal direction of force equal to 12 o'clock (using a clock face superimposed along the longitudinal axis of the vehicle with the center at the point of impact). We also used the CDC to further classify the vehicle damage distribution across the front plane as either wide or narrow. Per CDC standards, wide impacts were defined as having a wide damage distribution area (greater than 66% of the vehicle's frontal plane) and narrow impacts were defined as having a narrow damage distribution area (less than 41 cm and not at the corner). Only drivers protected by safety belts and deploying steering wheel air bags were included in this study.

2.3. Occupant variables

Information about the injured occupant also was obtained from the CIREN database. Occupant information is obtained from medical or autopsy records. Occupant variables used in analyses include age, gender, body mass index (BMI), injury severity, overall body damage, and safety belt use. Improper safety belt use was defined as wearing the lap portion of the belt over the abdomen (instead of across the pelvic girdle) or wearing the shoulder belt too far on the edge of the shoulder instead of across the rib cage.

Injury body region and severity coding for CIREN follows the National Automotive Sampling System Guidelines based on the abbreviated injury scale developed by AAAM (1998). The AIS is an anatomical injury scoring system ranging from minor (AIS 1), moderate (AIS 2), serious (AIS 3), severe (AIS 4), critical (AIS 5) to maximum (AIS 6) severity. It was originally developed to measure injury severity for blunt force trauma received during motor vehicle crashes. The maximum abbreviated injury scale (MAIS) is the greatest AIS injury sustained by the occupant, regardless of which region was injured. Occupants often have multiple injuries of varying severity and may have more than one injury in the same or in multiple regions. The injury severity score (ISS), developed by AAAM (1998) is used to provide an assessment of overall bodily damage and injury survivability. This score is the sum of the squares of the highest AIS codes in each of the three most severely injured AIS body regions (Baker et al., 1974).

2.4. Crash and vehicle variables

Crash related variables used in the analyses include measures of residual intrusion at the driver's seat position (measured in centimeters), the occupant's vehicle body type (passenger car vs. truck, van, or sport utility vehicle) and curb weight, delta *V* (change in velocity of the vehicle at the time of the crash), and driver frontal air bag deployment. If the delta *V* was not available, the barrier equivalent speed (BES) was used to determine the change in velocity due to the impact. During a crash, interior vehicle components (e.g., instrument panel, steering wheel, etc.) may become deformed due to the external damage of the vehicle. As these interior components deform, they may be displaced into the area of the vehicle interior designed for the occupant. This intrusion into the occupant compartment may be greater at the time of the impact but it is only possible to measure the remaining residual intrusion after the impact.

Delta *V* is typically used as a measure of impact severity when studying motor vehicle crashes. Both delta *V* and the barrier equivalent speed for CIREN crashes are determined by WinSmash computer algorithms discussed by Stucki and Fessahaie (1998). This software uses vehicle parameters and vehicle crush information to determine the delta *V* during impact. BES is calculated for multi-vehicle crashes when there is insufficient information regarding the second vehicle to calculate the delta *V*. BES is the speed at which the vehicle would have had to impact a fixed barrier to produce the measured amount of external crush. The WinSmash software takes into account the stiffness of the vehicle based on make and model. Because of the variation in passenger car size and weight, the vehicle curb weight in addition to body type was included in analyses.

2.5. Statistical analyses

Analyses were based either on drivers or on injuries. Open (i.e., incomplete) CIREN cases were excluded. Minor injuries (AIS 1) were excluded from analyses based on injuries. Drivers with missing data for specific variables were excluded only from analyses based on those variables. Therefore, the numbers may vary for some analyses.

Table 1
Demographic characteristics and injury severity for drivers in wide and narrow frontal crashes

Demographic characteristics	Narrow impact *N* (%)	Wide impact *N* (%)
Age (years)*		
16–20	4 (9.7)	28 (8.8)
21–40	10 (24.4)	132 (41.4)
41–60	12 (29.3)	101 (31.6)
60+	15 (36.6)	58 (18.2)
Mean, median, range	52, 52, 17–86	42, 40, 16–86
Male	26 (57.8)	168 (48.4)
Body mass index (BMI)		
Normal or underweight (BMI < 25)	15 (33.3)	123 (35.6)
Overweight or obese (BMI ≥ 25)	30 (66.7)	222 (64.4)
Proper safety belt use		
Proper	41 (91.1)	338 (95.2)
Improper	4 (8.9)	17 (4.8)
MAIS		
1 (minor)	2 (4.5)	8 (2.3)
2 (moderate)	10 (22.7)	48 (14.0)
3 (serious)	17 (38.7)	204 (58.8)
4 (severe)	10 (22.7)	49 (14.0)
5 (critical)	5 (11.4)	28 (8.0)
6 (maximum)	0 (0.0)	10 (2.9)
Injury severity score (ISS)		
0–15	21 (48.4)	194 (56.7)
16–25	11 (25.6)	78 (22.8)
26–49	11 (25.6)	57 (16.7)
50–75	0 (0.0)	13 (3.8)
Mean, median, range	17, 17, 1–43	18, 14, 1–75

* Statistically significant difference at 0.05 level.

SAS® software (Release 9.1.3) was used for data extraction from the CIREN Oracle database and data analyses (SAS Institute, 2002–2004). Chi square or Fisher Exact statistics and odds ratios (OR) with 95% confidence limits (CL) were used to assess statistical differences between occupant, vehicle, and crash characteristics when comparing drivers in wide frontal impacts with drivers in narrow frontal impacts (Tables 1 and 2). Differences were considered statistically significant based on a 0.05 level.

Logistic regression models were used to determine independent predictive factors for severe injury. Severe injury was defined as ISS equal to 25 or greater. Odds ratios were used to explain the importance of the predictor variables (i.e., estimating the odds of an occupant having severe injury). These models assessed whether a wide impact or a narrow impact were predictive for severe injury while controlling for other potential risk factors (i.e., age, delta *V*, intrusion, vehicle body type, vehicle curb weight, and proper safety belt use). The Hosmer–Lemeshow Goodness-of-Fit (Chi square) was used to test the fit of the logistic regression model (Hosmer et al. (1991)). A non-significant Chi square supports that the model adequately fit the data.

Table 2
Vehicle and crash characteristics for drivers in wide and narrow frontal crashes

Vehicle and crash characteristics	Narrow impact *N* (%)	Wide impact *N* (%)
Delta *V* (km/h) mean, standard deviation, range	49, 46, 21–113	49, 47, 13–126
Object struck*		
Other vehicle	1 (2.3)	263 (76.9)
Fixed object	42 (97.7)	72 (21.0)
Non-fixed object	0 (0.0)	7 (2.1)
Vehicle body type		
Passenger car	33 (76.7)	238 (69.6)
SUV, truck, van	10 (23.3)	104 (30.4)
Vehicle curb weight (kg)		
Light (≤1,089)	6 (13.9)	41 (12.0)
Medium (1,090–1,587)	23 (53.5)	200 (58.5)
Heavy (≥1,588)	14 (32.6)	101 (29.5)
Mean, median, range (kg)	1430, 1435, 1037–1971	1455, 1397, 820–2669
Intrusion at drivers location*		
≤2 cm	3 (11.0)	5 (1.6)
≥3 to <8 cm	9 (27.3)	35 (11.5)
≥8 to <15 cm	11 (33.3)	57 (18.8)
≥15 to <30 cm	5 (15.1)	91 (29.9)
≥30 to <46 cm	4 (12.1)	68 (22.4)
≥46 to <61 cm	1 (3.0)	33 (10.9)
Catastrophic	0 (0.0)	15 (4.9)

* Statistically significant difference at 0.05 level.

3. Results

3.1. Driver characteristics

There were 794 drivers in head-on frontal impacts with a PDOF equal to 12 o'clock who met study criteria. Three hundred fifty-seven drivers were in wide impact frontal crashes and 45 were in frontal impacts with a narrow damage distribution. Tables 1 and 2 describe the occupant, vehicle, and crash characteristics for the drivers included in this study. As shown in Table 1, there was a significant difference in age, with drivers in wide impacts more likely to be younger. There were proportionally more male drivers in wide impacts although this was not statistically significant. The Body mass index was similar for both groups of drivers with about two-thirds of drivers in both groups overweight or obese. Over 90% of drivers in both impact types were documented as properly wearing their safety belt. There were proportionally more drivers in narrow impacts improperly wearing their safety belt but this was not significant.

3.2. Vehicle and crash characteristics

Table 2 compares the vehicle and crash characteristics for drivers in wide and narrow impacts. The mean delta *V* (change in velocity) was the same for both groups, indicating the crash severity was similar for both wide and narrow impacts, regardless of the differences in the objects the vehicles struck. The objects the driver's vehicle contacted during the impact were significantly different, with drivers in wide impacts more likely to be involved with another vehicle (76.9%) compared to those in narrow impacts (2.3%). Drivers in narrow impacts were more likely to contact a fixed object (97.7%) than drivers in wide impacts (21.0%). The vehicle struck a pole or tree for 89% of the narrow impacts compared to only 4% of wide impacts. The other fixed objects struck by vehicles included traffic barriers, fences, walls, bridges, and buildings.

The vehicle body type and curb weight was similar for both groups. Passenger cars accounted for about three-quarters of vehicles for each group. Comparing narrow and wide impacts, there was a significant difference in the magnitude of intrusion of vehicle components displaced into the driver's seat position within the occupant compartment. Drivers in wide impacts had greater intrusion into their seat position compared to drivers in narrow impacts. This may be related to the location of the narrow frontal plane damage. If the exterior damage was narrow and only on the passenger side of the vehicle, then intrusion of interior vehicle components may not have occurred on the driver side.

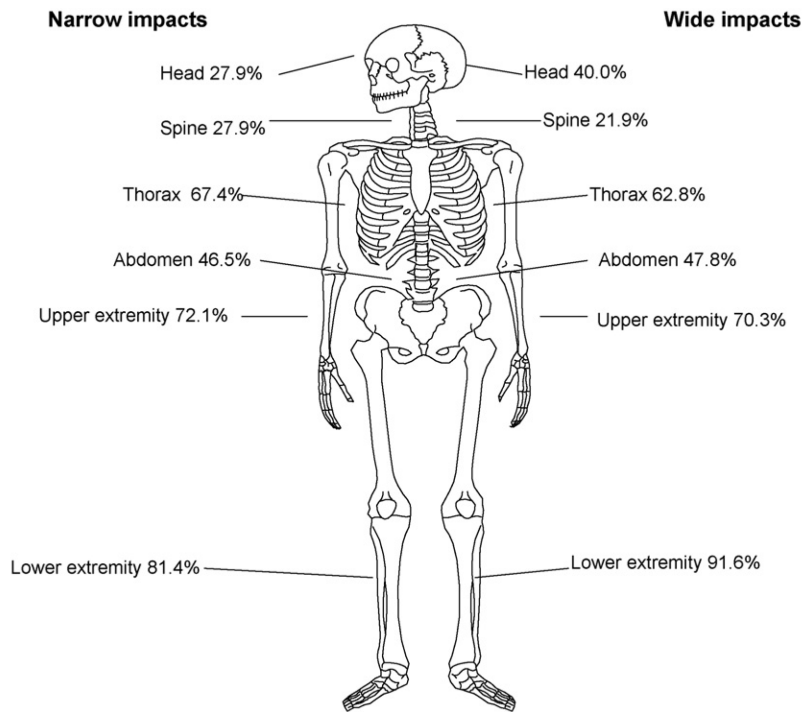

Fig. 1. Injury patterns for drivers in wide impacts compared to narrow impacts.

3.3. *Injury patterns and severity*

Injury patterns are similar with no significant differences between the two groups as shown in Fig. 1. Most drivers had lower extremity injuries and almost three-quarters of drivers in each impact group had upper extremity injury. Over 60% of drivers in each impact type had thoracic injury. Slightly less than half of drivers in each group had abdomen injury. More drivers in wide impacts had head injury compared to drivers in narrow impacts, but this was not statistically significant. The spine accounted for the least injured region for both groups.

Fig. 2 shows injury severity, based on the AIS score, by body region, comparing injuries of drivers in wide and narrow impacts. Injury severity varied depending upon the body region. The head region was the only region with a significantly different injury severity distribution for drivers in wide impacts compared to those in narrow impacts. The chance of having a head injury with an AIS of 3 or higher was almost 4 times greater (OR = 3.81, (95% CL 1.26, 11.5) for drivers in wide impacts compared to drivers in narrow impacts. There were no significant differences in AIS for spine, thoracic, or abdomen regions.

As shown in Table 1, drivers in wide impacts had slightly greater ISS scores, but, this was not significantly different from those in narrow impacts. Injury based on occupant's maximum AIS (MAIS) also was not significantly different (Table 1).

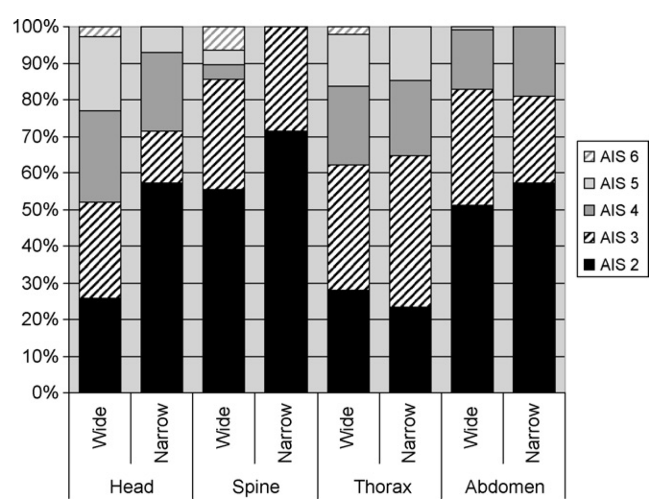

Fig. 2. Injury severity by body region for drivers in wide impacts compared to narrow impacts.

3.4. *Injury sources*

Fig. 3 compares injury sources by body region for drivers in wide compared to narrow impacts. Sources vary by body region although the greatest single proportion (40–70%) of spine, thorax, and abdomen injuries, regardless of whether the occupant was in

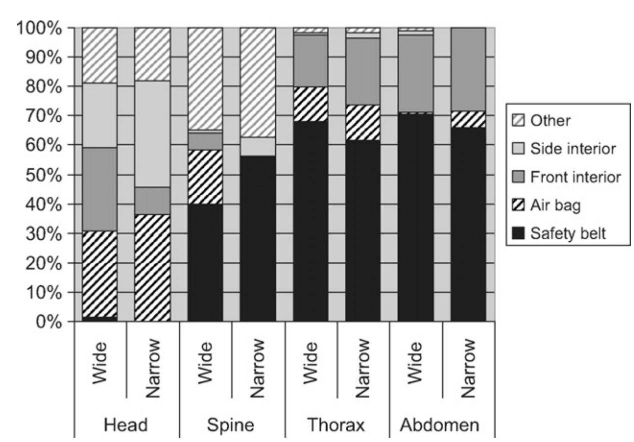

Fig. 3. Injury sources by body region for drivers in wide impacts compared to narrow impacts.

Table 3
Predictors of severe injury (ISS > 25) controlling for wide impacts

Independent variables	
Wide impact	0.54 (0.37, 0.79)*
Intrusion	1.84 (1.16, 2.9)*
Passenger car	1.88 (1.09, 3.24)*
Age	1.02 (1.01, 1.03)
Proper safety belt use	1.16 (1.00, 1.34)
Delta *V*	1.02 (1.01, 1.03)
Vehicle curb weight	1.00 (1.00, 1.00)

* Statistically significant ($p < 0.05$), Hosmer and Lemeshow Goodness-of-Fit Test Chi square = 8.91, 8, $p = 0.35$.

a wide or narrow frontal impact, were caused by safety belts. Many spinal injuries are caused by non-contact (included in the other category) for drivers in both impact types. Non-contact injuries are those resulting from occupant movement alone without contact with a vehicle component. For example, during a frontal impact, the driver's head and neck would move in a forward direction and the resulting flexion or extension may result in spinal injury. Although there are body region specific differences, injury sources do not differ significantly for drivers in wide impacts compared to those in narrow impacts.

3.5. Logistic regression models

Tables 3 and 4 show the logistic regression models used to assess potential predictors of severe injury (based on ISS >25). Variables were included in the model if they were potential confounders or known a priori to be associated with severe injury during motor vehicle crashes. Occupant factors included age and safety belt use. Vehicle factors (body type (passenger car vs. truck/SUV/van) and curb weight) also were included in the model. Finally, crash factors including the delta *V*, external damage distribution (narrow or wide) and whether there was intrusion into the occupant compartment at the driver seat location also were included.

Table 3 shows when drivers are in a wide impact (compared to other frontal impacts, including narrow), they are significantly less likely (OR = 0.54) to have severe injury when other potential risk factors are controlled. However, drivers with intrusion at their seat location (OR = 1.84) or who were driving a passenger car (instead of a truck, van, or sport utility vehicle) (OR = 1.88) had almost twice the odds of having severe injury, even when controlling for the influence of a wide impact. As Table 4 shows, intrusion (OR = 1.78) and driving a passenger car (1.96) again show drivers are almost twice as likely to have severe injury, even when controlling for the influence of being in a narrow impact. However, when controlling for other potential confounders, being in a narrow impact does not significantly affect a driver's odds of severe injury.

Table 4
Predictors of severe injury (ISS > 25) controlling for narrow impacts

Independent variables	
Intrusion	1.78 (1.13, 2.81)*
Passenger car	1.96 (1.14, 3.37)*
Narrow impact	0.87 (0.42, 1.83)
Age	1.02 (1.01, 1.03)
Proper safety belt use	1.17 (1.01, 1.35)
Delta *V*	1.02 (1.01, 1.03)
Vehicle curb weight	1.00 (0.99, 1.00)

* Statistically significant ($p < 0.05$). Hosmer and Lemeshow Goodness-of-Fit Test Chi square = 7.86, 8, $p = 0.45$.

4. Discussion

Crash factors, such as delta *V* and PDOF, are known to influence occupant injury patterns and severity. Our study considered whether the width of the exterior vehicle damage across the vehicle frontal plane also influenced injury characteristics. We studied only drivers in frontal head-on impacts (with PDOF equal to 12 o'clock). All drivers were wearing their safety belts and were protected by frontal deploying air bags. Comparing drivers in wide damage impacts with those in narrow impacts, except for the head, there were no significant differences in injury patterns and or sources. Drivers in wide frontal impacts were almost 4 times more likely to have a head injury than those in narrow impacts.

We found drivers in wide impacts were only half as likely to have severe injury (based on ISS greater than 25), when controlling for other factors (including age, delta *V*, intrusion (displacement of vehicle interior components into the occupants seat position), vehicle body type and curb weight). This suggests that when the vehicle frontal damage is over a wider area, it may allow the vehicle to better absorb the crash energy—therefore, protecting the driver from severe injury. Previous research shows that to decrease occupant injury, vehicles need to deform (as the structure absorbs energy during the crash) without intrusion into the occupant compartment (Witteman, 2005; Hollowell et al., 1999). The front frame rails are specifically designed to absorb energy by buckling (Brewer, 2001). Computer modeling has shown that there is a different distribution of energy absorption by different vehicle components (e.g., frame rails, bumper, engine, etc.) depending on whether the frontal impact is wide or a narrow impact at the vehicle corner (Zaouk et al., 1996).

Safety systems, including air bags and safety belts, currently are tested and designed to protect occupants in frontal crashes. Federal Motor Vehicle Safety Standard 208, using a wide barrier impact, sets vehicle performance requirements for occupants sitting in front outboard (right or left) seats during frontal impacts. Previous research supports proposing that vehicle crash testing include an off-set frontal test or frontal test involving a narrow object (Farmer, 2005). Because current federal testing of safety systems does not include narrow frontal impacts, real world crashes provide important clues on the performance of safety belts and air bags during frontal crashes with narrow impacts.

Intrusion into the passenger compartment at the driver seat location and driving a passenger car were significant predictors of severe injury regardless of whether the damage distribution across the frontal plane was over a wide or narrow area. This demonstrates that both intrusion and body type are important factors to consider when studying occupant injuries and developing safer vehicles and better safety systems.

4.1. Limitations

One of the main limitations of CIREN data is that cases are not selected in a statistically random method. CIREN based studies may have bias related to selection criteria. In general, CIREN cases are seriously injured occupants in severe motor vehicle crashes so the results of our analyses may apply only to seriously injured occupants. This study does not address occupants who were not injured or less severely injured in regards to the influence that the damage distribution across the frontal plane has on injury patterns or sources. This limits the conclusions that can be drawn regarding the influence of whether the vehicle's frontal plane damage distribution is wide or narrow on occupant injuries.

Another possible bias in this study, supported by previous research is that the computer program used in CIREN to estimate the delta *V* (WinSmash) may not be as accurate for narrow impact crashes (Gabler et al., 2004; Niehoff and Gabler, 2006). If the crash severity (delta *V*) is underestimated or overestimated for narrow impacts, it may bias the logistic regression model showing that a wide damage distribution is less likely to result in severe injury when controlling for delta *V*.

Currently, delta *T* (time that the change in velocity occurred over) and crash pulse data are not included in the CIREN database so it was not possible to include these parameters in the analyses. Others have suggested that obtaining these data, through the review of event data recorders ("black boxes") could provide additional crash parameters for use in studying motor vehicle crashes (Gabler et al., 2004). Research has shown a shorter delta *T* results in a "stiffer" crash pulse with increased risk of injury (Hollowell et al., 1999; Linder et al., 2003). These studies noted a longer delta *T* results in a "soft" pulse. Depending on the body region and direction of force, a soft pulse may result in lower injury risk (Hollowell et al., 1999). These and other important unmeasured potential confounders may have influenced study results.

Finally, the small number of drivers injured in narrow impacts in the CIREN database may have resulted in a lack of statistical significance at a 0.05 level when comparing occupants in narrow impacts with those in wide impacts.

4.2. Summary

This study suggests that intrusion into the occupant compartment at the driver seat location and driving a passenger car may increase the odds of severe injury during head-on frontal impacts. However, if the occupant is in an impact involving a wide area of exterior vehicle damage across the frontal plane, they are less likely to be severely injured even when controlling for other factors. Our study supports that the damage distribution across the frontal plane, intrusion, and vehicle body type are important characteristics to consider when studying occupant injuries from motor vehicle crashes.

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