

CHARACTERISTICS OF SMALL OVERLAP CRASHES

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ABSTRACT

Small overlap frontal crashes occur when vehicles are loaded outboard of their longitudinal structural members. Studies from the 1990s as well as current research have found that these crashes continue to account for a significant percentage of all serious frontal crashes. The National Automotive Sampling System/Crashworthiness Data System database was used to study the characteristics of these crashes in current model vehicles for drivers with injuries (excluding extremity injuries) rated 3 or greater on the abbreviated injury scale. Cases were individually analyzed to only include vehicles in which the majority of the loading was located outboard of the left longitudinal member. Occupant compartment intrusion was the primary factor in the resulting injuries, showing a strong correlation between the magnitude of intrusion and injury severity. Results suggest that vehicle designs must improve their ability to prevent occupant compartment intrusion when a vehicle is loaded at the outboard edges of its front end.

INTRODUCTION

Vehicle crashworthiness has improved greatly during the past 30 years, as indicated by the reduction in the occupant death rate per million vehicle registrations of 1-3 year old cars from 265 in 1979 to 98 in 2007 [1]. Despite these improvements, 28,869 vehicle occupants were killed in crashes in the United States in 2007. Frontal crashes accounted for half of these deaths even though new cars almost universally pass frontal crash tests with flying colors and have for several years. Ninety-five percent of 2008 model year vehicles earned 4 or 5 stars out of 5 for frontal crash protection in the National Highway Traffic Safety Administration's New Car Assessment Program [2] and 91% earned the Insurance Institute for Highway Safety's (IIHS) highest rating of good for frontal crashworthiness. Although these two consumer information programs can be credited for some of this progress, neither currently provides incentives to further improve frontal crashworthiness.

In an attempt to identify opportunities to advance crashworthiness beyond the current state of the art, researchers at IIHS recently studied frontal crashes of good-rated vehicles that resulted in serious injuries or deaths [3]. Crashes were sorted by type of front damage, and three major crash types were identified: narrow center damage (from crashes with trees and poles), moderate overlap damage (like that from the IIHS 64.4 km/h (40 mi/h) 40% offset test), and small overlap crashes (with the majority of loading outboard of the longitudinal member). Small overlap crashes tended to exhibit high levels of intrusion, similar to that observed in the early days of the IIHS frontal offset test program, suggesting that structural design improvements do not extend to crashes with small amounts of vehicle overlap.

Identification of small overlap crashes as a significant contributor to frontal crash injuries and fatalities is not new. In a study of fatal frontal crashes in the United Kingdom, Hobbs [4] found that 27% of the crashes had deformation in which neither longitudinal member was involved. O'Neill et al. [5] analyzed frontal crashes in the United States and determined that frontal crashes with less than 33% overlap accounted for 22% of fatal crashes. Scheunert et al. [6] examined real-world crash data in Germany to study the distribution of frontal crash types and determined that 26% of the crashes were equivalent to a 30% overlap crash test. In a more recent study of fatal frontal crashes in Sweden, Lindquist et al. [7] found that 34% of the deaths occurred in crashes in which there was no deformation of the outboard longitudinal members. The methodologies and terminologies varied among these studies, but results consistently indicated that about one-quarter of all serious frontal crashes involved loading substantially less than 40% of the vehicle's front end. The focus of the present study was to conduct an in-depth analysis of the characteristics of small overlap frontal crashes that resulted in serious injuries or deaths with the idea of understanding how vehicles can be improved to better protect people in this important frontal crash mode.

METHODS

Cases were obtained from the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) database. Small overlap crashes were defined as frontal crashes in which the majority of loading to the vehicle was outboard of the longitudinal member. The majority of these crashes should be captured by FLxx and FRxx SAE J224 Collision Deformation Classification (CDC) codes (Figure 1). There are instances, however, in which a small overlap crash may have been given a code suggesting a different type of crash. To capture all small overlap crashes, the initial inclusion criteria captured a much wider range of crash types, and then all cases were inspected in detail.

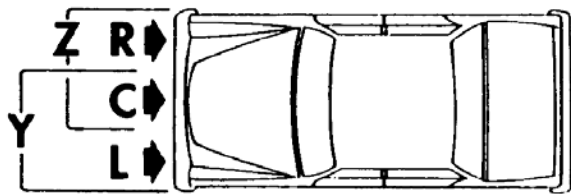


Figure 1. SAE J224 CDC horizontal damage codes for frontal crashes.

The SAE J224 code combinations were limited to those shown in Figure 2. The crash principal direction of force (PDOF) was between -30° and 0° , resulting in crash clock directions of 11 or 12 o'clock. All crashes had primary damage to the frontal plane (plane of damage = F) on either the left or left/center zones (horizontal damage = L or Y). Vehicles also had damage to (at a minimum) the bumper and other structures up to the level of the hood (vertical damage = E or A). Finally, the general damage code for the type of crash was either E (corner), W (wide), N (narrow), or S (sideswipe). There was no requirement on the deformation extent. Vehicles involved in a rollover or fire were excluded. All vehicles were model year 2000-08 passenger vehicles (body type = 1-49). Occupants were nonejected drivers ages 16 and older who were using lap/shoulder belts and who were fatally injured or had a maximum abbreviated injury score (MAIS) between 3 and 6. Because the point of this study was to understand how deaths and life-

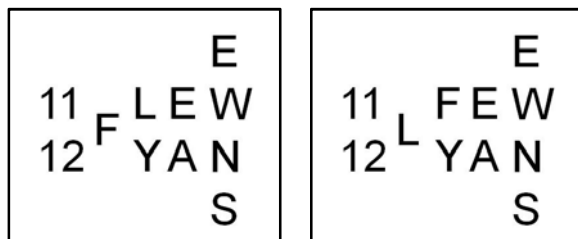


Figure 2. Possible CDC codes for inclusion criteria

threatening injuries might be prevented in small overlap crashes, drivers were excluded if the only MAIS 3-6 injury was to the lower or upper extremities.

In some small overlap frontal crashes there is almost no longitudinal deformation of the bumper or longitudinal members, and for this reason occasionally these cases are misinterpreted as lateral impacts. To capture all potential small overlap frontal crashes, some lateral impacts also were included for visual inspection. These crashes had the same search criteria as the frontal impacts with the following exceptions: plane of damage (left), horizontal damage (F or Y), and PDOF (-30° to 0°).

It is common for NASS/CDS cases to have fatalities with limited injury information, resulting in injury severity score (ISS) values of zero. Two of the fatalities in this study had these misleading ISS values. To better represent the severity of these injuries, they were given adjusted ISS values of 50. This estimate was based on the approximate average of the remaining six fatalities in the study. All ISS values included in the results are the adjusted ISS values.

The purpose of the present study was to analyze the injury mechanisms and crash characteristics in small overlap crashes that have some relevance to potential crash test scenarios. Cases with complicating factors such as multiple impacts, incorrect belt use, injuries caused by events unrelated to the primary impact, or injuries primarily due to pre-existing medical conditions were excluded.

RESULTS

A total of 21 cases met all inclusion criteria. The majority of the vehicles (17 of 21) had CDC codes with left horizontal damage (FLEE-10, FLAE-5, FLAW-2) denoting damage to the left third of the vehicle. Two of the vehicles had a left/center horizontal damage code (FYEW), and the remaining two vehicles were coded by NASS/CDS as having primary damage to the left plane (LYAW, LYES). The authors believe that the latter two vehicles actually were involved in small overlap frontal crashes. Both vehicles had initial contact on the bumper, had the wheels torn off the vehicle (rather than driven into the axle), and had longitudinal, as well as lateral, intrusion.

Fifteen of the case vehicles were cars and six were light trucks (pickups, SUVs, or vans). No case vehicles were minivans. Crash partners, in order of frequency, were light trucks (8), trees/posts/poles (TPP) (6), cars (3), minivans (2), and heavy vehicles (HV) (2). Heavy vehicles included a school bus and the rear

trailer tires on a tractor trailer. The combinations of case vehicles and crash partners are listed in Table 1, with TPP-HV denoting trees, posts, and poles combined with heavy vehicles. In 76% of the cases, the crash partner was a light truck or TPP-HV.

Table 1.
Case vehicle and crash partner combinations

Case vehicle	Crash partner	Number
Car	Car	3
Car	Minivan	2
Car	Light truck	5
Car	TPP-HV	5
Light truck	Light truck	3
Light truck	TPP-HV	3

All case vehicles had occupant compartment intrusion. Because the focus of this study was on life-threatening injuries to the driver, all intrusion values discussed in the paper are for the driver seating area (instrument panel, A-pillar, steering wheel, roof rail, door, etc.) and exclude measurements in the toepan region. Some vehicles had both longitudinal and lateral intrusion, although longitudinal intrusion generally was larger and occurred in more vehicles. Of the 21 vehicles, 16 had a maximum intrusion value that was longitudinal in direction, whereas 5 vehicles had a maximum lateral intrusion value. For the 18 vehicles with specific measurement values, the average maximum intrusion value was 32 cm. Vehicles with a maximum longitudinal intrusion had an average value of 34 cm, whereas vehicles with lateral intrusion had an average value of 25 cm.

To provide a comparison for the magnitude of intrusion in these vehicles, they were compared with those measured in the IIHS frontal offset crash test. Longitudinal intrusion at the left instrument panel is a common NASS/CDS measurement, and also is recorded by IIHS. There were 17 cases with measured longitudinal left instrument panel intrusion in which the same vehicle also had been tested by IIHS. The average IIHS intrusion value was 8 cm, whereas case vehicles had an average intrusion of 23 cm. When only the vehicles with maximum longitudinal intrusion (12) were included, the average IIHS intrusion value remained 8 cm, whereas the average vehicle intrusion increased to 29 cm. This comparison of instrument panel intrusion likely underestimates the difference in intrusion extent between these small overlap crashes and their frontal offset test counterparts because many of these vehicles had components with even higher intrusion values. These other components (A-pillar, steering wheel, roof rail) often were those contacted by the occupant resulting in injuries.

Eight of the 21 case vehicles did not have delta V values reconstructed, or the values were coded by investigators as “results appear low.” The remaining 13 vehicles had a mean value of 32 km/h (range 18-54 km/h). The method for determining delta V is based on stiffness estimates of a vehicle’s front structure, which are based on crash tests involving the longitudinal structural members. In small overlap crashes, these structures are not loaded, and in many cases the actual damage locations are not measured. For this reason, there is little confidence in the accuracy of the delta V estimates.

Case occupants had an average age of 44 years (range 19-69), with 15 males and 6 females. There were eight fatalities. Injury data for the drivers is shown in Figure 3. For two of the fatalities, there was limited injury information. For one driver, the only information was a statement by the investigator that the driver died of fatal head/neck injuries. This driver was assigned an AIS 6 head injury. For the second fatality, there was no injury information, and thus all data shown in Figure 3 is based on 20 occupants.

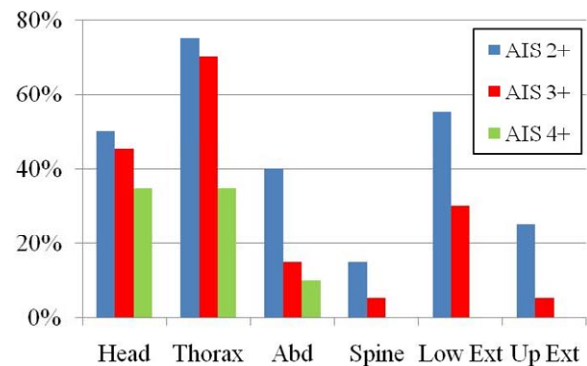


Figure 3. Percentage of drivers with injuries to each body region by AIS level.

For AIS 2+ injuries, the most commonly injured body regions were the thorax (75%), head/face (50%), lower extremities (55%), and abdomen (40%). For AIS 3+ injuries, the most commonly injured body regions were the thorax (70%), head/face (45%), and lower extremities (30%). These trends were slightly different for AIS 4+ injuries, for which injuries to the head/face and thorax were equal (35%). It should be noted that the percentage of lower extremity injuries was directly influenced by the study’s inclusion criteria, which excluded drivers whose only AIS 3+ injury was to lower (or upper) extremities.

There was a strong relationship between intrusion and injury severity. Figure 4 shows ISS values as a function of maximum occupant compartment intrusion.

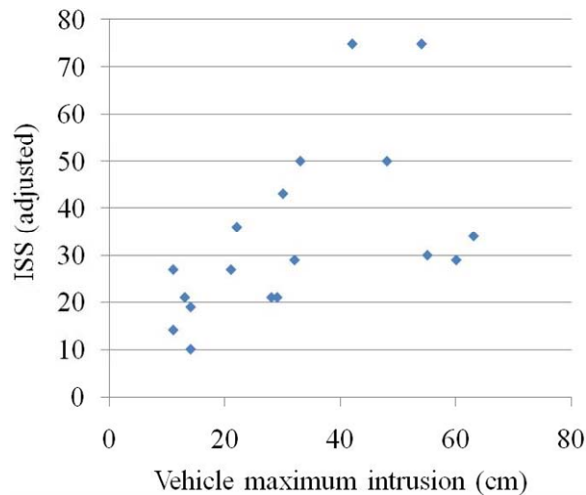


Figure 4. ISS as a function of vehicle intrusion.

For each driver’s most severe injuries, a proposed injury mechanism was determined. This determination was based on vehicle intrusion patterns, injury information, occupant contact points, etc. For the majority of crashes, there was sufficient intrusion that injuries clearly were due to contact with interior structures, and even an optimal restraint system could not have prevented them. Three distinct patterns of intrusion were associated with these injuries (Table 2). Both lateral and longitudinal intrusions were observed. Injuries associated with longitudinal intrusion tended to be more severe than those associated with lateral intrusion. There were four cases, however, in which the proposed injury mechanism was due to a combination of loads produced by the restraint system and longitudinal intrusion. Although these cases were characterized by lower levels of intrusion (11-14 cm), contact with intruding structures could not be ruled out as a possible injury source.

Table 2.
Injury mechanisms, intrusion amounts, and injury severity scores

Injury mechanism	Cases	Intrusion	ISS
Longitudinal intrusion	7	54 cm (long)	49
Lateral intrusion	5	25 cm (lat)	23
Longitudinal and lateral intrusion	5	27 cm (long)	31
Longitudinal intrusion and restraint system	4	12 cm (long)	18

Although small overlap crashes are a relatively specific crash type, there still were several crash scenarios and damage patterns among the case vehicles. Crashes were further organized to capture these different crash

scenarios based on several factors: crash partner, crash angle, and vehicle damage location.

Crash partners were divided into two categories: passenger vehicles and TPP-HV. Crash angles were classified as being either collinear or oblique. When a case vehicle and partner vehicle had similar damage patterns, crash angle was classified as collinear. However, if the partner vehicle’s front damage was more horizontally distributed than that of the case vehicle, such that the partner vehicle’s damage looked more like that associated with moderate overlap crashes, then the crash angle was classified as oblique. All of the crashes with different damage patterns for case and partner vehicles were described by NASS/CDS investigators as involving the partner vehicle crossing the roadway centerline and into the path of the case vehicle (Figure 5). The oblique nature of the crash could be caused either by the angle of the partner vehicle as it crossed the centerline or by the case vehicle steering away in a defensive maneuver. No attempt was made to further specify the oblique angle. All vehicles that struck TPP-HV were classified as collinear.

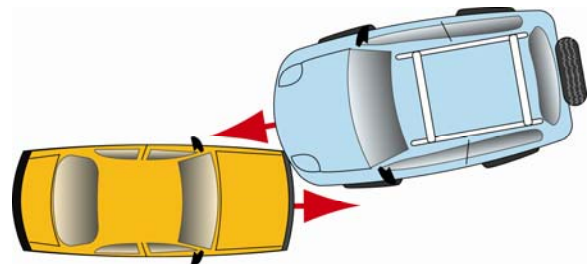


Figure 5. Diagram of vehicle-to-vehicle oblique small overlap crash (10° shown); case vehicle shown in yellow, partner vehicle in blue.

Vehicle damage location was divided into three possible groups: sideswipe, no sideswipe, and severe override. Sideswipe was defined as direct damage to the case vehicle by the partner vehicle rearward of the A-pillar. An example of sideswipe is shown in Figure 6. Induced damage to the occupant compartment — for example, rearward motion of the A-pillar resulting



Figure 6. Example of vehicle with sideswipe.

in driver door deformation — was not considered as sideswipe. There also were two cases with a distinctly different damage pattern in which there was severe override of the case vehicle and direct loading of the upper portion of the occupant compartment (Figure 7). In each case, the case vehicle was a car struck by an SUV. The distribution of the seven crash types and average ISS values is shown in Table 3.

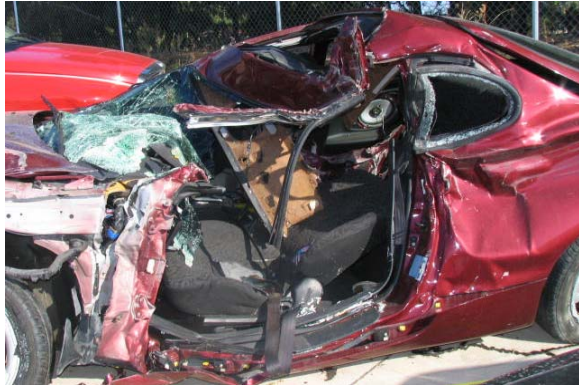


Figure 7. Example of vehicle with severe override.

Table 3.
Distribution of crash types
(number of cases) and ISS values

Small overlap crashes (21)							
Passenger vehicle (13)							
TPP-HV (8)		Oblique (9)		Collinear (4)			
No side	Side	No side	Side	No side	Side	Over	
(5)	(3)	(4)	(5)	(1)	(1)	(2)	
ISS-25	ISS-35	ISS-57	ISS-27	ISS-19	ISS-10	ISS-31	

Eighty-one percent of the cases (17 of 21) were either oblique crashes with passenger vehicles or crashes into TPP-HV. These two crash types also had the highest average ISS values, with the exception of the two severe override crashes. The remaining crashes were either vehicle-to-vehicle collinear crashes (two crashes with the lowest ISS values) or the two unusual severe override crashes.

Differences between sideswipe and no sideswipe crashes were caused by the initial impact location. In crashes with sideswipe damage, the partner vehicle struck the case vehicle farther outboard, engaging less of the vehicle front end than crashes without this damage. Sideswipe crashes also were more likely to result in injuries caused by lateral intrusion, with all but one sideswipe crash having lateral intrusion as a contributing factor.

DISCUSSION

The CDC designation often used to represent small overlap crashes, FLxx, accounted for only 81% of the cases identified in this study. Studies that limit their analyses to these CDC codes likely are missing a significant number of small overlap crashes. In fact, the definition of small overlap crashes in this study was relatively conservative, and it is likely there are additional cases with more damage to the longitudinal members that share many of the same factors.

The amount of occupant compartment intrusion was strongly related to injury severity. Previous attempts to correlate injury severity with other surrogates of crash severity (delta V, maximum vehicle crush, CDC extent zone) were not successful [8]. This likely was due to the fact that NASS/CDC measurement techniques and delta V reconstruction software are not particularly suited to small overlap crashes. The lack of confidence in the delta V estimates prevents determining whether differences in intrusion values were due to differences in crash severity or vehicle structural designs. The present study, however, shows a strong relationship between occupant compartment intrusion and injury severity.

Crashes into narrow objects and oblique crashes with other passenger vehicles accounted for the majority of cases in this study and resulted in some of the highest ISS values. It is not clear why collinear vehicle-to-vehicle crashes accounted for such a small number of cases. The study sample may not have been large enough to capture more cases. Another possibility is that these crashes result primarily in lower extremity injuries and not the severe injuries to the head, thorax, and abdomen that were required for inclusion in this study. One of the characteristics of many vehicle-to-vehicle small overlap crashes is the “rim-locking effect” resulting in significant deformation into the footwell area [9]. Studies of small overlap crashes including occupants with only serious lower extremity injuries likely will find crash populations with different characteristics.

Although there were few vehicle-to-vehicle collinear crashes, there were several vehicle-to-vehicle oblique crashes. In oblique crashes, the partner vehicle consistently had damage to a large proportion of the front end, including significant loading of the left longitudinal member. The oblique nature of these crashes likely allowed the partner vehicle to more fully engage the case vehicle, preventing a “sliding collision” or glance-off crash. Thus a greater proportion of the kinetic energy went into deformation of the occupant compartment of the case vehicle. Continued research

will focus on the importance of this oblique angle in vehicle-to-vehicle crashes.

The presence of sideswipe damage to a case vehicle was primarily a factor of the outboard location of the crash partner. These crashes were more likely to result in lateral intrusion and had lower ISS values than no sideswipe crashes (28 vs. 37 cm). Study vehicles all exhibited loading to the entire vertical profile of the front end because all had crashed into either a vehicle with an equal or taller profile or a TPP. None of the case vehicles had damage suggesting they had struck a vehicle with a shorter profile.

Crash tests devised to evaluate countermeasures for small overlap crashes should incorporate several factors. The test should fully engage the vehicle and occupant compartment in a longitudinal direction, rather than loading the vehicle far enough outboard to cause a sideswipe crash. The test barrier should be at least as high as current LTVs, if not higher. Shorter barriers will not engage the full vertical profile of the vehicle front end. The importance of the type of barrier (pole or simulated vehicle) or angle of impact (collinear or oblique) is not currently known. It should be noted, however, that these two different crash scenarios resulted in very similar damage patterns to the case vehicles in this study.

Small overlap crashes are defined as those in which the longitudinal members and other front structures typically designed to absorb crash energy are missed. Failure to engage this structure may account for the subsequent significant deformation of the occupant compartment that is the primary factor in the driver's injuries. Two countermeasures for this crash type are suggested in the literature. The first is a design that deflects the vehicles away from full engagement and result in "sliding collisions" [10]. Results suggest the potential for significant reductions in occupant compartment intrusions. The consequence, however, are vehicles that continue on the roadway in an uncontrolled manner. The possibility of secondary crashes should be considered. The second countermeasure involves modifications to the primary structural members of the vehicle front end, including increases to the width of these structures. Honda has redesigned many of its vehicle models to include this Advanced Compatibility Engineering™ (ACE™) structure [11]. Computer simulations show that the ACE™ structure, when compared with previous structural designs, reduces the amount of occupant compartment intrusion in small overlap vehicle-to-vehicle collinear crashes. The effect of these countermeasures in narrow object impacts or oblique vehicle crashes is not known.

CONCLUSIONS

Drivers in small overlap crashes are most likely to be seriously injured due to occupant compartment intrusion. There was a strong relationship between the magnitude of intrusion and injury severity. Among small overlap crashes with serious injuries, collinear crashes into narrow fixed objects and vehicle-to-vehicle crashes in which the partner vehicle strikes the case vehicle obliquely were the most common. Despite structural improvements prompted by frontal offset crash tests, this study suggests that vehicle structures must improve if they are to prevent occupant compartment intrusion when a vehicle is loaded outboard of the longitudinal members.

ACKNOWLEDGMENT

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