IMPACT AND INJURY PATTERNS IN FRONTAL CRASHES OF VEHICLES WITH GOOD RATINGS FOR FRONTAL CRASH PROTECTION

Matthew L. Brumbelow
David S. Zuby
Insurance Institute for Highway Safety
United States
Paper No. 09-0257

ABSTRACT

Modern vehicle designs tested as part of US consumer information programs achieve high ratings for frontal crash protection. Research is needed to determine how these tests can be upgraded to further improve occupant protection in real-world frontal crashes. The present study is a detailed analysis of real-world cases with serious injuries resulting from frontal crashes of vehicles rated good for frontal crash protection.

Queries of 2000-06 data from the National Automotive Sampling System-Crashworthiness Data System produced 116 occupants meeting selection criteria. These were drivers and right front passengers who sustained serious injuries in frontal crashes despite being coded as belted. Patterns of vehicle impact and occupant injury were categorized and discussed in the context of potential upgrades to current crash tests.

Asymmetric or concentrated loading across the vehicle front often resulted in occupant compartment intrusion and associated injury. However, just as many occupants were in crashes without substantial intrusion and were injured by restraint system forces or impacts with the vehicle interior not prevented by restraints. Crashes producing injury without intrusion involved multiple impacts more than twice as often.

Future test programs promoting structural designs that absorb energy across a wider range of impacts, such as small overlap, could reduce serious injuries in frontal crashes. Further restraint system improvements may require technologies that adapt to occupant and crash circumstances. It is unclear what types of full-scale crash testing would encourage these improvements.

INTRODUCTION

There are two consumer evaluation programs of vehicle frontal crashworthiness in the United States. The National Highway Traffic Safety Administration (NHTSA) assigns occupant protection ratings of 1 to 5 stars for drivers and right front passengers based on vehicle performance in a full-width test into a rigid wall at 35 mi/h (56 km/h). The Insurance Institute for Highway Safety (IIHS) assigns vehicle ratings of good, acceptable, marginal, or poor based on performance in a 40 mi/h (64 km/h) test in which 40% of the vehicle front impacts a deformable barrier. Since these programs were introduced, structural and restraint system designs have improved substantially, and high test performance now is treated as a *de facto* standard. Among vehicles rated in the IIHS frontal offset test between January 2005 and May 2008, 85% received good ratings, with the rest receiving the second highest rating of acceptable. Under NHTSA's frontal New Car Assessment Program (NCAP), 95% of 2008 model year vehicles achieved a 4- or 5-star rating for both the driver and right front passenger [1].

Consumer evaluation programs are most useful when they provide comparative information to those purchasing new vehicles. The consistent good performance under the current test configurations has prompted both NHTSA and IIHS to consider changes to their frontal crashworthiness programs. After researching various alternatives, NHTSA announced plans to keep the full width configuration but use different anthropomorphic test devices (ATDs) and include additional injury metrics [2]. IIHS has conducted pole impact research tests to determine whether this crash configuration poses problems that offset testing does not address. It is important that any test program be driven by the types of crashes occurring in the field so that the design changes the program encourages have benefits in real-world crashes. Studies have found that higher ratings in both NHTSA and IIHS test programs correlate to reduced injury risk [3][4]. To ensure this correlation continues, a better understanding of real-world crashes is needed to support informed decision making for future frontal test programs.

Progress made in improving the vehicle fleet's frontal crashworthiness and the promise of emerging active safety technologies such as electronic stability control [5] have resulted in less focus being placed on further passive safety improvements. Some new passive safety advancements are being developed, such as new

structural designs [6] and restraint systems [7], but the primary focus has shifted toward implementing active safety technologies while maintaining the current level of crashworthiness. However, no combination of active technologies is expected to completely prevent all crashes. A large number of fatal and serious injuries will continue to occur in frontal crashes, and further improvements in crashworthiness will be needed to address them.

The present study provides a new perspective on the frontal crash picture in the United States. Frontal crashes in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) that produced fatal or serious injuries to belted front-seat occupants were analyzed with the goal of categorizing them according to potential crash test configurations. For each case, vehicle structure performance and restraint system performance were assessed and compared with injury outcomes. Study findings allowed a more detailed understanding of the types of frontal crashes still producing injuries to occupants protected by modern safety technology and identified some remaining steps that can be taken to improve frontal crashworthiness.

METHODS

The NASS-CDS crash data collection program is conducted and maintained by NHTSA. Twenty-seven teams stationed around the United States investigate a sample of police-reported towaway crashes in their geographic regions. The annual number of total crashes investigated each year ranged from around 4,000 to 5,600 during 2000-06, the years used in the present study. Each case is assigned a sample weight based on its likelihood of being investigated. These weights are intended to allow nationwide estimates from the crash data.

Vehicles selected for analysis received good ratings in the IIHS frontal offset test because this is a design criterion for virtually every new vehicle model and the study objective was to identify crashworthiness issues not addressed by the test. A minimum level of performance in the frontal NCAP test was not required, but all the vehicles in the final sample had 4- or 5-star ratings for both occupants except one, which had a 3-star rating for the driver. Only vehicles of model year 2000 or later were included to capture restraint system changes such as depowered airbags, load-limiting seat belts, and belt crash tensioners. Frontal crashes were defined as those that were coded with primary general area of deformation values (GAD1) of "F" by the NASS-CDS investigators. All such cases were included when a belted outboard front-seat occupant sustained an injury with a severity of 3 or greater on the abbreviated injury scale (AIS $\geq$ 3), unless the only such injury was to the upper or lower extremities. All fatally injured occupants were included regardless of the coded maximum AIS.

Although extremity injuries are not inconsequential, the study objective was to identify the crash configurations that still are producing fatal or potentially fatal injuries. Injuries were categorized by the AIS body regions of head, chest, abdomen, spine, or pelvis.

Detailed reviews were conducted of each case meeting the inclusion criteria in 2000-06 NASS-CDS. Relevant coded variables were included, and crash descriptions, scene photographs, vehicle photographs, and injury diagrams were analyzed. Vehicles and occupants were grouped according to the various criteria outlined below.

Crash Configurations

Study vehicles were assigned a crash configuration based on photographs of damaged vehicle components and the struck object. Beyond the initial "F" code, the collision deformation classification (CDC) assigned by the NASS investigator was not used to designate any of these crash configurations. Instead, the configurations were defined in reference to the longitudinal structures typically designed to manage the crash energy involved in frontal crashes. Differences between CDC and the crash configurations used in this study, as defined below, are discussed later.

Center impact – major load path was between the two main longitudinals; all case vehicles in this configuration struck a pole, post, or tree, but this was not a specific requirement.

Small overlap – major load path was outboard of all major longitudinal structure; deformation of this structure may have occurred but was judged not a major source of energy absorption.

Moderate overlap – major load path was along one longitudinal member and associated structures; offside member may have been loaded, but this either was less substantial, was induced by cross beams connecting the two members, or occurred separate from the initial engagement with the struck object or partner vehicle.

Full width – major load paths were along both longitudinal structural members.

Underride – major load paths were along components vertically above the bumper bar and longitudinals.

Override – major load paths were along components vertically below the bumper bar and longitudinals.

Low severity – minor loading to all structural components; insignificant longitudinal crush, if any.

Nonfrontal/unreproducible – miscoded primary deformation location or extreme crash scenario with limited relevance to general crashworthiness.

The first four crash configurations, illustrated in Figure 1, describe lateral locations of vehicle structures loaded during the crash. In some instances, one of these configurations seemed applicable in addition to either underride or override, so a judgment was made about which configuration was most significant to crash outcome. However, in two cases, a vehicle was assigned the underride configuration in addition to one of the lateral configurations because both appeared to be major factors in producing occupant injury.

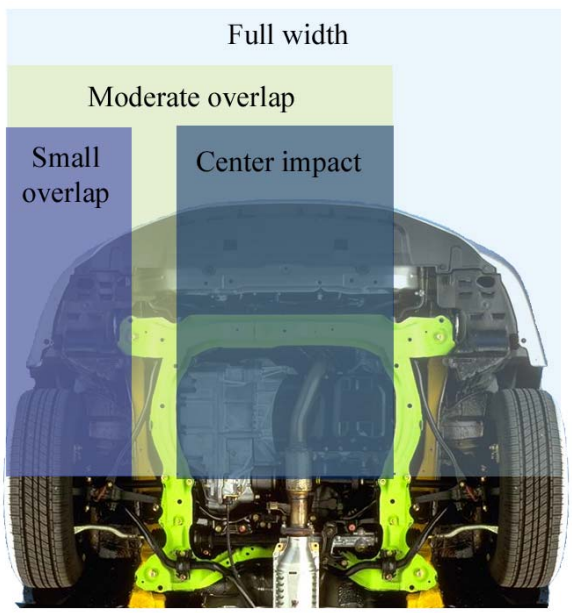

Figure 1. Locations of crash loading for various configurations

Cases categorized as nonfrontals or unreproducible were not analyzed further, as they were not meaningful for evaluating the types of frontal crashes with the potential to be addressed by crash test programs.

Injury categories

Although the crash configurations describe the types of impacts for case vehicles, on their own they do not explain how occupants were injured. The first requirement of a crashworthy vehicle design is a structure that is able to control deformation in such a way that the occupant compartment remains intact. Given sufficient survival space, the second requirement is a restraint system that controls occupant loading to minimize injury risk. In some cases, both of these criteria are met but injury still occurs due to some other factor such as safety belt misuse or loading from an unrestrained rear-seat occupant. To summarize the major factors producing injuries in the crashes being studied, each occupant was assigned to one of four injury categories, as described below:

Intrusion – injuries attributed mainly to compromise of occupant survival space.

Restraint factor – injuries attributed to inability of restraint system to sufficiently control occupant motion or loading; occupant compartment integrity was maintained, but occupant sustained injury either from loading by restraint system itself or from impact with interior component not prevented by restraints.

Occupant factor – occupant behavior or characteristic (e.g., misuse of restraint, loading by another occupant, extreme obesity with use of seat belt extender) likely contributed to injury more than any intrusion or restraint factor; age alone was not considered an occupant factor, but some fatally injured occupants were assigned to this category because they developed postcrash complications that may have been age related, or they had pre-existing health conditions.

Unknown: occupant/restraint – occupant behavior or other characteristic may have contributed to injury, but evidence was unclear; structural integrity was good, but injury still occurred due to restraint factor, occupant factor, or some combination of factors.

RESULTS

There were 116 occupants that met the initial inclusion criteria. In 8 cases, the driver and right front passenger in the same vehicle met the criteria. In one case, occupants of two different vehicles were included.

Twenty occupants were in crash configurations defined as nonfrontal or unreproducible. These cases were removed (see Appendix A), leaving 96 occupants for further analysis. Weighting factors for the remaining cases ranged from 1 to 1,722, with a total weighted count of 6,709. NASS-CDS weighting factors are more difficult to interpret when analyzing smaller case samples. For example, 3 of the 96 occupants studied represented 45% of the total weighted occupant count. To reduce the possibility that any single case could substantially affect the conclusions, only unweighted counts were analyzed.

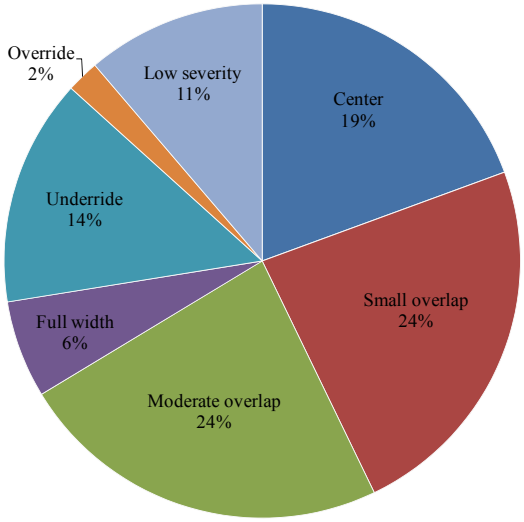

Figure 2. Distribution of crash configurations

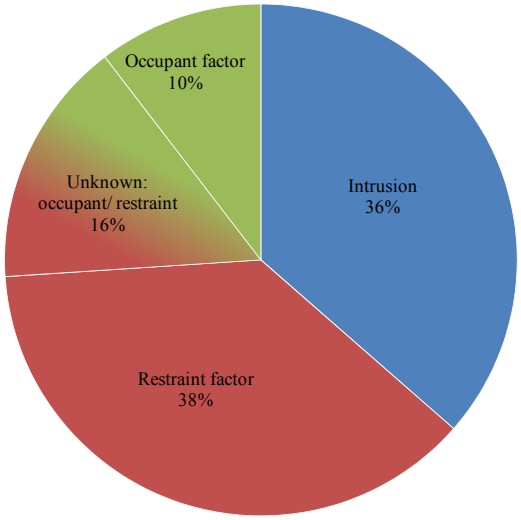

Figure 3. Distribution of injury categories

Figure 2 shows crash configurations for cases involving the 96 occupants. Center impact, small overlap, and moderate overlap configurations represented similar numbers of crashes and together comprised two-thirds of the cases. Underride and low-severity configurations were the next largest categories, together making up one-quarter of the total. Full-width and override configurations comprised the remaining 8% of crashes.

Figure 3 shows the distribution of injury categories. Intrusion and restraint factors each comprised more than one-third of the cases. Occupant factors made up 10% of the cases. For the remaining 16% of cases, it was not possible to determine whether occupant or restraint factors were predominant in causing injury.

Figure 4 shows the different contributions of injury factors for each crash configuration. Intrusion was most commonly related to injury in small overlap and underride crashes. For center, full-width, override, and low-severity crashes, restraint and occupant factors were predominant. Moderate overlap crashes had the most even mix among the various injury factors.

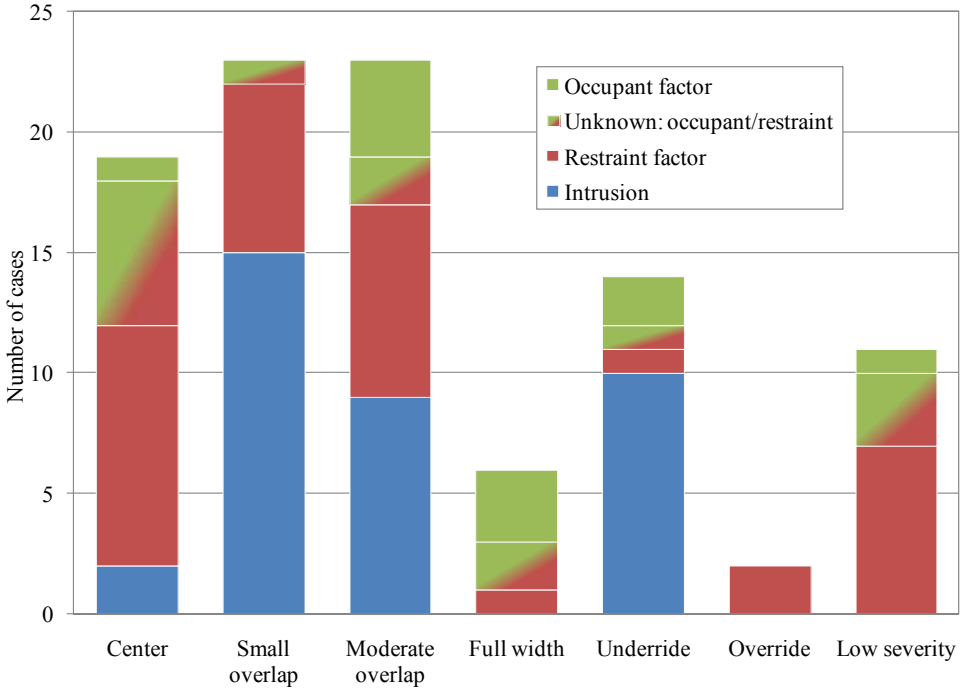

Figure 4. Distribution of injury categories by crash configuration

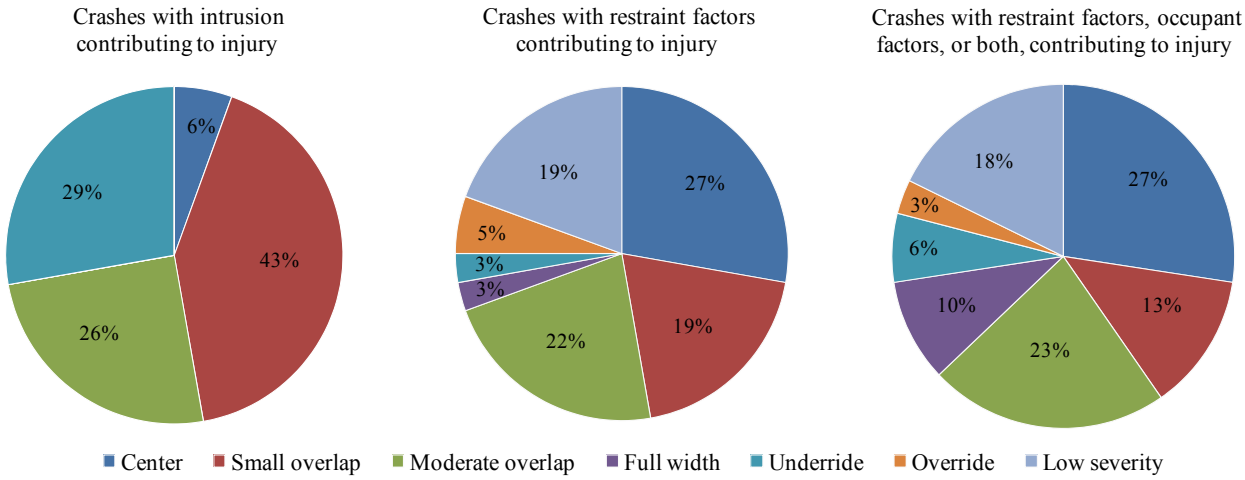

Figure 5. Distribution of crash configurations for various injury groups

Figure 5 shows the distribution of crash configurations for three injury category groups: crashes where intrusion contributed to injury, crashes where restraint factors contributed to injury, and all crashes where vehicle structure performed adequately but injury occurred from any restraint factor, occupant factor, or combination.

Injuries

Of the 96 occupants involved in crashes relevant to frontal crashworthiness analyses, 89 had detailed injury data available. Injury comparisons in this section are based on these occupants. The median injury severity scores (ISS) for occupants in each crash configuration and injury category are shown in Figure 6, with the number of occupants in parentheses. Occupants in underride and override crashes had the highest median ISS, although the override value is based on only two observations. Occupants in low-severity and moderate overlap crashes had the lowest median ISS. For injury categories, median ISS was higher for occupants with injuries attributed to intrusion than for other occupants.

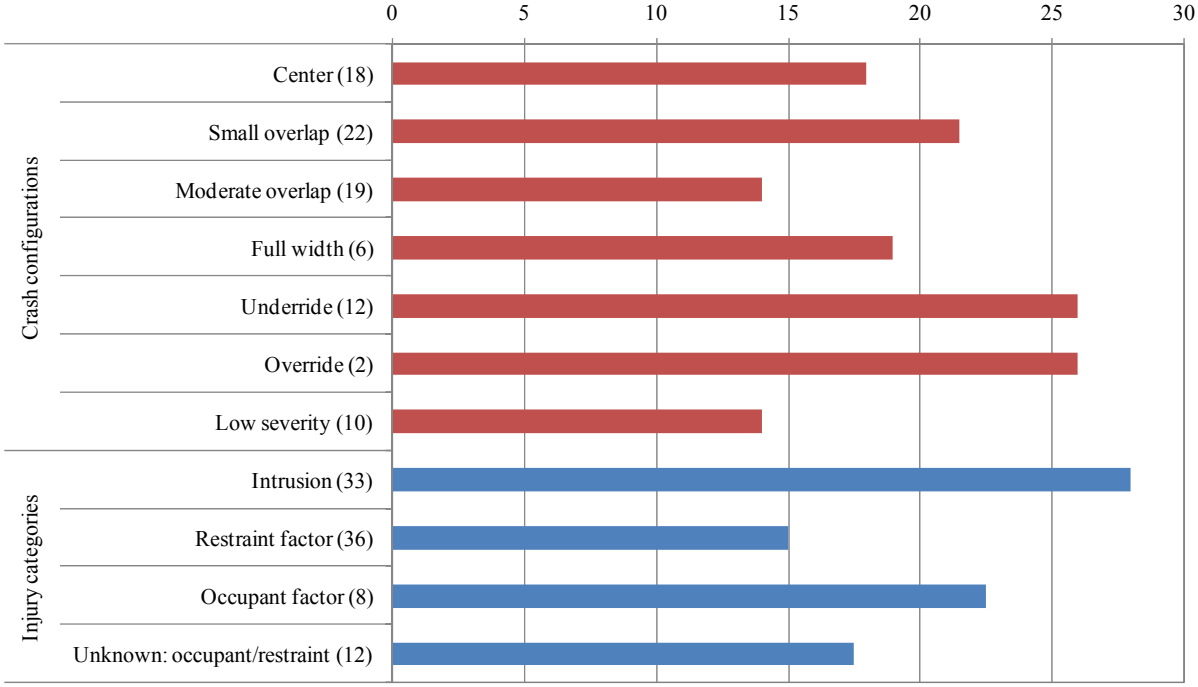

Figure 6. Median injury severity scores for occupants in each crash configuration and injury category, with number of occupants in parentheses

Figure 7 shows the percentage of occupants who sustained at least one AIS ≥ 3 injury to each body region. The chest was the most commonly injured body region at the AIS ≥ 3 level. This was true for the entire sample as well as for the subsamples of occupants in center, small overlap, moderate overlap, and full-width crashes. When injuries were attributed to intrusion or restraint factors, more occupants had serious chest injuries than any other injury type. After chest injuries, a higher percentage of occupants sustained serious injuries to the head than to other body regions. Head injuries were the most common type of AIS ≥ 3 injury for occupants in underride crashes and the second most common in center, small overlap, and moderate overlap crashes, as well as in crashes where injury was attributed to intrusion or restraint factors. Overall, a similar percentage of occupants sustained serious injuries to the abdomen, spine, or pelvis, but there was substantial variation across specific categories.

Many additional observations can be made about this sample of cases. Some of those most relevant to the present study are displayed in Figure 8 and Figure 9. The column names are descriptions of a certain number of cases in each category, not groupings that sum to 100%. For example, 11% of occupants in center impacts were fatally injured, whereas 50% of occupants in underride crashes were killed. The number of cases in each category is given in parentheses. Because there were only two override cases, they were not included in Figure 8.

DISCUSSION

Difference between Crash Configuration Groupings and CDC Values

Methods used in this study provide a more complete picture of factors contributing to crash severities and resulting injuries than can be obtained by grouping crashes according to CDC codes. NASS-CDS investigators assign CDC codes based on evidence of direct damage to any part of the vehicle exterior. This can result in an overestimate of the extent to which structural members were significantly loaded during the crash. Figure 10 shows the distribution of CDC codes for the specific lateral area of damage (SHL1) by crash configuration for the study sample.

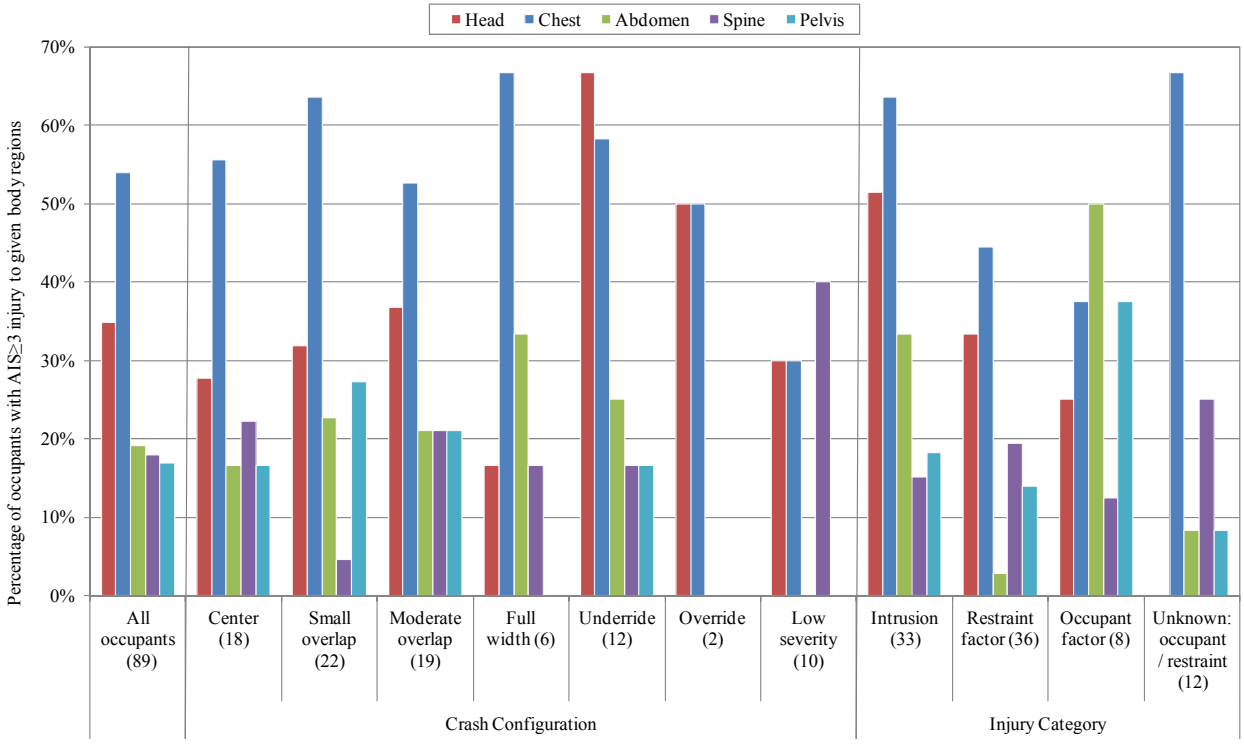

Figure 7. Percentage of occupants with AIS ≥ 3 injuries to given body regions, with number of occupants in parentheses

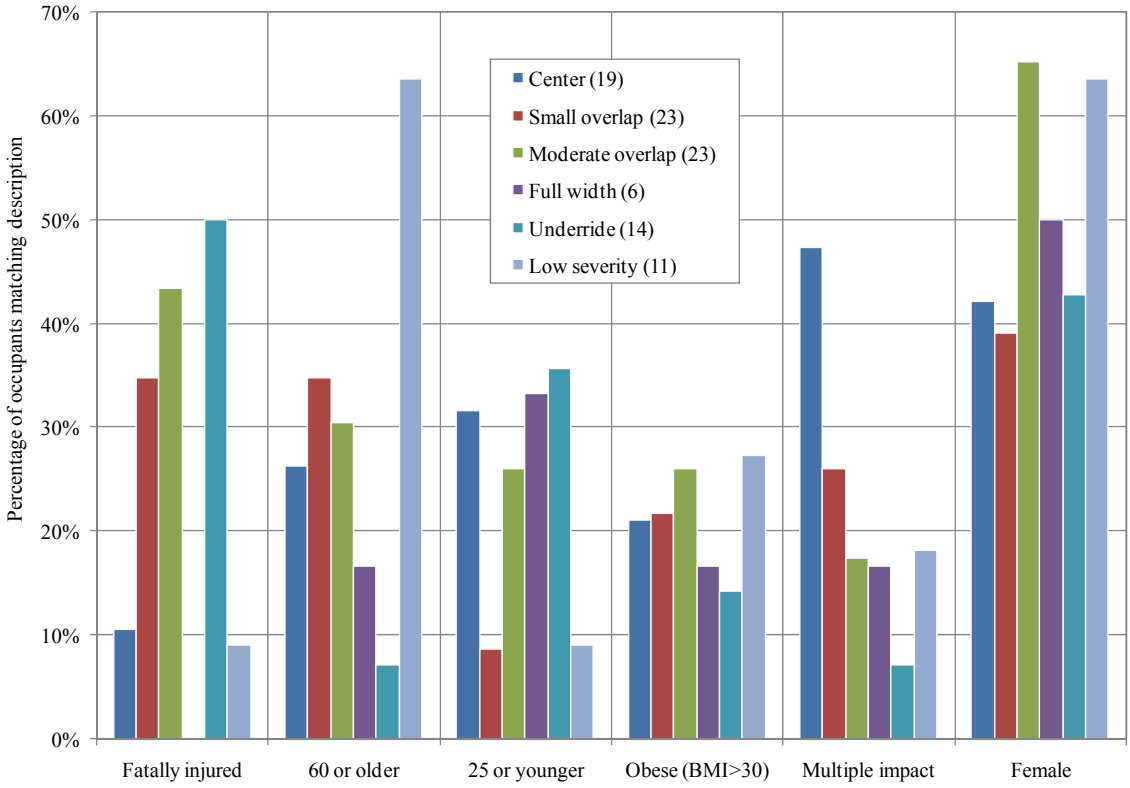

Figure 8. Relevant characteristics for each crash configuration

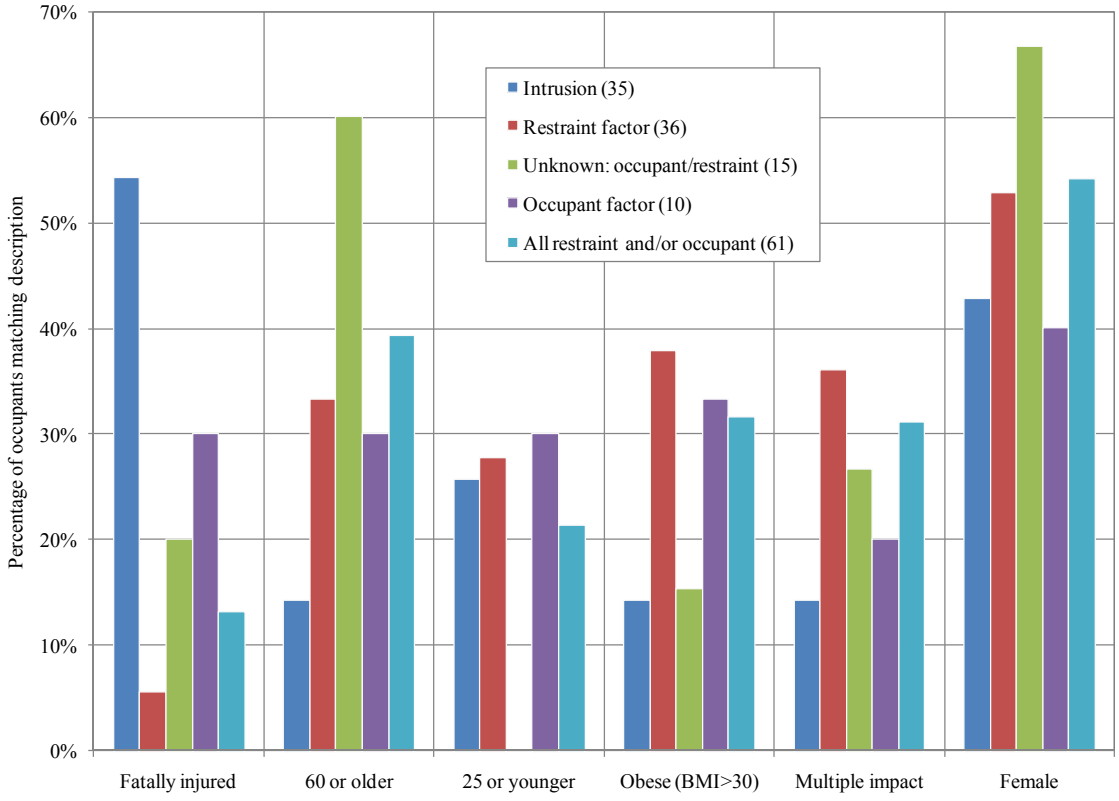

Figure 9. Relevant characteristics for each injury category

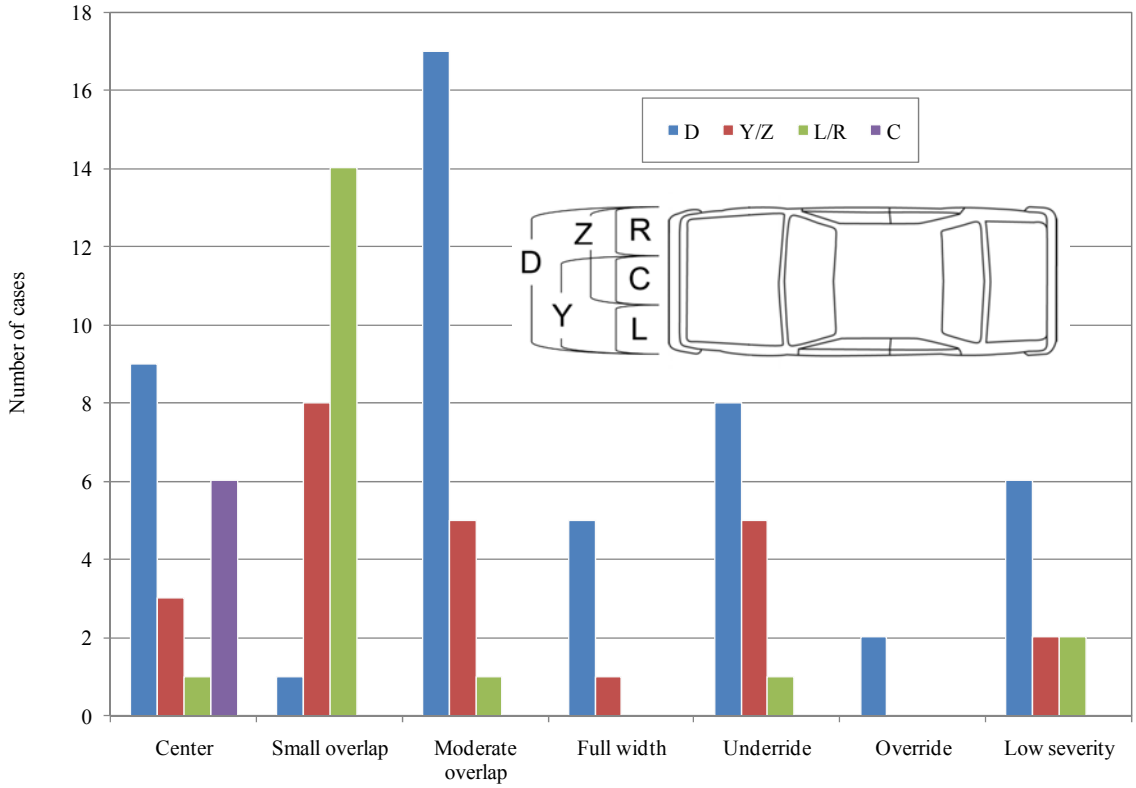

Figure 10. Distribution of CDC SHL1 codes for study crash configurations

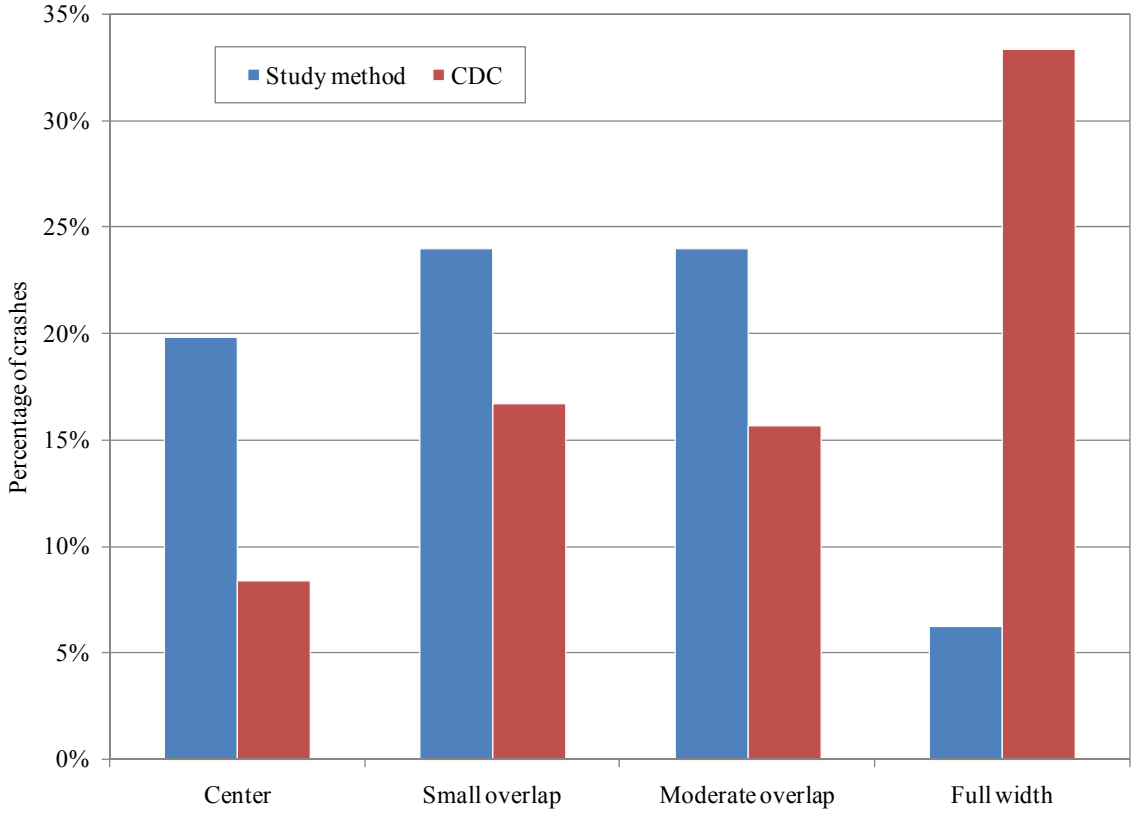

Figure 11. Distribution of crashes for study crash configurations and CDC codes

Figure 11 shows how the crashes in the sample might be categorized according to CDC compared with the configurations using the study methods. Underride, override, and low-severity crashes were removed because CDC codes for vertical area of damage and longitudinal extent of damage had very little correlation with these categories. Center impacts were defined with SHL1 values of C or, if damage distribution was coded as narrow, Y/Z. The remaining Y/Z codes were considered moderate overlap, L/R codes small overlap, and D codes full width. Figure 10 and Figure 11 show that the larger areas of direct damage in CDC can obscure patterns in the structural loading of underlying vehicle components. This is similar to findings by Lindquist et al. [8] who used a different method to study a sample of fatal crashes in Sweden.

Current Crashworthiness Evaluation Programs

Analyzing CDC codes alone could lead to an overestimate of the number of real-world crashes represented by the full-width NCAP test [9][10]. Only 6% of occupants in this sample were in full-width crashes. No occupants were killed, and all vehicles had very little intrusion or none at all. Based on this sample of cases, relatively few restrained occupants seriously injured in frontal crashes are in impacts that resemble the NCAP test configuration.

Moderate overlap is the other crash configuration currently used to evaluate the frontal crashworthiness of the fleet. This configuration was one of the two largest categories of crashes in the sample, even though good performance in the IIHS offset test was an inclusion requirement. However, as shown in Figure 12, one-third of the occupants in these crashes were seated on the opposite side of the impact (i.e., drivers injured in front-right overlap crashes, or passengers injured in front-left overlap crashes). Among occupants seated on the same side as the impact, about half (8 of 15) were in crashes where substantial intrusion occurred, likely contributing to injury. Calculated delta-Vs for these 8 crashes ranged from 70 to 94 km/h. This compares with an average delta-V of 44 km/h for the IIHS test when calculated with the SMASH algorithm used by NASS investigators [11]. The moderate overlap crashes with substantial intrusion in this study all likely were higher speed crashes than the IIHS frontal offset test.

Of the 23 occupants in moderate overlap crashes, 14 were injured due to factors other than intrusion; there appeared to be adequate postcrash survival space for the restraint system to operate. Because the selection criteria for the present study included the requirement that an occupant sustain an AIS ≥ 3 injury, it is unknown how many occupants survived serious moderate overlap crashes without such injury. Nevertheless, the sample suggests that many injuries sustained by restrained occupants in moderate overlap and other frontal crashes can be attributed to the interaction between the occupant and restraint system in the absence of substantial structural collapse.

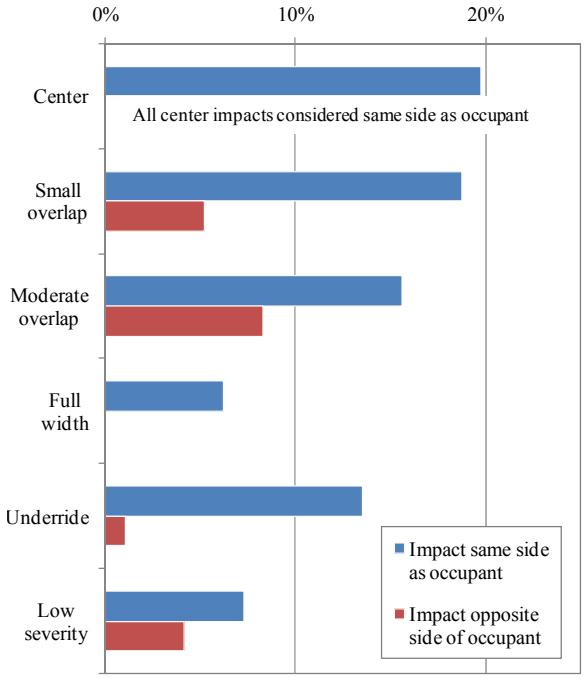

Figure 12. Crash configurations relative to injured occupant's seat position

Potential Future Test Configurations

The test configurations used in the current NCAP and IIHS frontal evaluations represent 22% of the crashes in the study sample (full-width and moderate overlap crashes on the same side as the injured occupant). The remaining crashes warrant further discussion with respect to potential future test programs.

Crashworthiness evaluations must encourage design changes that are beneficial in real-world crashes. It is not obvious from this sample of cases that injuries related to restraint and occupant factors require countermeasures that can be evaluated adequately with current full-scale crash testing. These are cases where the structural design prevented intrusion into the occupant compartment but serious injury still occurred. Figure 9 shows that occupants who were injured due to factors other than intrusion were more than twice as likely to be 60 or older or to be obese (defined as having a body mass index exceeding 30), compared with those injured in crashes with intrusion.

The ATDs currently available have only limited ability to address the unique risks of the populations of older or overweight occupants [12][13]. The most commonly used ATDs represent the 50th percentile male, but more than half of the case occupants injured in crashes without occupant compartment intrusion were female.

An additional consideration is that occupants who sustained injury from factors other than intrusion were more than twice as likely to have been in multiple-impact crashes. These were crashes in which some initial event (e.g., striking a curb, running over a small tree, being sideswiped) preceded the primary impact. Initial events could lead to occupants being out of position for the subsequent crash event, or to airbag deployment in some cases. In many of the multiple-impact cases, overall injury risk may be related less to the specific configuration of the most severe crash event than to the occupant not being in an ideal position for the event.

The center impacts in the sample highlight some of the complications involved in designing future crash test programs. Center impacts were the most common configuration when accounting for the side of the vehicle being impacted (Figure 12). Vehicle structure prevented substantial intrusion in all but 2 of the 19 cases. Because all center impacts were to trees, poles, or posts, they all were off-road crashes, and almost half involved initial impacts preceding the primary crash event. Due to these factors, it is unclear what design changes are necessary to reduce injury risk in center impacts, and whether these changes could be driven by a single standardized laboratory test condition.

Fewer occupants were injured in crashes with substantial intrusion than without (Figure 3). However, when intrusion was a factor in producing injury, the median ISS was higher (Figure 6) and occupants more often were killed (Figure 9). Figure 5 shows that more than 70% of these crashes were either small overlap or underride, with most of the remainder being moderate overlap crashes at higher speeds than the IIHS test speed, as discussed above.

Half of the 14 underride crashes produced fatalities. In 8 cases, underride occurred when the case vehicle struck a medium- or heavy-duty truck or trailer (4 front and 4 rear), suggesting a need for improved underride protection on large commercial vehicles. Federal Motor Vehicle Safety Standards 223 and 224 establish requirements for rear-impact guards on heavy-duty trailers in the United States. However, crash tests showing that underride still can occur with these guards prompted Canadian regulators to develop stricter standards [14]. One case in the present study included on-scene photographs showing that the trailer's guard deformed during the crash and failed to prevent underride. There are no front underride prevention requirements for large trucks in the United States. Research in Europe [15][16] has investigated front underride guards, and United Nations Economic Commission for Europe Regulation 93 contains requirements for such guards [17].

The remaining 6 underride cases in the sample involved impacts with light truck vehicles (LTVs). Three of these were front-to-front crashes. This configuration is being addressed to some extent by manufacturers' voluntary commitment to lower the front-end structures of their LTVs [18]. One of the partner vehicles in the underride cases was an SUV that met the criteria of the voluntary agreement, and occupant compartment intrusion was limited. However, the SUV structure did not actually engage the main longitudinals of the case vehicle, and a higher severity crash may not have been survivable. Vehicles underrode the rear of an LTV in two cases and the side in another case. High-speed compatibility is not being addressed in either of these configurations.

A crash test designed to represent a real-world underride configuration could produce vehicle structures that are compatible with a larger range of partner vehicles, or that reduce the severity of intrusion when there is incompatibility. However, such a test may have only limited effect in the field until there is some improvement in the design and implementation of underride prevention for the fronts, sides, and rears of large trucks, trailers, and LTVs.

The small overlap configuration was the most common among crashes where intrusion contributed to injury (Figure 5) and the second most common in the entire sample when accounting for the side of the vehicle being loaded (Figure 12). Of the 22 small overlap crashes, 19 were impacts with the front or side of another vehicle and 3 were impacts with a pole, post, or tree. When included, delta-V estimates for these crashes likely were inaccurate because they were based on crush measurements taken at the bumper bar, which was loaded very little or not at all.

Currently there are no regulatory or consumer test programs evaluating protection in small overlap crashes. Such a program could result in vehicle design changes that expand the structural protection across the full width of the vehicle. Some occupants in moderate overlap and full-width crashes also would likely benefit from this increased load sharing, as well as occupants in some crashes with CDC codes indi-

cating left or right side impacts where oblique loading leads to some front structure involvement.

Restraint Factor Injuries

Many cases evaluated had little intrusion in the areas of the injured occupants. In 37 of these cases, restraint factors appeared to contribute to injury. It was not always clear exactly how these injuries occurred. In some cases, there appeared to be an injury pattern consistent with belt-induced loading. In other cases, steering wheel deformation or other evidence suggested restraint forces from the airbag and seat belt were insufficient to prevent hard contacts with the vehicle interior. Of 32 drivers with injuries attributed to restraint factors, 10 had evidence of steering wheel loading. However, in most cases it was unclear whether the coded injuries were caused by excessive or insufficient restraint loads. This especially was true for chest injuries, the body region most commonly injured at the AIS ≥ 3 level (Figure 7).

Among occupants injured due to restraint factors, the specific body regions sustaining AIS ≥ 3 injuries varied by occupant age (Figure 13). The biggest disparity was in the distribution of chest and head injuries. Occupants 60 or older more often received at least one serious chest injury than a serious head injury. The opposite was true for occupants younger than 30. Other research has found that belt force thresholds related to chest injury risk vary widely with occupant age [19]. Although not conclusive, the cases analyzed

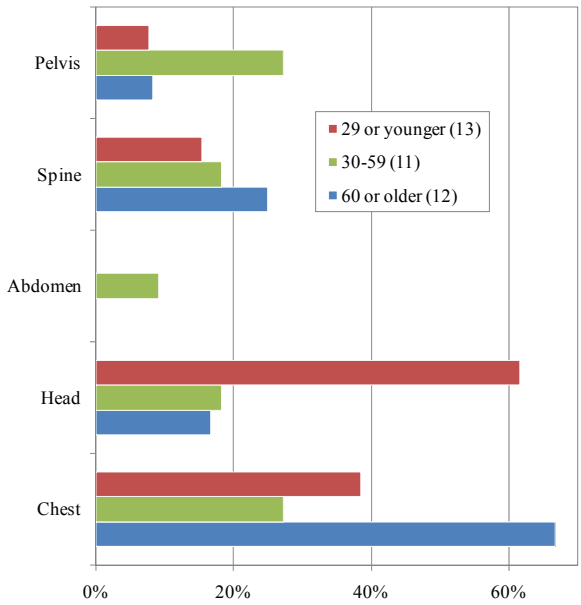

Figure 13. Occupants with AIS ≥ 3 injuries to certain body regions by age for restraint factor crashes

in this study suggest that increasing excursion to reduce belt forces also may have an age-related effect with respect to the occurrence of head injuries.

NASS-CDS contains codes for the sources attributed to each injury by the case investigator. However, there was inconsistency in these codes, and some seemed highly improbable given the loading direction. Often the "source confidence" codes were questionable as well. Many investigators listed the same confidence level for every injury to an occupant, even when more than 20 injuries occurred with a wide range of severities. In some cases, the source confidence was listed as "certain" even though no details of the injury were known. For these reasons, and to limit influence of the differences in the investigators' techniques, the "injury source" and "source confidence" variables were not analyzed for this study.

The crash sample suggests current restraint systems can be improved. Occupants with injuries attributed to restraint factors in the absence of intrusion were involved in multiple impact crashes nearly 40% of the time (Figure 9). If airbags deploy or load-limiting seat belts spool out during initial impacts, occupants may be more vulnerable during subsequent impacts. Even if the initial impact is the most severe, it is possible that a less severe subsequent impact could cause serious injury if the airbag and seat belt no longer offer sufficient protection. Additionally, many occupants in real-world crashes may be loading restraint systems more obliquely than the loading in crash tests. Of the 8 moderate overlap crashes with injuries attributed to restraint factors, 5 were impacts to the opposite side of the front from the injured occupant, and the other 3 were crashes against vehicles moving perpendicularly to the case vehicle.

Study Limitations

A clear limitation of the present study is the sample size. Patterns of crashes and injuries that exist in the sample may vary from the larger population of frontal crashes producing injury in the United States. Additionally, the sample only includes occupants with serious injuries, so there is no way to know the injury risk for the different crash types that have been described. For example, it might be assumed that underride and small overlap crashes have a higher rate of serious injury per involvement than moderate overlap or full-width crashes, but there is no way to determine this with the current dataset.

CONCLUSIONS

The present study analyzes the types of frontal crashes causing serious injuries and fatalities to belted

front-seat occupants in vehicles achieving good performance in current crashworthiness evaluation programs. Potential future test programs are considered by describing the real-world crash configurations in relation to the major longitudinal structures designed to absorb energy in most modern vehicles. Based on this sample, it is apparent that a large number of serious injuries occur in frontal crashes despite good structural integrity. A variety of factors may contribute to injury risk in these cases, such as occupants being out of position due to preceding impacts, loading from other occupants, or restraint misuse. In addition, restraint systems may be unable to adequately balance the need for varying restraint forces based on occupant age, size, and crash severity.

These restraint and occupant factors merit continued research to develop improved countermeasures that adapt to the occupant and crash circumstances and to determine which test conditions would allow meaningful evaluation of the countermeasures. Until this research is complete, it appears more promising for crashworthiness evaluation programs to address the substantial number of frontal crashes that are producing collapse of the occupant compartment and resulting injuries. Small overlap, underride, and high-velocity moderate overlap crashes are the most common configurations producing substantial amounts of intrusion in frontal crashes. Full-scale crash testing may have the greatest potential to improve fleet crashworthiness in small overlap crashes.

ACKNOWLEDGMENT

This work was supported by the Insurance Institute for Highway Safety.

REFERENCES

[1] National Highway Traffic Safety Administration. 2007. Buying a safer car, 2008. Report no. DOT HS-810-872. Washington, DC: US Department of Transportation.

[2] Office of the Federal Register. 2008. *Federal Register*, vol. 73, no. 134, pp. 40016-40049. National Highway Traffic Safety Administration – Final decision notice. Docket no. NHTSA-2006-26555; Consumer Information; New Car Assessment Program. Washington, DC: National Archives and Records Administration.

[3] Farmer, C.M. 2005. Relationships of frontal offset crash test results to real-world driver fatality rates. *Traffic Injury Prevention* 6:31-37.

[4] Kahane, C.J.; Hackney, J.R.; and Berkowitz, A.M. 1994. Correlation of vehicle performance in the New Car Assessment Program with fatality risk in actual head-on collisions. Paper no. 94-S8-O-11. *Proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles*, 1388-1404. Washington, DC: National Highway Traffic Safety Administration.

[5] Farmer, C.M. 2006. Effects of electronic stability control: an update. *Traffic Injury Prevention* 7:319-24.

[6] Honda Motor Company Ltd. 2003. Honda introduces new crash compatibility body frame structure that both enhances self protection and reduces aggressivity. Press release. Tokyo, Japan.

[7] Rouhana, S.W.; Bedewi, P.G.; Kankanala S.V.; Prasad, P.; Zwolinski, J.J.; Meduvsky, A.G.; Rupp, J.D.; Jeffreys, T.A.; and Schneider, L.W. 2003. Biomechanics of 4-point seat belt systems in frontal impacts. SAE Technical Paper Series 2003-22-0017. Warrendale, PA: Society of Automotive Engineers.

[8] Lindquist, M.; Hall, A.; and Bjornstig, U. 2004. Car structural characteristics of fatal frontal crashes in Sweden. *International Journal of Crashworthiness* 9:587-97.

[9] Park, B.T.; Partyka, S.C.; Morgan, R.M.; Hackney, J.R.; Lee, J.; Summers, L.; Lowrie, J.C.; and Beuse, N.M. 2000. Comparison of vehicle structural integrity and occupant injury potential in full-frontal and offset-frontal crash tests. SAE Technical Paper Series 2000-01-0879. Warrendale, PA: Society of Automotive Engineers.

[10] Stucki, S.L.; Hollowell, W.T.; and Fessahaie, O. 1998. Determination of frontal offset test conditions based on crash data. Paper no. 98-S1-O-02. *Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles*, 164-84. Washington, DC: National Highway Traffic Safety Administration.

[11] Aylor, D.A.; Nolan, J.M.; Zuby, D.S.; and Baker, B.C. 2006. How the 64.4 km/h (40 mi/h) frontal offset deformable crash test relates to real-world crash severity. *Proceedings of the Second International Expert Symposium on Accident Research* (CD-ROM). Hannover, Germany: Hannover Medical School.

[12] Li, G.; Braver E.R.; and Chen, L-H. 2003. Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel

among older drivers. *Accident Analysis and Prevention* 35:227-35.

[13] Mock, C.N.; Grossman, D.C.; Kaufman, R.P.; Mack, C.D.; and Rivara, F.P. 2002. The relationship between body weight and risk of death and serious injury in motor vehicle crashes. *Accident Analysis and Prevention* 34:221-28.

[14] Boucher, D. and Davis, B.T. 2000. Trailer underride protection – a Canadian perspective. SAE Technical Paper Series 2000-01-3522. Warrendale, PA: Society of Automotive Engineers.

[15] Riley, B.S.; Penoyre, S.; and Bates, H.J. 1985. Protecting car occupants, pedestrians, and cyclists in accidents involving heavy goods vehicles by using front underrun bumpers and sideguards. *Proceedings of the 10th International Technical Conference on Experimental Safety Vehicles*, 883-96. Washington, DC: National Highway Traffic Safety Administration.

[16] Goudswaard, A.P.; Nieboer, J.J.; and Janssen, E.G. 1991. Truck front underrun protection. *Proceedings of the 1991 International IRCOBI Conference on the Biomechanics of Impacts*, 185- 203. Bron, France: International Research Council on the Biomechanics of Impacts

[17] United Nations Economic Commission for Europe. 1994. UNECE Vehicle Regulations – 1958 Agreement (E/ECE/324, E/ECE/TRANS/505, Rev.1/Add.92); Addendum 92 (Feb 1994) – Regulation no. 93: Uniform Provisions Concerning the Approval of: I. Front Underrun Protective Devices. Geneva, Switzerland. Available: http://www.unece.org/trans/main/wp29/wp29regs81-100.html.

[18] Baker, B.C.; Nolan, J.M.; O'Neill, B.; and Genetos, A.P. 2008. Crash compatibility between cars and light trucks: benefits of lowering front-end energy-absorbing structure in SUVs and pickups. *Accident Analysis and Prevention* 40:116-25.

[19] Foret-Bruno, J.Y.; Trosseille, X.; Le Coz, J-Y.; Bendjellal, F.; Steyer, C.; Phalempin, T.; Villeforceix, D.; Dandres, P.; and Got, C. 1998. Thoracic injury risk in frontal car crashes with occupant restrained with belt load limiter. SAE Technical Paper Series 983166. Warrendale, PA: Society of Automotive Engineers.

APPENDIX A

Cases excluded from injury analysis due to their irrelevance to frontal crashworthiness evaluation programs.

Year	PSU	Case	Details
2002	45	39	Vehicle traveled down slope, pitched downward at impact with trees.
2003	11	18	Oncoming snowmobile became airborne, crashed through windshield.
2004	43	343	(2 occupants) Postcrash fire destroyed vehicle, may have contributed to injury.
2004	45	118	Rollover was most severe event.
2004	72	40	After pole impact, electrical utility box fell from pole through windshield.
2005	9	64	Vehicle struck trees while airborne and pitched forward, involving roof.
2005	49	137	Unreproducible kinematics resulting from three impact events with vehicles, two with poles and an unrestrained rear occupant.
2005	82	18	Vehicle traveled off end of open drawbridge, fell 40 feet to ground.
2006	9	131	Subsequent rollover likely contributed to injury.
2006	11	106	(2 occupants) Vehicle traveled up steep slope to contact underside of overpass.
2006	13	213	Rollover was most severe event.
2006	41	132	Rear impact was most severe event.
2006	43	89	Vehicle traveled down slope, pitched downward at tree impact, involving roof.
2006	50	120	Rollover was most severe event.
2006	75	37	Injury caused by side mirror being knocked through window into driver's face.
2006	76	72	Rollover was most severe event.
2006	81	39	(2 occupants) Subsequent rollover likely contributed to injury.