

EVALUATION OF FRONTAL OFFSET/OBLIQUE CRASH TEST CONDITIONS

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ABSTRACT

As part of the effort underway for the National Highway Traffic Safety Administration's long-term advanced frontal research program, crash data were analyzed to determine representative crash conditions for establishing more effective frontal crash test procedure(s). These crash conditions were then analyzed to determine their significance to injury causation. Crash conditions were defined by nine different configurations for vehicle-to-vehicle head-on collisions. These crash configurations were examined to determine if a relationship existed between crash type and occupant injury in terms of either severity or location of injury.

Detailed weighted and unweighted crash statistics in the United States were obtained from the Crashworthiness Data System (CDS), a component of the National Automotive Sampling System (NASS). Data from the CDS were collected from 1995 to 1999 to determine the importance of crash parameters in establishing an improved frontal crash test procedure(s). Several parameters were considered: principal direction of force (PDOF), impact orientation angle, overlap percentage, crush profile, and change in velocity (ΔV). All vehicle-to-vehicle frontal two-car crashes in which the vehicles were inspected were used to establish baseline data. These baseline data were used to determine distribution of crash types and injuries. They were compiled to determine the number of moderate and severe injuries by crash condition. Data are presented to show the injury occurrence by crash type. The significance of these parameters were examined to determine their contribution to injury causation. Finally, selected crash tests were examined to determine the correlation of the dummy's injury assessment measurements in these tests with occupant injuries from similar type crashes in the NASS data.

INTRODUCTION

This study focused on better understanding of head-on frontal crashes and the resulting injury risks and injury types associated with the various possible crash configurations. Since every vehicle had a driver and many vehicles did not have a right front passenger, only driver injuries were considered. Considering only vehicles with drivers, maximized the data set and improved the statistical reliability of the data. In addition, specific angled and offset crash configurations affect drivers and passengers differently. Future studies could examine passenger injuries in a similar manner.

Two-vehicle head-on crashes were analyzed from NASS CDS crash data from 1995 to 1999. Only frontal, non-rollover crashes were considered, in which two vehicles collided with each other in front-to-front configurations. Front-to-side, front-to-rear, and fixed-object crashes were not considered, as some of these crash types are less severe (i.e. front-to-side), while others are very severe due to collisions involving non-compatible structures or narrow objects. Vehicles in the data set were constrained to those with valid occupant injury data and those in which both vehicles were inspected and measured for crush. Driver injuries were examined by crash configuration to better relate the types and severities of injuries to the type and severity of the crash. This study was conducted primarily for the purpose of determining the crash test configuration(s) that has the best potential to measure the real world performance of a vehicle in protecting its occupant(s).

Most studies of crash statistics have examined NASS data with a more general definition of crash types [1]. In these typical studies, crash variables such as overlap and PDOF were analyzed for each vehicle independently, without regard for

the other vehicle. This analysis will attempt to formulate a method to better categorize crash configurations by considering detailed crash parameters for both vehicles involved in a head-on frontal collision. In this study several crash data variables were combined to identify the specific crash configuration of each vehicle involved in the crash. These data were then analyzed by crash configuration and injury producing mechanisms for determining the most appropriate crash condition or conditions to address a wide range of occupant injuries.

NEW METHODOLOGY FOR CRASH DATA ANALYSIS

The NASS CDS data were divided into nine different crash categories based on relative angle between two vehicles at impact, damage pattern, and offset. The nine categories are defined in figures 1 through 9 relative to the subject vehicle (S) shown on the left side and the partner vehicle (P) shown on the right side. Figures 1 and 2 show collinear, right and left-offset crashes respectively.

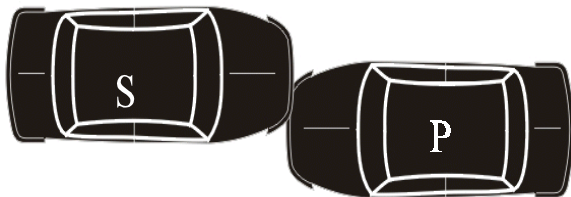


Figure 1. Case 1 - right-offset crash configuration.

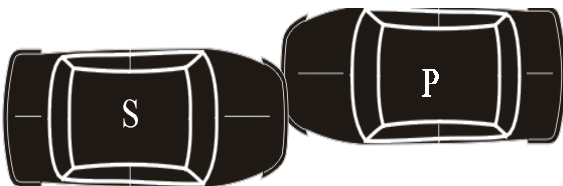


Figure 2. Case 2 - left-offset crash type.

Figures 3 and 4 show offset-oblique crashes. In figure 3 the vehicle is struck in the drivers-side front plane (left front corner) in a left offset-oblique configuration by the front plane of the striking vehicle. Figure 4 shows the front-to-left corner crash configuration. Note in case 4 the striking vehicle in figure 3 (P) is now the subject struck vehicle (S) in figure 4. Thus from a crash perspective figures 3 and 4 represent the same crash. In case 3, case 4, and other oblique cases, the subject and partner vehicle experience different crash responses in the same crash. Therefore, each subject and partner vehicle will be considered separately. Figure 5 shows the full frontal crash configuration.

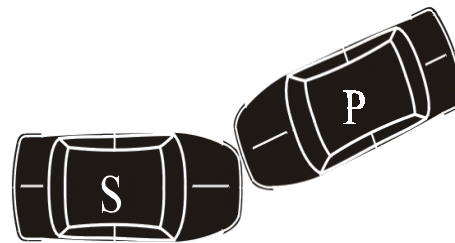


Figure 3. Case 3 - left-offset oblique crash case.

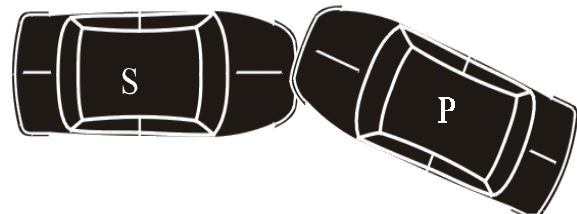


Figure 4. Case 4 - front-to-left corner crash.



Figure 5. Case 5 - full-frontal centered crash.

Figure 6 shows a right-oblique offset crash for case 6. This crash, complemented by case 7, is similar to case 3 and 4 in that case 7 is the counterpart, or partner vehicle, of case 6. Figure 7 shows this complement as the front-to-right offset oblique configuration. Case 8, shown in figure 8, is a left, full-oblique crash, which is the complement of case 9. Figure 9 shows this complement as the right full oblique crash configuration. Only the collinear crashes are symmetrical with nearly identical crash conditions for both the subject and partner vehicles. These symmetrical crashes can be seen in cases 1, 2, and 5.

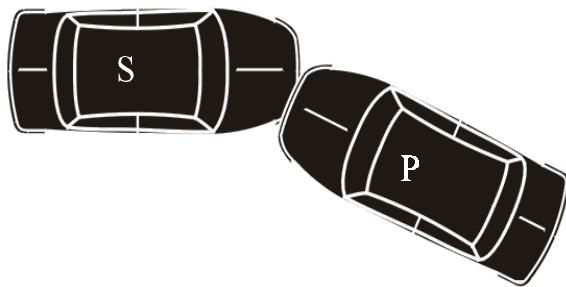


Figure 6. Case 6 - right-offset oblique crash configuration.

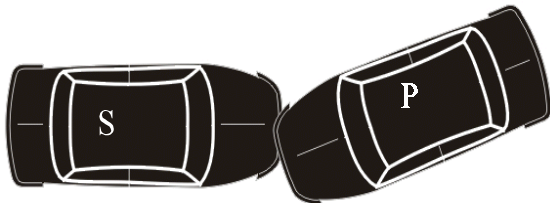


Figure 7. Case 7 - front-to-right offset oblique.



Figure 8. Case 8, left full-oblique crash.

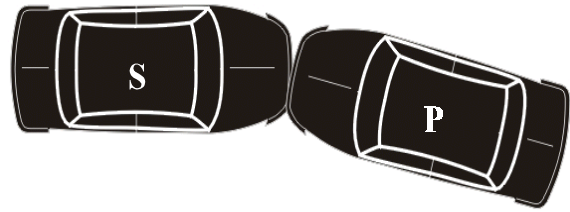


Figure 9. Case 9 - right full-oblique crash configuration.

After determining the crash configurations for this study, logical equations were developed that would best categorize the crashes from NASS CDS data, based on NASS coded parameters. To differentiate between crash configurations, it was observed from crash testing that certain crush profiles fit in each of the listed categories. Using knowledge of the crush profiles for NASS data, along with knowledge of the angles between the two vehicles at the time of impact, allowed an almost complete classification of the NASS crash data into the nine crash configurations. A first attempt to categorize the crashes used PDOF, which was coded in 10 degree increments starting in 1997, as one of the primary crash parameters. This attempt resulted in a large number of cases that were either not categorized or improperly categorized. To reduce the number of uncategorized cases, orientation angle as determined from each vehicles' heading angle was used in place of PDOF. Further refining the criteria to identify configurations for the NASS cases required the determination of offset amounts to distinguish between collinear offset crashes and full frontal crashes. Crush pattern combined with angle of impact were sufficient for differentiating between different oblique configurations. Therefore, the offset amount was unnecessary for identifying oblique crashes.

From NASS data the parameters were determined as follows for the set of vehicles included in the study. The relative angle between the two vehicles in each crash was calculated from the heading angle of each vehicle. Heading angle is given in degrees from 0 through 359, measured from north to a vector representing the travel direction of the vehicle. The relative angle is then calculated by the following formulas:

IF ANGOTH>ANGTHIS, THEN:
 ANGREL=ANGOTH-ANGTHIS-180 (1.)

IF ANGOTH≤ANGTHIS, THEN:
 ANGREL=ANGOTH-ANGTHIS+180 (2.)

Where ANGTHIS = Heading Angle of subject Vehicle
 ANGOTH = Heading Angle of partner vehicle
 ANGREL= Approach angle of partner vehicle relative to driver in subject (note: plus angles are clockwise and negative angles are counter-clockwise)

The overlap was determined by combining the NASS variables DIRDAMW (Direct Damage Width) and DVL (undeformed end width). Overlap percent is determined by the formula:

$$\text{OVERLAP} = (\text{DIRDAMW} / \text{DVL}) \times 100\% \quad (3.)$$

The crush location was determined from the location of the maximum measured crush, CMAX, based first on the NASS measurement protocol for C1 to C6 crush measurements (C1 is left and C6 is right), or DVD (distance to the center of damage from the vehicle centerline).

The above described parameters were used to sort the two-vehicle crashes in NASS into the respective categories as shown in figures 1 through 9. The following equations were developed to best describe these crashes. These equations describe the conditions that must be met for the subject vehicle, denoted by the subscript "S", and for the partner vehicle denoted by the subscript "P".

Case 1 - Right Offset

$$\begin{aligned} &\text{OVERLAP}_S \leq 85\% \text{ \#AND\#} \\ &-10 \leq \text{ANGREL}_S \leq 10 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C6} \text{ \#OR\# } \text{DVD}_S > 0 \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C6} \text{ \#OR\# } \text{DVD}_P > 0 \end{aligned} \quad (4.)$$

Case 2 - Left Offset

$$\begin{aligned} &\text{OVERLAP}_S \leq 85\% \text{ \#AND\#} \\ &-10 \leq \text{ANGREL}_S \leq 10 \text{ \#AND\#} \end{aligned}$$

$$\begin{aligned} &\text{CMAX}_S = \text{C1} \text{ \#OR\# } \text{DVD}_S < 0 \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C1} \text{ \#OR\# } \text{DVD}_P < 0 \end{aligned} \quad (5.)$$

Case 3 - Left offset oblique

$$\begin{aligned} &-90 < \text{ANGREL}_S < -10 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C1} \text{ \#OR\# } \text{DVD}_S < 0 \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C1,C2,C3,C4, OR C5} \end{aligned} \quad (6.)$$

Case 4 - Center-to-left offset oblique

$$\begin{aligned} &\text{CMAX}_S = \text{C1,C2,C3,C4, OR C5} \\ &\text{ \#AND\#} \\ &-90 < \text{ANGREL}_P < -10 \text{ \#AND\#} \\ &\text{CMAX}_P = \text{C1} \text{ \#OR\# } \text{DVD}_P < 0 \end{aligned} \quad (7.)$$

Case 5 - Full frontal

$$\begin{aligned} &\text{OVERLAP}_S \geq 85\% \text{ \#AND\#} \\ &-10 \leq \text{ANGREL}_S \leq 10 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C2,C3,C4, OR C5} \\ &\text{ \#OR\# } \text{DVD}_S = 0 \end{aligned} \quad (8.)$$

Case 6 - Right offset oblique

$$\begin{aligned} &10 < \text{ANGREL}_S < 90 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C6} \text{ \#OR\# } \text{DVD}_S > 0 \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C2,C3,C4,C5,OR C6} \end{aligned} \quad (9.)$$

Case 7 - Center-to-right offset oblique

$$\begin{aligned} &10 < \text{ANGREL}_P < 90 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C2,C3,C4,C5, OR C6} \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C6} \text{ \#OR\# } \text{DVD}_P > 0 \end{aligned} \quad (10.)$$

Case 8 - Left full oblique

$$\begin{aligned} &-90 < \text{ANGREL}_S < -10 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C1} \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C6} \end{aligned} \quad (11.)$$

Case 9 - Right full oblique

$$\begin{aligned} &10 < \text{ANGREL}_S < 90 \text{ \#AND\#} \\ &\text{CMAX}_S = \text{C6} \\ &\text{ \#AND\#} \\ &\text{CMAX}_P = \text{C1} \end{aligned} \quad (12.)$$

Using the above logic, the primary distinction between a full frontal crash (case 5) and an offset crash (case 1 or 2) is the overlap. Testing has shown a significant difference in the crash pulse and intrusion characteristics between identical car-to-car tests at 90 percent overlap and full engagement [2]. Therefore, to be conservative, overlaps above 85 percent were chosen as the definition of full-frontal crashes. Oblique crashes did not need such a distinction since the crush pattern was unique for full-engagement versus partial- engagement oblique crashes. The definition of crashes by angle may at first appear somewhat arbitrary. However, the angles were chosen primarily based on a sample of case reviews that appeared to represent the crash types described.

CRASH ENVIRONMENT IN THE UNITED STATES

Crash categories were sorted for 1995 to 1999 NASS data based on the logical equations (equations 4 - 12) as described in the preceding sections. These crash categories, which are consistent with observed hard copy case reviews and crash test observations, were sufficient to define 1,723, out of 1,826 (approximately 94 percent) of the vehicles in this five-year NASS study.

The NASS data analysis will be based on the 1,723 vehicles accurately categorized by the logical equations for each crash configuration. When statistical weights are applied to determine a nationally representative number of crashed vehicle, there are 410,957 vehicles represented by this count. Figure 10 shows the involvement by case type as a percentage of the unweighted and weighted cases. As seen from this figure, the largest crash type combination is the case 3 and case 4 crash type which accounts for approximately 36 percent of the 1,723 unweighted NASS vehicles and 40 percent of the weighted (410,957) NASS vehicles. This crash type involves two vehicles, one as shown by the subject in figure 3 and the other as shown by the subject in figure 4. The next significant crash type is case 6 combined with case 7, the right offset-oblique vehicle struck by the front of a partner vehicle (see subject vehicles in figures 6 and 7). This crash category represents approximately 24 percent of the unweighted vehicles in NASS and 27 percent of the weighted vehicles. The third largest crash category

is the case 2 crash, which is a left collinear offset. The unweighted case 2 vehicles account for approximately 17 percent of

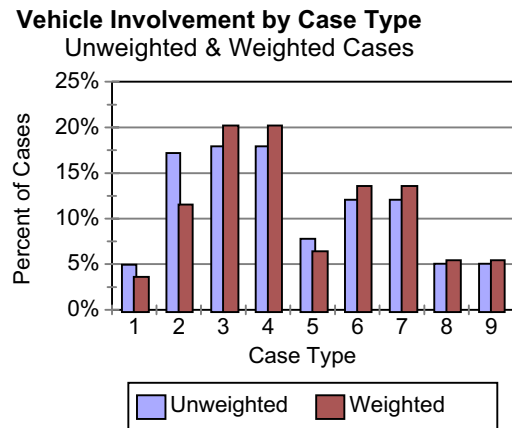


Figure 10. Percentage of NASS vehicles involved in 2 vehicle frontal crashes by crash configuration.

the total NASS vehicles, while the weighted cases only account for approximately 12 percent of the NASS vehicles. Combining all oblique cases (case 3, 4, 6, 7, 8, and 9) and all collinear cases (case 1, 2, and 5) show that 70 percent of the unweighted and 78 percent of the weighted NASS vehicles were involved in oblique crashes, with the remainder involved in collinear crashes. Combining the offset cases (case 1, 2, 3, 4, 6, and 7) show that 82 percent and 83 percent of the unweighted and weighted (respectively) vehicles from the NASS data are offset crashes with the remainder being full engagement (greater than 85 percent overlap).

Next, injuries were examined for the crash cases listed by first looking at maximum injury on the abbreviated injury scale (AIS) which is coded in NASS as MAIS [3]. When looking at moderate and higher injuries, the data were sorted by crash type for MAIS of 2 or greater as shown in figure 11. This figure shows that the left offset crash case accounts for the largest number of overall moderate and greater injuries. From a crash viewpoint, case 3 and 4, which occur in the same crash, account for a substantially larger number of injuries. The importance of the left oblique crash becomes even more apparent when considering only minor and moderate injuries, as is typical of high intrusion related cases resulting in lower-extremity injuries. The distribution of minor and moderate injuries is

shown in figure 12. These data show that there are more minor and moderate injuries from case 3 crash types than any other. This finding is consistent with results from crash testing conducted by NHTSA research which show that the highest femur and tibia loads are seen in left oblique car-to-car crash tests. The fact that case 4 has less minor and moderate injuries than case 3 is also consistent with crash test results. Oblique car-to-car crash tests were conducted in case 3 and case 4 configurations using similar size vehicles. Additionally, one test was conducted with identical vehicle models, but only the case 3 vehicle had an instrumented dummy. Higher intrusions and resulting higher leg forces were consistently observed in case 3 vehicles.

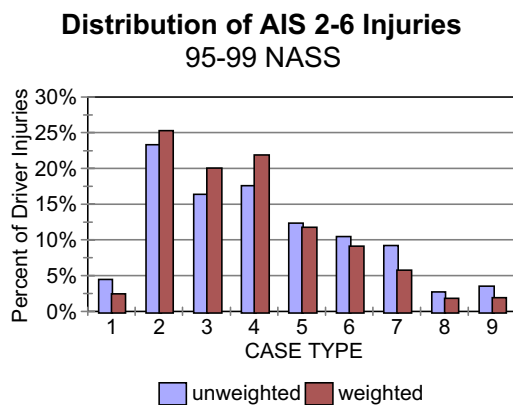


Figure 11. Percentage distribution of MAIS for drivers by crash type.

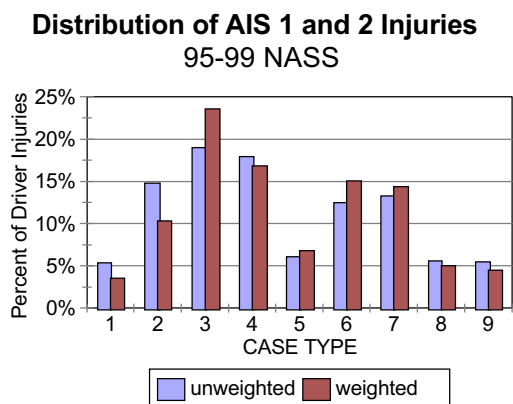


Figure 12. Distribution of minor and moderate injuries by crash case type.

Figure 13 shows the average results of driver IAV (injury assessment values) as a percent of IARV (injury assessment reference values) for three offset oblique crash tests conducted with 1993 Chevrolet Corsicas as the case 3 subject car (figure 3) and 1991 Honda Accords as the case 4 subject car (figure 4). The tests were conducted at speeds ranging from 53 - 66 km/h (33-41 mph), overlaps from 50 percent to 80 percent, and at a minus 30 degree orientation angle with respect to the driver in the subject case 3 car. These data show that for head, neck and chest injury assessment values shown as HIC (head injury criteria for 36 milliseconds), NIJ (maximum neck injury criteria), CH (chest acceleration for 3 milliseconds), and CTI (combined thoracic index), there is little difference between the two vehicle results. This upper body comparison is somewhat obscured by the fact that the Honda driver was restrained only by the three-point belt, while the Corsica driver was restrained by an airbag and the three-point belt. However, there is substantial difference for the lower-extremities injury measures, which are relatively unaffected by the presence of the airbag. The symbol “FEM” on the graph indicates the average of the maximum femur loads in terms of percentage of allowable criteria. The nomenclature “TIB” shows the average of the maximum tibia index expressed as a percentage of the IARV. Both leg injury indicators are substantially higher for the average of the case 3 vehicles. The IARV reference values used for the upper body injury criteria are

Percent of Average IARV for 3 Crashes
(Injury Assessment Reference Value)

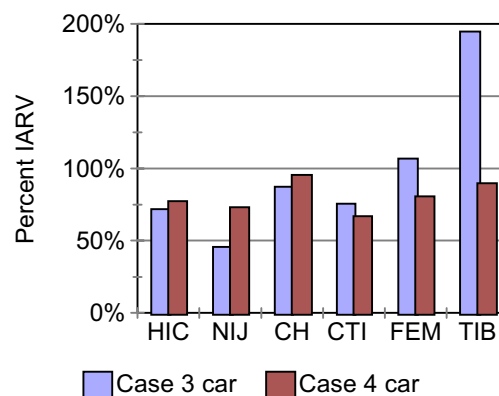


Figure 13. Hybrid III injury assessment measured from the results of three crash tests

HIC= 1000, NIJ=1, CH = 60, and CTI = 1. For the lower extremity, FEM = 1008, and TIB = 1 were used as the reference values.

From the subset of 1,723 NASS unweighted cases, there were 184 cases in which an airbag equipped vehicle hit another airbag equipped vehicle. Assuming crashworthiness and belt usage differences are insignificant between the partner and subject vehicles allowed a comparison to be made between the subject and partner injury rates. Figure 14 shows this comparison. Note that these data were not weighted because weighting would skew results and prevent direct comparison between collision partners. These data confirm the results of crash testing in that the case 3 (left oblique) is more injurious than the case 4. Also case 6 (right oblique) is more injurious than case 7, apparently due to the higher intrusion levels as witnessed in crash tests. Also, as expected, case 8 (left full oblique) is more injurious than case 9, even though only a small number (16 case vehicles) of crash cases are in this category. Comparing figure 14 to figure 11 (all AIS 2+ injuries) shows that the airbag equipped cars in figure 14 have similar injury distributions by case type as all vehicles as seen in figure 11. One exception is that the airbag cars have proportionally higher case 3 injuries than the overall population of vehicles. This may be because the airbag is effective in protecting the upper extremity, but not the lower-extremity and the case 3 crash type is more likely to produce lower-extremity injuries.

**Distribution of AIS 2-6 Injuries
95-99 NASS Airbag Cars**

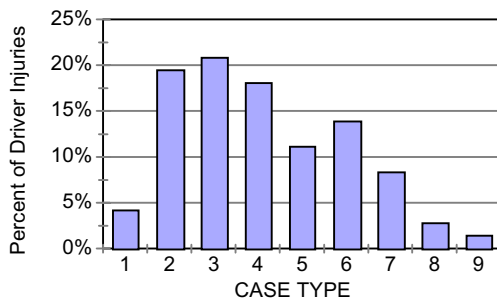


Figure 14. Distribution of moderate to severe injuries for airbag equipped cars by case type.

Lower-extremity injuries were examined by case type. Since airbags are not effective in

protecting the lower extremities, all case vehicles were examined for this purpose. From the previously described 1,723 NASS cases there were 1,107 lower-extremity injuries, including injuries to the pelvis, femur, lower leg, foot or ankle. These injuries ranged from AIS 1-3. The distribution of these injuries by crash case type is shown in figure 15. This distribution of leg injuries compares well with overall injuries as seen in figures 11 and 14. However, the comparison is best with figure 14 for the airbag vehicles, indicating that most injuries in airbag vehicles are to the lower extremities, as previously speculated.

**Distribution of AIS 1-3 Leg Injuries
95 - 99 NASS**

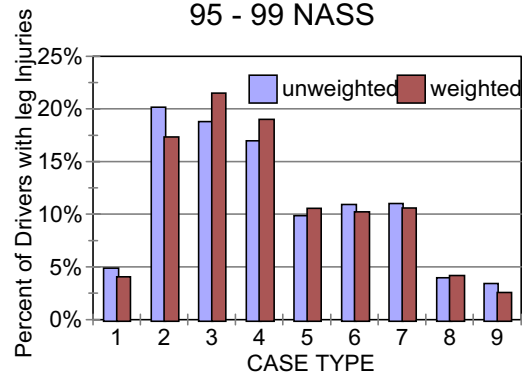


Figure 15. Distribution of lower-extremity injuries by crash case type.

To examine the specific crash conditions typical of the case 3 crash type, the overlap percentages and angles were calculated for the NASS cases. Overlap was computed using equation (3). Data for calculating overlap were available for 299 of the 309 cases. The cumulative frequency distribution

**Percentage Distribution of Overlap %
For Case 3 Vehicles**

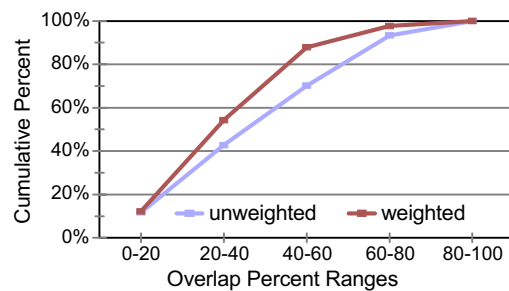


Figure 16. Cumulative frequency distribution of overlap percentage for case 3 vehicles.

is shown in figure 16. These data show that overlaps up to 60 percent include approximately 75 percent of the unweighted cases and almost 90 percent of the weighted cases. Figure 17 shows similar data for the angle of impact for case 3. These data show that the 50 percentile level of angle, in which half of the cases are above and half are below that level, is approximately 30 degrees for the unweighted cases and 33 degrees for the weighted cases.

Percentage Distribution of Angle For Case 3 Vehicles

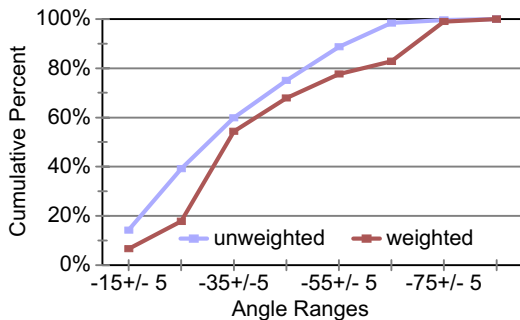


Figure 17. Cumulative frequency distribution of angle for case 3 vehicles.

CONCLUSIONS

As part of the effort underway for the National Highway Traffic Safety Administration's long-term advanced frontal research program, crash data were analyzed to determine representative crash conditions for establishing more effective frontal crash test procedure(s). The method described in this paper provides a means to conduct a more meaningful statistical analysis of NASS data. The methodology was applied to examine the best crash condition to evaluate lower-extremity injuries. However, there are numerous possibilities for examining many other crashworthiness problems.

Specific findings are that the left offset oblique configuration (figure 3) represents the most common crash condition. It was also shown that this crash condition accounts for the largest number of lower-extremity injuries.

ACKNOWLEDGMENTS

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