

A Frontal Impact Taxonomy for USA Field Data

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ABSTRACT

An eight-group taxonomy was created to classify real-world frontal crashes from the Crashworthiness Data System (CDS) component of the National Automotive Sampling System (NASS). Three steps were taken to develop the taxonomy: (1) frontal-impact towaway crashes were identified by examining 1985-2005 model year light passenger vehicles with Collision Deformation Classification (CDC) data from the 1995-2005 calendar years of NASS; (2) case reviews, engineering judgments, and categorization assessments were conducted on these data to produce the eight-group taxonomy; and (3) two subsets of the NASS dataset were analyzed to assess the consistency of the resulting taxonomic-group frequencies. "Full-engagement" and "Offset" crashes were the most frequent crash types, each contributing approximately 33% to the total. The group identified as "D,Y,Z No-Rail" was the most over-represented crash type for vehicles with at least one seriously-injured occupant. However, that group represented only 2.6% of the crash-involved vehicles. The taxonomy provides a consistent way to categorize frontal impacts beyond that afforded by the CDC itself. Moreover, the taxonomy provides the basis for potential future studies (e.g., more comprehensive risk assessments and related countermeasure designs).

INTRODUCTION

A taxonomy is a system for classifying and organizing data into groups which share similar qualities. Accordingly, nearly all fields of science use taxonomies to classify data. In the present context, the data being classified are real-world frontal crashes — crashes that involve a wide variety of crash circumstances and damage patterns.

Present regulatory and public-domain frontal crash tests focus on two modes: full-engagement and offset-engagement. These test modes have real-world relevance. For instance, Huelke and Compton (1995) estimated that about 36% of 1982-1992 frontal crashes in NASS were "distributed" crashes where direct damage spanned across all three front-end zones. Those authors also reported that 31% of the frontal crashes involved damage contained within the left or left-and-center zones; another 30% involved damage contained within the right or right-and-center zones. The authors summed the two

and reported that 61% were "offset" crashes. However, Huelke and Compton noted the lack of a generally accepted definition for offset frontal crashes.

In the present investigation, we extended the study from Huelke and Compton by using more field data, and by formulating more taxonomic groups. These groups were established by conducting detailed case reviews, by applying engineering data and engineering judgment, and by iterating to a tractable number of taxonomic groups. While developing the frontal impact taxonomy, we had two goals: (1) the taxonomy should contain the most common laboratory frontal crash test modes, and (2) the remaining crashes should be classified into groups with reasonably similar damage patterns. The definitions for and an example of each taxonomic group will be given and discussed. Moreover, the SAS coding algorithm for the frontal impact taxonomy (FIT) will be provided. Finally, a brief summary of the injury rates for each taxonomic group will be reported.

1.0 NASS DATA

The NASS is a sample of U.S. motor vehicle crashes that is maintained by the National Center for Statistics and Analysis, an office of the National Highway Traffic Safety Administration. Because not all crashes in the USA can be inspected and reported, a means to estimate the entire field experience is necessary. The Crashworthiness Data System component of NASS provides detailed data from a multi-stage, stratified, unequal probability sample of thousands of minor, serious, and fatal crashes. The sampling intervals are designed to select a greater proportion of higher-severity crashes than lower-severity crashes, so a weighting factor that is inversely proportional to the selection probability is calculated for each crash. These weighting factors are applied to the sampled data to produce an unbiased estimate of USA field experience.

In NASS, the vehicle crash damage is coded according to the SAE-recommended practice (1980) known as the "Collision Deformation Classification," or CDC. The CDC provides a consistent means for classifying the patterns of vehicle deformation caused by real-world crashes. Consequently, the CDC itself affords a taxonomy. A brief discussion of each element of the CDC, as it pertains to frontal crashes, is provided in Appendix

1.1 SELECTION CRITERIA: FRONTAL CRASHES

The NASS data used in the present study were based on the following selection criteria:

- 1985-2005 model-year light passenger vehicles (cars and light trucks), in
- towaway, non-rollover crashes, whose
- General Area of Damage was to the front (i.e., GAD=F), from
- 1995-2005 calendar years (CY) of NASS, as some of the vehicle specifications necessary for the taxonomy were not reported in NASS until 1995.

These selection criteria were applied via the analysis software SAS (version 9.1.3 SP4, 2002), and the corresponding CDC data were studied. The resulting sample of 21,923 vehicles in NASS represented a weighted estimate of 9,652,027 frontal crash-involved light passenger vehicles.

Unless otherwise noted, weighted estimates were used in the subsequent analyses.¹

1.2 CDC ELEMENTS FOR FRONTAL CRASHES

The other CDC variables were considered for the selected frontal impact (GAD=F) data:

- Direction of Force (DOF): Figure 1 shows that 11-1 o'clock crashes were predominant (i.e., approximately 95%).
- Specific Longitudinal Location (SHL): Figure 2 shows that distributed crashes (Zone D) were the largest single contributor (i.e., approximately 48%).
- Specific Vertical Location (SVL): Figure 3 shows that everything- below-the-belt-line crashes (Zone E) were predominant (i.e., approximately 95%).
- Type of Damage Distribution (TDD): Table 1 shows that wide-impact-area crashes (Code W) were

¹ "Special study" cases were excluded to avoid over-representing the sample size for the weighted national estimates. Examples of special study cases include "Run off road" crashes and "Redesigned Air Bag" deployment cases. Special study cases may be selected within or in addition to the normal NASS sampling; cases selected outside of the normal NASS sampling are assigned a sampling weight of 0. Inclusion of these cases in analyses of weighted estimates would, therefore, overstate the sample size on which those estimates are based.

predominant (i.e., approximately 80%).

- Deformation Extent (EXTENT): Figure 4 shows that Zone 1 and Zone 2 crashes were the largest contributors (i.e., approximately 44% and 37%, respectively).

The CDC data of Figures 1-4 and Table 1 were considered in the development of the frontal impact taxonomy.

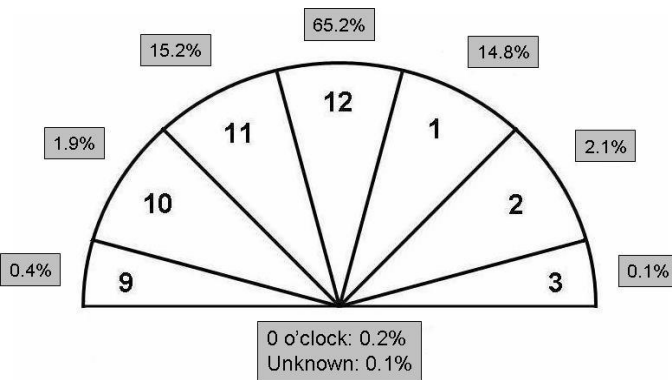


Figure 1. Distribution of Frontal Crashes, by DOF

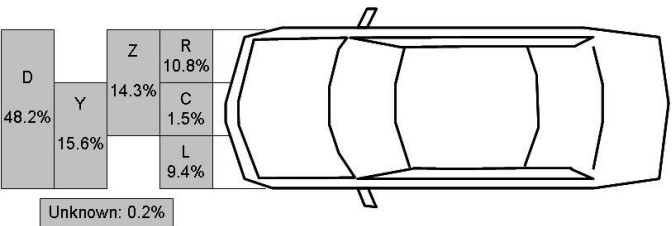


Figure 2. Distribution of Frontal Crashes, by SHL Zones

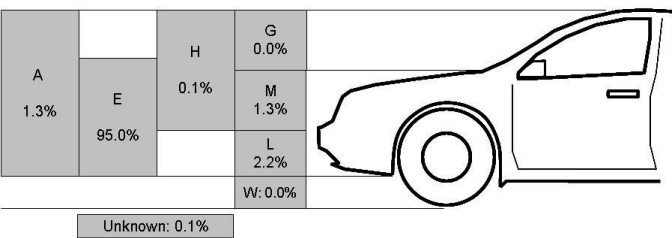


Figure 3. Distribution of Frontal Crashes, by SVL Zones

Table 1. Distribution of Frontal Crashes, by TDD

TDD	Code	Direct Damage:	Fraction (%)
Sideswipe	S	corner overlap <=4inches	1.3%
Corner	E	corner overlap, 4-16 inches	13.0%
Narrow impact area	N	<16 inches	4.9%
Wide impact area	W	>=16 inches	80.0%
Overhanging structure	A	shaped like inverted step	0.6%
Conversion in impact typ	K	single impact converts from W.	0.0%
Unknown	9		0.2%
			100.0%

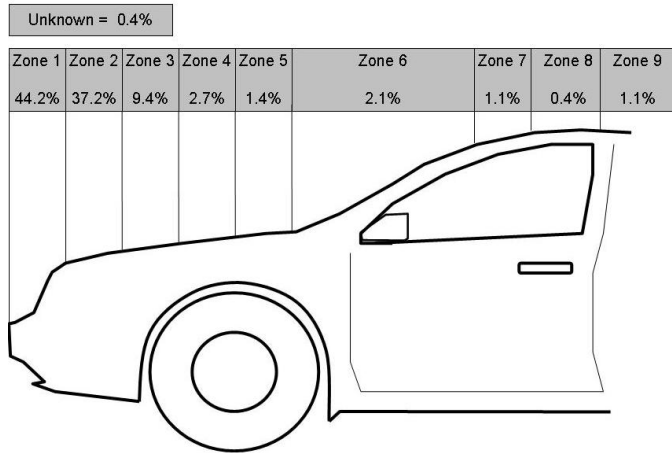


Figure 4. Distribution of Frontal Crashes, by EXTENT Zones

2.0 FRONTAL IMPACT TAXONOMY (FIT)

Recall that the initial subset of crashes considered in the present study consisted of vehicles with GAD=F. The frontal impact taxonomy was refined beyond that of the CDC by applying two concepts based on engineering judgment:

1. Crashes that share similar qualities relative to general occupant kinematics can be categorized, by determining the extent of frame rail engagement and the ratio of longitudinal and lateral speed changes. Related details are in Section 2.1.
2. An iterative process employing case reviews can be used to define a taxonomy with a tractable number of groups. Related details are in Section 2.2.

2.1 INTERMEDIATE CALCULATIONS

Rail-Engagement:

The frame rails are a vehicle's primary energy-absorbing components in a frontal crash. While unibody vehicles do not have frame rails, they do have longitudinal structural components that serve a similar function in a crash. For

the present study, those longitudinal structural components were regarded as "frame rails."

The NASS field data do not include explicit information about rail engagement in crashes. Thus, individual rail involvement was approximated as follows.

First, we considered the data typically provided in the NASS field report:

- original average track width (ATW)²,
- damage length (DIRDAMW), and
- center of damage in relation to the centerline of the vehicle (DVD), where

Figure 5 depicts ATW and DIRDAMW; Figure 6 depicts DVD.

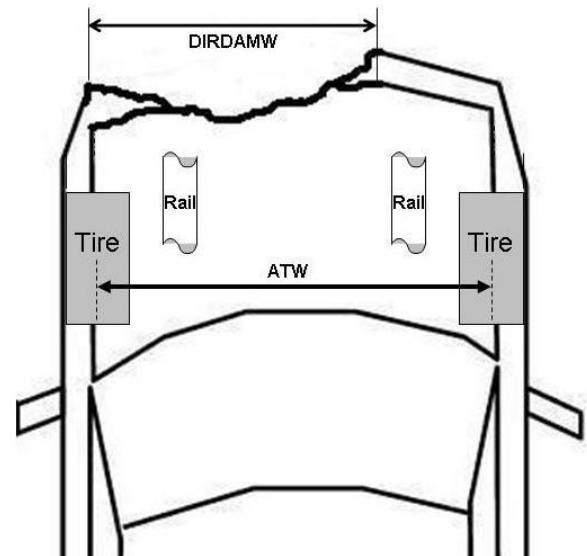


Figure 5. Illustration of ATW and DIRDAMW

Next, the data depicted in Figures 5 and 6 were combined in Figure 7. Therein, we also included data not provided in NASS, where

- "W_T" represents the tire width,
- "W_O" represents the tire-to-rail offset, and
- "AdjATW" represents the concept of an adjusted average track width (i.e., the distance between frame rails).

² The original average track width (SAS variable, ORIGAVTW) has been available in the analytic NASS file since 1995 CY.

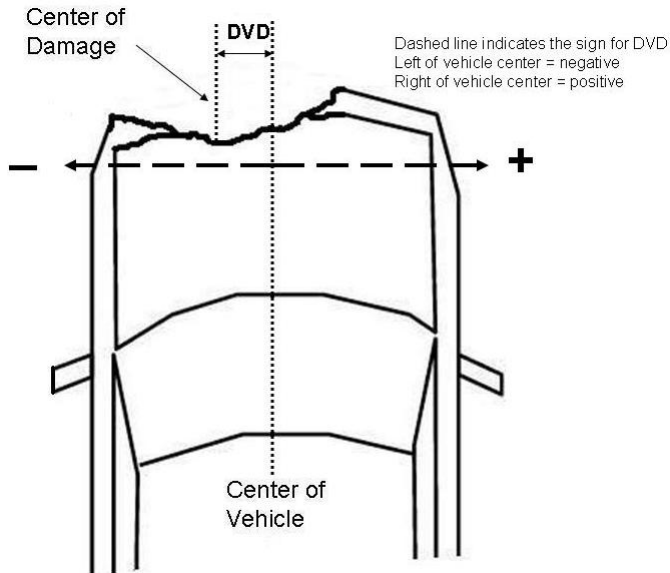


Figure 6. Illustration of DVD³

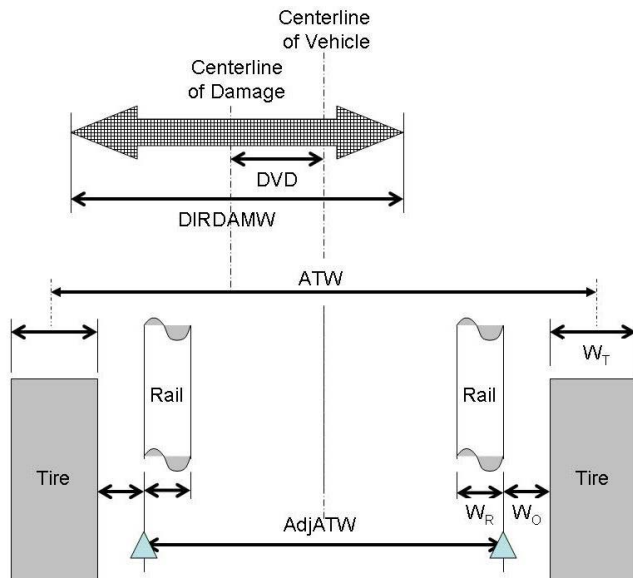


Figure 7. Crash and Vehicle Data, Plan View Relative to the Centerline of Vehicle

Finally, from inspection of Figure 7, the "adjusted average track width" was computed as follows:

$$\text{AdjATW} = \text{ATW} - W_T - 2W_O. \quad (1)$$

³ DVD is the distance between the center of damage and the center of the vehicle; it has a sign convention (i.e., left of the center of the vehicle is negative and right is positive). In contradistinction, DIRDAMW is a measure of the length of the direct damage; it is always positive.

Equation 1 was used to compute the adjusted average track widths for 12 vehicles (model years 2000-2008) with known W_T and W_O data; those data are shown in Table 2.

Table 2. Vehicle Dimensional Data

Vehicle Type	W_O (mm)	W_T (mm)	ATW (mm)	AdjATW (mm)	AdjATW/ATW
Small Car	110	219	1494	1055	0.71
Mid-sized Car	120	240	1646	1166	0.71
Mid-sized Car	120	231	1571	1100	0.70
Mid-sized CUV	120	242	1646	1164	0.71
Large Car	115	215	1631	1186	0.73
Compact Pickup	202	272	1471	795	0.54
Pickup	234	285	1702	949	0.56
Pickup	174	247	1731	1136	0.66
Small CUV	127	242	1543	1047	0.68
Mid-sized SUV	220	260	1558	858	0.55
Mid-sized CUV	156	267	1651	1072	0.65
Large SUV	240	247	1699	972	0.57

where CUV = Crossover Utility Vehicle

The last column of Table 2 shows that AdjATW was approximately 70% of the ATW for car-based vehicles (including CUVs); it was approximately 60% for truck-based vehicles. Thus, frame-rail involvement was estimated according to the following three-step algorithm:

- 1) Establish the corner points of the adjusted track width:

$$\text{Left Corner Point} \equiv \frac{-\text{AdjATW}}{2} \quad (2)$$

$$\text{Right Corner Point} \equiv \frac{\text{AdjATW}}{2}, \quad (3)$$

where $\text{AdjATW} = 0.7 \cdot \text{ATW}$ for car-based vehicles; $\text{AdjATW} = 0.6 \cdot \text{ATW}$ for truck-based vehicles. (These corner points are shown as triangles in Figure 7.)

- 2) Locate the edges of damage:

$$\text{Left Edge of Damage} = \text{DVD} - \frac{\text{DIRDAMW}}{2} \quad (4)$$

$$\text{Right Edge of Damage} = \text{DVD} + \frac{\text{DIRDAMW}}{2}. \quad (5)$$

- 3) Evaluate potential frame-rail engagement:

- The left rail was likely engaged if

$$\text{Left Edge of Damage} \leq \text{Left Corner Point} \quad (6)$$

- The right rail was likely engaged if

$$\text{Right Edge of Damage} \geq \text{Right Corner Point}. \quad (7)$$

Thus, each frontal-crash-involved vehicle may have zero, one, or two rails engaged.

Ratio of Longitudinal and Lateral Speed Changes:

To help characterize both the kinetics of a crash and the related potential occupant kinematics, a ratio of the longitudinal and lateral speed changes was considered:

$$\eta \equiv \frac{\Delta V_{\text{long}}}{\Delta V_{\text{lat}}}, \quad (8)$$

where the requisite data for Equation 8 were estimated in the NASS data.

Figure 8 illustrates the application of Equation 8 to three distinct groups of NASS data. The left bar shows the average speed-change ratio for 11-1 o'clock frontal crashes — the DOF used in conventional frontal impact regulatory testing. The center bar shows the average speed-change ratio for the frontal crashes with DOF of 9, 10, 2, or 3 o'clock. These "oblique" frontal crashes had a significantly different average speed-change ratio than 11-1 o'clock frontal crashes. The right bar in Figure 8 shows the average speed-change ratio for a subset of side crashes (i.e., GAD=R or L) that have damage forward of the passenger compartment (i.e., GAD=R,L and SHL=F). Thus, the average speed-change ratio for these side crashes was comparable to the speed-change ratio for the highly oblique frontal crashes.

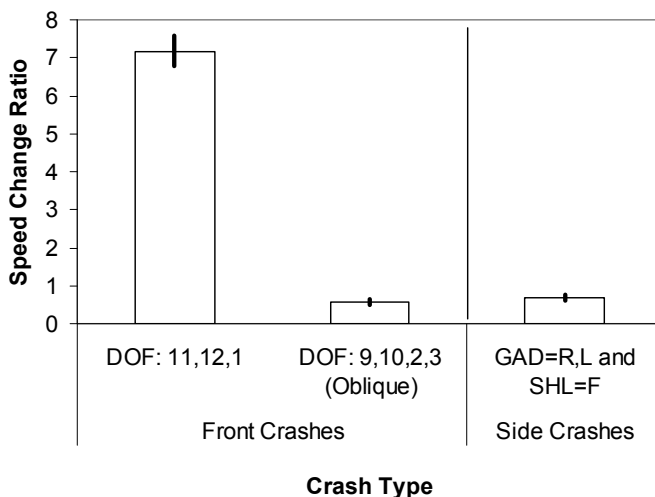


Figure 8. Speed-Change Ratios ($\Delta V_{\text{long}} / \Delta V_{\text{lat}}$) for Various Crashes, with 95thile Confidence Intervals

2.2 FIT CATEGORIZATION

With the established data-ordering of the CDC and with the intermediate calculations (viz., frame rail engagement and ratio of speed changes), an iterative process was developed to construct a comprehensive frontal impact taxonomy, with a tractable number of groups.

The iteration process consisted of six steps:

1. Define a candidate taxonomy, comprised of candidate groups.
2. Process all frontal-crash cases with SAS and bin them subject to the candidate groups.
3. Review a small random subset of the cases in each candidate group by considering the general characteristics of the damage patterns. These reviews involved the use of online NASS data (i.e., vehicle photographs, scene diagrams, and other information not available in the NASS analytic files).⁴
4. Check for appropriate binning of cases in each group. By inspection, the damage pattern in each case was determined to be either:
 - consistent with the expected damage pattern, or
 - inappropriately classified.
5. Identify the characteristics of any inappropriately binned cases. Use that information to refine the definitions for the existing groups or to define a new candidate group.
6. Repeat until all cases are appropriately binned. A final and separate group was established for the unclassified cases. This group was constrained to include no more than 1% of the total frontal crashes.

The iteration process yielded eight mutually exclusive taxonomic groups to categorize the frontal crashes in the 1995-2005 calendar years of NASS.

A short discussion of each taxonomic group follows. Appendix 2 contains the SAS code used to define the eight groups and Appendix 3 contains an example case for each group.

(1) Oblique Crashes:

"Oblique" crashes were defined in the taxonomy. The involved vehicles had DOF equal to 9, 10, 2, and 3 o'clock. As illustrated in Figure 8, the occupant kinematics in these crashes were expected to contain higher lateral components than 11-1 o'clock frontal crashes.

A typical "Oblique" crash in NASS was as follows: The collision partner was usually another vehicle (about 80% of the crashes), and this vehicle was typically entering an intersection or pulling into traffic. Often, the other vehicle was traveling at a higher speed. Lateral shifting of the frame rails ("end-shifting") was frequently recorded for these crashes.

⁴ Online NASS case data became available in 1997.

(2) High/Low Vertical-Engagement Crashes:

Recall from Figure 3 that SVL = A and E contained nearly all of the vehicle's frontal structural components; the remaining SVL zones did not. Accordingly, vehicles with less common patterns of vertical damage were combined and defined as a group in the taxonomy. The vehicles involved in these "High/Low Vertical-Engagement" crashes — labeled "Hi/Lo Vert" — had damage in the following SVL zones: H, G, M, L, or W.

The most common "Hi/Lo Vert" crash in NASS involved damage confined to the vertical location of the "frame" (SVL = L), accounting for about one-half of the "Hi/Lo Vert" crashes. While the damage from these crashes was contained within the vertical location of the frame, most commonly the vehicles had negligible rail involvement. The most common collision partner was a curb or ditch for these SVL = L crashes. The disabling damage was typically to the tire/wheel or steering components, so that the vehicle could not be driven from the scene.

(3) Side-Swipe/Corner Crashes:

Side-swipe and corner impacts with no more than one frame rail engaged were combined and defined as a group, labeled "SS/Corner." Thus, the following crashes were included: Side-swipe crashes (Table 1: TDD=S, i.e., direct damage contained within four inches of the corner of the vehicle) and corner crashes (TDD=E, i.e., direct damage contained within 16 inches of the corner of the vehicle).

A typical "SS/Corner" crash in NASS had another vehicle as the collision partner (about 70% of "SS/Corner" crashes); however, sideswipe/corner collisions with trees or poles were also reported for about 20% of these crashes. The damage from these collisions ranged from fairly minor to quite severe. A fairly minor impact directly to the wheel may have disabled the vehicle. More severe impacts had damage extending to the passenger compartment.

(4) Narrow Crashes:

"Narrow" crashes were defined in the taxonomy. The involved vehicles had damage to only one of the front-end zones defined in the SHL (Figure 2: L, C, or R) and with no more than one rail engaged. The "Narrow" category also included vehicles with damage on the borders of the front-end zones defined in the SHL (i.e., Y or Z), with the breadth of damage less than 16 inches (i.e., TDD=N), and with no more than one rail engaged.

Approximately 40% of the "Narrow" crashes involved a complex crash sequence (i.e., more than one recorded event). Nearly one-half of the "Narrow" crashes in NASS were off-road collisions with a tree or pole; more than 40% were collisions with other vehicles.

(5) Full-Engagement Crashes:

"Full-engagement" crashes were defined in the taxonomy. The involved vehicles had damage in all three front-end zones (i.e., SHL=D), with both rails engaged.

A typical "Full-engagement" crash in NASS was an on-road crash. The collision partner for nearly 90% of these crashes was another vehicle. More than three-quarters of the "Full-engagement" crashes had only one event in the collision sequence.

(6) Offset Crashes:

"Offset" crashes were defined in the taxonomy. The involved vehicle had damage in at least two of the three zones defined in the SHL (i.e., D, Y, or Z), with exactly one rail engaged. SHL=D crashes were included as possible offset crashes; the damage may have extended only slightly into one of the outer front-end zones, resulting in no rail engagement in that zone. Narrow impacts (i.e., TDD=N) were explicitly excluded because narrow collisions to the borders of the SHL sections R, C, or L might satisfy the aforementioned damage criterion.

The most common "Offset" crash in NASS involved another vehicle as its collision partner (approximately 85%); however, offset crashes with larger-diameter trees and poles were also reported (approximately 6%). Nearly 80% of the "Offset" crashes were single-event collisions.

(7) D,Y,Z No-Rail Crashes:

"D,Y,Z No-Rail" crashes were defined in the taxonomy. The involved vehicles had damage to one of the larger SHL zones (SHL=D, Y, or Z), while having none of the rails engaged.

While about one-third of "D,Y,Z No-Rail" crashes in NASS were off-road collisions with a larger-diameter tree or pole, collisions with another vehicle were more common (about 50%). Nearly 40% of the "D,Y,Z No-Rail" crashes involved a complex crash sequence (i.e., more than one recorded event).

(8) Other (Frontal) Crashes:

"Other" crashes were defined in the taxonomy. The involved vehicles had damage that did not satisfy the criteria for the aforementioned groups. As a constraint on the taxonomy, this final group was targeted to comprise less than 1% of the total number of frontal crashes.

Generally, there were three conditions under which the crash damage was categorized as "Other": (1) crashes with "conversion" recorded for type of damage distribution (i.e., TDD = K), (2) crashes with one or more missing elements in the CDC, and (3) crashes with all other combinations of CDC elements and frame rail engagements.

3.0 RESULTS

Recall one of the goals for the taxonomy: it should contain the most common laboratory frontal crash test modes. By creating the full-engagement and offset taxonomic groups, that goal was achieved. Note, however, that regulated laboratory crashes generally involve much more severe conditions than those of real-world crashes; severity was not considered in developing the taxonomy.

The specifications of the resulting frontal impact taxonomy are summarized in Table 3. (Recall that the CDC details are discussed in Appendix 1, and the SAS code for the FIT is in Appendix 2.) With this taxonomy, the 1995-2005 NASS data were revisited by the considering the 9.7 million frontal crashes from the standpoint of the eight taxonomic groups.

Table 3. Summary of Frontal Impact Taxonomy by CDC Coding and Number of Rails Engaged

FIT Group	DOF	SHL	SVL	TDD	Rails
1) Oblique	9,10,2,3				
2) Hi/Lo Vert			G,H,L,M,W		
3) SS/Corner				A	
4) Narrow		L,C,R		S,E	0,1
5) Full-Engagement		D,Y,Z		N	
6) Offset		D			2
7) D,Y,Z No-Rail		D,Y,Z		≠ N	1
8) Other				K	0
----- All remaining cases -----					

Figure 9 shows the distribution of frontal crashes, by the eight taxonomic groups. Full-engagement and offset crashes were the most frequent crash types, with each contributing approximately 33% to the total. Therefore, approximately 66% of the frontal crashes had distributed loading across the front-end width of the vehicle. Note also that approximately 23% of the total had more concentrated loading (i.e., the sum for SS/Corner and Narrow crashes).

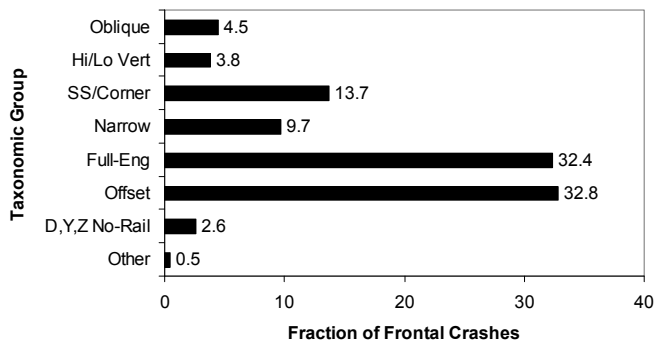


Figure 9. Frontal Crashes, by Taxonomic Group

Recall that Huelke and Compton (1995) reported that 36% of frontal crashes were "distributed" and that 61% were "offset." The data they used are shown in the top portion of Figure 10, such that "distributed" is labeled D, and "offset" was the sum of L, R, Y, and Z. For comparison purposes, the lower portion of Figure 10 shows the more recent NASS data, from the present study.

Applying Huelke's definitions to the 1995-2005 CY NASS data yielded "distributed"=48% and "offset"=50%. The difference between the two SHL distributions shown in Figure 10 was possibly due to the selection criteria for the underlying data (i.e., older vs. newer NASS⁵). However, the primary difference between the two studies involved the definition of offset crashes:

- "offset" crashes in Huelke and Compton (1995) were those with neither center-only damage nor distributed damage, from the SHL coding, and
- "offset" crashes in the present frontal impact taxonomy were selected to exhibit damage patterns generally consistent with public domain offset crash testing.

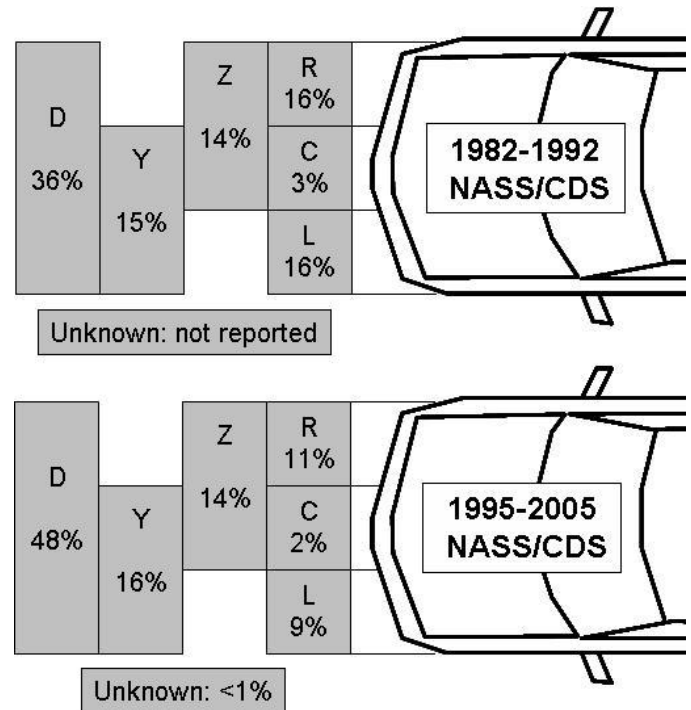


Figure 10. Comparison of SHL Distributions for Frontal Crashes in NASS

3.1 ASSESSMENT OF CONSISTENCY OF THE FIT

The analysis in the present study included frontal crashes from 1995-2005 CY NASS. However, the FIT categories were originally developed from 1995-2002 CY. The FIT distributions for the original time frame and for the

⁵ The current NASS sampling scheme began in 1988.

2003-2005 CY were compared. Figure 11 shows the results of this comparison. All of the fractions for the two time frames were within three percentage points of the reference (i.e., 1995-2005 CY). Accordingly, the taxonomy yielded reasonably consistent results for these two time frames.

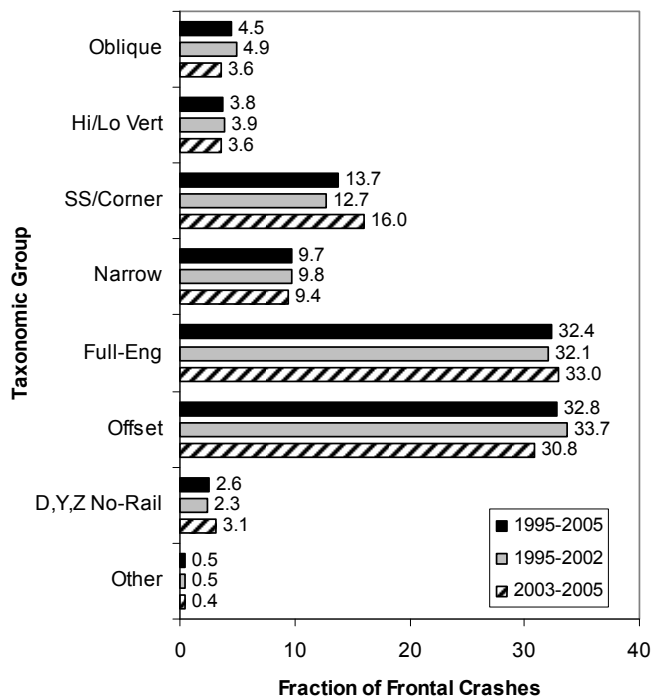


Figure 11. Frontal Crashes, by Taxonomic Group and Calendar Year Range

3.2 OVERVIEW OF INJURY DATA

A preliminary investigation of the injury data was also conducted on the FIT data from the 1995-2005 CY of NASS. The Abbreviated Injury Scale (AIS90) was used, where AIS1 is minor injury on this threat-to-life scale; AIS2 is moderate; AIS3 is serious; AIS4 is severe; AIS5 is critical; AIS6 is maximum (of which 99% are fatal).

The injury data were evaluated at the vehicle level. For example, "VAIS3+" is the weighted estimate of the number of vehicles with at least one occupant that sustained an AIS3-AIS6 (or fatal) injury. Similarly, "VFatality" is the weighted estimate of the number of vehicles with at least one occupant fatality. The distributions of injury by specified level and by taxonomic group are reported in Table 4. (Sample sizes are also reported in this table.)

Figures 12-14 show the resulting VAIS1+, VAIS3+, and VFatality distributions, respectively. Each of the distributions necessarily sums to 100 percent, and the figures are shown on identical scales for easier comparisons.

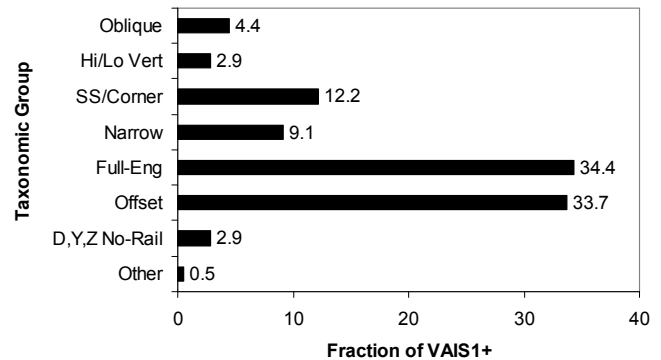


Figure 12. VAIS1+ Fraction; 1995-2005 CY of NASS

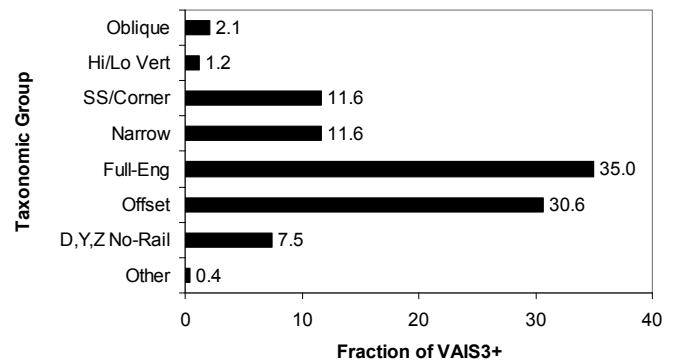


Figure 13. VAIS3+ Fraction; 1995-2005 CY of NASS

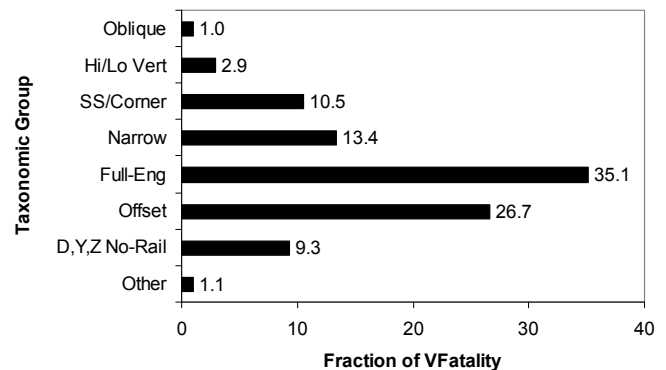


Figure 14. VFatality Fraction; 1995-2005 CY of NASS

The relative injury rate (i.e., the number of vehicles at an injury level divided by the number of crash-involved vehicles) was chosen as an additional metric, designed to assess aggregate risk relative to crash mode. Figures 15-17 pertain to the aforementioned VAIS1+, VAIS3+, and VFatality levels of injury, respectively. These figures are shown on identical scales for easier comparisons.