Frontal Corner Impacts – Crash Tests and Real-World Experience

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Abstract - In North America, frontal crash tests in both the regulatory environment and consumer-based safety rating schemes have historically been based on full-width and moderate-overlap (40%) vehicle to barrier impacts. The combination of improved seat-belt technologies, notably belt tensioning and load limiting systems, together with advanced airbags, has proven very effective in providing occupant protection in these crash modes. Recently, however, concern has been raised over the contribution of narrower frontal impacts, involving primarily the vehicle corners, to the incidence of fatality and serious injury as a result of the potential for increased occupant compartment intrusion and performance limitations of current restraint systems. Drawing on data documented in the National Automotive Sampling System (NASS)/ Crashworthiness Data System (CDS) for calendar years 1999 to 2012, the present study examines the characteristics of existing and proposed corner crash test configurations, and the nature of real-world collisions that approximate the test environments. In this analysis, particular emphasis is placed on crash pulse information extracted from vehicle-based event data recorders (EDR's).

INTRODUCTION

In North America, light-duty vehicles are subject to frontal crash tests in the regulatory environment and as part of consumer-based safety rating schemes. Historically, these tests have been based on full-width and moderate-overlap (40%) vehicle-to-barrier impacts. Improvements to occupant restraint technologies, notably seat-belt tensioning and load limiting systems, together with advanced airbags, have proven very effective in mitigating occupant injury in these crash modes. Recently, however, concern has been raised over the contribution of narrower frontal impacts, involving primarily the vehicle corners, to the incidence of both fatalities and serious injuries, as a result of the potential for increased occupant compartment intrusion and performance limitations of current restraint systems.

This has prompted both the Insurance Institute of Highway Safety (IIHS) and the National Highway Traffic Safety Administration (NHTSA) to investigate additional test configurations for frontal impacts. IIHS has implemented a 25% offset, frontal crash test, referred to as a Small Overlap Impact (SOI), as part of their safety rating scheme. In this test, the front rail of the vehicle is not engaged [1]. Meanwhile, NHTSA has embarked on a research project that would lead them to adopt a somewhat different small overlap test configuration. In a study of real-world fatal crashes, where belted occupants were further protected by air bag systems, structural interactions between the striking and the struck vehicles were judged to be inadequate [2]. NHTSA's proposed countermeasure is most likely to be an oblique-frontal test involving a small overlap between the front-end of a vehicle and a movable deformable barrier (MDB) [3].

The present study reviews data from a subset of real-world crashes captured as part of the National Automotive Sampling System (NASS)/Crashworthiness Data System (CDS) that approximate the conditions of crash tests undertaken by NHTSA. Crash pulse profiles and airbag firing times obtained from vehicle EDR's for both field collisions and crash tests are used in the evaluations. Opportunities to improve the field relevance of crash test configurations that have been developed to evaluate the levels of vehicle safety in frontal corner impacts are discussed.

METHODOLOGY

Drawing on data documented in NASS/CDS for calendar years 1999 to 2012, the present study examines the characteristics of existing and proposed corner crash test configurations, and the nature of real-world collisions that approximate the test environments. The analyses seek to quantify the nature of the frontal corner impact problem in the context of the residual frontal problem which produce serious or fatal injury in the 2000-on model year passenger vehicle fleet with emphasis on collisions which continue to result in serious-to-fatal head or chest injury.

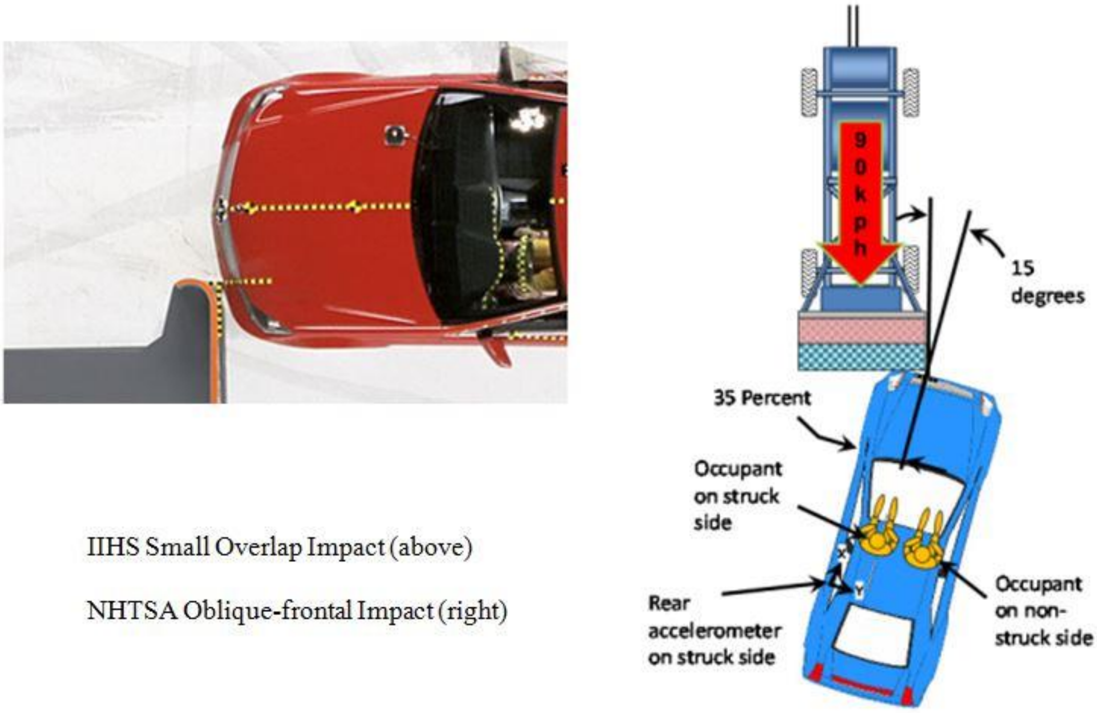

Figure 1. Small-overlap crash tests

Particular emphasis is placed on a comparison of crash pulses and airbag firing times for the subject vehicles based on the data obtained in field collisions and crash tests from on-board event data recorders for vehicles that were so equipped. The EDR data are drawn from an inventory of more than 7300 EDR reports documented as part of NASS and a further 255 reports downloaded from staged laboratory tests performed by NHTSA.

Event Data Recorders

The introduction of frontal airbags into North American vehicles, with their reliance on electronic sensors and microprocessor-based control systems, also saw the development of in-vehicle crash recorders. Early versions of these EDR's, notably those produced by General Motors, were limited to recording the vehicle's change in longitudinal velocity (delta-V) in 10 ms increments over either a 150 or 300 ms time interval. In addition, the EDR could capture certain occupant-related data such as seat belt use, and a time history (five, one-second snapshots) of pre-crash vehicle parameters such as travel speed, engine RPM, brake and throttle application [4)].

Over time, as more sophisticated occupant protection systems and collision avoidance technologies have been introduced into vehicles, the functionality of EDR's has been expanded to capture a wider range of parameters at a greater level of detail. In particular, current EDR's may include both longitudinal and lateral vehicle accelerations and/or delta-V's in 1 ms increments over a 250 ms time interval. [5] Additional data elements that may be recorded include the firing times for seat belt pre-tensioners dual-stage frontal air bags, head curtains, and knee bolsters. Pre-crash time histories of vehicle speed, engine speed (RPM), accelerator pedal and engine throttle position, and brake application may be recorded at 0.1 or 0.2 s intervals over a 5 s period. Data may also be recorded on the involvement of collision avoidance systems such as anti-lock brakes (ABS) and electronic stability control (ESC).

Prior research has shown that the crash-pulse data captured by EDR's installed in various vehicle makes and models that were subject to several types of staged collisions are accurate to within a few percent [5-7]. The delta-V obtained from the EDR is generally under-reported since the initial portion of the crash pulse is not processed due to the algorithm only being enabled after a preset vehicle acceleration threshold is reached. In the present paper, extensive use has been made of crash-pulse data obtained from vehicles that were equipped with EDR's and were either subject to crash tests or involved in real-world collisions.

RESULTS

Residual Belted Driver Safety Problem in Frontal Crashes

To gain insights on the nature of the residual frontal safety problem, the NASS/CDS database for calendar years 1999-2010 was examined to quantify the characteristics of frontal crashes which resulted in Maximum Abbreviated Injury Scale (MAIS) 3 or greater injury among belted drivers in vehicles fitted with frontal airbag systems. The analysis was confined to 2000 model year or newer vehicles involved in planar frontal collisions, with a Collision Deformation Classification (CDC) general area of damage of "F", and a direction of force assignment of 11 to 01 o'clock for the primary impact. Collisions involving secondary impact were permitted, but only if the damage extent associated with any non-frontal impact was confined to a CDC extent value of either 1 or 2. To be included in the sample, the age, gender and MAIS of the driver had to be known. Drawing on the injury data provided for vehicle occupants, drivers who sustained at least one head/face or chest injury of AIS 3 or greater were also identified.

	Weighted			**Raw**		
GAD1/SHL1 GROUP	**Exposed**	**MAIS>=3**	**AIS Head/Face and/or Chest>=3**	**Exposed**	**MAIS>=3**	**AIS Head/Face and/or Chest>=3**
FD	49.3%	**47.41%**	44.4%	48.9%	**51.5%**	51.0%
FY	12.5%	**21.71%**	25.3%	14.3%	**17.6%**	18.2%
FL	12.4%	**15.20%**	9.2%	12.6%	**14.7%**	15.9%
FR	12.5%	7.49%	12.0%	10.2%	5.4%	5.2%
FZ	12.2%	6.75%	7.5%	12.4%	7.6%	6.6%
FC	1.1%	1.45%	1.7%	1.6%	3.2%	3.2%
All	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Population Counts	**3,219,979**	**57,924**	**26,217**	**8,664**	**746**	**347**

Table 1. Composition of Driver Sample by General Damage Group

The driver sample consisted of 8,664 individuals representing 3,219,979 drivers when the NASS weights are applied. The subset of drivers with MAIS 3 or greater injury consisted of 746 individuals representing 57,924 drivers when weighted. Of the MAIS 3 or greater driver subset, 347 (26,217 when weighted) were determined to have sustained at least one AIS 3 or greater injury to either the head/face region and/or the chest region. The unweighted and weighted distributions of the exposed and injured driver populations, as a function of damage grouping based on the 3rd and 4th characters of the primary CDC, are depicted in Table 1. Here we can see that the "FD" (distributed) category accounted for the highest percentage of drivers injured at the AIS 3 or greater level. This was followed by the “FY” category (between 1/3 to 2/3 overlap of the front on the left side), and the “FL” category (less than 1/3 overlap of the front on the left side). This ranking order can be seen to apply for both the unweighted and weighted percentages. In the case of the injured driver subsets, the representation of “far” side impacts, “FZ” and “FR”, is low except for the weighted “FR” estimate (12%) among drivers who sustained at least one AIS 3 or greater head/face or chest injury. The weighted estimate is at odds with the unweighted percentage (5.2%). Examination of the NASS weights associated with this subset of drivers revealed that two of the crashes had very elevated weights accounting for 80% of the weighted “FR” estimate.

The driver subset was partitioned into four areas of damage/direction of force groupings. The first of these consisted of “FL” impacts with a principal direction of force (PDOF) of 11 or 12 o’clock. The second grouping consisted of “FY” impacts with a PDOF of 11 or 12 o’clock. These assignments were done to render the groupings more consistent with crash testing protocols addressing SOI and oblique frontal impacts. The third grouping consisted of “FD” with a PDOF of 11 or 12 or 01 o’clock. The remaining area of damage and direction of force pairings were consolidated in the “Other” category. From the distributions presented in Table 2, it can be observed that, for all four defined groupings, 12 o’clock direction of force crashes predominate.

		Weighted			Raw		
GAD1/SHL1 DOF GROUP	**PDOF**	**Exposed**	**MAIS>=3**	**AIS Head/Face and/or Chest >=3**	**Exposed**	**MAIS>=3**	**AIS Head/Face and/or Chest >=3**
FL, PDOF= 11, 12	11 O' Clock	1.9%	1.09%	0.6%	2.7%	2.3%	2.3%
	12 O' Clock	**10.2%**	**14.11%**	**8.6%**	**9.7%**	**12.5%**	**13.5%**
FY, PDOF= 11, 12	11 O' Clock	3.4%	1.62%	2.1%	3.6%	2.4%	2.6%
	12 O' Clock	**8.2%**	**19.08%**	**21.8%**	**9.6%**	**13.9%**	**13.8%**
FD, PDOF= 11, 12, 01	01 O' Clock	5.5%	5.34%	2.4%	8.4%	6.6%	4.0%
	11 O' Clock	7.2%	5.26%	2.8%	9.1%	6.3%	4.9%
	12 O' Clock	**36.6%**	**36.80%**	**39.2%**	**31.4%**	**38.6%**	**42.1%**
OTHER	01 O' Clock	6.8%	4.95%	8.6%	7.1%	3.8%	4.9%
	11 O' Clock	1.5%	0.71%	0.1%	1.2%	0.4%	0.3%
	12 O' Clock	**18.8%**	**11.03%**	**13.8%**	**17.2%**	**13.3%**	**11.5%**
All		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Population Counts		**3,219,979**	**57,924**	**26,217**	**8,664**	**746**	**347**

Table 2. Composition of Driver Sample by Direction of Force

The above driver subsets were further partitioned by CDC damage extent intervals. Three intervals, CDC damage extents 1-2, damage extents 3-6, and damage extents 7-9, were defined. The middle damage extent interval, 3-6, corresponds closely with the range of CDC damage assignments typically associated with existing frontal regulatory tests, as well as the CDC extent assignments observed in SOI and oblique crash tests. From the results presented in Table 3, it can be seen that, in the case of “FD” and “FY” crashes, this CDC extent interval accounts for the majority of drivers with AIS 3 or greater injury.

		Weighted			Raw		
GAD1/SHL1 DOF GROUP	**CDC Extents**	**Exposed**	**MAIS>=3**	**AIS Head/Face and/or Chest >=3**	**Exposed**	**MAIS>=3**	**AIS Head/Face and/or Chest >=3**
FL, PDOF= 11, 12	1 to 2	5.4%	3.50%	2.0%	4.8%	2.4%	2.6%
	3 to 6	4.8%	**6.58%**	**3.9%**	5.4%	**6.3%**	6.1%
	7 to 9	1.9%	5.12%	3.2%	2.3%	6.0%	**7.2%**
FY, PDOF= 11, 12	1 to 2	10.0%	7.05%	11.7%	9.8%	3.4%	2.0%
	3 to 6	1.4%	**13.59%**	**12.1%**	3.3%	**12.6%**	**13.5%**
	7 to 9	0.1%	0.07%	0.1%	0.1%	0.4%	0.9%
FD, PDOF= 11, 12, 01	1 to 2	45.1%	14.70%	10.9%	40.1%	16.6%	11.5%
	3 to 6	4.0%	**31.05%**	**31.7%**	8.2%	**31.6%**	**34.6%**
	7 to 9	0.1%	1.65%	1.7%	0.6%	3.2%	4.9%
OTHER	1 to 2	17.8%	6.93%	9.1%	16.6%	5.5%	4.0%
	3 to 6	7.2%	**8.21%**	**10.7%**	7.3%	**10.1%**	**10.7%**
	7 to 9	2.1%	1.55%	2.7%	1.5%	1.9%	2.0%
All		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Population Counts		**3,219,979**	**57,924**	**26,217**	**8,664**	**746**	**347**

Table 3. Composition of Driver Sample by Damage Extent

EDR Field Data

Currently EDR data, in the form of individual EDR reports, are available for over 7,300 vehicles represented in NASS. These reports were secured and stored on a local server so as to allow direct access to the reports via links embedded in Excel databases of the NASS cases of interest. Although data reporting formats vary widely, data elements such as the maximum longitudinal velocity change and frontal airbag fire times are common to almost all of the EDR reports. These data are summarized in Figures 2 and 3 for EDR field cases drawn for NASS calendar years 2001-2010 and in Figures 4 and 5, for EDR field cases drawn for NASS calendar years 2011-2012. Note that whereas the 2001-2010 data reflect vehicle pairings to belted drivers, the vehicle pairings in the 2011-2012 data are based solely on vehicle damage. The 2011-2012 data analysis was undertaken to capture maximum lateral velocity change data. Such data are typically only available for newer vehicle models fitted with side airbag protection. The lateral velocity change data obtained from the 2011-2012 NASS database are summarized in Figure 6.

EDR Crash Test Data

EDR reports are also available for many of the crash tests conducted by NHTSA [8]. As in the case of the NASS EDR reports, the crash test EDR reports were secured and stored on a local server so they too could be accessed via Excel databases. To date, a total of 255 NHTSA crash test EDR reports have been obtained. The EDR vehicle velocity change and airbag fire time data for the subset of crashes identified as either “SOI” or “OBL” in NHTSA’s vehicle database are summarized in Figures 7-9. These are accompanied by vehicle velocity change and airbag fire time data in frontal NCAP tests performed in 2012 and for which EDR data were available.

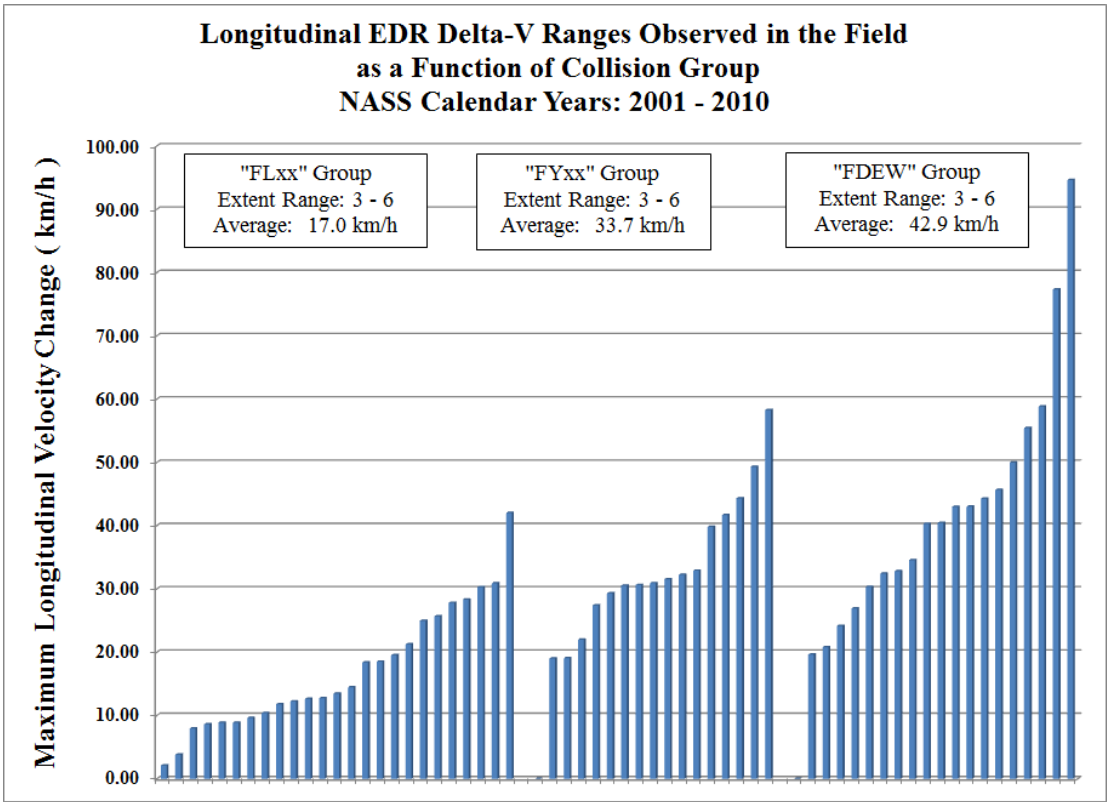

Figure 2. Longitudinal Delta-V in 2001-2010 NASS Cases

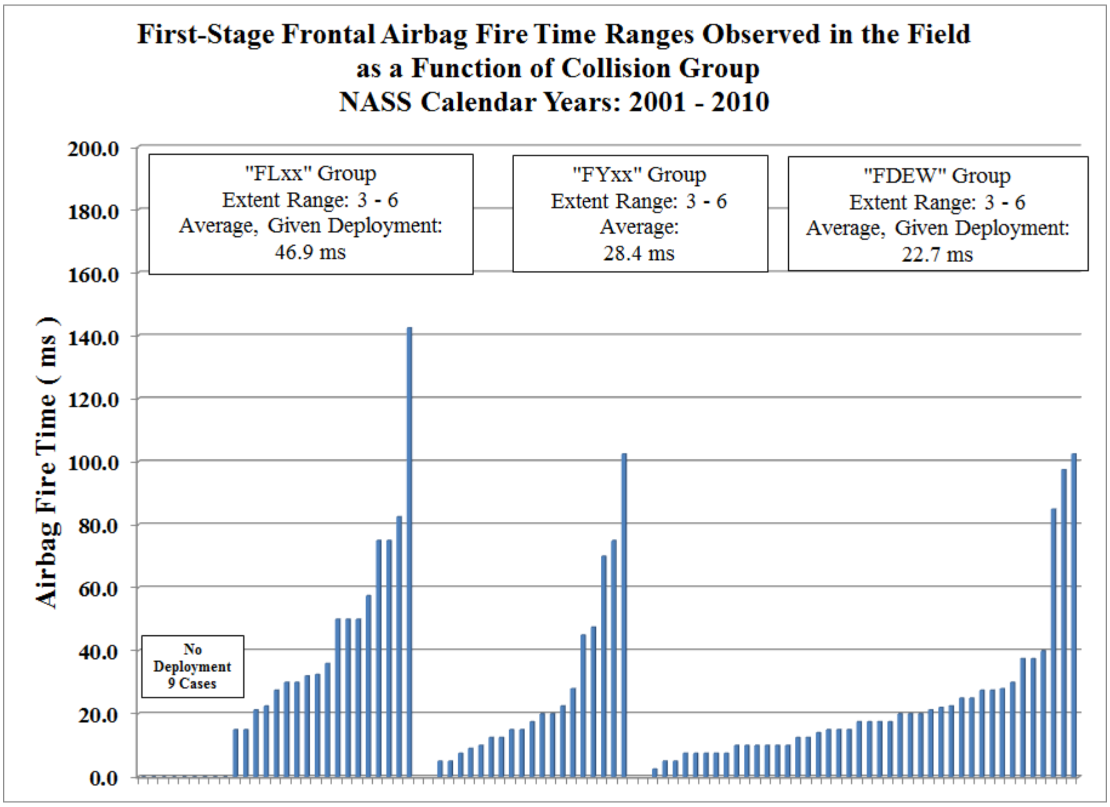

Figure 3. Frontal Airbag Fire Times in 2001-2010 NASS Cases

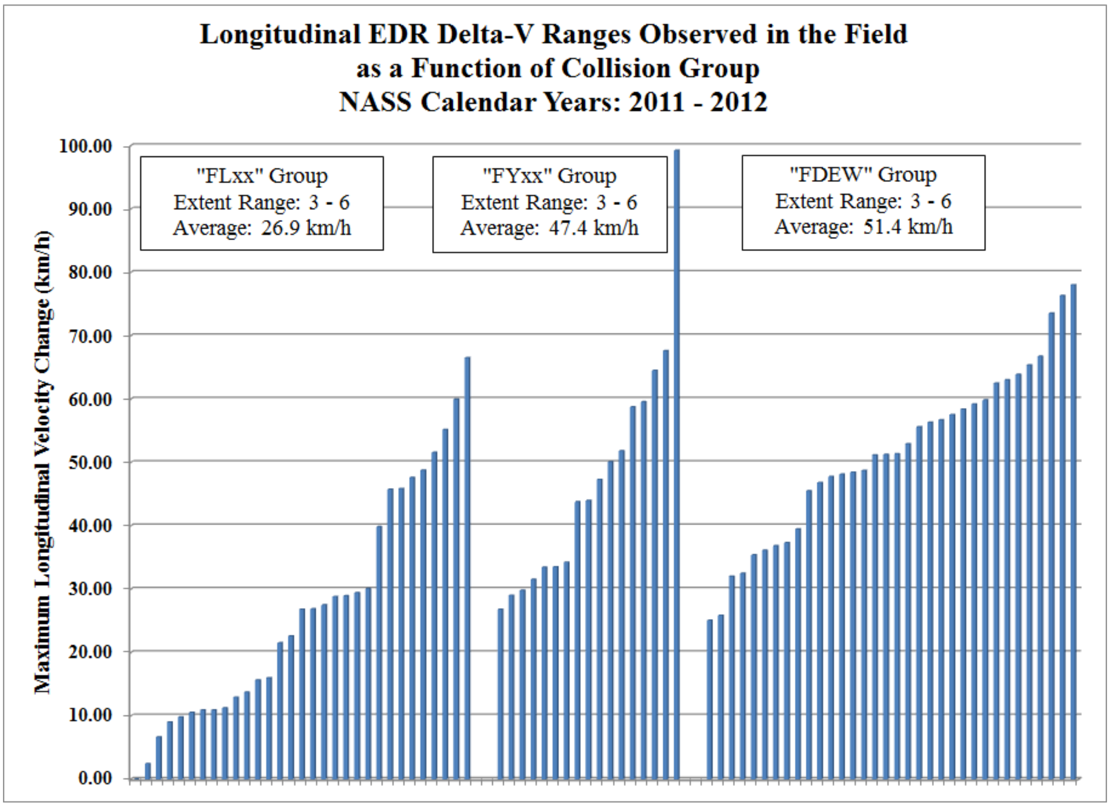

Figure 4. Longitudinal Delta-V in 2011-2012 NASS Cases

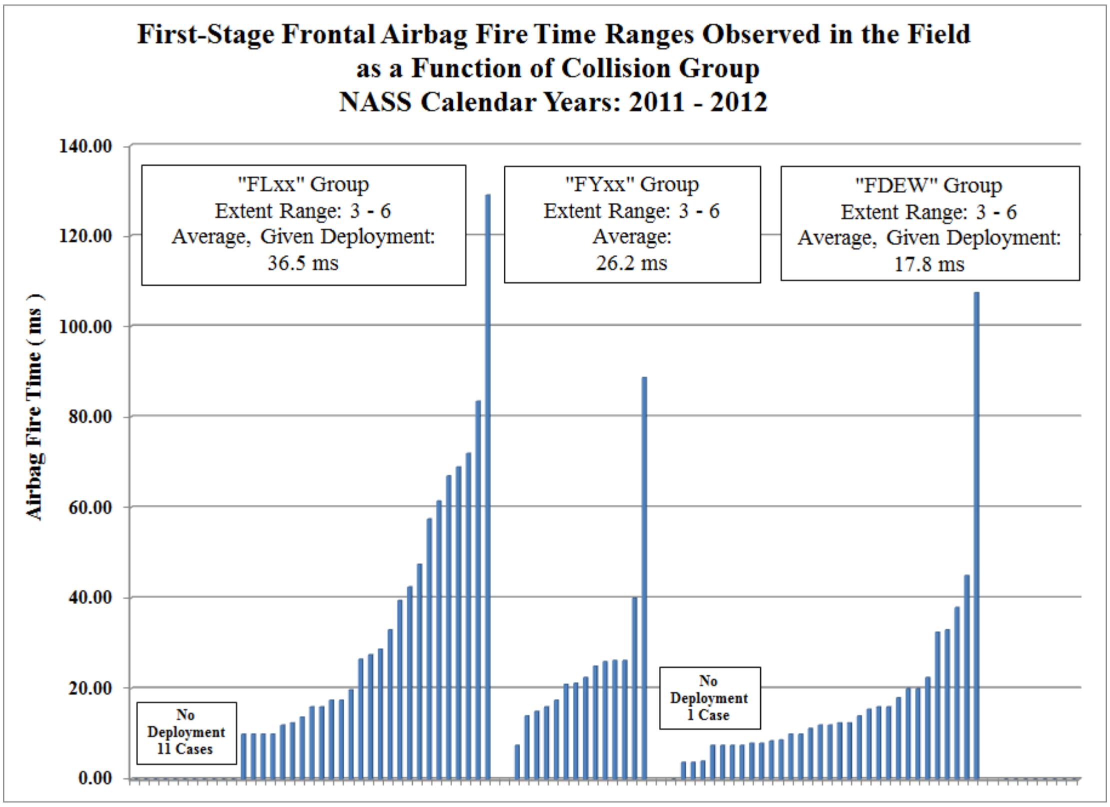

Figure 5. Frontal Airbag Fire Times in 2011-2012 NASS Cases

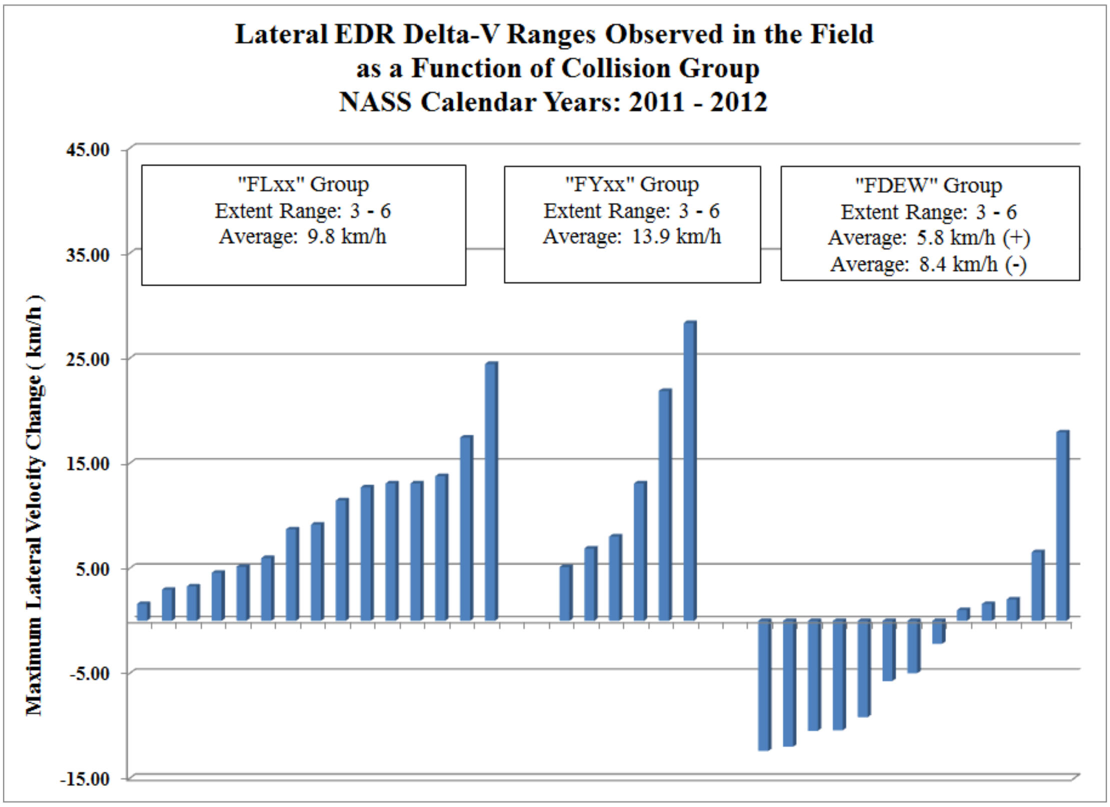

Figure 6. Lateral Delta-V in 2011-2012 NASS Cases

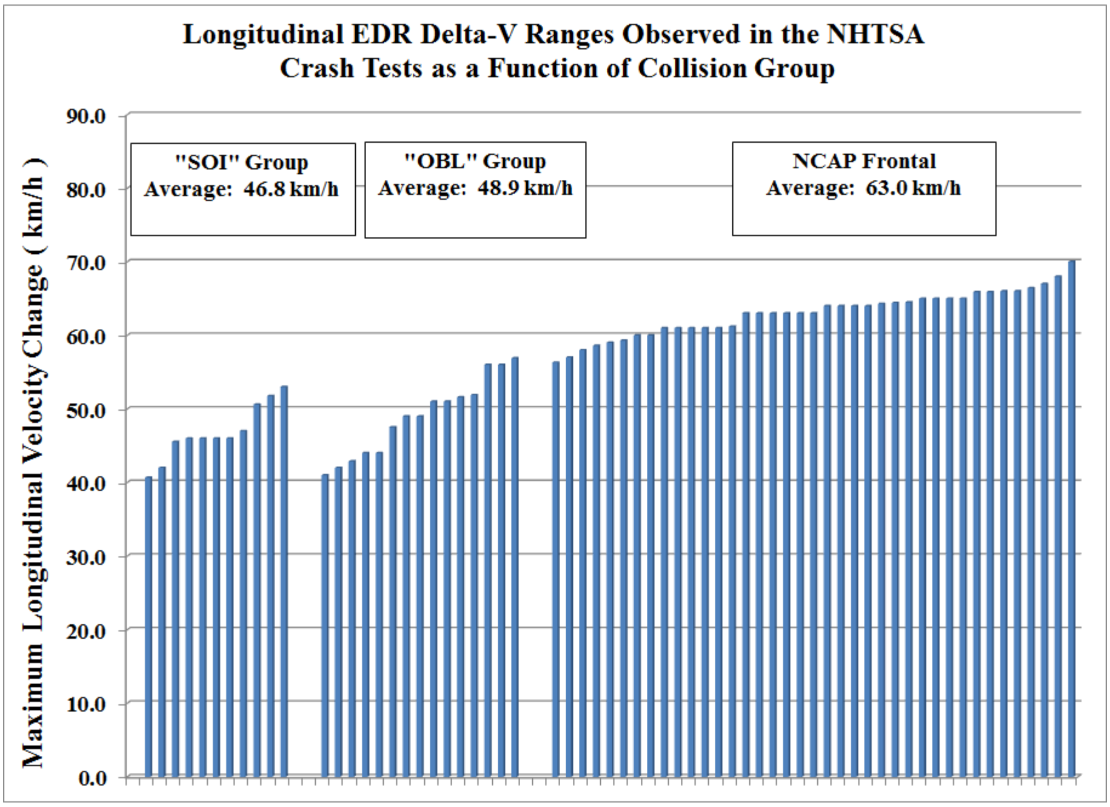

Figure 7. Longitudinal Delta-V in NHTSA Crash Tests

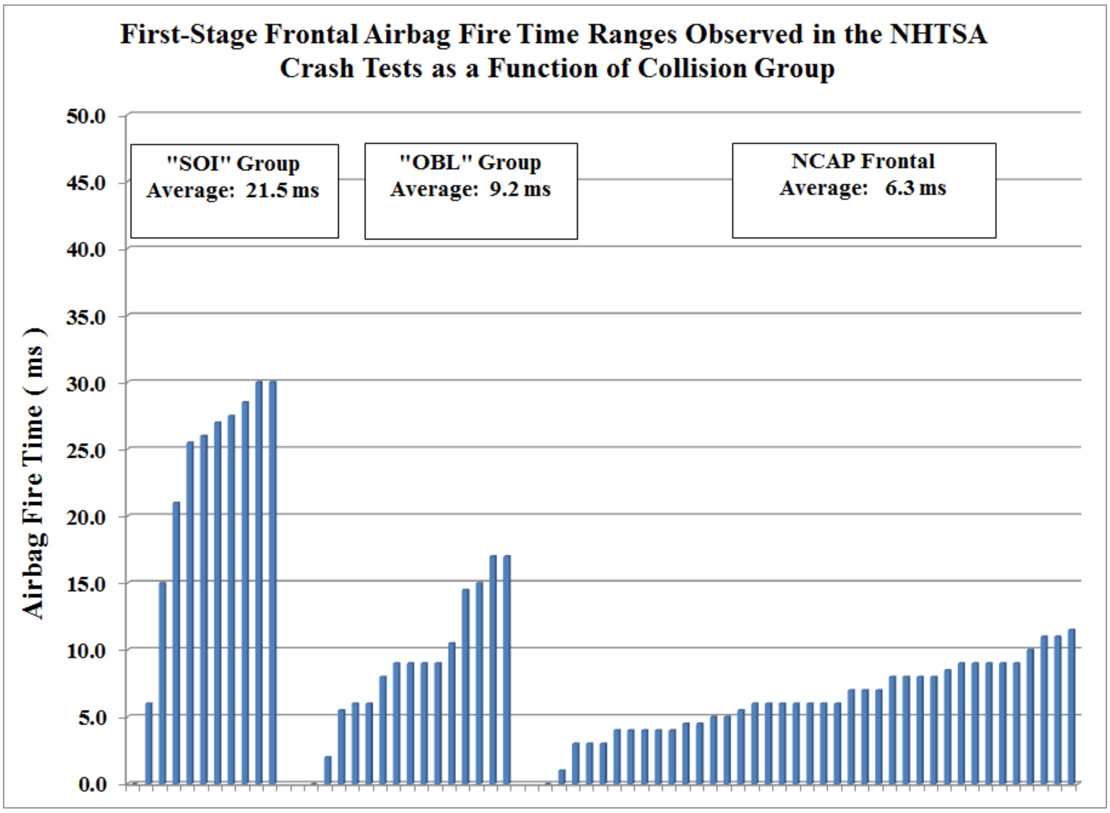

Figure 8. Frontal Airbag Fire Times in NHTSA Crash Tests

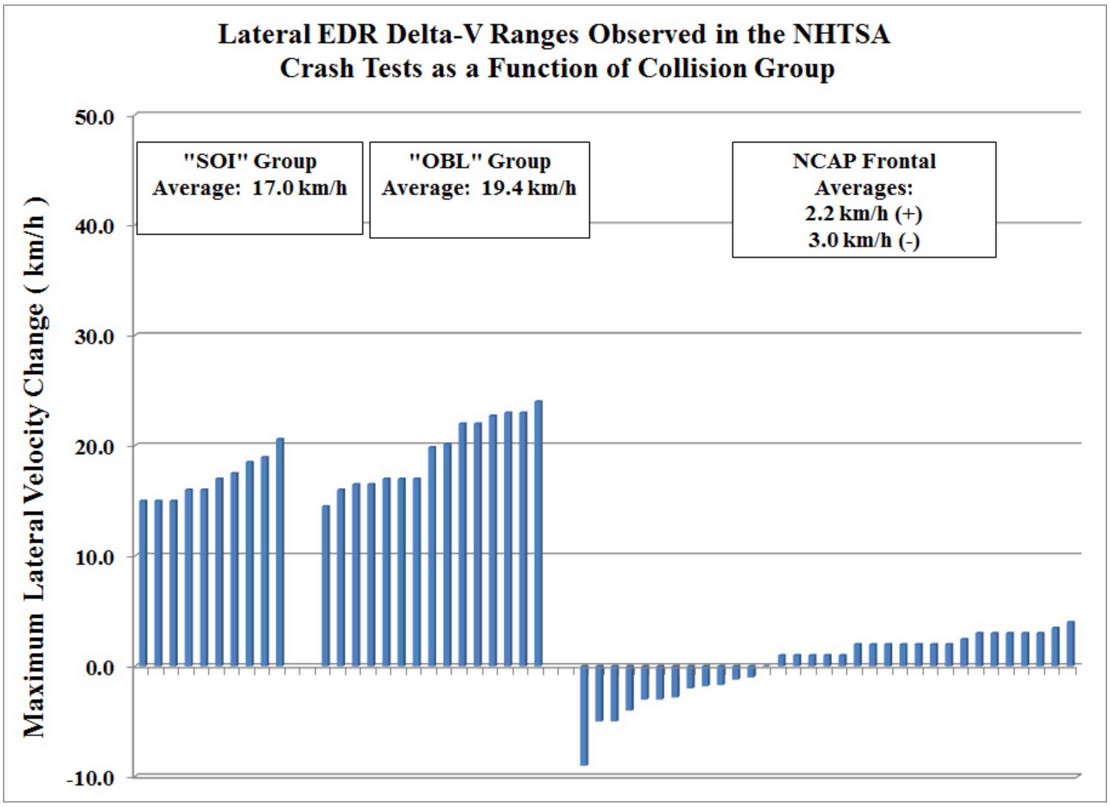

Figure 9. Lateral Delta-V in NHTSA Crash Tests

When we compare the crash test EDR data with the field EDR data, we can see that the airbag fire times and lateral velocity changes recorded in staged crash tests differ greatly from those recorded in the field. Note that the airbag “fire times” denote the time between when the collision sensing algorithm is “woken up” and the time when the command is issued to initiate deployment of the airbag. From the data presented in Figure 8, it can be seen these decisions are made earlier in crash tests than in the NASS cases for which EDR data are available. What is particularly striking is the amount of overlap between the firing times observed in “OBL” tests and those observed frontal NCAP tests. Recorded airbag fire times of the order of 10 milliseconds or less are infrequently observed in field collisions in the FLxx and FYxx groups. As shown in Figure 3, in only 5 out of 37 cases in these groups, the recorded airbag fire times are less than or equal to 10 ms. Similarly, Figure 5 shows that 5 out of 40 cases in the FLxx and FYxx groups have recorded airbag firing times of less than or equal to 10 ms. Based on limited EDR data, the EDR lateral velocity changes recorded in NHTSA’s SOI and OBL crash tests (Figure 9) appear to be more elevated than those recorded in the field (Figure 6). Further analysis on these issues will be conducted as more EDR data become available in NASS.

DISCUSSION AND CONCLUSIONS

Historically, testing protocols employed in regulations have attempted to advance safety by presenting collision environments which are sufficiently severe to promote the fitment of new safety technologies or structural changes to the design of the vehicle. With the advent of technologies such as airbags, the operation of which is being influenced by the crash environment it is experiencing, it becomes important to ensure that testing protocols are field relevant in terms of the collision environment they impose on the vehicle.

The analyses presented in this paper are somewhat preliminary in nature, being limited by the number of cases involving EDR’s, and the lack of consistency in the data obtained from these devices, in both staged crashes and real-world collisions. Nevertheless, the data that are available are indicative of the power of this relatively new tool for safety researchers.

In particular, EDR’s can play a vital role in the process of developing improved test methods. Not only do they afford a means of quantifying the nature of the residual safety problem, but they can also assist in developing and validating testing protocols. Implementing testing protocols that are field relevant provides the most efficient means of ensuring that safety systems and vehicle structures are optimized in terms of their performance.

Relative to current efforts to develop testing protocols to assess frontal corner safety using an MDB, the initial review of available field EDR data suggests that these protocols would benefit from changes in the shape, stiffness and mass of the MDB, in addition to a reduction of the impact angle. These changes would promote airbag firing times and lateral vehicle responses that are more consistent with those observed in the field.

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