Investigating a Relationship Between Standardised Crash Classification and Occupant Kinematics in Real-World Frontal Crashes

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Abstract With increasing interest in mitigating occupant injuries in non-collinear crashes, it is necessary to develop a clear understanding of the scope of the problem in real-world crashes. Observations from experimental and field data studies indicate that oblique occupant motion can affect restraint interaction, and the direction of force of the impact alone may not sufficiently describe occupant motion. The objective of this study is to define a relationship between coded, vehicle-based crash deformation descriptors and the kinematics of belt-restrained occupants in frontal crashes. Cases involving seriously-injured, restrained first-row occupants in frontal crashes were selected from two US field data collection programmes: the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS); and the Crash Injury Research and Engineering Network (CIREN). Crash analysis experts examined available case evidence to assess occupant kinematics and restraint interaction. A total of 230 case occupants were assessed – 187 drivers and 43 right front passengers – in crashes with varying degrees of front overlap and directions of force. The findings suggest that occupant kinematics may not be sufficiently described by crash damage measures, and that oblique and collinear occupant trajectories appear to occur in crashes with similar damage descriptors.

Keywords Case review, frontal crash, kinematics, oblique crash, target population.

I. Introduction

In an attempt to continue advancing frontal impact crashworthiness and occupant protection, the National Highway Traffic Safety Administration (NHTSA) and the Insurance Institute for Highway Safety (IIHS) commenced independent studies to identify areas where further improvements could be made to reduce fatalities and injuries to restrained motor vehicle occupants [1-2]. While the specific methodologies of those two studies were not exactly the same, the generalised approach was to examine real-world frontal crashes, in which restrained occupants sustained serious injuries or were killed, and identify causative factors. Both studies queried the National Automotive Sampling System-Crashworthiness Data System for qualifying cases occurring in the United States and performed manual reviews of coded variables, scene and vehicle photographs, and other available evidence. Conclusions from those studies led both organisations to pursue new frontal crash test programmes to address shortcomings in frontal crash safety for small overlap and oblique frontal impacts.

In response to their findings, the IIHS developed a small overlap frontal crash procedure in which the vehicle engages a rigid, flat barrier with 25% of its frontal width in a collinear manner [3]. This configuration was found to reproduce characteristics of small overlap crashes occurring in the real-world, including little or no engagement of the main frontal load paths, occupant compartment intrusions, and lateral occupant motion consistent with outboard contact points and injury sources. Since the introduction of this new test procedure in 2012, vehicle manufacturers have responded with structural improvements to reduce occupant compartment intrusion and better manage crash energy [4]. Despite these structural improvements, some vehicles were noted to still require restraint optimisation in order to improve occupant protection. Lateral motion of the driver Hybrid III 50th percentile male anthropomorphic test device (ATD) affected interaction with the steering wheel airbag, and the head sometimes moved toward the edges of the bag or into the space between the steering wheel airbag and door or side curtain airbag.

As NHTSA began to conduct research into test procedures to address the subset of frontal impacts identified in its 2009 study [1], vehicle-to-vehicle crash tests were performed to provide a baseline for small overlap and moderate overlap conditions with an obliquely-oriented moving deformable barrier (MDB) [5]. One of the primary objectives of NHTSA's research efforts was to produce occupant kinematics similar to those thought to

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occur in the field crashes, where the occupant moves outboard and experiences an off-centre, and potentially ineffective, engagement with the airbag restraint. The MDB test configurations investigated by Saunders *et al.* in [5] demonstrated this behaviour with the THOR 50th percentile male ATD. As the procedure development evolved, NHTSA decided to proceed with a test configuration where an MDB impacts a stationary subject vehicle at a speed of 90 km/h, with a 15° angle between the longitudinal axes, and overlapping 35% of the subject vehicle's frontal width [6]. This paper also demonstrated results from oblique impacts to the left front and right front corners of the subject vehicle, and includes responses of the THOR ATD seated in both outboard positions of the first row. The seating position closest to the impacted corner is considered the struck side and the occupant farthest from the impacted corner is considered to be on the non-struck side. From the beginning, NHTSA has been interested in developing a test procedure that produces occupant responses similar to those observed in field data studies – characterised by forward and outboard motion (or forward and inboard for an occupant seated on the non-struck side) with suboptimal engagement of the restraints and vehicle interior.

While the field data studies that led to the inception of the IIHS small overlap and NHTSA oblique programmes generally identified forward and outboard occupant kinematics as an important factor in the targeted crash types [1-2], those studies did not include the type of detailed injury analysis necessary to establish occupant response targets for laboratory crashes. Such studies had been conducted to some extent, with many works suggesting unique injury patterns when compared to collinear crashes with more engagement of the vehicle front [7-9]. An angled trajectory of the occupant, changing principal directions of force, and inadequate coverage by inflatable restraints were generally found to be the factors leading to different injury distributions under the oblique or small overlap condition compared to more fully-distributed collinear frontal impacts. During the earlier phases of NHTSA's oblique research programme, Rudd *et al*. [10] examined driver injury outcomes in a subset of left-sided, small and moderate overlap frontal crashes in order to identify injury trends by crash parameters. The injury distributions observed in that in-depth case study of NASS-CDS and CIREN cases have served as a guide for assessing the applicability of the test procedure, as measured with the THOR ATD, to the real-world occupant experience. Further testing, published by NHTSA in [11-12], showed that the oblique MDB laboratory procedure produces repeatable occupant response, with injury risk predictions generally in-line with the observations from the field data studies.

Throughout the development of the NHTSA oblique crash test programme, NHTSA has sought to identify a relevant target population based more on occupant response than on specific vehicle damage characteristics. Oblique occupant kinematics can occur in different types of frontal crash, and the impetus for the NHTSA oblique crash test programme is the range of frontal impacts where occupant response is characterised by trajectories with lateral components, off-centre and incomplete loading of the frontal airbags, and contact to interior structures that do not offer adequate levels of energy absorption.

The approach taken to identify the relevant oblique frontal target population (OFTP) for the oblique frontal crash test programme has been described in [13] and generally divides frontal crashes into groups based on the characteristics of the direct front damage and the principal direction of force (PDOF) as determined by the field crash investigator. In NASS-CDS and CIREN, PDOF is assigned primarily based on estimation from sheet metal deformation, with consideration of crash scene and vehicle interior evidence as well. The overall subset of frontal crashes in the OFTP approach was expanded from prior efforts to include some crashes coded as side impacts based on the Collision Deformation Classification (CDC) scheme or crush profile [14-15]. While CDC rules require their classification as a side impact based on the nature of the damage, the shallow PDOF angle in some cases leads to more of a frontally-oriented occupant response, which appears to be relevant to the problem of oblique frontal crash protection.

The OFTP approach apportions frontal crashes to either a collinear, oblique, or other crash type group, as shown in Table I, based on coded vehicle damage parameters in the NASS-CDS database [13]. Observations from field data and laboratory crash tests led to a decision to categorize crashes with non-zero PDOF values to the oblique crash categories for all types of frontal damage due to the potential for lateral occupant motion in response to the non-zero PDOF. Findings from studies on small overlap front impacts suggest that even with collinear directions of force, subsequent vehicle rotation and lateral translation lead to oblique occupant motion relative to the vehicle interior, so the 0° small overlap crashes were assigned to an oblique crash category associated with the side struck [3][9]. Based on the 2011 study by Rudd *et al*. [10], in which reviewers assessed whether the crash was oblique, approximately 20% of the 0° PDOF moderate overlap crashes were considered oblique by the reviewers. The eccentric loading relative to the vehicle centre of gravity and potential for subsequent vehicle rotation, even with a collinear initial impact, led to the decision to split these crashes into both collinear and oblique crash types (the 20%/80% split was applied for analyses of weighted data).

TABLE I
NHTSA FRONTAL CRASH CLASSIFICATION FOR OFTP [13]

Damage Category	PDOF	Crash Type in OFTP
Left small overlap	330°–350° 0°	Left oblique Left oblique
Right small overlap	0° 10°–30°	Right oblique Right oblique
Left moderate overlap	330°–350° 0°	Left oblique Split: 80% collinear, 20% left oblique
Right moderate overlap	0° 10°–30°	Split: 80% collinear, 20% right oblique Right oblique
Full overlap	330°–350° 0° 10°–30°	Left oblique Collinear Right oblique
Other, narrow, variant, etc.	-	Other

The objective of this study was to conduct an examination of recent real-world frontal crashes to identify a relationship between the kinematics of belt-restrained occupants and conventional crash damage measures. The outcome of the study can be used to assess NHTSA's approach to identifying the target population of frontal crashes resulting in oblique versus collinear occupant kinematics.

II. METHODS

This study involved an in-depth review of real-world frontal crashes occurring in the United States in order to characterise occupant kinematics using evidence available in the NHTSA NASS-CDS and CIREN databases. Four NHTSA researchers experienced in collection and analysis of field crash data reviewed eligible cases and completed a standardised survey form to gather study-specific findings. The reviewer-determined findings were analysed in conjunction with the coded variables to explore the relationship between vehicle damage coding and occupant response.

Data Selection

A prior study [10] included NASS-CDS and CIREN cases through the 2009 calendar year, so this study focused on crashes occurring from 2010 onward. NASS-CDS cases were queried from the publicly-accessible data tables for calendar years 2010–2013 [16]. The CIREN cases included in this study were deemed to be suitable for internal research at the time of study commencement, but not all were published and available via the CIREN Internet site [17]. The vehicle and occupant inclusion criteria applied for this study were:

- 2006 model year and newer passenger vehicles (cars, vans, utility vehicles, light trucks);
- belt-restrained drivers and right front passengers with frontal airbag deployment;
- occupant age 13 years and older;
- AIS3+ injury to the head, neck, thorax, or knee/thigh/hip (KTH) region of lower extremity using the 2005/2008 revision –
    - fatalities were not excluded, but were required to have coded injuries meeting the criteria,
    - brainstem, vertebral artery, and carotid artery codes are considered neck injuries for this study,
    - cervical spine codes are considered neck injuries for this study;
- Collision Deformation Classification codes for the most significant crash event were:

  - Direction of force (DOF1) of 11, 12, or 1 o'clock (the DOF component of the CDC is in 30° increments while the PDOF is in 10° increments),
  - General area of damage (GAD1) of front (F) with any specific horizontal location (SHL1),
  - GAD1 of left (L) or right (R) with SHL1 of side-front (F) or side-front+side-centre (Y);
- narrow-overlap centre impacts and rollovers were excluded.

Crashes were further characterised based on a method first described in [14], where the extent of front overlap was determined to be small, moderate, or full, and then categorised based on the principal direction of force (PDOF) as either left-oriented (320°–350°), right-oriented (10°–40°), or collinear (0°). Note that this study included crashes with PDOF angles of 320° and 40° whereas the efforts described for the OFTP in [13] did not.

Field investigators for the NASS-CDS and CIREN programme adhere to the same protocols for coding vehicle damage, intrusions, and contacts. While both programmes utilise the same AIS coding version to identify injuries, CIREN codes injury causation differently than NASS-CDS. CIREN teams have the ability to code multiple involved physical components (IPCs), depending on the available evidence and required injury mechanism [18], while NASS-CDS is limited to one injury "source" element. For this study, only the first IPC, which is considered the most likely, from the CIREN injury causation coding was included for the injury source analysis.

Statistical weights were not applied to any portion of this analysis. First, CIREN is a convenience sample, and does not assign weights, so a combined dataset should also be treated as a convenience sample. Secondly, the intent of this study was to assess occupant kinematic response in the context of reported vehicle damage characteristics; the study was not intended to provide representative injury counts or risk estimates.

Reviewer Survey Form

In order to standardise the in-depth case review analysis, reviewers were given a survey form consisting of questions on crash characteristics, restraints, contacts/intrusions, and occupant factors. Guidelines and examples were provided to assist the reviewers in responding to the survey and to maximise inter-reviewer repeatability of the responses. As the primary objective of this study was to establish a relationship between occupant kinematics and vehicle damage measures, the overall aim of the survey was to provide a structured framework for reviewing case evidence to determine the nature of the occupant's motion in the frontal crash event. The Rudd *et al*. study in 2011 [10] included similar questions, but the specific task of identifying occupant kinematics was not a clear objective of that work, so the survey was changed substantially for this study. The survey contained many questions with responses based on the reviewer's judgement (e.g. which type of laboratory crash test produces damage most similar to this crash?) and others that were evidence-based (e.g. did a pretensioner actuate?). The responses to be included in this analysis are crash type (CT), overlap (OL), rail engagement (RE), and occupant kinematic descriptor (KD), as described in Table II. The characterisation of the occupant's kinematics, KD, was the final question of the survey and was intended to capture all of the available evidence to determine how the occupant moved relative to the vehicle interior during the frontal impact event. Reviewers were asked to consider contact evidence and injury patterns for all occupants of the case vehicle to reach their conclusions about the case subject's kinematics.

Case Review

The total number of cases was divided evenly among the reviewers, and a subset of cases was assigned to all four reviewers to check for consistency among the reviewers [19]. Intra-class correlations (ICC) were calculated for this subset of cases using methods described in [20] for a fixed set of raters. A two-way mixed, consistency, average-measures ICC was calculated for four variables to assess the extent to which reviewers reached consistent conclusions about the crashes. Assessment of agreement was judged according to a set of guidelines by Cicchetti [21]. Calculations were performed using SAS 9.3 and a macro written by Hamer [22].

Following the case review, the survey results were combined with the variables queried from the databases. Cases from CIREN and NASS-CDS were combined into a single dataset for analysis. For the cases reviewed by all four reviewers, the mode of the reviewer responses was used for the collective analysis.

TABLE II
REVIEWER-DETERMINED VARIABLE DEFINITIONS

Variable	Definition	Values
Crash type (CT)	Extent of direct damage across the front of the vehicle, namely the extent of compression of longitudinal rails	Small overlap – crush entirely outboard of rail Moderate overlap – compression of one rail Full overlap – compression of both rails
Overlap (OL)	Portion of vehicle front width sustaining direct damage	<25% 25%-50% 50%-75% >75%
Rail engagement (RE)	Indication of which longitudinal rails experienced compression	None Left only Both left and right Right only Unclear
Kinematic descriptor (KD)	Assessment of the direction the occupant moved relative to the vehicle during the crash based on all available case evidence	Outboard with no significant engagement of frontal airbag (OB2) Outboard with partial engagement of frontal airbag (OB1) Mostly forward with full engagement of frontal airbag (Fwd) Inboard with partial engagement of frontal airbag (IB1) Inboard with no significant engagement of frontal airbag (IB2)

III. RESULTS

A total of 260 occupants, from model year 2006 and newer vehicles, were initially found in NASS-CDS or CIREN that met the study criteria. Some of those cases were not well-suited for the intended analysis due to circumstances such as in-vehicle fires or complex crash scenarios with multiple events, so the final case count dropped to 230 after removing certain cases. A listing of case identifiers for the included NASS-CDS and CIREN cases is given in Table A1, Appendix. Eighteen cases were reviewed by all four reviewers to examine consistency among the reviewers and perform ICC calculations. Some demographic information on the 230 case occupants is shown in Table III. Two-thirds of the cases in this study were identified in the CIREN database, which contained a greater proportion of female occupants compared to the NASS-CDS cases. The age range and breakdown by occupant position was similar for cases from both databases. Despite identical injury severity requirements for both databases in this study, the mean Injury Severity Score (ISS) was higher in the NASS-CDS cases compared to the CIREN cases.

TABLE III
BASIC DEMOGRAPHICS

	CIREN	NASS-CDS	Total
Case count	153	77	230
% male	37%	49%	41%
Minimum age [years]	14	17	14
Maximum age [years]	90	90	90
Mean age [years]	56	50	54
Minimum ISS[1]	9	10	9
Maximum ISS	59	75	75
Mean ISS	19	25	21
% vehicle-to-vehicle	77%	66%	73%
% driver (left front)	80%	84%	81%

[1] Injury Severity Score based on AIS 2005/08 codes.

Coded Variables

Using the damage descriptors from the CDC assigned by the field investigators, the entire group of cases was broken down by the general area of damage (GAD) and specific horizontal location (SHL), as shown in Fig. 1. The two-letter combinations along the horizontal axis are made up of the GAD and SHL, which are described in the Methods section. The differently-shaded columns represent the direction of force (DOF) clock-face value where end-shift codes are included in their respective clock-face group. Further breakdown by the specific vertical location (SVL) or type of damage distribution (TDD) is not shown. The vast majority of the crashes were assigned SVL codes of A or E, corresponding to damage sustained across all vertical regions or those below the beltline. The TDD was generally E or W, corresponding to damage that was isolated to the corners or spread across a wide area greater than 410 mm in length. To examine the percentage of frontal overlap for GAD=F cases, the direct damage width was divided by the un-deformed end width. This percentage of direct damage overlap is plotted by GAD and SHL in Fig. 2. Some cases did not have sufficient measurements to calculate the overlap percentage.

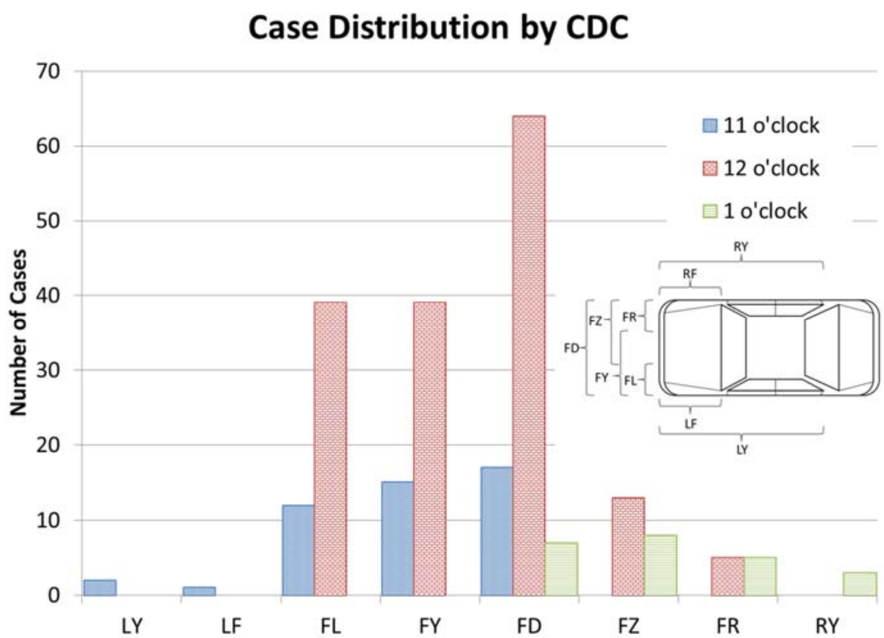

Fig. 1. Number of cases grouped by the coded CDC crash damage descriptors. Grouping on horizontal axis refers to the general area of damage (GAD, first character) and specific horizontal location (SHL, second character), as depicted in the inset schematic.

The total change in velocity for the most severe (frontal) impact event, Delta-V, is shown in Fig. 3, with groupings by the type of object struck. Delta-V was available for 170 cases and was calculated using the WinSmash algorithm [23]. For vehicle-to-vehicle crashes, the mass ratio, r_m, was calculated as:

$$r_m = \frac{m_{case\ vehicle}}{m_{opposing\ vehicle}}, \quad (1)$$

where the case and opposing vehicle masses, $m_{case\ vehicle}$ and $m_{opposing\ vehicle}$, are the coded curb weights from the database. Total Delta-V was plotted as a function of r_m in Fig. 4 for the vehicle-to-vehicle crashes in this study as well as for a selection of NHTSA crash tests using the Oblique Moving Deformable Barrier (OMDB) according to procedures in [12] for comparison purposes (see Table A2, Appendix, for test details). Mean and standard deviation values for the r_m and Delta-V of the groups shown in Fig. 4 are given in Table IV. The case vehicle overlap classification is based on the approach used in [13].

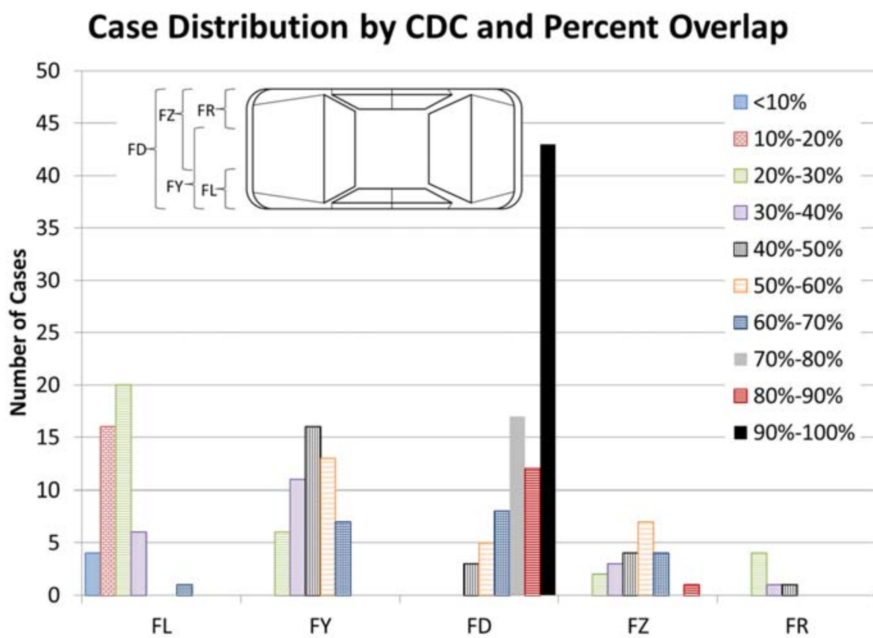

Fig. 2. Number of GAD=F cases grouped by the CDC crash damage descriptor and percentage of frontal damage overlap relative to un-deformed end width. Grouping on horizontal axis refer to the general area of damage (GAD, first character) and specific horizontal location (SHL, second character), as depicted in the inset schematic.

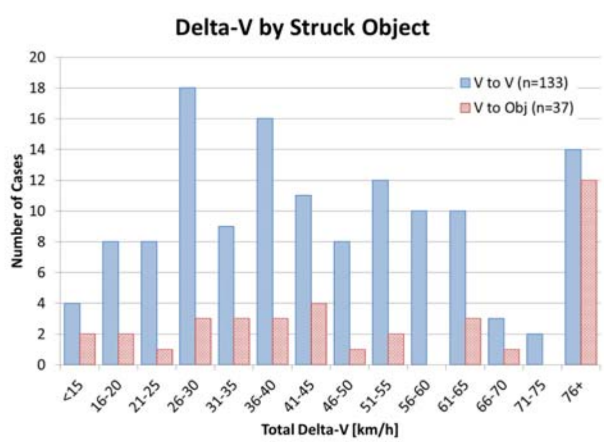

Fig. 3. Distribution of case vehicle total Delta-V by object struck.

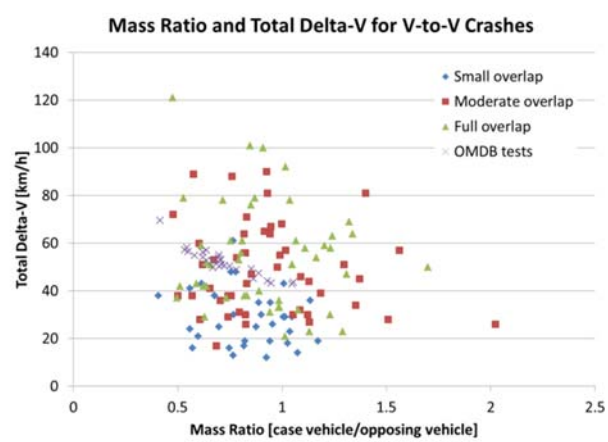

Fig. 4. Scatter plot of Delta-V versus mass ratio, r_m, for case vehicles (with known opposing vehicle mass) and OMDB test vehicles.

TABLE IV
DISTRIBUTION STATISTICS FOR DELTA-V AND MASS RATIO FOR FIG. 4

Crash type	r_m mean	r_m SD	Delta-V mean	Delta-V SD
Small overlap	0.83	0.18	29.6	11.9
Moderate overlap	0.95	0.31	49.5	18.6
Full overlap	0.92	0.27	53.8	21.7
OMDB laboratory test	0.72	0.16	51.8	5.7

The overall prevalence of serious injury by body region was determined for each seat position for all crashes combined and is shown in Fig. 5. The chart shows the proportion of occupants with serious injury by body region, so the same occupant may represent a portion of more than one column.

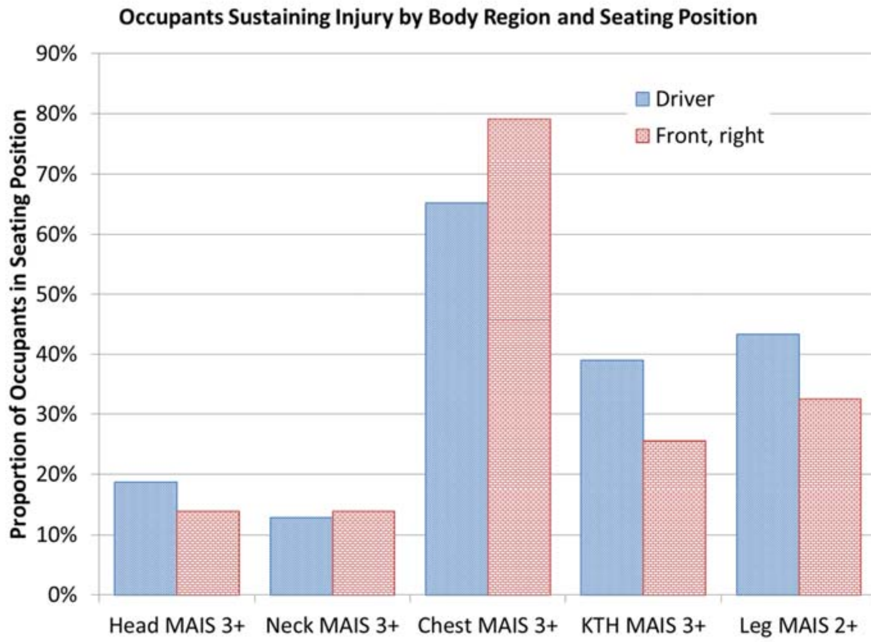

Fig. 5. Prevalence of injury by body region and indicated severity for driver and right front passenger positions in all crashes.

Multi-Reviewer Agreement

Eighteen cases were reviewed by all four expert reviewers, and the results were compared to evaluate similarity in scoring of certain case variables on the survey form. The ICC(3,4) values and qualitative degree of assessment are shown in Table V. The Shrout-Fleiss ICC(3,4) is a correlation coefficient applicable to a fixed set of subjects evaluated by four raters. An ICC value of 1.0 indicates perfect agreement and a value of 0.0 indicates only random agreement. Values between 0.75 and 1.0 are associated with excellent agreement.

TABLE V
INTRA-CLASS CORRELATION RESULTS FOR CT, OL, RE, AND KD
REVIEWER-DETERMINED VARIABLES

Variable	Shrout-Fleiss ICC(3,4)	Degree of agreement
CT: Crash Type	0.965	Excellent
OL: Overlap	0.964	Excellent
RE: Rail Engagement	0.953	Excellent
KD: Kinematics Descriptor	0.870	Excellent

Reviewer-Determined Variables

The reviewer survey included questions about the vehicle damage characteristics and occupant kinematics, as described in the Methods section. Assessment of reviewer-determined variables was focused on the occupant kinematics, though other crash damage-related assessments will be presented as well to convey the characteristics of the dataset.

Reviewer-determined crash type, basically the extent of front overlap (defined in Table II), is shown in Fig. 6, based on the combinations of coded CDC GAD1 and SHL1 for all crashes. The first character of the horizontal axis label is the general area of damage (GAD1) and the second character is the specific horizontal location (SHL1), which correspond to the third and fourth positions in the full CDC code. The reviewer-determined occupant kinematics descriptor is shown in Fig. 7, based on the relative PDOF for the occupant's seating position. The horizontal axis represents the angle from the longitudinal axis of the vehicle in either the occupant's inboard (i) or outboard (o) direction. That is, a right front passenger in a 330° PDOF crash would be represented in the 30i column. The meanings of the KD values are provided in Table II.

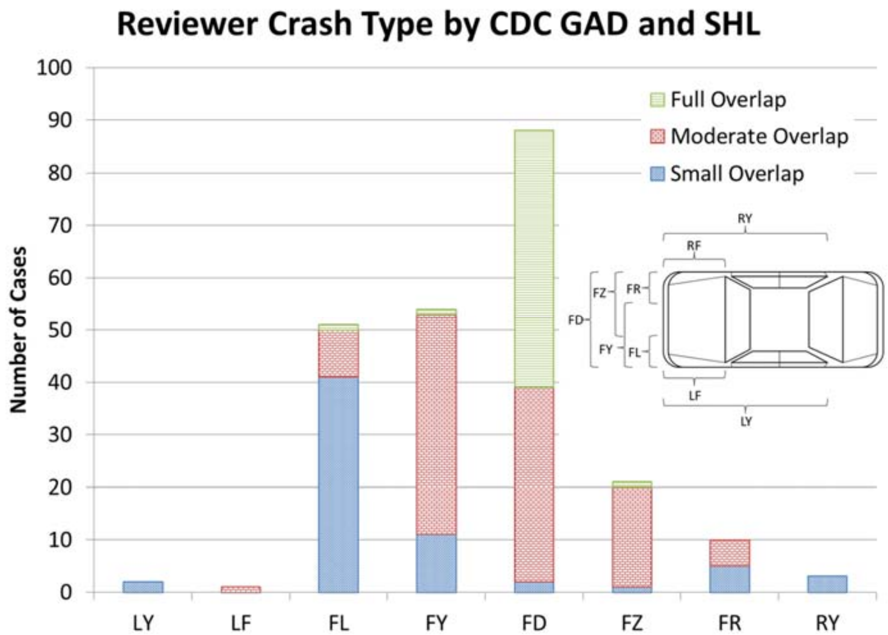

Fig. 6. Reviewer-determined crash type (CT) by coded CDC combination. The first character is the GAD, general area of damage (L=left, F=front, R=right), and the second character is the SHL, specific horizontal location, as depicted in the diagram.

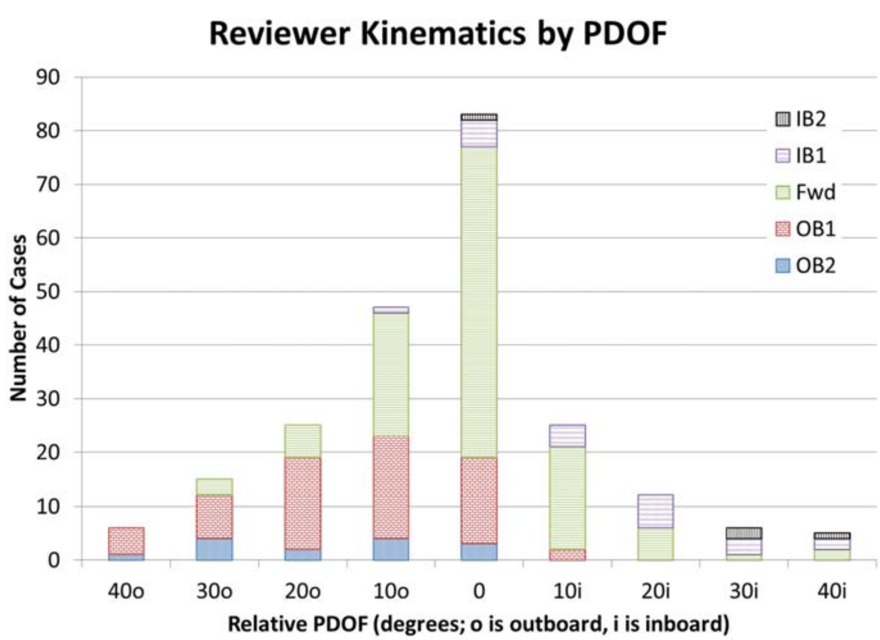

Fig. 7. Reviewer-determined occupant kinematics (KD) by PDOF for drivers and right front passengers, where the horizontal axis is the relative angle (inboard or outboard) of the coded PDOF relative to collinear.

Figure 8 shows the prevalence of injury in the body regions based on the reviewer-determined kinematics descriptor, KD. Drivers and passengers have been combined for this chart.

Using crash type criteria described in Table I for the OFTP, the distribution of reviewer-determined KD for drivers in left oblique crashes is shown in Fig. 9. The data are grouped by the PDOF, and collinear (PDOF=0°) small overlap crashes are considered oblique using these criteria. Also using the criteria from Table I, driver KD is shown for the collinear (PDOF=0°) moderate and full overlap crashes in Fig. 10.

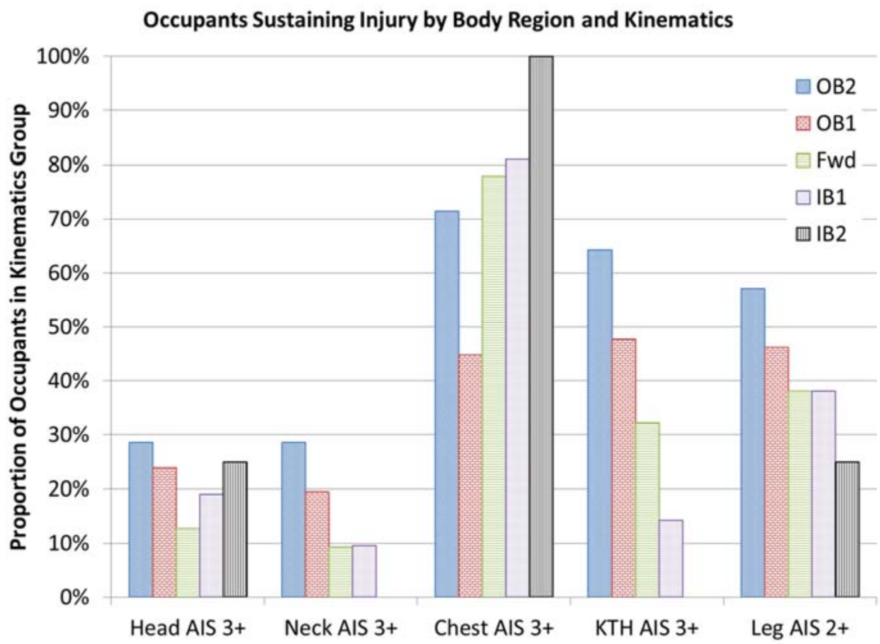

Fig. 8. Prevalence of injury by body region and indicated severity for all occupants grouped by reviewer-determined kinematics.

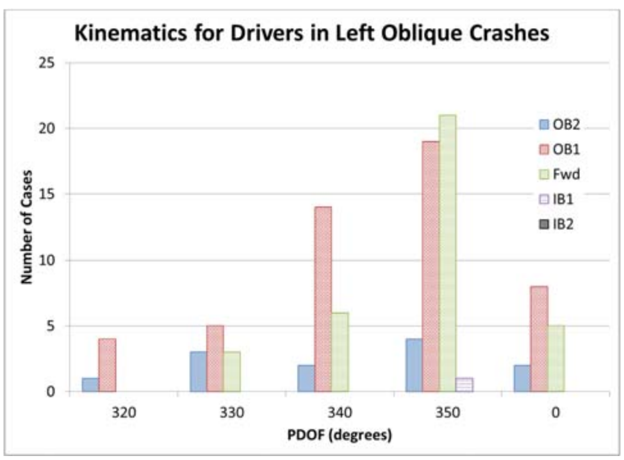

Fig. 9. Reviewer-determined driver kinematics, KD, by PDOF for crashes assigned to the left oblique crash type groups in Table I.

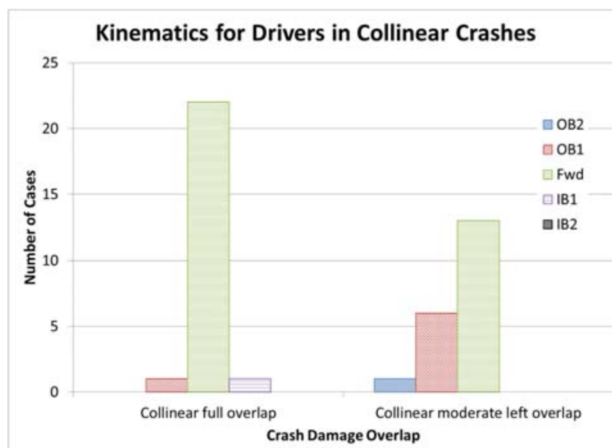

Fig. 10. Reviewer-determined driver kinematics, KD, for crashes assigned to the split (collinear moderate left overlap) and collinear (full overlap) crash type groups in Table I.

IV. Discussion

The primary objective of this study was to examine occupant kinematics in frontal crash events in the context of coded vehicle damage descriptors in order to validate methods used to study frontal crash target populations. Occupant motion during a crash event plays a large role in determining occupant outcome, and the NHTSA has taken the approach in its oblique frontal programme of prioritising oblique occupant kinematic response, since that was one of the key factors identified in the foundational study [1].

The collection of cases generated for this study was pooled from two US crash databases, with two-thirds coming from the CIREN system and one-third coming from NASS-CDS. Some of the general characteristics, such as average occupant age and driver versus passenger portion, of the two subsets of cases are similar, though CIREN had a larger percentage of female case occupants (63% vs. 51% for NASS-CDS). Reasons for this difference aren't clear without a broader examination, but the difference is not expected to have a negative impact on the findings. Occupants in the left front (driver) position make up the majority of the cases, and about three-quarters of the crashes are vehicle-to-vehicle. The mean Injury Severity Score (ISS) was notably higher for NASS-CDS due to six fatality cases with AIS6 injuries. While fatal cases also existed in the CIREN subset, none was coded with AIS6 injuries. For the purposes of this study of occupant kinematics in real-world crashes, there is no indication that combining data from both sources would create any problems.

The distribution of crashes by damage characteristics in Fig. 1 shows that impacts with directions of force in the 12 o'clock sector dominate, and 11 o'clock impacts outnumber 1 o'clock impacts two-to-one. The greater number of 11 o'clock impacts compared to 1 o'clock impacts is likely a result of right-hand traffic regulations in the US where oncoming traffic generally strikes the vehicle from the left front corner – an opposite phenomenon would likely be present in environments with left-hand traffic regulations. As stated in the Introduction, the definition of frontal impacts was expanded to include some left- or right-plane impacts if the impact location included the front fender and the direction of force was within one clock-face sector from 12 o'clock. For this study, only six of the 230 crashes were included based on those criteria.

Examining further the nature of the crashes from a damage perspective, Fig. 2 showed that the percentage of front overlap calculated from the coded variables was generally in agreement with the definition of the SHL classification based on the CDC. Considering the front plane of the vehicle should be divided into three equal-width sections to assign the horizontal damage indicator, the percentages of front overlap fit within the appropriate ranges, despite some of the SHL=D (distributed – damage in all three front width sections) cases showing overlap percentages less than 60%. This finding suggests that filtering frontal crashes by the CDC values for GAD and SHL alone may not capture all of the relevant impacts.

The total velocity change associated with the frontal events was available for 170 crashes and ranged from 12 km/h to 134 km/h. Half of the impacts had a Delta-V below 43 km/h. Considering these real-world impacts in the context of the NHTSA oblique MDB laboratory procedure, as in Fig. 4, reveals that the severity of the laboratory procedure for a given mass ratio is well within the range of Delta-V values occurring in these injurious field crashes, with similar values of r_m. While there are documented limitations in the WinSmash algorithm used to calculate Delta-V, calculations for moderate overlap and full overlap impacts are generally closer to values reported from on-board event data recorders than those for smaller overlap impacts [23]. This issue could partially explain the clustering of the small overlap impacts in a lower range of Delta-V values compared to the moderate and full overlap crashes.

Injury prevalence among all cases was highest in the chest region for AIS3 and higher injuries (Fig. 5). Two-thirds of drivers, and almost 80% of right front passengers, sustained AIS3 or higher injury to the chest region. The difference in prevalence for the driver compared to passenger was also notable in the knee/thigh/hip (KTH) region for AIS3+ and below the knee for AIS2+ injuries. Figure 5 doesn't consider the crash direction, which is oriented toward left oblique overall in this cohort. Right front passengers in left oblique impacts are considered non-struck-side occupants, which causes them to experience different loading than a driver (struck-side occupant) in the same crash. A larger portion of involved drivers sustained lower extremity injuries, which may be related to the larger portion of left-sidedness among the crashes creating more frequent intrusion on the driver's side. Head and neck injury prevalence was similar for drivers and passengers, and was lower overall than the other body regions considered in this study.

A comparison to the 2011 study, which examined injuries in small and moderate left overlap frontal crashes that has served as a guide for the oblique frontal programme development [10], shows differences in prevalence compared to this study, but this study considers a wider range of crash types. Restricting the current study to similar occupant and crash criteria (Fig. 11) shows the prevalence of head AIS3+ injuries is greater for the small overlap condition than moderate overlap, but that prevalence is similar to what was shown in Fig. 1 of that paper [10]. The prior study showed slightly higher chest injury prevalence for the left moderate offset group, while this study has higher prevalence in the small overlap group, though the overall prevalence is similar in value. Lower extremity injuries are less prevalent in the current study compared to the prior study, though relative trends between small and moderate overlap are similar among the two studies. These differences are likely related to vehicle factors, with the current study limited to 2006 model year and newer vehicles and the prior study including an older cohort of vehicles that may not have similar levels of occupant protection. Injury coding differences associated with using different versions of the AIS are also possible reasons for changes in prevalence.

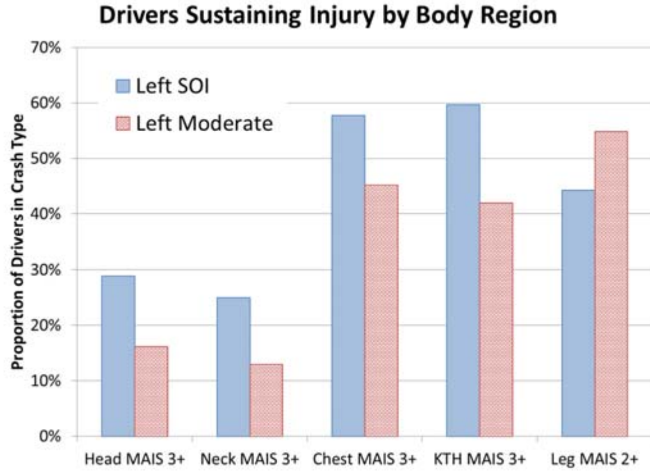

Fig. 11. Prevalence of injury by body region and indicated severity for drivers in left small overlap and moderate overlap crashes (extent of overlap based on OFTP methodology using coded damage values).

A discussion of the reviewer reliability is warranted before discussing the analysis of the reviewer-determined variables. For the subset of cases reviewed by all four reviewers, the overall level of agreement was strong based on the ICC values presented in Table V. For the three damage-specific assessment variables – crash type (CT), overlap (OL) and rail engagement (RE) – the intra-class correlation values indicated strong consistency among the reviewers. These variables can be considered more objective, and should result in a high level of agreement. For the kinematic descriptor (KD) rating, which serves as a primary basis for much of the analysis presented, the ICC was also excellent for this group of reviewers and cases. These results suggest that performing analysis of the KD variable for all of the cases combined is a reasonable approach that should yield reliable results.

Occupant motion relative to the vehicle interior in a crash depends on a number of factors, but reviewers were advised to consider all available evidence when selecting their response for KD, as described in Table II. As one of the primary questions of this study was what types of frontal crash lead to oblique occupant kinematics, the results shown in Fig. 7 suggest that there is no clear definition based on the coded PDOF. Outboard kinematics leading to reduced or minimal interaction with the frontal airbag were found for outboard PDOFs from 0° to 40°, and oblique kinematics were noted for 23% of the 0° cases (19 of 83). At the same time, some cases with outboard PDOFs up to 30° were noted to have forward occupant kinematics. While the investigator-determined PDOF may serve as a generalised indicator of how the occupant moves in response to the crash, it is likely that many factors affect occupant kinematics such that care must be exercised when interpreting field data based on PDOF. As an example, an occupant sitting close to the steering wheel may engage the airbag in the centre, even in a 30° outboard crash, due to the small distance allowed for occupant motion prior to engaging the airbag. A tall occupant sitting further rearward in the same impact may undergo more lateral motion during the time leading up to contact with the airbag, resulting in an off-centre engagement of the airbag and thus demonstrating more of an oblique kinematic response. The dynamic nature of a crash event can lead to a change in PDOF throughout the impact, and vehicle rotations can influence occupant trajectories as well.

The injury prevalence for occupants in the different KD groups in Fig. 8 show differences that further support prior literature claims of increased injury risk in non-collinear impacts. Head injury prevalence increases as occupant motion moves further inboard or outboard. Neck and lower extremity injuries become more prevalent with outboard motion and chest injuries showed a slight trend of being more prevalent with inboard motion. An analysis of the injury sources may further inform this conclusion, but case counts within each category and injury source are too small to draw strong conclusions. Of note, are the larger numbers of outboard contact sources, such as the A-pillar and door, in the cases with outboard KD classification – see Fig.

A1 to Fig. A4, Appendix.

Viewing the results of this paper in the context of the OFTP methodology (Fig. 9), it is evident that crashes assigned to the left oblique category, as described in Table I, exhibit outboard driver kinematics (OB1 or OB2) about twice as much as forward kinematics. This suggests the left oblique category includes some cases that demonstrate forward occupant motion, and thus may overestimate the true number of crashes producing oblique outboard kinematics. Additional analysis of the 350° crashes involving drivers in the left oblique group reveals that moderate left offset crashes were assigned forward kinematics (Fwd) more often than outboard kinematics (OB1 or OB2) by a factor of 1.6 (11 cases versus 7 cases). For full overlap crashes with a 350° PDOF, there were seven forward (Fwd) kinematics driver cases compared to only one outboard (OB2). For the driver cases assigned to the split (collinear moderate offset) and full overlap collinear categories in Fig. 10, the vehicles with full overlap damage and PDOF of 0° are almost all rated as having forward occupant kinematics. This is not a surprising result as the full damage distribution with an initial 0° direction of force is unlikely to lead to inboard or outboard occupant motion. The left moderate offset driver cases with 0° PDOF include seven cases with some extent of outboard motion (OB1 or OB2) and 13 cases with forward motion. This subset of crashes was found in [10] to be oblique about 20% of the time, suggesting that assigning a portion of the moderate overlap collinear crashes to the oblique category for the OFTP is reasonable. While the OB1 cases likely experienced partial engagement of the frontal airbag, this finding agrees with prior studies that have noted oblique outboard kinematics in collinear moderate offset crashes [3][9][24]. As stated previously, occupant kinematics are affected by numerous factors, and it may not be feasible to develop a clear definition of what type of vehicle damage constitutes an oblique crash from an occupant kinematics perspective.

Regarding the inclusion of left and right fender impacts with frontal PDOF (GAD of L or R), they make a small contribution to the overall collection of cases and demonstrate occupant kinematics relevant to the oblique crash problem. Of the six total in this study (2 LY, 1 LF, 3 RY), five were assigned OB1 or OB2 kinematics and one was left blank by the reviewer. Injury sourcing in these crashes was consistent with the others in this study, and structural and restraint improvements for oblique front-plane (GAD=F) impacts would likely benefit these scenarios as well.

Prasad *et al*. discussed the field relevance of the NHTSA oblique frontal crash test procedure, and concluded that the procedure was applicable to specific CDC codes that represented a small portion of frontal crashes occurring in the field [25]. Based on the damage inflicted to the test vehicles using NHTSA's oblique frontal crash test procedure, they considered crashes with CDC codes of 11FYEW and 12FYEW (extent zones 3-6). While their claims may be valid regarding those specific CDC codes being representative of the damage produced by the oblique crash test and the frequency of those exact damage characteristics in the field, such a claim does not reflect the objective of the NHTSA oblique programme to address a wider range of crashes in which occupants move in an oblique direction. Of the cases in this study, nine drivers were involved in crashes described as 11FYEW and 22 drivers were involved in 12FYEW events (including extent zones 2-6). Figure 12 shows the contributions of driver cases for each of these CDC codes to their respective KD classifications. Viewing the relevance of the oblique MDB procedure in field data through the CDC lens does not capture the full range of frontal crash occupants undergoing oblique motion, and these results indicate that only about one-quarter of drivers experiencing outboard kinematics are in crashes with these two specific CDC codes.

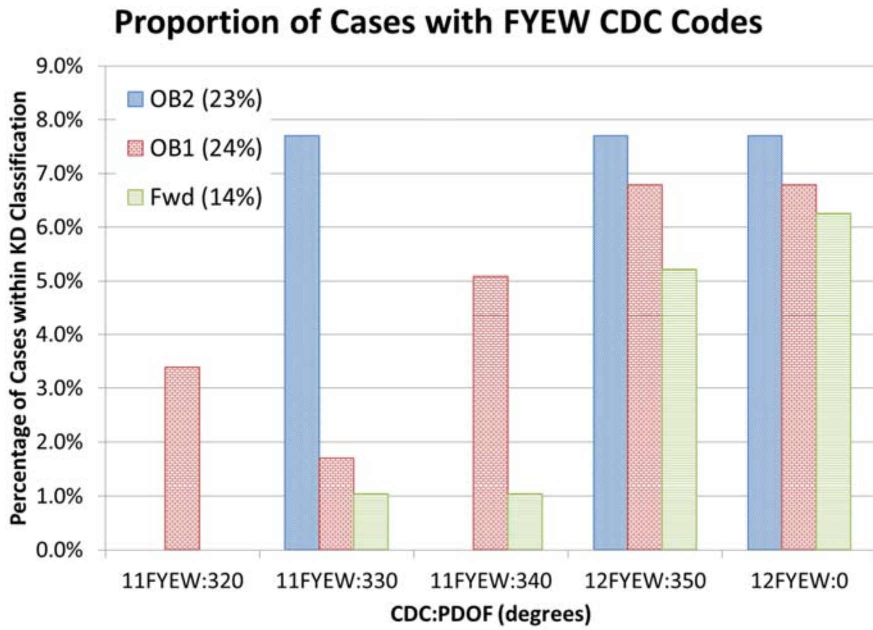

Fig. 12. Driver cases in the current study with CDC codes of 11FYEW or 12FYEW. The percentages in parentheses for each KD group in the legend indicate the proportion of all driver cases in each KD group that are captured by the FYEW CDC filter.

This study has attempted to draw a link between documented evidence from post-crash inspections and occupant kinematics that occur during the dynamic crash event. As with any study of field data, there are numerous limitations that affect the ability to draw such conclusions, either through in-depth or high-level analyses. This study used a convenience sample of NASS-CDS and CIREN cases that should not be generalised to the population, although the relationships between crash damage measures and occupant response within the range of frontal crashes examined are sufficient for the purpose of this study. Documentation of evidence in field crash vehicles can be hampered by factors such as preexisting or extrication-related damage, time between crash and inspection, and the lack of visible contact damage on some interior materials. Documentation of occupant injuries, and especially the exact locations of integumentary injuries, may not always provide the level of detail necessary to assess occupant and vehicle interaction in order to establish kinematics. Due to the amount of time required to perform manual case reviews, the total number of cases must be kept to a reasonable level. This study examined data spanning four years of field data collection, and was limited to model years 2006 and newer. While these inclusion criteria emphasised newer vehicles and recent crash trends, there will always be a lag between the latest vehicle designs and available field data. Finally, even with a standardised survey form guiding the reviewers, subjective evaluation of field data may lead to bias in the results.

V. Conclusions

This study examined occupant kinematics based on evidence available in real-world frontal crashes to identify whether conventional vehicle-based damage measures can be used to distinguish collinear and oblique occupant motions relative to the vehicle. The results indicate that there is no clear distinction using CDC and PDOF to define a cutoff between oblique and collinear kinematics, as the evidence-based assessment in this study found substantial overlap across a range of damage characteristics. Collinear (0°) moderate overlap crashes demonstrated forward kinematics in most cases, but evidence of oblique kinematics was present in some impacts. Similarly, crashes with a PDOF ten degrees either side of collinear (350° or 10°) also demonstrated a mix of forward and oblique kinematics for crashes with moderate overlap and mostly forward kinematics for full front overlap crashes. Variability in crash and occupant factors in real-world crashes prevents establishing a unique relationship between vehicle damage and occupant kinematics. The results do confirm prior studies that oblique occupant kinematics can occur in collinear crashes with small and moderate front overlap, and that such impacts result in injury sources such as the door and A-pillar. The degree of obliquity of the occupant kinematics affected prevalence of serious injury in several body regions, with the head injury prevalence increasing with greater inboard or outboard motion and lower extremity injury prevalence increasing with greater outboard motion.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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VIII. APPENDIX

TABLE A1
CASE IDENTIFIERS FOR INCLUDED CASES

NASS-CDS[1]		CIREN[2]			
2010-02-020-1-1	2012-12-056-1-2	286036988	338111398	352419450	425538922
2010-11-019-2-1	2012-13-060-2-1	286038480	338111911	352430744	425565495
2010-11-155-2-2	2012-41-183-1-1	286038496	338112840	352437160	425578830
2010-11-184-1-1	2012-43-194-2-1	317086120	338114937	352441412	425638866
2010-13-180-2-1	2012-43-196-1-1	317087296	338309794	352442353	425647090
2010-41-130-1-1	2012-49-063-1-1	317091478	338314859	357135746	431208557
2010-41-135-1-1	2012-49-118-2-1	317093805	338383720	359501964	431208606
2010-45-050-2-1	2012-49-195-2-1	317100639	338396147	359532120	431234785
2010-45-124-2-1	2012-81-074-1-1	317100687	338401900	359544180	431382835
2010-45-237-1-1	2013-02-010-2-1	317101783	338452530	359551223	431406944
2010-49-104-1-1	2013-04-005-1-2	317102861	339050695	359563226	431540650
2010-49-170-1-1	2013-05-052-1-1	317105886	340549824	359565772	431556255
2010-76-069-2-1	2013-05-105-1-1	317112541	352173925	359593322	431587536
2010-78-038-1-1	2013-05-117-1-1	317118245	352174784	359606065	431623506
2010-78-054-1-2	2013-08-038-2-1	317118408	352178641	359633620	431631537
2010-79-167-2-1	2013-08-084-1-1	317119724	352179094	359639103	431644617
2011-04-095-1-1	2013-11-067-1-1	317359216	352179139	359687409	431646337
2011-05-065-1-1	2013-11-121-1-1	317379789	352188210	359687421	431728323
2011-11-110-1-1	2013-12-024-1-1	317400319	352191965	360206102	431728326
2011-11-121-1-1	2013-12-045-2-1	317404193	352197079	360206546	588451794
2011-11-244-2-1	2013-13-023-2-2	317408491	352203647	360208682	588467517
2011-12-181-2-1	2013-41-076-1-1	317447095	352203957	360222793	588478638
2011-12-224-1-1	2013-45-040-2-1	317459732	352216057	360235938	588488413
2011-41-117-1-2	2013-48-010-2-1	317538009	352217171	360239432	588496336
2011-45-169-2-1	2013-48-012-1-1	317545259	352217379	360252640	588530588
2011-48-096-1-1	2013-49-007-1-1	317545449	352221317	360252646	588552417
2011-48-111-1-1	2013-49-085-1-1	317550075	352229395	360252648	588557587
2011-48-160-1-1	2013-49-105-1-1	317577033	352229593	360258996	588557685
2011-49-090-1-2	2013-49-116-1-1	317651312	352233229	360259001	588588658
2011-49-139-1-1	2013-73-106-1-1	318689065	352233424	360325067	588589147
2011-78-021-2-2	2013-73-125-1-1	327100825	352240643	360385382	588607922
2011-79-138-1-1	2013-74-028-1-1	328077625	352241113	385164043	791512628
2011-79-138-1-2	2013-74-097-2-2	338050691	352349902	385165412	852190681
2012-04-065-2-1	2013-76-101-2-1	338054039	352362600	385165500	852194550
2012-11-040-1-1	2013-79-092-1-1	338055907	352362614	385165679	852197595
2012-11-101-1-1	2013-79-161-1-2	338056052	352371576	425415250	904435317
2012-11-133-1-1	2013-81-032-1-2	338101562	352372535	425422674	
2012-12-038-2-1	2013-81-157-1-1	338103733	352404228	425467073	
2012-12-047-1-1		338108966	352408982	425511260	

[1] Case identifier format is YEAR-PSU-CASENO-VEHNO-OCCNO [16]

[2] Case identifier is CIRENID [17]

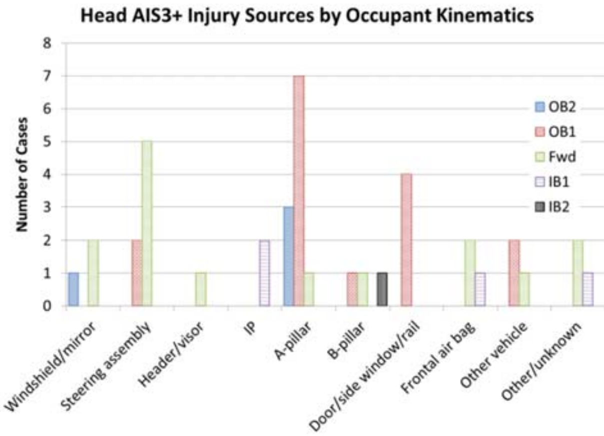

Fig. A1. Head injury sources for all occupants grouped by reviewer-determined kinematics.

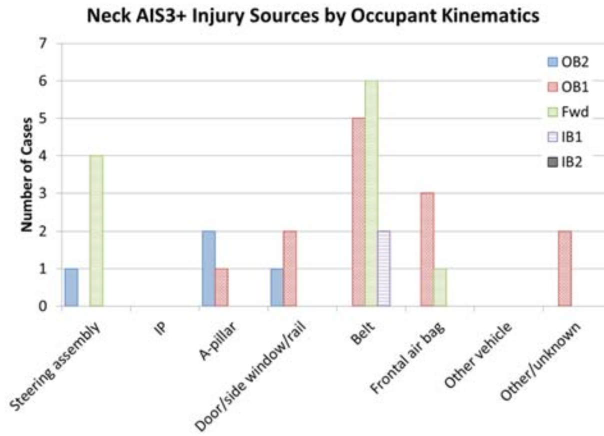

Fig. A2. Neck injury sources for all occupants grouped by reviewer-determined kinematics.

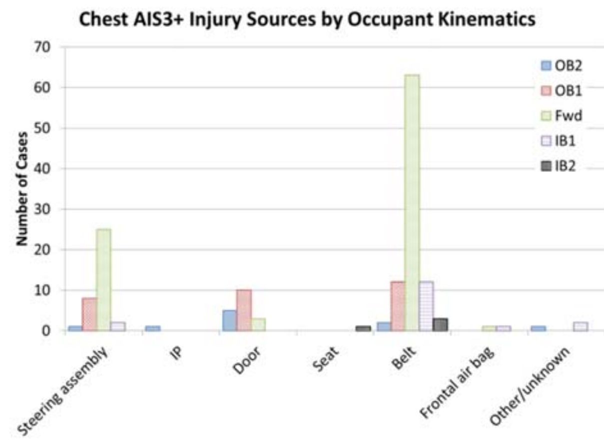

Fig. A3. Chest injury sources for all occupants grouped by reviewer-determined kinematics.

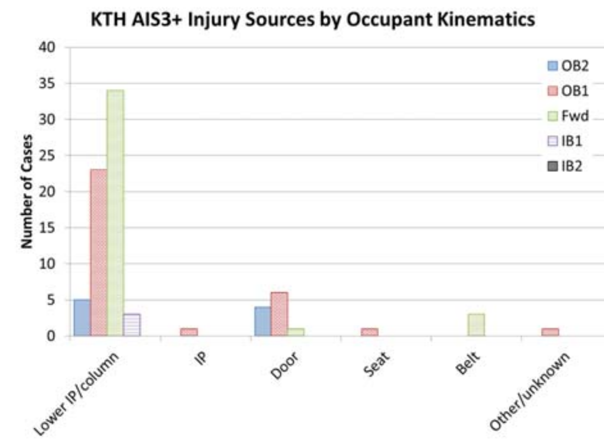

Fig. A4. Knee/thigh/hip injury sources for all occupants grouped by reviewer-determined kinematics.

TABLE A2
NHTSA OMDB TEST DETAILS

Model Year	Make	Model	Test Number	Total Delta-V [km/h]	r_m
2011	Smart	Fortwo	7459	69.5	2.4081
2011	Toyota	Yaris	7441	57.2	1.8708
2011	Ford	Fiesta	7428	56.4	1.8162
2013	Nissan	Versa	8084	56.0	1.7161
2013	Honda	Civic	8477	56.0	1.6127
2013	Hyundai	Elantra	8089	57.0	1.5660
2011	Chevrolet	Cruze	7431	52.4	1.4982
2012	Volvo	S60	8488	50.3	1.3323
2013	Dodge	Dart	8476	55.0	1.4327
2012	Honda	CR-V	8096	53.3	1.4172
2012	Toytota	Camry	8088	52.8	1.4156
2014	Subaru	Forester	8478	50.7	1.3810
2011	Buick	Lacrosse	7467	48.8	1.2809
2012	Ford	Taurus	8087	49.2	1.1729
2013	Volvo	XC60	8475	45.0	1.1565
2012	Honda	Odyssey	8097	47.3	1.1267
2011	Ford	Explorer	7476	43.3	1.0537
2011	Dodge	Ram 1500	7457	43.0	0.9537
2012	Chevrolet	Silverado	8099	43.6	0.9489
2014	Chevrolet	Spark	8882	58.1	1.8349
2014	Subaru	Impreza	8881	49.7	1.4964
2014	Mazda	3	8787	52.6	1.5680
2013	Hyundai	Elantra[1]	8875	54.2	1.6106
2014	Toyota	Camry	8790	54.0	1.4360
2014	Honda	Accord	8789	50.4	1.4278
2014	Mazda	CX-5	8788	51.1	1.4076
2014	Honda	Odyssey	8791	44.1	1.0756

[1] Modified with structural countermeasure.