Front Crash Injury Risks for Restrained Drivers in Good-rated Vehicles by Age, Impact Configuration, and EDR-based Delta V

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Abstract The risk of injury in a front crash depends on both severity and impact configuration, but the accuracy of crush-based estimates of the former depends on the latter. In the current study, output from event data recorders (EDRs) was used to establish estimates of configuration-specific severity and real-world injury risk in crashes similar to consumer test programs. NASS-CDS was queried for all front crashes of vehicles with good IIHS 40% overlap crash test ratings in which the driver was restrained by a belt and deployed front airbag. Vehicles with a complete EDR crash pulse (n=764) or crush-based delta-V calculated from vehicle-specific stiffness values (n=1902) were assigned a crash configuration through photographic review. Cases with delta-Vs from both methods were used to establish configuration-specific EDR-equivalent delta-Vs. The effects of various crash, vehicle, and occupant factors on injury risk were estimated using logistic regression. For large overlaps, moderate overlaps, and center impact crashes, driver age and delta-V had strong effects on the risk of sustaining an MAIS≥3 non-extremity or fatal injury. Vehicles with good ratings in the IIHS moderate overlap test still allow high risk of serious injury in real-world crashes with severities similar to the crash test, especially to older drivers.

Keywords Crashworthiness, Delta-V, Front impact, IIHS, NASS-CDS

I. INTRODUCTION

In 2016, frontal non-rollover crashes accounted for 49% of all passenger vehicle occupant fatalities [1]. The proportion is even greater when considering restrained occupants in modern vehicles, with front crashes accounting for 60% of belted occupant deaths in 2013-17 model year vehicles. Previous research has shown that frontal crash tests conducted by the Insurance Institute for Highway Safety (IIHS) and the National Highway Traffic Safety Administration (NHTSA) have resulted in improved crashworthiness and lower fatality risk [2,3]. However, the magnitude of the remaining problem indicates that any additional improvements could still have a substantial effect. It is important to understand whether these improvements can be driven by existing tests or whether other approaches are needed.

Three questions must be answered in order to assess the field relevance of existing crash tests. First, do the tests represent the configurations that produce field injuries? Second, are the tests conducted at severities that produce injuries in the field? And third, do current tests indicate injury risks that correlate to real-world outcomes? The first question is the most straightforward and requires studying only the field crashes that result in injury. After reviewing 116 cases from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS), Brumbelow and Zuby [4] found that the moderate overlap and small overlap configurations each represented around one-quarter of the crashes resulting in serious or fatal injury to belted front-seat occupants. Center impacts accounted for another 19%, underride 14%, and full-width crashes 6%. Two outcomes from this finding were the IIHS evaluation of semi-trailer underride guards and the small overlap crash test program, both introduced in 2012.

Comparisons of severity and injury risk between tests and field crashes are more difficult to make. Crash severity typically has been assessed using delta-V estimates calculated from static post-crash crush measures in combination with stiffness values measured during full-width crash testing [5-7]. This method is not accurate for cases in which the impact is focused on an isolated portion of the structure which does not represent the entire front-end stiffness of the vehicle. Thus, overall assessments of field crash severities also will be inaccurate

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unless they are restricted to cases with sufficient horizontal and vertical overlap of the primary longitudinal structures that are loaded in full-width crash tests. For example, in three different types of small-overlap tests, Sherwood et al. [8] found that crush-based delta-Vs were 50% lower, on average, than actual delta-Vs calculated from accelerometers. In addition to these challenges, injury risk assessments are further complicated by the need for severity data from the set of crashes in which injury does not occur.

Event data recorders (EDRs) provide a source of delta-V that does not depend on vehicle crush measurements. When able to capture the complete deceleration pulse, EDRs generally report delta-Vs in crash tests that are close to values calculated using laboratory-grade accelerometers. In 56 km/h full-width rigid barrier tests of 2012 model vehicles (n=41), Tsoi et al. [9] found that EDR-reported delta-Vs were an average of 3.8 km/h, or 5.9%, lower than laboratory measurements. This was similar to earlier studies [10,11]. Hampton and Gabler compared EDR and crush-based delta-Vs in front NASS-CDS crashes, finding that the EDR-reported values were an average of 13% higher [12]. They performed an additional analysis based on the Collision Deformation Classification (CDC) for each case, finding that those with a narrower damage area had greater mismatch between EDR and crush-based delta-V. These values would be expected to diverge even further if distinctions were made using the actual loaded structures rather than the CDC damage area, which typically is wider [4]. Funk et al. [13] showed how the difference in delta-V methods could affect the overall estimated injury risks in frontal crashes, although differences in crash configuration were not addressed.

Previous research has reported injury risk as a function of EDR delta-V, but these studies cannot be directly applied to assessment of current crash test programs for various reasons. Injury risk curves calculated by Gabauer and Gabler [14] were used solely to compare differences between severity variables and so did not make use of the NASS weighting factors to provide an overall risk. The small number of belted occupants (n=158) also would have precluded an analysis of the effect of age or a comparison of different frontal crash configurations. Stigson et al. [15] studied 489 occupants of vehicles equipped with an EDR as part of an insurance plan in Sweden. Most of the vehicles were Toyota models and dated back to 1992. Stigson et al. modeled the risk of sustaining an injury of level two or greater on the Abbreviated Injury Scale (AIS) as a function of crash severity (delta-V and peak acceleration) and age. While this study is helpful in understanding human injury tolerance, it is less relevant to current test programs given the difference from the fleet of vehicles that perform well in these programs. In addition, while many test metrics are based on AIS ≥ 3 risks, these could not be calculated by Stigson et al. given that only 13 occupants sustained injuries at this level. Craig et al. [16] used EDR delta-V to estimate injury risk as part of advanced automatic crash notification algorithm development. Given the focus, the analysis did not include factors that are important for assessing test relevance but that cannot currently be recorded by an EDR, such as occupant age and crash configuration. Injury risk calculations also were based on unweighted data, limiting their direct application to all field crashes.

A common challenge faced by all the previous studies is the limited number of crashes with EDR data available to researchers. The low case counts restrict the ability to make distinctions by age and vehicle loading configuration. In order to perform these analyses, a unique approach is required to take advantage of the more accurate EDR-based delta-Vs without reducing the sample to an insufficient size. The current study represents one such approach.

II. METHODS

NASS-CDS was a sample-weighted survey of police-reported crashes in the US conducted from 1979-2015. For the current study, NASS-CDS was queried for all front crashes (CDC GAD1 = "F") of vehicles with good ratings in the IIHS 40% moderate overlap crash test in which the driver was aged at least 18 years old and was restrained by a belt and deployed front airbag. Cases with positive belt use attributed solely to the driver interview (BELTSOU = 3) were excluded. Cases with subsequent rollovers or multiple severe impacts were excluded. Included vehicles had longitudinal delta-Vs recorded by an EDR and/or calculated using crush-based measurements. For vehicles with EDR delta-Vs, all years were used in which NASS-CDS contained these data (2000-15). Vehicles with delta-V based only on crush measures were limited to 2008-15 years, the timeframe in which the WinSMASH damage algorithm used vehicle-specific stiffness values rather than less accurate categorical values. Hampton and Gabler [12] found a "step-change" occurred when the vehicle-specific stiffness values were incorporated, resulting in an average WinSMASH delta-V increase of 8% after controlling for EDR-reported delta-V.

In order to establish which case vehicles had valid EDR longitudinal delta-Vs, the individual Crash Data Retrieval (CDR) output files were investigated rather than relying on the EDR values displayed in the NASS-CDS XML case viewer. This was necessary for multiple reasons. First, many vehicles, most notably older Chrysler models, had no coded delta-V even though the CDR file contained vehicle acceleration data. In these cases, delta-V was calculated despite not being reported directly by the EDR. Additionally, there is no defined value that reflects the completeness of an EDR crash pulse. For the current study, inclusion criteria were at least 100 ms of post-impact delta-V or acceleration data, with a pulse that returned to a -4.6 g or greater (closer to positive) level after this time (4.6 g = 1 mi/h per 10 msec, the most common EDR sample rate). All deployment and non-deployment events stored on the EDR were compared to the NASS-CDS scene diagram and crash narrative to ensure that the appropriate delta-V was obtained for the event in question.

All subject vehicles were assigned a front crash configuration based on review of the case photographs. While the CDC indicates the extent of any exterior damage, photographic review is necessary to determine what underlying structures sustained loading and in which direction the loading occurred. Table 1 shows the configurations and their definitions. The categories were established to define the loading relative to the main longitudinal structures designed to absorb energy in a frontal crash. The configurations are similar to those used by Brumbelow and Zuby [4] with the exception that the direction of loading (colinear vs oblique) was considered as an additional factor in the current study since this could affect the relationship between longitudinal delta-V and injury outcome.

In addition to crash configuration assignment, the photographic review process was used to assess the validity of the crush measurements used in the WinSMASH delta-V calculation. Cases were excluded from the delta-V analyses when the crush was measured above the height of the bumper/frame in the absence of underride, when crush was measured on a bumper bar that had detached from the frame, when the main damage was to the undercarriage, or when the recorded crush values were clearly contradicted by photographs of the measurement rods. Vehicles with a calculated delta-V but without any crush measurements also were excluded.

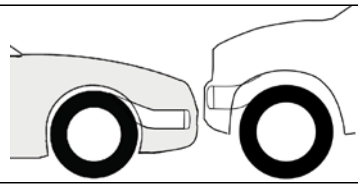
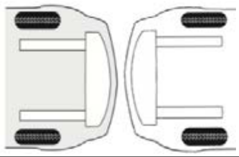
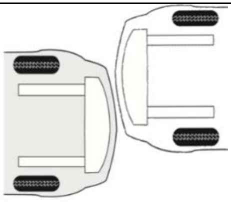
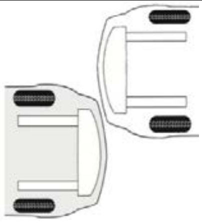
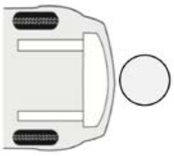
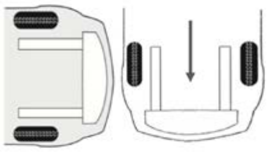
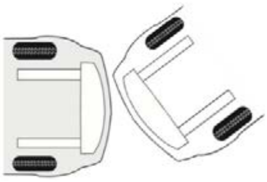
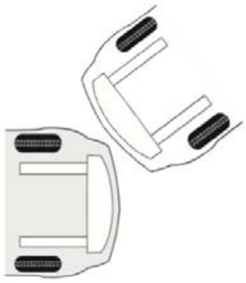
After all cases were categorized based on crash configuration, linear regression models were used to describe the ability of WinSMASH delta-V (2008-15) to predict EDR delta-V. The models were fit using all the vehicles for a given configuration which had valid delta-Vs calculated from both methods. The regression intercepts were not forced to zero since the WinSMASH algorithm allows for some restitution of the loaded vehicle structures, meaning that a crash without any measured damage is still assumed to have a nonzero delta-V. Since the specific adjustment for restitution in a given case could be greater or less than the actual energy associated with the elastic structural deformation, the inclusion of the intercepts in the regression models is warranted. After fitting a model for each crash configuration, the R-squared values were used to determine whether the regression line fit the data for that configuration reasonably well. The regression coefficients for those configurations then were used to calculate "EDR-equivalent" delta-Vs for cases that had a 2008-15 WinSMASH delta-V but no EDR delta-V. The final dataset used to study the relationship between delta-V and injury risk consisted of all cases with an EDR delta-V (2000-15) as well as cases with an EDR-equivalent delta-V (2008-15).

NASS-CDS case weights

The NASS-CDS sampling procedure was designed to intentionally sample crashes of greater interest at a higher frequency. Factors used to identify these crashes included the involvement of a newer vehicle, an occupant fatality, an occupant requiring transportation to a hospital, an occupant being admitted to a hospital, and police reporting an incapacitating injury (an A-level injury on the KABCO scale). In order to account for the bias that these factors would introduce, analyses of injury rates or risk must utilize the weighting factors that are assigned to each case. However, a selection of cases often includes a small number with very high weights relative to other cases with similar outcomes, giving them the potential to dominate the weighted results and potentially obscure meaningful findings. In the sample used in this study, 184 raw cases had an AIS ≥ 3 injury but four of these accounted for 41% of the weighted data.

The current study accounted for two common sources of relatively inflated case weights. First, as reported by Brumbelow and Farmer [17], sometimes police reports include errors that only are discovered during the investigation or that are revised by the police after stratification has been performed. For example, an officer may initially indicate that an occupant did not require hospitalization when they actually were admitted. If that case is selected for inclusion in the NASS-CDS sample, the resulting weighting factor will be much higher than other similar cases in which an occupant was hospitalized. Such cases can be identified by checking the assigned case strata against the values of the variables used in the stratification process. In the current study, 3% of the original sample had coded values that did not match the definition of the stratum in which it was placed.

Table 1. Crash configurations assigned during photographic review

Configuration	Description	Example (case vehicle shaded)
Underride	Primary loading occurred above the bumper/longitudinal height (with any amount of horizontal overlap)	
Large overlap	Colinear loading of both longitudinals	
Moderate overlap	Colinear loading of only one longitudinal	
Small overlap	Colinear loading outboard of both longitudinals	
Center impact	Colinear loading between longitudinals	
Perpendicular	Lateral loading of both longitudinals resulting from perpendicular partner vehicle velocity	
Oblique center	Initial loading between longitudinals; often produces outboard deformation of single longitudinal	
Oblique corner	Initial loading outboard of longitudinals; often produces inboard deformation of single longitudinal	

A second issue arises from the implicit assumption in the sampling procedure that admission to the hospital will be associated with a police-reported incapacitating injury. Hospitalization status only is considered for occupants with an A-level injury; there is a unique stratum for occupants with an A-level injury who aren't hospitalized, but not for occupants with lesser B/C/O/U injuries who do require hospitalization. This means that, in a NASS-CDS sample of hospitalized occupants with AIS ≥ 3 level injuries (the outcome of interest in this study), those whose injuries were not reported as incapacitating on the police report are weighted up to 100 times more heavily than those whose injuries did meet this criterion. In the current sample, 4% of cases involved occupants who were hospitalized without an injury reported as incapacitating by the police.

One approach to handling cases in both groups would be to drop them from analyses of injury rate or risk. However, this would result in a loss of all information associated with cases that would have been even more likely to be sampled with an accurate police report. Others have approached the problem by capping all weights at a certain value [16,18], but this method requires selecting an arbitrary maximum weight and does not account for any differences that are intended to be part of the sampling process. For the current study, the weights for cases that fell in the two groups described above were reduced to the value they would have been assigned with an accurate police report or with an A-level injury, respectively. While this retains the maximum number of cases while minimizing the influence of any single case, the overall injury rates and risks reported in this study may be lower than true nationwide values. The extent to which they are lower depends upon the degree to which this sample of cases represents the inaccuracies of police accident reporting on a national scale.

Injury risk curves

Logistic regression was used to model the effects of driver age and EDR or EDR-equivalent delta-V on different injury outcomes. The primary outcome of interest was the presence of an AIS ≥ 3 non-extremity injury or a fatality in the absence of known AIS injury level (hereafter “MAIS3+F”). Although extremity injuries are not inconsequential, the study objective was to identify the conditions that are producing elevated risks of the potentially life-threatening outcomes that crash test programs primarily are designed to prevent. For the same reason, pelvic injuries were counted as “non-extremity” injuries in the current study despite being classified as lower-extremity injuries in the AIS. AIS 1998 codes were used since many of the cases were from years prior to 2010, the first year AIS 2008 codes were included. Because the effect of increasing age on injury tolerance may not be linear across the range of drivers included in this study (18 and older) [19], when there were sufficient data driver age was transformed into a categorical variable with three levels: 18-39, 40-59 and 60+. Secondary models were constructed to investigate the effects of age and delta-V on the risk of injury to specific body regions as well as the effects of age and crash configuration using only cases with EDR delta-Vs. Preliminary models also considered the effects of driver sex, height, mass, and body mass index (BMI) as well as vehicle mass. All models were calculated using the “survey” package [20] in the R programming language [21] to account for sampling weights.

Of particular interest is the risk of injury in a crash with an EDR/EDR-equivalent delta-V of 70 km/h. From 2001-18, the 64.4 km/h IIHS moderate overlap crash test has produced a median longitudinal delta-V of 69.9 km/h as measured with laboratory accelerometers. In 24 of these tests, downloaded EDR data would have met the definition of a complete crash pulse used for the NASS-CDS cases in the current study. The average EDR longitudinal delta-V in these tests was 69.1 km/h (SD=2.7).

A summary of the major components of the study methodology is given in the Appendix (Fig. A1).

III. RESULTS

There were 2,666 cases that met the inclusion criteria for photographic review. Weighted distributions of crash configurations for all cases and for cases resulting in MAIS3+F injury, as well as the weighted injury rate for each configuration are shown in the Appendix (Fig. A2). The underride and moderate overlap configurations each accounted for 20% of all the cases, with moderate overlap crashes accounting for the largest proportion of cases with serious injury (MAIS3+F). Without accounting for any potential differences in crash severity, center impacts had the highest rate of injury.

There was a difference in the distribution of crash configurations that produced serious injury to each body region (Fig. A3). Taken together, large overlap, moderate overlap, and center impact crashes accounted for 61% of the weighted drivers with an AIS ≥ 3 thoracic injury and 77% of those with an AIS ≥ 3 abdominal injury, but less than 35% of those with an AIS ≥ 3 injury to the head, pelvis, or neck/spine. Conversely, the small overlap and oblique corner impact configurations represented over half of the weighted drivers with an AIS ≥ 3 head (52%) or pelvic (58%) injury but much smaller percentages of those with a serious thoracic (23%), abdominal (9%) or neck/spine (22%) injury. Underride crashes accounted for 37% of drivers with a serious neck/spine injury but 12% or less of those with serious injuries to other body regions.

EDR vs. SMASH delta-V

Of all studied cases, 764 included EDR-based delta-Vs and 515 of these also had WinSMASH delta-Vs calculated using vehicle-specific stiffness values. Linear regression models were fit to describe the relationship between the two delta-V methods by crash configuration (Fig. A4). The R-squared values for the large overlap, moderate overlap, and center impact regression models ranged from 0.73-0.90. For these configurations, the regression estimates were used to calculate EDR-equivalent delta-Vs for other crashes with WinSMASH delta-Vs but no EDR data. The regression models for the other crash configurations did not sufficiently describe the relationship between the two methods (R-squared values 0.14-0.41) to calculate EDR-equivalent delta-Vs.

Underrides represented the largest configuration for which EDR-equivalent delta-Vs could not be calculated. A basic analysis of crash partners was performed to provide more insight into these crashes. SUV and pickup crash partners accounted for 61% of the weighted case total and 67% of the total for drivers with an MAIS3+F injury. Front-to-rear crashes accounted for 84% of the underride cases, but just 19% of those with serious injury. Conversely, 8% of underrides were front-to-front crashes but these accounted for 65% of the serious injuries.

Primary MAIS3+F injury risk curves

The primary injury risk curves were developed using the 911 large overlap, moderate overlap, and center impact crashes with EDR (n = 313) or EDR-equivalent (n = 598) delta-Vs. Preliminary logistic regression models indicated there was no significant difference in injury risk between these three configurations while controlling for the effects of delta-V and driver age, so they were combined for the main analyses. Delta-V, driver age, and injury status for each case is shown in Figure 1. The weighted median delta-V and age for drivers who sustained an MAIS3+F non-extremity injury was 63 km/h and 57 years, respectively. This compared to weighted median values of 24 km/h and 36 years for drivers who did not sustain an injury at this level (Fig. 2).

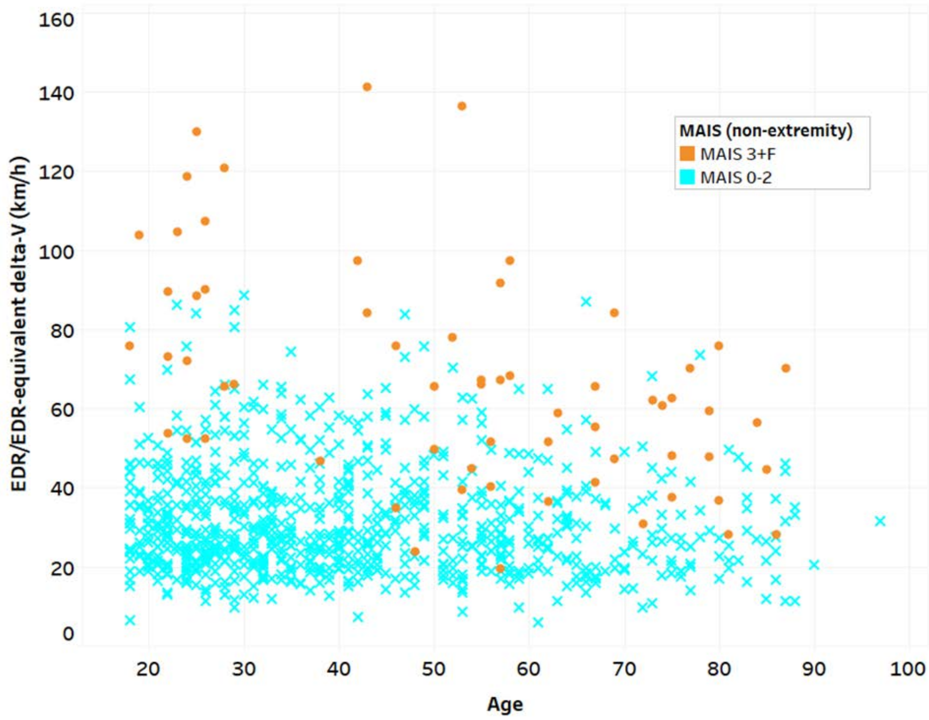


Fig. 1. Delta-V, driver age and MAIS3+F injury status for large overlap, moderate overlap and center impacts

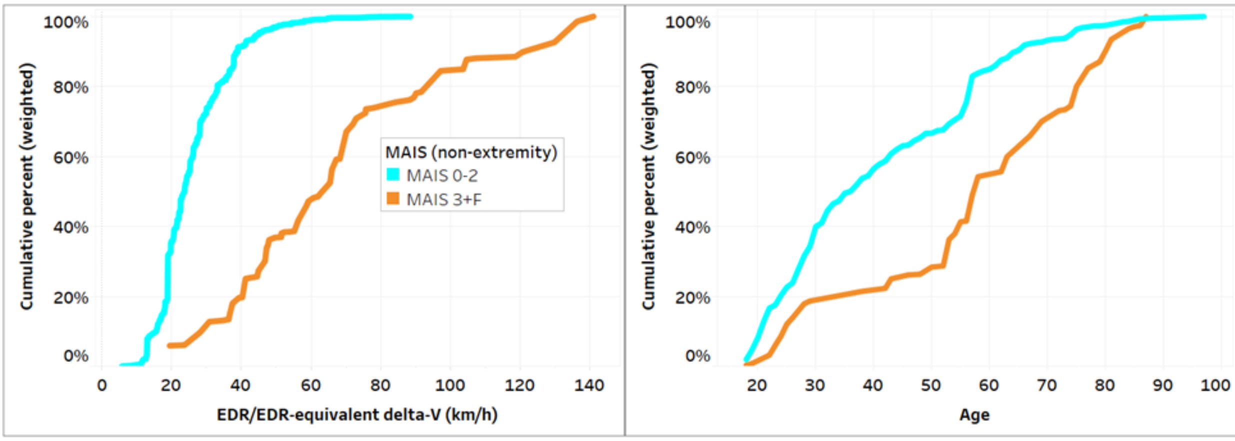


Fig. 2. Delta-V and driver age for large overlap, moderate overlap and center impact crashes by injury status

Figure 3 shows the logistic regression model estimates and 95% confidence intervals for the risk of MAIS3+F non-extremity injury as a function of delta-V and driver age group. The estimated effect of increasing delta-V by 10 km/h was a 225% increase in the odds of injury (odds ratio (OR)=3.25, $p<0.001$). The model estimated increased odds of injury for the oldest age group relative to the middle (OR=6.2, $p=0.009$) and youngest groups (OR=20.5, $p<0.001$) and for the middle age group relative to the youngest group (OR=3.3, $p=0.04$). For a real-world crash with a 70 km/h delta-V, the estimated risk of injury was 7.6% (95% CI: 3.3%, 16.8%) for 18-39 year-old drivers, 21.5% (10.8%, 38.2%) for 40-59 year-olds, and 63.0% (29.1%, 87.6%) for drivers 60 and older. Overall, the model showed very good discrimination between cases with and without an MAIS3+F injury, with an area under the receiver operator characteristic curve of 0.93.

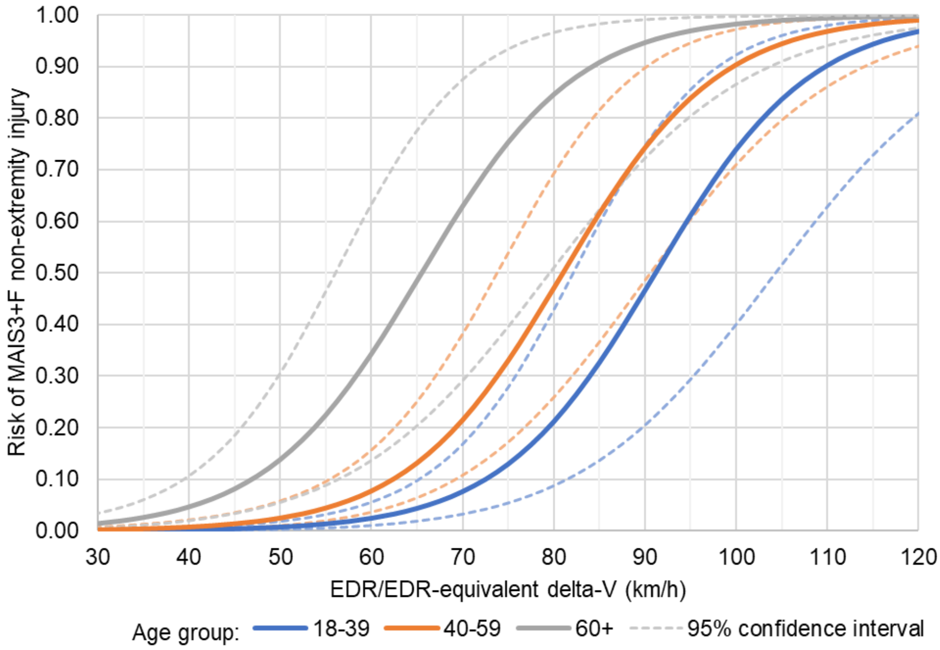


Fig. 3. Injury risk by delta-V and driver age in large overlap, moderate overlap and center impact crashes

Preliminary models using the same set of crashes also considered the effects of driver sex, height, mass, and BMI as well as the effect of vehicle mass on the risk of MAIS3+F injury. While controlling for driver age and delta-V, individual models including each of these variables indicated that none of them had a statistically significant effect on the odds of injury (female OR=1.02, $p=0.97$; +10 cm height OR=1.06, $p=0.14$; +10 kg driver mass OR=1.09, $p=0.46$; +1-unit BMI OR=1.07, $p=0.34$; +100 kg vehicle mass OR=0.97, $p=0.65$). Including driver mass, height, or BMI also resulted in the loss of 11%-17% of raw cases due to missing data. None of the additional variables were included in the final model.

Eighty-eight percent of the drivers in the primary regression dataset who sustained an MAIS ≥ 3 non-extremity injury had an AIS ≥ 3 thoracic injury, making the thorax the most common body region injured at this level in these crash configurations. Figure 4 shows logistic regression estimates for the risks of thoracic injury and all other non-extremity injuries combined. The estimated risk of a thoracic injury was greater than the risk of any other non-extremity injury for the two oldest age groups at all delta-Vs, with a larger difference for the oldest group. For the youngest group of drivers, the estimated risk of a serious thoracic injury was very close to or even slightly lower than the estimated risk of a serious injury to another body region.

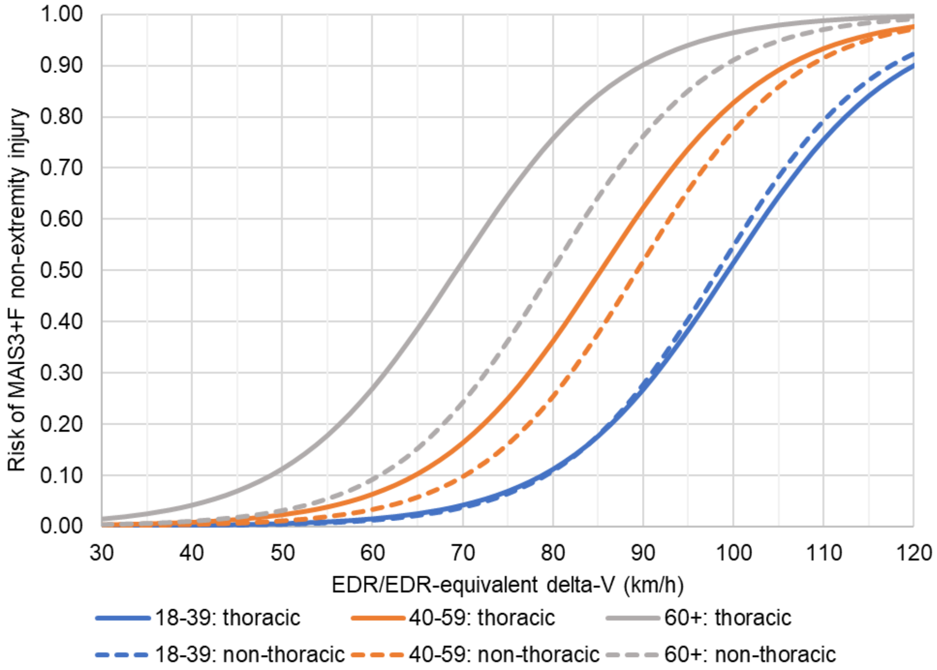


Fig. 4. Thoracic vs. non-thoracic (non-extremity) injury risk by delta-V and driver age in large overlap, moderate overlap and center impact crashes.

Secondary MAIS2+F injury risk curves

Because SMASH delta-V could not be used to calculate EDR-equivalent delta-Vs for several configurations, secondary models based only on cases with EDR data were constructed to compare injury risk between different crash configurations. There were only sufficient data to define a two-level crash configuration variable. As in the primary regression analyses, large overlap, moderate overlap (driver- or passenger-side) and center impact crashes were grouped. The second configuration group consisted of driver-side small overlap and driver-side oblique corner impacts. Given the much lower overall injury rates for passenger-side small overlap and oblique corner crashes (Fig. A2), as well as for perpendicular crashes, these configurations were not analyzed. Underride and oblique center crashes had a higher injury rate but insufficient cases with EDR data to study individually. Based on the potential for different driver kinematics they also were excluded.

There were only four drivers (unweighted) with associated EDR data and an AIS ≥ 3 injury from a driver-side small overlap or oblique corner crash, so the presence of an AIS ≥ 2 non-extremity injury or fatality (MAIS2+F) was used for the crash configuration comparison (raw cases shown in Fig. 5). Using the weighted data, a logistic regression model estimated the effects of crash configuration, driver age and EDR-reported delta-V on the likelihood of sustaining an MAIS2+F injury. There were statistically significant interactions between crash configuration and age ($p = 0.003$) as well as between crash configuration and delta-V ($p < 0.001$), with larger estimated effects of increasing driver age or delta-V on the odds of injury in the group of small overlap/oblique crashes. For the group of moderate overlap, large overlap and center impact crashes, the effect of driver age on the likelihood of sustaining an MAIS2+F injury was not significant ($p = 0.36$). This result was found to be consistent with a model based on the primary regression dataset of 911 crashes with an EDR or EDR-equivalent delta-V. For this larger dataset there was no significant effect of driver age on MAIS2+F injury risk, despite the strong effect of age on MAIS3+F injury risk. Figure 6 shows the estimated risk of MAIS2+F injury by EDR delta-V for the two crash configuration groups along with 95% confidence intervals. The risk in small overlap/oblique crashes is estimated for a 42 year-old driver, the weighted median age of drivers in this group. Since the effect of driver age on MAIS2+F injury risk was not significant in the other configurations, it was dropped from the final model; the estimated risk presented in Figure 6 is for all ages.

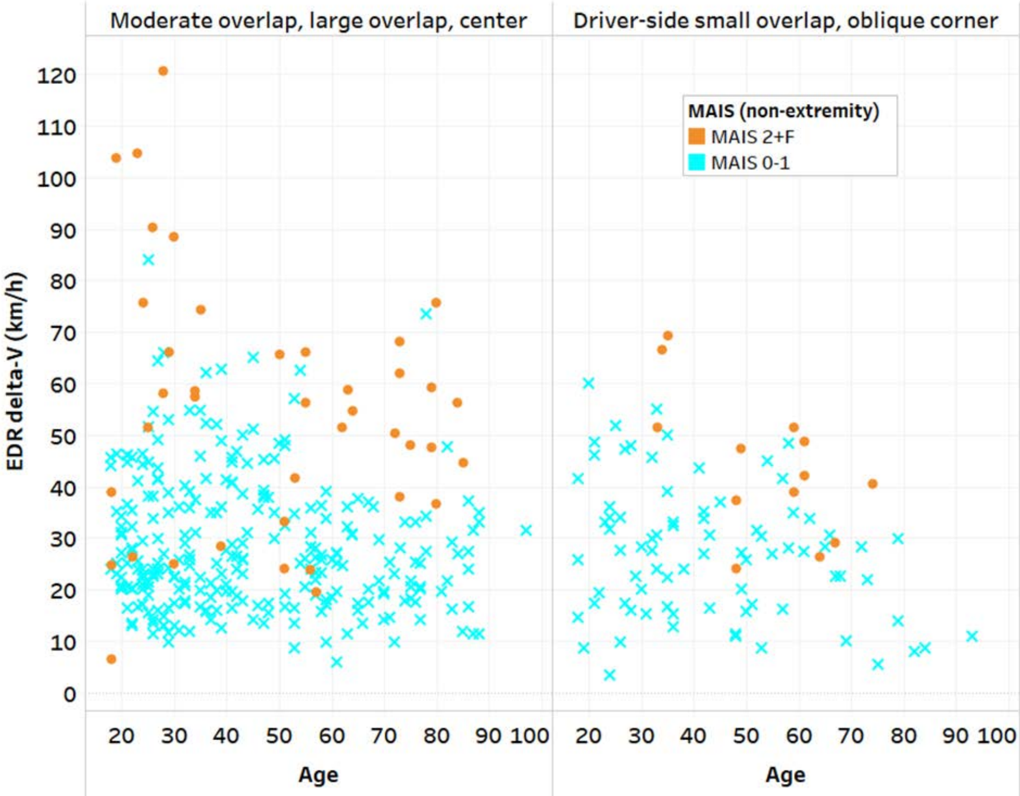


Fig 5. EDR delta-V, driver age and MAIS2+F injury status by crash mode

IV. Discussion

Front crash evaluation programs in the US consist of NHTSA's New Car Assessment Program (NCAP) full-width test, the IIHS 40% moderate overlap test, and the IIHS 25% small overlap tests on the driver and passenger sides. After controlling for driver age and delta-V, regression models did not find a significant difference between injury risk in real-world large overlap, moderate overlap, and center impact crashes. It was not possible to estimate differences between injury risk in colinear small overlaps and oblique corner impacts since WinSMASH delta-Vs could not be used to estimate EDR delta-Vs in these two modes, but previous crash testing suggests that while risk magnitudes may be different in these modes, the sources of risk are similar [22]. Based on these observations, around three-fourths of the real-world impact configurations that produced serious injury in the NASS-CDS dataset are at least somewhat represented by existing front evaluation programs. The current study was focused on vehicles with good performance in the IIHS moderate overlap test, which has been in place for the longest period of time without significant changes to the rating procedure.

The IIHS moderate overlap test is conducted at an impact speed of 64.4 km/h, which has produced a median longitudinal delta-V of 69.9 km/h. This is greater than the median EDR-based delta-V (63 km/h) for drivers of good-rated vehicles who sustain an MAIS3+F injury in a real-world moderate overlap, large overlap, or center impact crash. By definition, good-rated vehicles have a low risk of injury as predicted by the measurements taken on the anthropometric test device (ATD) in this test. But the estimated risk of injury to a human driver at this speed is highly dependent on age, with drivers 60 and older facing a serious injury risk around 60%, or 8 times greater than drivers aged 18-39 (Fig. 3). There likely is an even greater disparity in fatality risk, as previous research has shown higher mortality risk for older occupants with the same AIS level injury [19,23]. The current study is further evidence of the need for improved protection of older drivers, especially related to the risk of thoracic injury (Fig. 4).

Additional research will investigate whether the NASS-CDS dataset utilized in this study can provide insight into which specific ATD or vehicle measurements taken in the IIHS moderate overlap test and NHTSA's full-width NCAP test are most relevant to the risk of thoracic injury. Brumbelow and Farmer [17] found a general relationship between Hybrid III chest deflection in the IIHS test and thoracic injury risk in similar crash modes, but they were not able to establish age-specific risks and they used only a coarse control for crash severity. It is possible that the set of good-rated vehicles offer a wide range of thoracic protection. If some of the metrics already being collected in test programs are able to predict the real-world risks to specific age groups, they could be given greater emphasis in an updated rating system or a supplemental rating for older drivers.

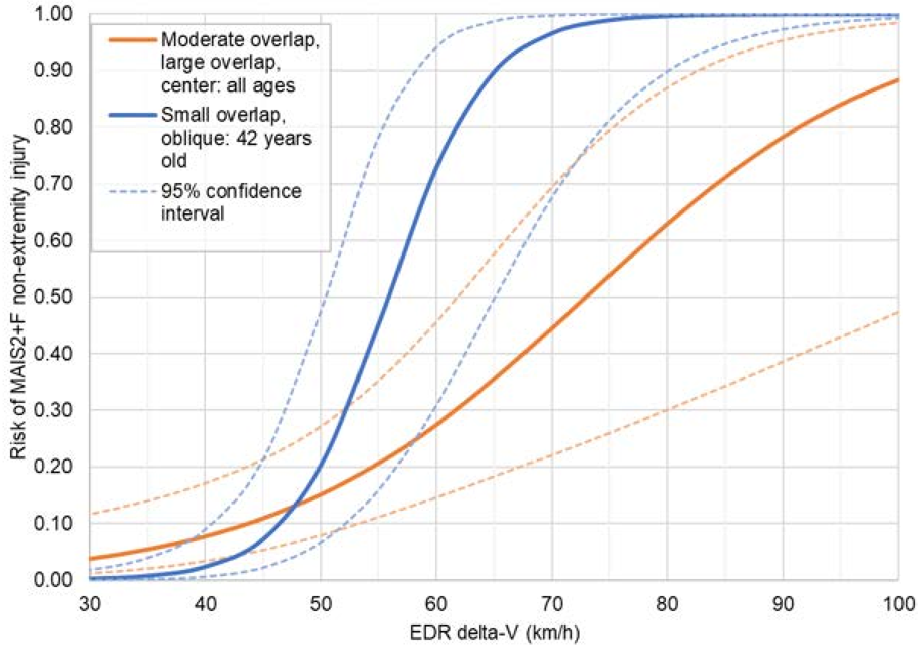


Fig. 6. MAIS2+F injury risk by EDR delta-V and crash configuration

Another finding by Brumbelow and Farmer [17] was the indication that the overall risk of serious driver injury in a vehicle in a real-world small overlap crash was inversely related to the ATD chest deflection measured in the moderate overlap crash test of the same vehicle. In other words, there was an apparent trade-off between thorax protection in crashes with more overlap and overall protection in crashes with less overlap. The current study provides additional insight into why this may be the case, finding that most serious head injuries were sustained in small overlap and oblique crashes but most serious thoracic injuries resulted from crashes with more overlap. In the IIHS small overlap test program there have been many instances of minimal or no interaction between the ATD head and airbag [22]. In such scenarios, seat belt systems that reduce chest deflection but allow greater excursion could increase the risk of head injury. Since the small overlap evaluation was introduced, the proportion of good ratings has increased from 12% of 2012 model year vehicles to 74% of 2018 models. The current study is limited by the fact that only 14% of the included vehicles were model year 2012 or later, so it was not possible to analyze whether improved performance in the small overlap crash test program has helped minimize the apparent trade-off between protection in different front crash configurations. This will be an important topic for future research.

Using only cases with an EDR, the current data do indicate a significant difference in MAIS2+F injury risk between small overlap/oblique crashes and those with more overlap after controlling for longitudinal delta-V. Longitudinal delta-V is only one measure of severity, and it is possible that the injury risks are similar in terms of resultant acceleration, barrier equivalent speed, or other metrics. For example, the IIHS moderate and small overlap tests are both conducted at an impact speed of 64.4 km/h, but have produced median longitudinal delta-Vs of 69.9 and 51.7 km/h, respectively. Applying these values to the configuration-specific regression models (Fig. 6) results in a greater estimated MAIS2+F injury risk for a 42 year-old driver in a moderate overlap crash with a 70 km/h delta-V than in a small overlap with a 52 km/h delta-V (45% and 29%, respectively). However, for drivers older than 45 the estimated MAIS2+F risk is greater in the small overlap crash.

The lack of a significant effect of age on the odds of MAIS2+F injury in moderate overlap, large overlap, and center impact crashes is a noteworthy finding. Given the well-established relationship between age and reduced injury tolerance—even in these crashes, age had a strong effect on the likelihood of MAIS3+F injury—this result implies that after controlling for crash configuration and severity, the presence of an AIS2 non-extremity injury may not be a sufficiently precise metric for assessing the potential benefits of front crashworthiness countermeasures. Measuring the ability of a countermeasure to eliminate less serious injuries may require considering the number of AIS2 injuries, the specific type of AIS2 injury being targeted, or using a different metric such as recovery time. Gustafsson et al. found that AIS1-2 injuries were associated with a greater risk of long-term impairment for older occupants [24].

The magnitude of any injury risk increase resulting from vertically misaligned vehicle structures could not be quantified in the current study. While underride occurred in 18% of the cases with a severe injury, the poor correlation between EDR and SMASH delta-V, and the small number of EDR underride cases with serious injury (n=5), meant that the effect of underride could not be studied while controlling for crash severity. The study does demonstrate the necessity of photographic review for identifying such cases in NASS-CDS, as only 37% of the cases with visually apparent underride were coded as such. Most of the underride cases result in serious injury were front-to-front crashes involving two passenger vehicles. Previous research has indicated that SUV and pickup compatibility with other vehicle types has improved [25,26], but given the limited data the effect of partner model year could not be studied here.

It also is important to note that the inclusion requirements may have reduced the number of underride cases in the study, especially those with the most extreme underride. Cases with SMASH delta-Vs were included only if they were based on deformation measurements of the case vehicle, but since extreme underride focuses crush on vehicle structures with unknown stiffnesses these vehicles may not be measured as frequently. In addition, only cases with deployed airbags were included but airbag deployment algorithms may not trigger in vehicles with extreme underride. In IIHS crash tests conducted between 2010-17, the front airbag did not deploy in four out of eleven tests in which a 2010 midsize sedan underrode the rear or side of a semi-trailer. These factors might help explain why the current study included only one driver with a serious injury from an underride crash involving a commercial vehicle. In 2016, 11% of passenger vehicle occupant fatalities occurred in crashes involving a large truck [27].

Linking EDR and SMASH delta-Vs based on crash configuration provides a more accurate crash severity control than simply using SMASH delta-V, while allowing the inclusion of more cases than restricting to those with EDR output. Other research has found that EDRs may still underreport delta-V relative to more accurate measurements taken in crash tests [9] but the additional EDR inclusion requirements applied in the current study may have reduced this disparity. Regardless, longitudinal delta-V is just one crash severity metric and does not fully capture the risks associated with a given crash. Stigson et al. found that a combination of peak acceleration and delta-V predicted MAIS2+ injury outcomes better than delta-V alone [15]. Since peak acceleration is not known for the cases with SMASH delta-Vs, and would be of questionable accuracy from the large number of 100 Hz EDRs, it could not be included.

V. CONCLUSIONS

The ability of crush-based delta-V to accurately estimate the severity of a frontal crash as reported by an EDR depends upon the impact configuration. Photographic review allows crashes to be categorized and risks assessed using more accurate delta-V estimates. Impact configuration, driver age, and delta-V all have significant effects on the risk of injury in frontal crashes of vehicles with good ratings in the IIHS moderate overlap program. In real-world crashes of similar severity to the crash test, there is substantial risk of serious injury, especially of thoracic injuries of older drivers.

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VII. APPENDIX

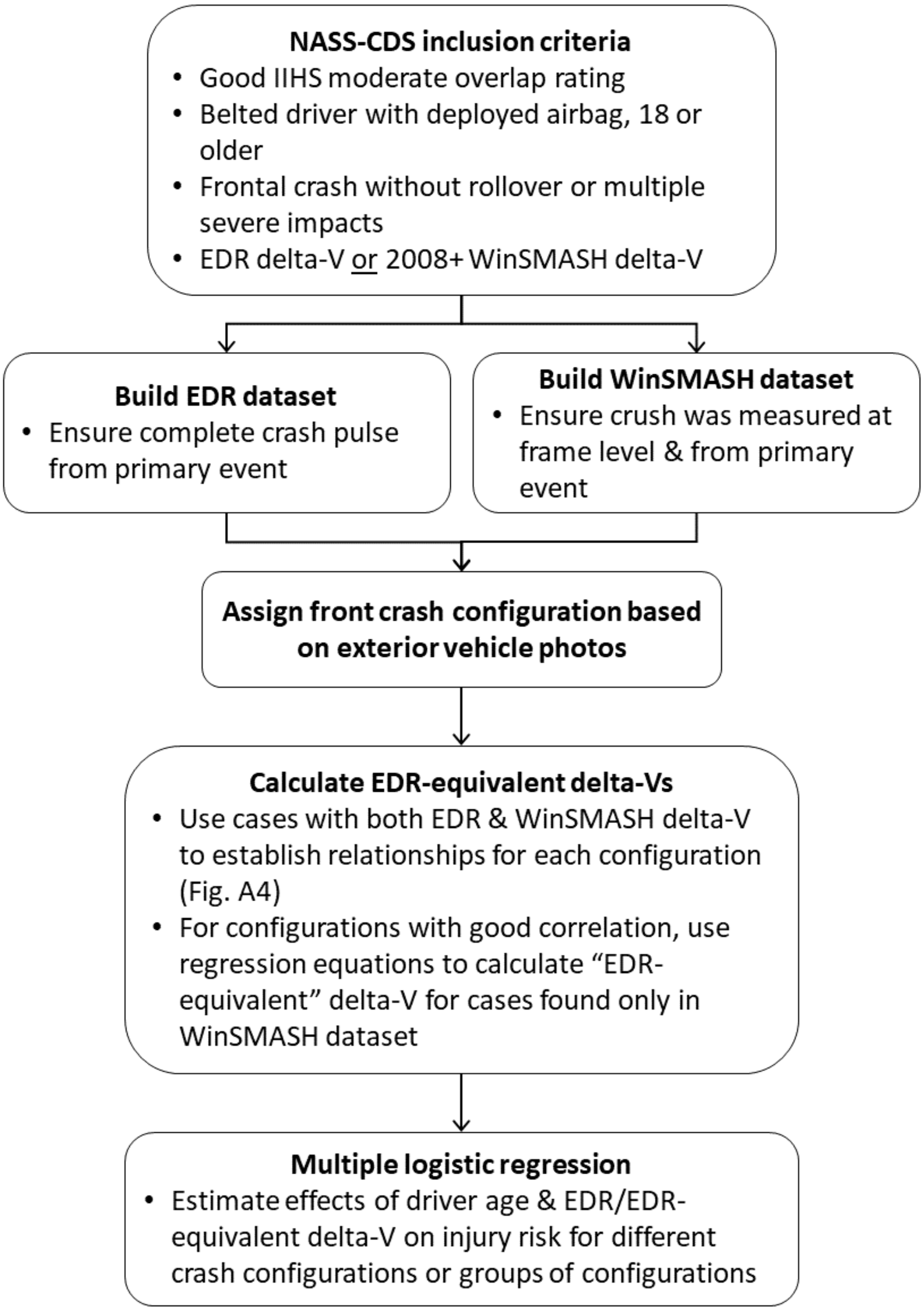

Fig. A1. Summary of study methodology

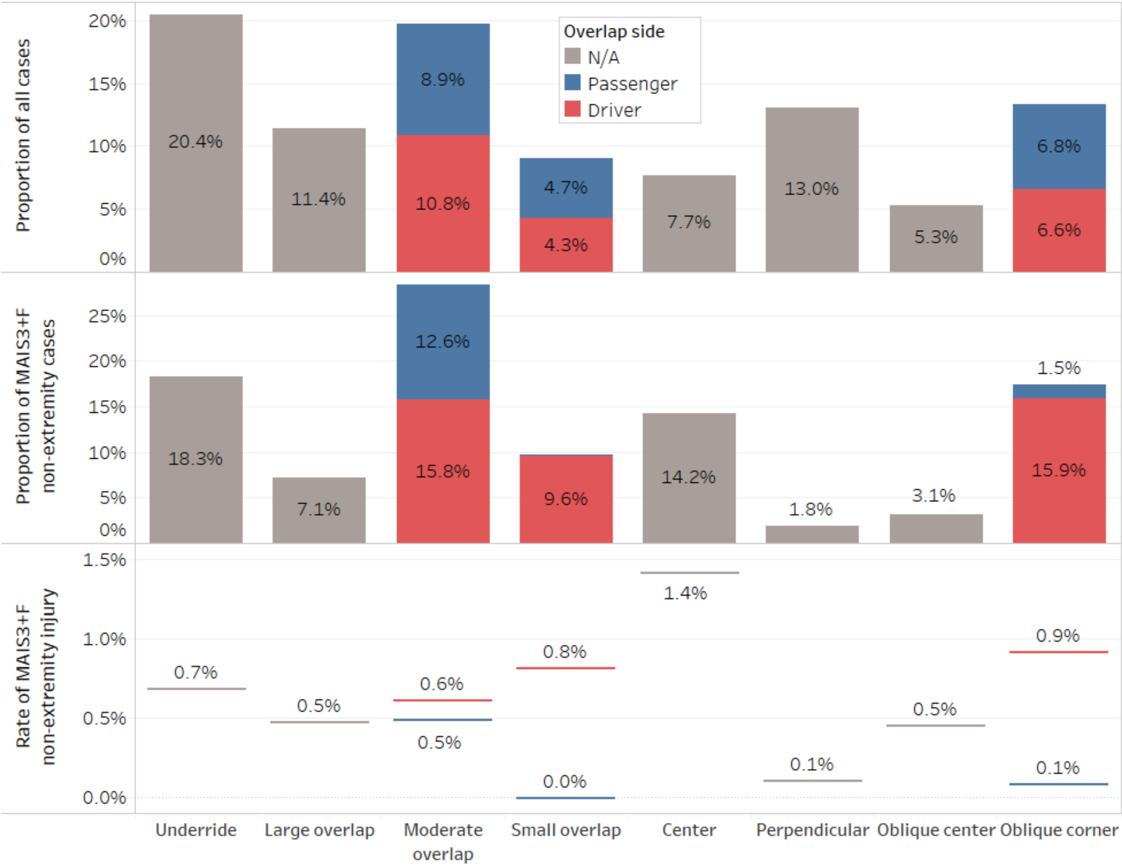

Fig. A2. Weighted crash configuration distributions and injury rates

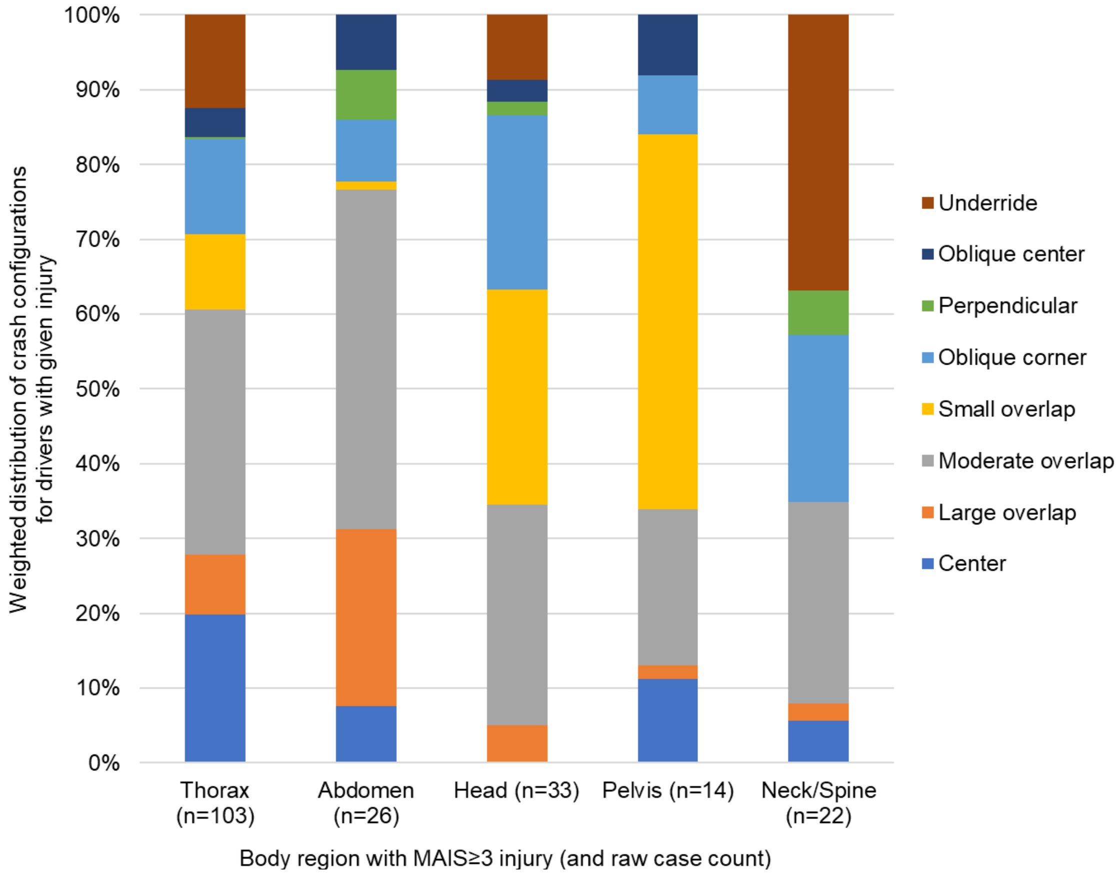

Fig. A3. Weighted crash configuration distributions by injured body region

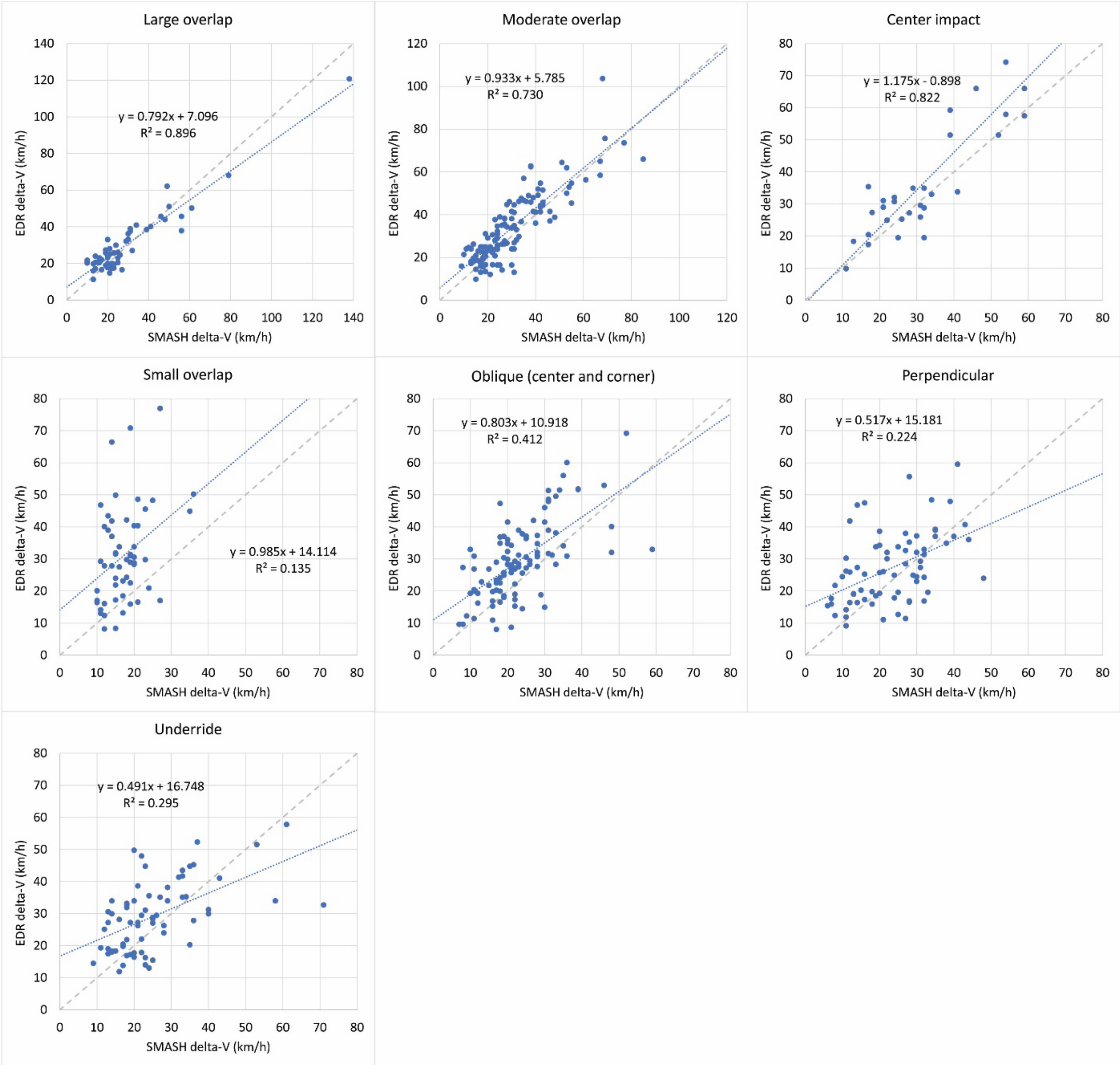

Fig. A4. SMASH vs EDR longitudinal delta-Vs by crash configuration