



# Automated crash notification: Evaluation of in-vehicle principal direction of force estimations



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## ABSTRACT

Advanced Automated Crash Notification (AACN) algorithms use telemetric data from vehicles to notify emergency services of a collision involving the vehicle. The aim is to quickly dispatch the appropriate medical response to the crash scene. An important part of AACN systems is predicting occupant injury, which is highly dependent on the side of the vehicle that is struck in a crash. A given frontal collision has a 9% probability of serious injury. A collision with the same speed and conditions to the left side of the vehicle results in a predicted 38% probability of serious injury.

One method for estimating the damage side is to use in-vehicle sensors available on current vehicles by using the Principal Direction of Force (PDOF) derived from accelerometer-based measurements. PDOF is only the direction of the crash impulse, it does not specify the damage side. For example a PDOF of 45° could as easily be a front impact as a side impact. Using PDOF as a surrogate for damage side may be appropriate in many collisions but not in others. This study examined the accuracy of PDOF estimates made from in-vehicle sensors recorded by the Event Data Recorder (EDR) and the implications of using these PDOF estimates as a surrogate for estimating damage side in real-world collisions.

We found that PDOF estimates made from in-vehicle sensors were accurate compared to crash test instrumentation examined in 54 side impact tests. PDOF estimates based on the EDR sensors and crash test instrumentation were within 10° of each other and had a root mean squared difference of 4.4°. In 10% of the 146 real-world collisions examined, using PDOF computed by the EDR as a surrogate for damage side would incorrectly identify the damage side. Furthermore, the PDOF estimated by crash investigators and the EDR differed by up to 45° in crashes. These discrepancies have major implications for the accuracy of AACN systems because injury risk estimates are derived from investigator PDOF estimates. A possible solution is to use EDR data to develop future AACN injury risk predictions instead of investigator PDOF estimates.

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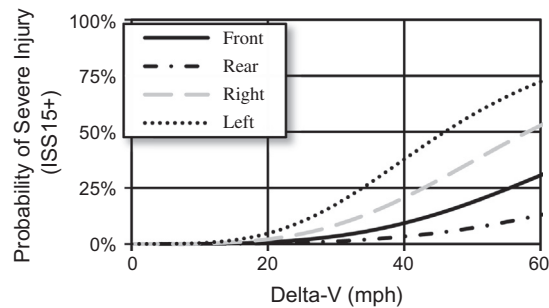
## 1. Introduction

Automated crash notification algorithms use telemetric data from vehicles to notify emergency services of a collision involving the vehicle. The aim is to quickly dispatch the appropriate medical response to the crash scene. Appropriate field triage, or the decision of how to transport and treat a trauma victim, can greatly reduce mortality. Trauma victims who are transported to a Level 1 trauma center have 20% decreased mortality compared to those treated at a regular hospital

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**Fig. 1.** Probability of serious injury (ISS15+) in a vehicle by damage side as a function of  $\Delta V$  (mph). These curves compare similar crashes involving a car, single impact, all occupants belted, no females, and no older occupants (Kononen et al., 2011).

(MacKenzie et al., 2006). On the other hand, the activation of trauma teams for minor injuries is costly. Therefore, a correct triage decision is crucial. Recent recommendations from the American College of Surgeons suggest that trauma management systems should include vehicle telemetric data as part of their triage system (ACOS, 2006).

One promising strategy for Advanced Automated Crash Notification (AACN) systems is to transmit the data currently being stored in Event Data Recorders (EDRs) to a trauma center to allow prediction of occupant injury risk almost instantly after a crash occurs. In a crash the EDR now in most passenger cars and light trucks record many important components related to injury risk including occupant belt use, crash change in velocity ( $\Delta V$ ), airbag deployment timing, and the number of impact events in the crash. Some EDRs store this information using onboard memory that can be accessed after a crash occurs. The instrumentation in current EDRs cannot, however, determine the impact location or damage side of a crash. Injury risk is a strong function of damage side (front, left, right, or rear) as shown in Fig. 1.

Previous studies have found that damage side, when used in conjunction with other crash characteristics (e.g.  $\Delta V$ , multiple impacts, occupant age), is significantly correlated to occupant injury outcome. One model developed by Bahouth et al. (2004) called the URGENCY algorithm found that for every 10 kph increase in  $\Delta V$ , occupants involved in frontal collisions had a 3.7 times increase in the odds of injury compared to a 5.0 time increase for nearside impact occupants. Another quantitative injury risk function developed by Kononen et al. (2011) found damage side was also a significant predictor of serious injury. Fig. 1, from Kononen et al., shows the risk of serious injury by damage side for any occupant in the vehicle. In their study, serious injury was defined as an Injury Severity Score (ISS) greater than 15 (ISS15+). For a collision with a  $\Delta V$  of 40 mph, the risk of serious injury for front, rear, right, and left impacts is 9%, 3%, 21%, and 38%, respectively, all other factors in the crash the same. This demonstrates that damage side can dramatically influence the injury outcome in a crash. If an AACN algorithm picks the incorrect damage side for a collision, the subsequent injury risk predictions will be severely biased.

Principal Direction of Force (PDOF) is often used as a surrogate for damage side in automated crash notification systems (Geisler and Michelini, 2011). PDOF is defined as the direction of the resultant crash force upon the subject vehicle. PDOF can be computed using data from biaxial accelerometers that are in the airbag control modules of some vehicles. The accuracy of EDR  $\Delta V$  measurements have been examined in the past (Niehoff and Gabler, 2005). The accuracy of PDOF estimates derived from EDR data has not been investigated, however. In full engagement collisions, PDOF is relatively constant through the crash (Rose et al., 2004). However, real-world collisions often are not full engagement collisions and may involve sliding (e.g. against a guardrail or side of another vehicle).

Although technically an improper use of PDOF, PDOF may be a reasonable indicator of damage side in some crashes, but not in others. In the URGENCY algorithm PDOF was used to classify damage side. Kononen et al. also used PDOF to determine damage side: 11, 12, or 1 o'clock was frontal damage, 2–4 o'clock was right damage, 5–7 o'clock was rear damage, and 8–10 o'clock was left damage. Therefore, PDOF estimates made in the vehicle are directly related to the accuracy of damage side predictions. Because of AACN algorithms' heavy dependence on PDOF estimates, it is vital to assess the accuracy of PDOF measurements made in the vehicle and the implications of using PDOF as an estimate of damage side. This assessment has not been previously done using EDR data, the basis for these PDOF predictions in future AACN systems.

The objectives of this study are to (1) determine the accuracy of PDOF estimates made by the EDR and (2) determine the implications of using PDOF as a surrogate for damage side in real-world for use in AACN algorithms.

## 2. Methodology

The first phase of this study was to examine a set of EDR Data downloaded from vehicles involved in staged crash tests which were equipped with laboratory instrumentation in order to assess the accuracy of PDOF predictions made by the EDR. The second phase was to examine a set of EDRs recovered from real-world collisions.

## 2.1. Event data recorders and PDOF computations

EDRs can provide an important record of the vehicle kinematics during a crash. In most vehicles, EDRs are part of the airbag control module which contains one or more accelerometers used to detect the occurrence of a crash. Proprietary algorithms are used to analyze vehicle acceleration to determine when the airbag should fire in the event of crash. If the module has determined a crash event is likely, the EDR ‘wakes up’ and begins to compute the vehicle change in velocity, or  $\Delta V$ , by integrating the vehicle acceleration. After each event, the  $\Delta V$  time history and other data, e.g. belt use and airbag deployment time, are stored in the memory of the EDR. In the event of an airbag deployment, the data is locked in the memory and cannot be overwritten.

With the proper download tool, e.g., the Bosch Crash Data Retrieval (CDR) System, the data can be recovered. The publicly available Bosch CDR tool originally supported select GM, Ford, and Chrysler vehicles. Within the last year, the tool has added support for Toyota/Lexus/Scion, Honda/Acura, Mazda, Nissan/Infiniti, Isuzu, and Saab vehicles as well as limited models of Mitsubishi and Suzuki vehicles. GM modules have been supported since model year 1994 and Ford modules have been supported since model year 2001. Other makes have been added only recently (model years 2006–2011). For this study, we focused on GM and Ford modules, as these two makes have the most EDR data available from staged crash tests and real-world collisions.

Until recently, most EDRs only recorded longitudinal change in velocity, as early models only contained driver and/or right front passenger frontal airbags. With the introduction of vehicles with side deploying airbags, additional accelerometers were added allowing both the longitudinal and lateral acceleration of the vehicle to be recorded. In these newer EDRs, both the longitudinal and lateral  $\Delta V$  are stored in the EDR. At any given point in time, a resultant  $\Delta V$  can be computed, as shown in Fig. 2. The angular direction of the resultant acceleration on the vehicle, and thus the angular direction of change in resultant  $\Delta V$ , is the PDOF. In this paper, all angular directions will be reported using the sign convention shown in the right of Fig. 2. The positive  $x$ -direction is oriented in the longitudinal direction, and the positive  $y$ -direction is oriented toward the right front passenger side door of the vehicle. Angles were restricted to between  $-180^\circ$  and  $180^\circ$ .

Using this convention, the PDOF at any given time during an event can be computed as:

$$\text{PDOF} = \tan^{-1} \left( \frac{-\Delta V_y}{-\Delta V_x} \right) \quad (1)$$

where  $\Delta V_y$  is the change in velocity in the lateral direction and  $\Delta V_x$  is the change in velocity in the longitudinal direction.

Four-quadrant corrected tangent functions should be used in this computation (e.g.  $\text{ATAN2}$ ). This ensures that the direction of the longitudinal and lateral change in velocities is accounted for. Also, special care should be taken for cases where the longitudinal change in the velocity is equal to zero, as this produces a non-real result. In the algorithms implemented in this study, if both longitudinal and lateral  $\Delta V$ s were equal to zero, there was no PDOF because the vehicle is not being accelerated. Otherwise, if the longitudinal  $\Delta V$  was equal to zero and there was a lateral  $\Delta V$ , the PDOF was set to positive or negative  $90^\circ$ , depending on the direction of the lateral  $\Delta V$ . PDOF could also be computed using similar algorithms which use arcsine or arccosine functions.

The PDOF computed in Eq. (1) is an instantaneous value that reflects the longitudinal and lateral forces on a vehicle. For the purposes of AACN algorithms, the crash event must be reduced to a characteristic PDOF that represents the entire crash event. There are many possible algorithms to reduce the time history of PDOF into a single characteristic PDOF. One of the simplest is to compute the PDOF using the maximum magnitude of the longitudinal and lateral  $\Delta V$  recorded in the crash, which we will refer to as the  $\Delta V_{\max}$  algorithm. The aim of the  $\Delta V_{\max}$  algorithm is to capture the most characteristic PDOF (i.e. resulting from the largest magnitude impulse) in the crash. The longitudinal and lateral maximum  $\Delta V$  may occur at different points in time, however, and the result of the  $\Delta V_{\max}$  algorithm may be a PDOF that is never experienced by the vehicle. Another possible algorithm is to use the maximum longitudinal  $\Delta V$  and the lateral  $\Delta V$  that corresponds to that point in time, which we will refer to as the  $\Delta V_{\max,x}$  algorithm. Alternatively, the maximum lateral  $\Delta V$  and longitudinal  $\Delta V$  at that time will be called the  $\Delta V_{\max,y}$  algorithm. Table 1 summarizes the three proposed PDOF algorithms.

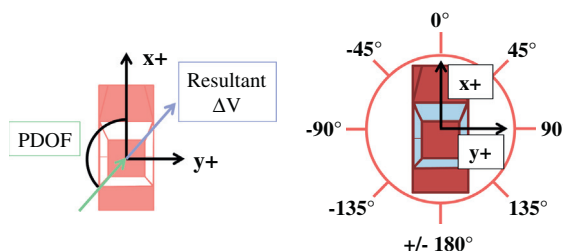


Fig. 2. Schematic of resultant  $\Delta V$  and PDOF (left) and angular direction convention (right).

**Table 1**  
Description of PDOF estimate algorithms.

Algorithm name	Formulation
$\Delta V_{\max}$	Maximum $\Delta V_x$ and maximum $\Delta V_y$
$\Delta V_{\max,x}$	Maximum $\Delta V_x$ and $\Delta V_y$ at maximum $\Delta V_x$
$\Delta V_{\max,y}$	Maximum $\Delta V_y$ and $\Delta V_x$ at maximum $\Delta V_y$

## 2.2. Staged crash tests

Cases were selected from a set of over 170 EDRs recovered from New Car Assessment Program (NCAP) frontal and side impact crash tests. NCAP is a program sponsored by the National Highway Traffic Safety Administration (NHTSA) which provides consumers with star safety ratings for new vehicles. The NCAP includes three types of crash tests used to compute the vehicle's star rating: (1) a frontal collision with a rigid barrier at 56.3 kph (35 mph), (2) a driver- or passenger-side impact from a vehicle surrogate, called a Moving Deformable Barrier (MDB) at 62.0 kph (38.5 mph), and (3) a side impact at the driver position with a rigid pole at 32.2 kph (20 mph). All of the MDB tests examined for this study were driver-side impacts. The NCAP crash tests were updated starting with model year 2011 to include the pole side impact test. Prior to model year 2010, vehicles were only required to undergo the frontal barrier and MDB tests in order to receive a star rating. PDOF estimates are not possible in frontal barrier crash because frontal barrier crash tests typically only include longitudinal accelerometers. Even if there were lateral accelerometers in frontal barrier crash tests, the PDOF estimates would all be nearly head-on because the entire vehicle frame engages the barrier with no offset. Therefore, this study only examined PDOF estimates from MDB and pole side impact tests.

The approach to validate PDOF measurements made by the EDR was to compare the EDR to the crash test instrumentation. Accelerometers in NCAP tests are not placed directly on the EDR module. All vehicles examined in this study had the EDR located in the center tunnel of the vehicle, near or on the vehicle centerline. Most EDRs that record dual axis acceleration are placed near the vehicle C.G. in order to best capture the crash pulse experienced by the vehicle. Precise locations of the EDR were not available, however. In this study, the crash test instrumentation from the vehicle C.G. was compared to the EDR. In some cases the accelerometer located at the vehicle C.G. failed. These cases were excluded from the analysis. Crash test accelerometer data was filtered to a Channel Frequency Class (CFC) of 180 Hz according to SAE J211, which is standard practice for analysis of crash test accelerometer data (SAE, 2007).

If vehicle acceleration is measured only at one location, vehicle rotation during in the collision cannot be computed. As a result, PDOF estimates derived from different accelerometer locations in the same crash could potentially produce different results because of the rotating coordinate frame of the vehicle. The PDOF in a collision is defined as the direction of linear impulse at the vehicle center of gravity. Therefore, regardless of vehicle rotation the EDR will be exposed to the true PDOF if the EDR is located at the vehicle C.G. As stated above, most EDRs are placed near or at the vehicle C.G. The vehicle C.G. may be modified due to cargo in the vehicle, however. Rotational effects may especially affect PDOF estimates in crashes where the primary damage location is at the edges of the vehicle, e.g. small frontal offset crashes, where there is a potential for large moment arms between the crash force and vehicle C.G. The data recorded in current EDRs does not allow for correcting for rotation. Future vehicles with multiple accelerometer locations or rotational rate sensors may be able to account for rotation.

## 2.3. Real-world collisions

Real-world collisions were extracted from the National Automotive Sampling System, Crashworthiness Data System (NASS/CDS). NASS/CDS is a nationally representative sample of passenger vehicle collisions that occur in the US. Approximately 5000 collisions are investigated in depth each year by crash investigation teams throughout the country. Investigators visit the collision scene, interview those involved, acquire medical and police records, and inspect vehicles. When available, investigators extract the data from the vehicle's EDR. From NASS/CDS years 2000 to 2010, NASS/CDS has recovered the data from over 4000 EDRs in passenger vehicles involved in real-world crashes. Year 2010 is the most recent year of NASS/CDS that has available EDR data.

For analysis, only cases with complete, locked deployment records were used. EDRs can store data associated with events that did not deploy the airbags. However, these events are not locked in the memory of the device, so it cannot be known with certainty whether these non-deployment events correspond to the investigated crash events. Furthermore, only single event collisions were used. In the case of multi-event crashes, the event which corresponds to the locked EDR event cannot be determined with certainty. Collision involving rollover were also excluded.

## 3. Results

### 3.1. Exemplar PDOF estimates from crash test instrumentation and EDR

NHTSA test number 7352 and 7349 involved a 2011 Ford F-150 XLT Supercrew being impacted by a MDB and into a rigid pole, respectively. Fig. 3 shows pre- and post-test photographs for the F-150 in the MDB side impact test. This vehicle re-



Fig. 3. Pre-test (left) and post-test (right) photographs from NCAP MDB side impact test for 2011 Ford F-150 XLT Supercrew (test number 7352).

ceived a 5-star side crash test rating. The vehicle's overall star rating, which combines front, side, and rollover ratings, was 4 stars.

Fig. 4 shows the vehicle  $\Delta V$  found by integrating the biaxial accelerometer data from the vehicle C.G. and as recovered from the EDR for the MDB side impact test. In this test the  $\Delta V$  recorded by the EDR and computed from the instrumentation at the vehicle C.G. were very similar.

Fig. 5 shows the computed PDOF from the crash test instrumentation at the C.G. and the EDR for the MDB side impact test. Because the magnitude of the  $\Delta V$  is small in magnitude at the beginning of the impact compared to the end of the impact, PDOF measurements at the beginning of the test are sensitive to small variations in  $\Delta V$ . Taking the largest magnitude PDOF from the entire event would not be representative of most crashes, as there are large variations in the first 50 ms of all crash tests observed. The characteristic PDOF estimates using the  $\Delta V_{\max}$ ,  $\Delta V_{\max,x}$ , and  $\Delta V_{\max,y}$  algorithms are also marked on the graph. The PDOF estimates using the  $\Delta V_{\max}$  algorithm are similar:  $-78.7^\circ$  for the EDR and  $-79.0^\circ$  for the crash test instrumentation. The two dashed lines fall almost on top of each other in the figure, with the EDR slightly closer to zero than the crash test instrumentation.

Fig. 6 shows the instrumentation and EDR  $\Delta V$  for the same F-150 model in the pole side impact test. In the pole test the vehicle is slid laterally with a  $15^\circ$  angle into a rigid pole with a speed of 32.3 kph (20 mph). As a result, the vehicle has both initial  $x$ - and  $y$ -components of velocity. The PDOF estimates from the instrumentation and EDR visually do not appear as similar as in the MDB side impact test, but still have the approximate magnitude and shape as the crash test instrumentation.

Fig. 7 shows the PDOF estimates for the instrumentation and EDR for the pole side impact test. Visually the curves are not as well matched as the MDB EDR and crash test instrumentation. The  $\Delta V_{\max}$  algorithm for the EDR produced a PDOF estimate of  $-74.0^\circ$  compared to the crash test instrumentation estimate of  $-75.4^\circ$ .

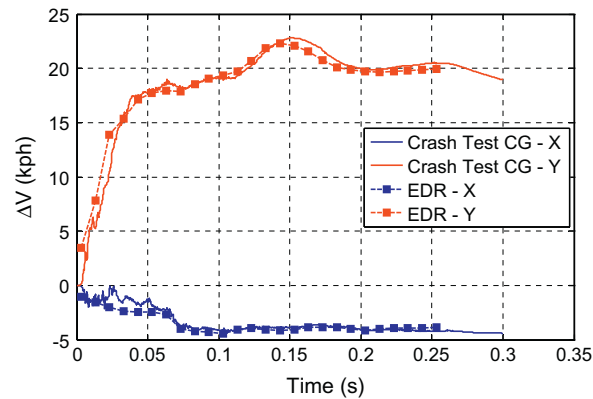
### 3.2. Staged crash tests

We extracted 36 NCAP MDB and 27 NCAP pole side impact crash tests that had GM and Ford EDRs with dual axis  $\Delta V$  information. Of these tests, 5 MDB and 4 pole tests were discarded because the vehicle C.G. accelerometers failed, leaving a total of 54 crash tests that were analyzed. In total, 27 unique makes and models were tested (14 GM and 13 Ford). Not all vehicles were tested under all test conditions and some vehicles were tested multiple times under the same conditions. The vehicles and test numbers used for this analysis are tabulated for reference in the Appendix.

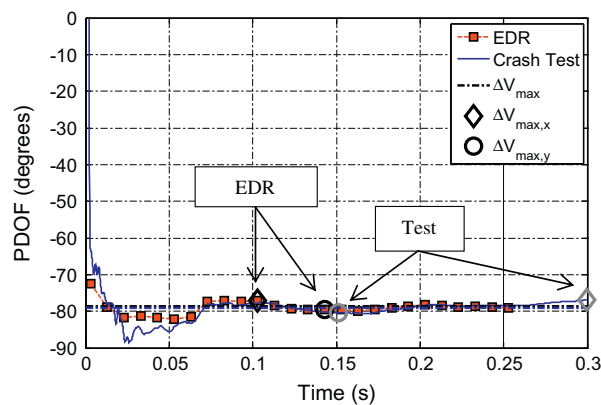
Fig. 8 compares PDOF estimates using the  $\Delta V_{\max}$ ,  $\Delta V_{\max,x}$ , and  $\Delta V_{\max,y}$  algorithms using the crash test instrumentation. If the algorithms produced identical PDOF estimates, all of the points would lie along the solid diagonal line. The graph on the left separates tests by test configuration (MDB or pole) and the graph on the right separates tests by body type (car or light truck or van, LTV). In all cases, the  $\Delta V_{\max,x}$  algorithm produced a PDOF closer to zero and the  $\Delta V_{\max,y}$  algorithm produced a PDOF oriented further from zero compared to the  $\Delta V_{\max}$  algorithm. Based on paired  $t$ -tests, all three algorithms ( $\Delta V_{\max}$ ,  $\Delta V_{\max,x}$ , and  $\Delta V_{\max,y}$ ) produced statistically different PDOF estimates from one another. In most cases the estimates are within  $5^\circ$  of each other. The accuracy of PDOF estimates did not seem to be affected by test configuration or vehicle type.

In case number 6720, a pole impact test of a 2010 Ford Mustang, the  $\Delta V_{\max,x}$  estimate was  $-62.7^\circ$  compared to the  $\Delta V_{\max}$  estimate of  $-75.1^\circ$ . Upon examination of the  $\Delta V$  histories for this test, the maximum longitudinal value occurred early in the test as an acute spike, which did not appear to be the result of accelerometer failure. The maximum longitudinal  $\Delta V$  was still on the rising portion of the lateral  $\Delta V$  pulse. As a result the  $\Delta V_{\max,x}$  estimate was different from the  $\Delta V_{\max}$  estimate. This illustrates that when the majority of an impulse is along one of the primary axes, e.g. laterally dominated as in side impact tests, small variations in the  $\Delta V$  in the other axes can influence the PDOF estimate. The  $\Delta V_{\max}$  algorithm is not as sensitive to this phenomenon because it considers the largest component of both axes.

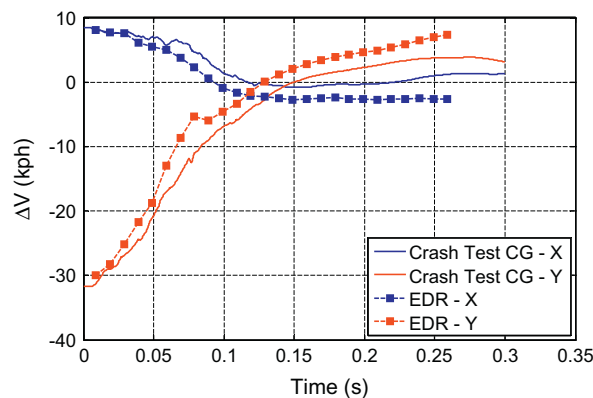
Table 2 shows the mean differences between PDOF algorithms computed from crash test instrumentation. In magnitude, on average the three algorithms are more similar in MDB tests than pole tests. The  $\Delta V_{\max,x}$  and  $\Delta V_{\max,y}$  algorithms are the furthest apart on average. The  $\Delta V_{\max}$  algorithm appears to be between the  $\Delta V_{\max,x}$  and  $\Delta V_{\max,y}$  algorithms, which makes the  $\Delta V_{\max}$  algorithm a good candidate to produce a representative PDOF estimate. All of the crash tests here were side impact tests where the  $\Delta V$  in the lateral direction is much greater than that in the longitudinal direction. In crashes with a larger range of PDOF, the  $\Delta V_{\max}$  algorithm may provide a better estimate of PDOF. The conclusion is that in side impacts all three



**Fig. 4.** Longitudinal ( $x$ ) and lateral ( $y$ )  $\Delta V$  from integrating crash test accelerometers and recorded by EDR for MDB side impact of Ford F-150 XLT Supercrew (test number 7352).



**Fig. 5.** PDF estimates derived from crash test instrumentation at vehicle C.G. and EDR for MDB side impact test of Ford F-150 Supercrew (test number 7352).

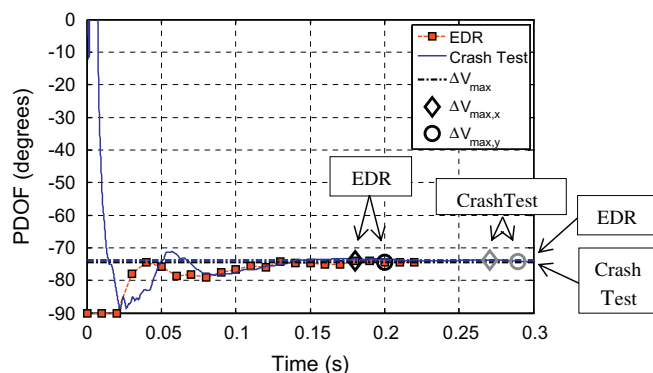


**Fig. 6.** Longitudinal ( $x$ ) and lateral ( $y$ )  $\Delta V$  from integrating crash test accelerometers and recorded by EDR for pole side impact of Ford F-150 Supercrew (test number 7349).

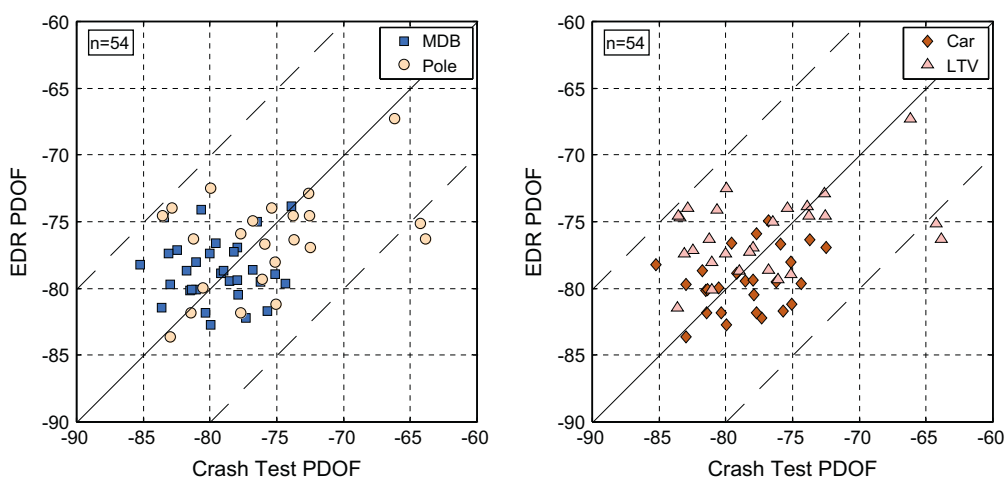
algorithms produce similar PDF estimates for the level of accuracy required by AACN systems. The  $\Delta V_{\max}$  algorithm will be presented exclusively for the remainder of this study.

Fig. 9 compares the  $\Delta V_{\max}$  PDF estimates from the crash test instrumentation and EDR. For most tests the two estimates were within  $10^\circ$  of each other, shown by the dashed lines. The root mean squared difference between the crash test instrumentation and EDR PDF estimates was  $3.7^\circ$  for MDB tests,  $5.2^\circ$  for pole test, and  $4.4^\circ$  for all tests. Based on a paired  $t$ -test,





**Fig. 7.** PDOF estimates derived from crash test instrumentation at vehicle C.G. and EDR for pole side impact test of Ford F-150 Supercrew (test number 7349).



**Fig. 8.** Comparison of  $\Delta V_{\max}$ ,  $\Delta V_{\max,x}$ , and  $\Delta V_{\max,y}$  PDOF algorithms using crash test instrumentation.

**Table 2**

Mean differences between PDOF algorithm estimates for crash test instrumentation in MDB and pole side impact tests.

	MDB (deg)	Pole (deg)	All (deg)
$\Delta V_{\max}$ to $\Delta V_{\max,x}$	-1.3	-1.9	-1.5
$\Delta V_{\max}$ to $\Delta V_{\max,y}$	1.7	2.6	2.1
$\Delta V_{\max,x}$ to $\Delta V_{\max,y}$	2.9	4.5	3.6

there is no statistically significant difference between EDR and crash test instrumentation ( $p = 0.81$ ). As a point of reference, Smith and Noga (1982) found that PDOF estimates from field measurements can vary as much as  $\pm 20^\circ$ . We conclude that the EDR produces reasonable PDOF estimates compared to crash test instrumentation for use in AACN systems.

In conclusion, by examining PDOF estimates from the EDR and crash test instrumentation from MDB and pole side impact tests we found that:

- The three algorithms ( $\Delta V_{\max}$ ,  $\Delta V_{\max,x}$ , and  $\Delta V_{\max,y}$ ) produced PDOF estimates within  $5^\circ$  of each other.
- The EDR produces PDOF estimates that are within  $10^\circ$  of the crash test instrumentation located at the C.G. of the vehicle.
- The EDR estimates produce reasonable approximations of PDOF that could be used in AACN systems.

### 3.3. Real-world collisions

#### 3.3.1. PDOF estimates as a surrogate for damage side

Of 4649 GM EDRs from NASS/CDS 2000–2010 cases, 195 had dual-axes  $\Delta V$  with a locked deployment event. Of these, 134 were from single event collisions. From the 338 Ford EDRs from the same time period, 23 had dual-axes  $\Delta V$  with a locked

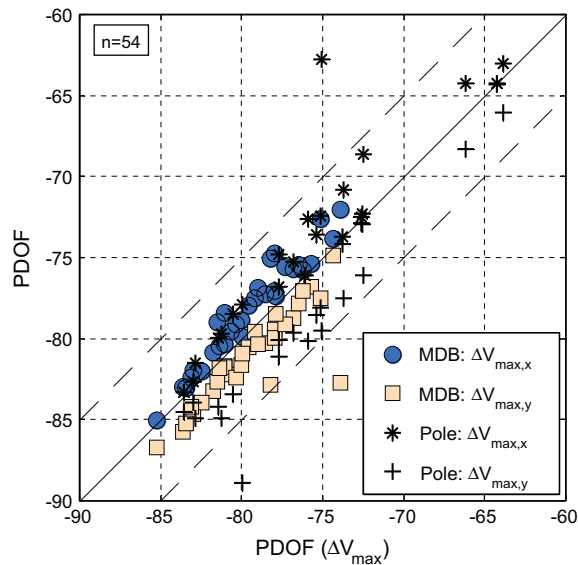


Fig. 9. Comparison of PDOF estimates from crash test instrumentation and EDR for  $\Delta V_{\max}$  algorithm.

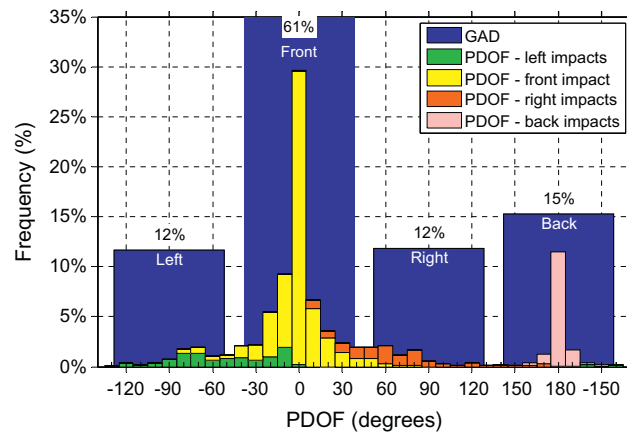


Fig. 10. Distribution of damage side (GAD) and PDOF for all vehicles in NASS/CDS year 2010.

deployment event. Of these, 14 were from single event collisions. The resulting dataset contained the records of 146 real-world collisions. The investigators found that 117 vehicles sustained frontal damage, 18 sustained right side damage, and 11 sustained left side damage.

The investigation teams in NASS/CDS determine the damage side and estimate the PDOF for each damaged vehicle. Fig. 10 shows the distribution of General Area of Damage (GAD) and PDOF estimated for all vehicles involved in collisions from NASS/CDS year 2010. Only passenger vehicles with known GAD and PDOF that did not rollover were included to capture the characteristics of planar collisions. There were 5536 of these vehicles corresponding to approximately 2.05 million crashes. The smaller bars show the proportion of cases with a PDOF of a given value, stacked by investigator reported damage side. For example, at a PDOF of  $-40^\circ$ , there were almost an equal number of crashes with damage side of front and left. The distribution of PDOF shows overlap between damage sides; therefore, using PDOF as a surrogate for damage side may not be appropriate, especially for PDOF close to  $\pm 45^\circ$ . Left damaged vehicles appear to especially overlap into frontal crashes with a considerable proportion of left damage vehicles having PDOF between  $-20^\circ$  and  $0^\circ$ .

Similarly, Fig. 11 shows a histogram of the number of cases per EDR PDOF estimate by damage side. Frequencies are normalized to the number of cases for each damage side. Although the majority of frontal damage cases are those that some automated collision notification systems have considered “frontal PDOFs” (i.e. PDOF of  $\pm 45^\circ$ ), cases with frontal damage had PDOFs ranging from  $-70^\circ$  to  $60^\circ$ . AACN systems using PDOF as a surrogate for damage side would misclassify many of these left or right side crashes as frontal crashes. The data from the EDRs and NASS/CDS suggests that using the PDOF for a surrogate for damage side may lead to erroneous damage side predictions at angles between  $30^\circ$  and  $60^\circ$  for right side damage and  $-60^\circ$  and  $-30^\circ$  for left side damage.



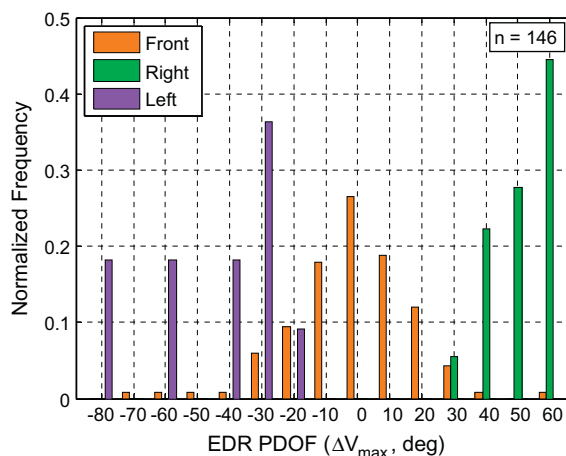


Fig. 11. Histogram of EDR PDOF by estimated damage side in NASS/CDS collisions.

In the sample of NASS/CDS cases with EDRs, the damage side estimated from the PDOF and the actual damage side matched in most, but not all, cases. Using conventions from previous studies ( $\pm 45^\circ$  as frontal,  $45^\circ$  to  $135^\circ$  as right,  $\pm 135^\circ$  as rear, and  $-135^\circ$  to  $-45^\circ$  as left), we can compare the accuracy of using PDOF as a surrogate for damage side (Bahouth et al., 2004; Kononen et al., 2011). Table 3 summarizes the number of cases where the damage side estimated using PDOF did match the actual observed damage side. The most accurate was the  $\Delta V_{\max}$  algorithm with 10% of cases not matching, followed by the  $\Delta V_{\max,x}$  algorithm (12%) and  $\Delta V_{\max,y}$  algorithm (15%). Using the PDOF estimated by the NASS investigator, 15% of cases were misclassified. Using the Kononen injury risk function, a frontal collision with a  $\Delta V$  of 40 mph has a 9% probability that at least one occupant is seriously injured. A similar collision to the left side of the vehicle results in a predicted 38% probability that at least one occupant is injured. In this model, a prediction of serious injury is a recommendation that the occupants of the vehicle be sent directly to a trauma center.

### 3.3.2. Difficulties in assessing PDOF

Fig. 12 compares the NASS/CDS investigator and EDR estimated PDOF as a function of object struck. Of the 146 vehicles, 125 struck other vehicles, 12 struck a tree or pole, and 9 struck other objects (e.g. guardrail). There is a wide degree of scatter for vehicle to vehicle collisions. The dashed lines show a band of  $\pm 45^\circ$ .

PDOF is determined by the investigator in NASS/CDS by inspecting damage to the involved vehicle(s). The damage from a tree, pole, or other narrow object leaves a characteristic deep pocket damage pattern which is readily identifiable. Estimating the PDOF from damage from other sources, such as metal guardrail or a sideswipe collision with another vehicle, however, may not be as straight forward.

One case where the NASS/CDS investigator was not consistent with the EDR PDOF was NASS/CDS case 2006-73-170. This impact involved a 2006 Chevrolet Impala which departed from the roadway on the left and impacted a concrete barrier. The scene diagram for this collision prepared by the investigator is shown in Fig. 13. The investigator recorded the PDOF of the single impact as zero degrees while the EDR estimated the PDOF as  $-66^\circ$ .

The damage to the vehicle was primarily to the left side of the car, shown in photographs in Fig. 14. Analyzing the damage for this vehicle may be difficult, as the vehicle sheet metal shows signs of both scraping and crumpling. The vehicle may have traveled downstream in contact with the guardrail causing this damage. This crash was likely of longer duration than could be captured in the 220 ms recorded by the EDR. As the vehicle struck at an angle, rotated, and then slid along the barrier, we would expect PDOF to not be constant, but rather to vary as a function of time. The EDR showed that the airbag deployed early in the event at 14 ms during the initial angular impact. Hence the EDR record corresponds to the initial angular impact and captures only the early part of the sliding portion of the event.

Fig. 15 shows the PDOF as computed using the  $\Delta V$  stored from the event on the EDR. Unlike the crash tests, this collision does not feature a PDOF that is relatively constant after the onset of the collisions. It appears the impact occurred in two phases: one with a PDOF of approximately  $-55^\circ$  and a second with a PDOF of approximately  $-71^\circ$ . Using the  $\Delta V_{\max}$  algorithm the PDOF was estimated as  $-66^\circ$ . In this case, as in many real-world cases, it is difficult to assess what the “true” PDOF from the available information. However, this case illustrates both the difficulty in examining damage on vehicles and assigning a characteristic PDOF to some events.

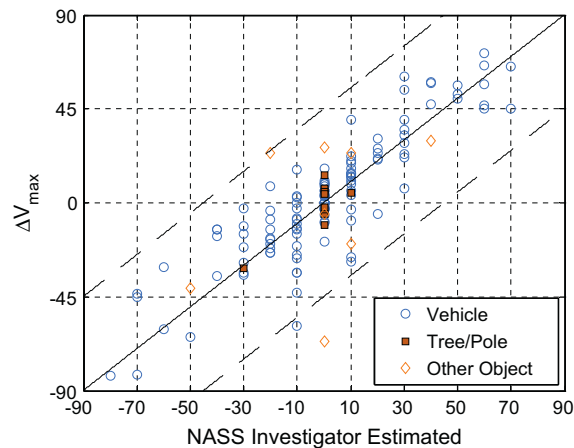
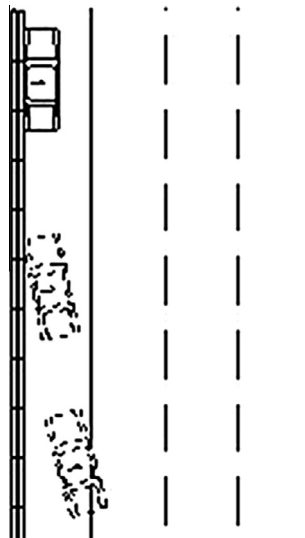
## 4. Discussion

Because the number of cases examined in this study is small, it is difficult to assess what the overall impact of using PDOF as a surrogate for damage side has on injury risk predictions for the entire fleet. More EDR data is likely to be available in future

**Table 3**

Number of cases where damage side estimated from PDOF did not match the actual damage side.

Algorithm	Incorrect number	Incorrect percent
NASS PDOF	21	14
$\Delta V_{\max}$	15	10
$\Delta V_{\max,x}$	17	12
$\Delta V_{\max,y}$	22	15

**Fig. 12.** Comparison of NASS/CDS investigator and EDR estimated PDOF ( $\Delta V_{\max}$ ) by object struck.**Fig. 13.** Scene diagram for NASS/CDS case 2006-73-170.

years of NASS/CDS. In the US, all vehicles with EDRs are now required to report standard data elements with accessible by a publically available download tool ([Office of the Federal Register](#)).

The injury risk function developed by Kononen was developed using PDOF to place cases into one of four groups (frontal, right, left, and rear impacts). Therefore, the function does not depend on damage side *per se*. However, this study has shown that PDOF estimations by investigators and the EDR are often very different. Cases with PDOF near the thresholds for PDOF directions used in the Kononen model would be especially sensitive to error in PDOF. Another issue is that previous



Fig. 14. Vehicle damage in NASS/CDS case 2006-73-170.

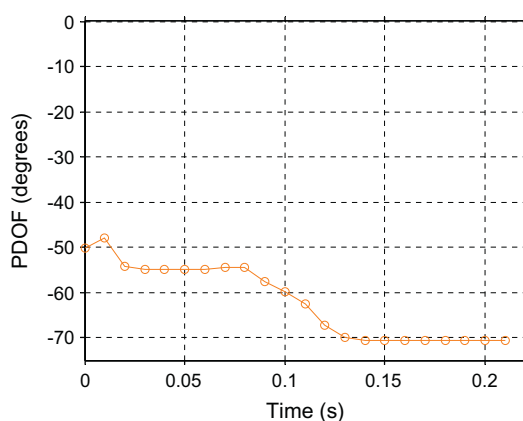


Fig. 15. PDOF computed from EDR data for NASS/CDS case 2006-73-170.

algorithms were developed using the PDOF estimated by the crash investigator, not that estimated by the EDR, which will ultimately be the source of PDOF predictions in AACN algorithms.

A possible solution to this problem is to use PDOF as a continuous variable in the model instead of a categorical variable. Using PDOF as a continuous variable would decrease the sensitivity to PDOF estimation. Another alternative is to develop injury risk curves using EDR data. If the sample is representative, using EDRs as a data source for telemetric data ensures the model will match what is encountered in the field. The challenge with EDR data is that it is available only for a limited number of cases.

In this paper, we examined three algorithms for determining the crash PDOF using  $\Delta V$  recorded by the EDR. The three methods we examined were chosen (1) for their simplicity and (2) because these algorithms were similar to the algorithms considered by a current AACN algorithm in production vehicles. A natural variant of the  $\Delta V_{\max}$  algorithm presented in this paper would be to evaluate PDOF at the maximum resultant  $\Delta V$ . This result  $\Delta V$  algorithm was very similar to the  $\Delta V_{\max}$  algorithm with regards to predicting damage side. There are other possible ways to determine PDOF with the goal of better predicting the damage side in crashes.

Future work should investigate improving methods for PDOF estimates. Possible improvements could include classifying PDOF using the entire  $\Delta V$  time history, not only maximum values. The GM and Ford EDRs that we examined in this study usually only store a single event. Future EDRs may record data on multiple crash events. The methods presented in this paper could be adapted to account for multiple event crashes. Accurate damage side estimation is vital for successful AACN algorithms. In the literature, however, many use PDOF and damage side estimates interchangeably. The results of this study show PDOF estimates are not always accurate predictors of damage side. Developers of future AACN algorithms should take this into consideration as part of their systems' design. It is possible that collisions that result in large moment arms with the vehicle C.G. could be affected by rotational effects, although we did not assess rotational effects in this study. Developers of AACN algorithms should also consider incorporating vehicle rotational effects into their algorithms. Some EDRs record vehicle yaw-rate as part of their rollover sensors which could be used to compute PDOF.

## 5. Conclusion

This study assessed the accuracy of PDOF estimates derived from Event Data Recorders (EDRs) and the implications of the common practice of using PDOF as a surrogate for damage side for use in Advanced Crash Notification (AACN) algorithms. We found that EDRs produce accurate PDOF estimates in staged crash tests. Of the 54 MDB and pole side impact tests examined, EDR PDOF estimates were within 10° and had a root mean squared difference 4.4° compared to the crash test instrumentation. The EDR and crash test instrumentation were statistically similar, using a paired *t*-test.

In 10% of the 146 real-world collisions, using PDOF computed by the EDR as a surrogate for damage side would produce the incorrect damage side. Because injury risk predictions used in AACN algorithms are heavily influenced by damage side in a collision, using PDOF as a surrogate for damage side may yield inaccurate predictions. Furthermore, we found that for the real-world cases examined the PDOF estimated by the NASS/CDS investigator and by the EDR were over 45° different in some cases. Injury risk functions are often derived from real-world crash databases such as NASS/CDS using PDOF as a surrogate for damage side. This study shows this method may misclassify collision types. A possible solution to this problem is to use EDR data, the ultimate data source for AACN algorithms in the field, in the development of future injury risk curves for AACN systems.

## Appendix A

See Table A1.

**Table A1**

Vehicles tested in NCAP MDB and pole side impact tests with dual-axis EDRs.

MDB cases	Pole cases	Make	Model	Model year(s)	CDR module type
6792, 7367	7369	Buick	Lacrosse	2010, 2011	SDM10
7070, 7363	7365	Buick	Lucerne	2011	SDMC2008V
7519		Cadillac	CTS	2012	SDM10
6827		Cadillac	SRX	2010	SDM10
6746, 7493		Chevrolet	Camaro	2010	SDM10
6479		Chevrolet	Equinox	2009	SDMC2006
6789	7037	Chevrolet	Equinox	2010, 2011	SDM10
7000	6997	Chevrolet	Malibu	2011	Epsilon2006
7073	7104	Chevrolet	Silverado 1500	2011	SDM10
7563		Chevrolet	Sonic	2012	SDM10
7510	7506	Chevrolet	Suburban	2012	SDM10
	7025	Chevrolet	Tahoe	2011	SDM10
6988	6985	Chevrolet	Traverse	2011	SDM10
7392	7394	Chevrolet	Volt	2011	SDM10
7151		Ford	Edge	2011	FordRC62011CGEAB
7117	7113	Ford	Escape	2011	FordRC6_2011
7492	7487	Ford	Explorer	2012	FordRC62011CGEAD
7355, 7352	7351, 7349	Ford	F150 Supercab	2011	FordRC62011CGEAC
7650	7651	Ford	F250 Pickup	2012	FordRC62011CGEAD
	6990	Ford	Fiesta	2011	FordRC6_2011_EU
7470	7462	Ford	Focus	2012	FordAB10
6743		Ford	Fusion	2010	FordRC6_2010
7130	7132	Ford	Fusion	2011	FordRC6_2011
6652, 6653, 6734, 6737	6720, 6730	Ford	Mustang	2010	FordRC6_2010
7465	7463	Ford	Mustang	2012	FordRC6_2011
7341		Ford	Ranger	2011	FordRC6_2011
	6967	Ford	Taurus	2011	FordRC6_2011

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