AUTOMATED CRASH NOTIFICATION ALGORITHMS: EVALUATION OF IN-VEHICLE PRINCIPAL DIRECTION OF FORCE (PDOF) ESTIMATION ALGORITHMS

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ABSTRACT

Automated Crash Notification (ACN) algorithms utilize telemetric data from vehicles involved in collisions to notify the appropriate emergency services with the aim to elicit the appropriate medical response. One vital piece of telemetric data is the Principal Direction of Force (PDOF) of the collision, which can be determined from data stored in the Event Data Recorder (EDR). This study examined PDOF estimation algorithms using EDRs recovered from staged crash tests and real-world collisions. In crash tests, PDOF estimated by the measurements from the EDR were comparable to laboratory-grade instrumentation. In 4 side impact crash tests, the average PDOF measured by crash test instrumentation and computed from the EDR differed by 7% on average. In some proposed ACN systems, real-world collisions, PDOF is used as a surrogate for damage side of the crash (i.e. front, side, rear) which may not be appropriate in many crashes. In 91 EDRs recovered from real-world collisions, oblique PDOF estimates near 45° could be interpreted as either frontal and side damage; 18 cases of 91 would have been misclassified as damage side using PDOF as a surrogate, which would have resulted in an incorrect assessment of injury risk. For example, using a previously developed ACN algorithm that predicts risk of serious injury in a crash, misclassifying the damage side as a frontal collision instead of a side collision would result in a risk prediction of 9% instead of 38%.

Keywords: Event Data Recorders, Automated Crash Notification, Principal Direction of Force

INTRODUCTION

Automated Crash Notification (ACN) 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 (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 ACN systems would be to transmit the data currently being stored in Event Data Recorders (EDRs) to a trauma center to allow prediction of severe occupant injury risk almost instantly after a crash occurs. EDRs record many important components related to injury risk including occupant belt use, crash ΔV, airbag deployment timing, and the number of impact events in the crash. However, the limited instrumentation in an EDR cannot 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 Figure 1.

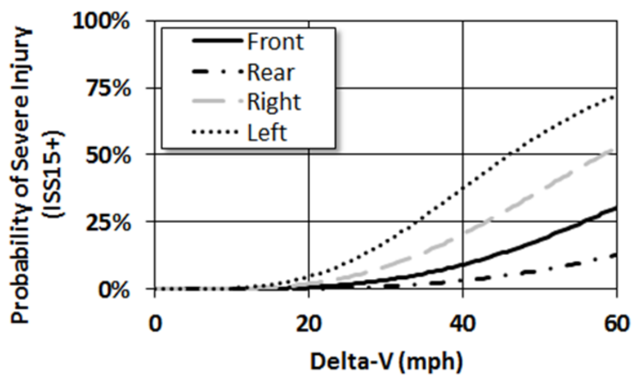

Figure 1. Probability of Serious Injury (ISS15+) by Damage Side as a Function of ΔV (mph). These curves compare similar crashes involving a car, single impact, all occupants belted, no females, and no older occupants (Kononen, Flannagan, & Wang, 2011).

Previous studies have found that damage side, when used in conjunction with other crash characteristics (e.g. ΔV, multiple impacts, occupant age), is significantly correlated to occupant injury outcome. One model developed by Bahouth *et al* called the URGENCY algorithm found that for every 10 kmph increase in ΔV, 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 (Bahouth et al., 2004). Another quantitative injury risk functions proposed developed by Kononen *et al* found damage side to also be a significant predictor of serious injury (Kononen, et al., 2011). Figure 1 shows the probability of an occupant in a vehicle sustaining serious injury by damage side for this previous study. In their study, serious injury was defined as an Injury Severity Score (ISS) greater than 15 (ISS15+). For a collision with a ΔV of 40 mph, the risk of serious injury for front, rear, right, and left impacts is 9%, 3%, 21%, and 38%, respectively, all

else equal. This demonstrates that damage side can dramatically influence the injury outcome in a crash. If an advanced ACN algorithm picks the incorrect damage side for a collision, the subsequent injury risk predictions will be severely biased because the EDR is unable to directly measure the damage side of the collision.

PDOF is often used a surrogate for damage side (Geisler & 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. In full engagement collisions, PDOF is relatively constant through the crash (Rose, Fenton, & Ziernicki, 2004). However, real-world collisions often are not full engagement 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 impact location 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 to 4 o'clock was right damage, 5 to 7 o'clock was rear damage, and 8 to 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 advanced ACN 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 advanced ACN systems.

OBJECTIVE

The objective of this study is to 1) determine the accuracy of competing PDOF algorithms using EDR data that could be transmitted from vehicles involved in crashes and 2) determine the accuracy of using PDOF as a surrogate for damage side for use in advanced ACN algorithms.

METHODOLOGY

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

Event Data Recorders and PDOF

EDRs, now installed in most late model U.S. passenger vehicles, 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 ΔV, by integrating the vehicle acceleration. The time at which the module activates is referred to the time of algorithm enable (AE) in GM EDRs and algorithm wakeup in Ford EDRs. After each event, the ΔV 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 System for GM vehicles, the data can be recovered.

Until recently, most EDRs only contained longitudinally oriented accelerometer(s), as these 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 sensed. In these newer EDRs, both the longitudinal and lateral ΔV are stored in the EDR. At any given point in time, a resultant ΔV can be computed, as shown in Figure 2. The direction of the resultant acceleration on the vehicle, and thus the change in resultant ΔV, can also be computed.

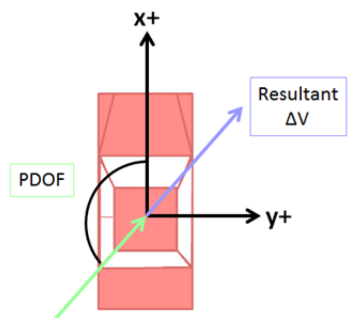

Figure 2. Schematic of Resultant ΔV and PDOF.

In this paper, all angular directions will be reported using the sign convention shown in Figure 3. The positive x direction is oriented longitudinally with the vehicle, and the positive y direction is out the front passenger side door of the vehicle. Angles were restricted to between -180° and 180°.

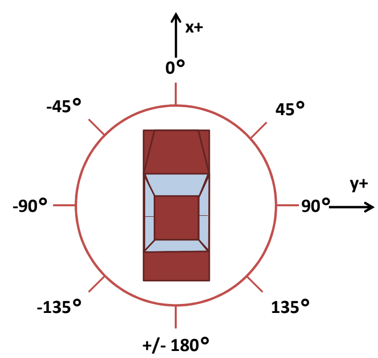

Figure 3. Schematic of Angular Direction Convention used in this Study.

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

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

where:

ΔV_y is the change in velocity in the lateral direction

ΔV_x is the change in velocity in the longitudinal direction

Equation 1 computes the PDOF at any given moment in time. This expression can either be used to compute PDOF as a function of time or to compute a characteristic PDOF for the entire event at a particular time of interest, for example at the time of maximum ΔV. Each PDOF estimation algorithm would use a different method of determining a characteristic PDOF for the crash as discussed in detail below.

Four-quadrant corrected tangent functions should be used in this computation (e.g. *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 ΔVs were equal to zero, there was no PDOF because the vehicle is not being accelerated. Otherwise, if the longitudinal ΔV was equal to zero and there was a lateral ΔV, the PDOF was set to positive or negative 90 degrees, depending on the direction of the lateral ΔV. PDOF could also be computed using similar algorithms which use arcsine or arccosine functions.

Staged Crash Tests

Cases were selected from a set of over 100 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 which provides consumers with star safety ratings for new vehicles. Currently, there is only a publically available tool to recover data from select Ford, General Motor, Chrysler, and Toyota vehicles. The tool, the Bosch Crash Data Recovery (CDR) Tool, allows users to download data directly from the EDR onto a PC. The tool then generates PDF reports where the data can be viewed. In early versions of the software (CDR version 2.8 and prior), PDOF was reported for GM models equipped with certain modules. This field was removed, however, in subsequent versions of the software. Using version 2.8 of the CDR tool, the EDR estimated PDOF was recovered. This PDOF will be abbreviated as "EDR" in the following analysis.

The CDR v 2.8 reports did not specify how the ΔV time history was reduced to a single PDOF for GM EDRs. One possible algorithm, investigated in this paper, was that the CDR tool assessed the PDOF using the maximum longitudinal and lateral ΔV, referred to as ΔV_{max} in remainder of the paper. The ΔV_{max} method was compared to the EDR estimated PDOF. ΔV is stored on GM EDRs every 10 milliseconds for up to 300 milliseconds. In the dual axis modules examined for this study, ΔV was recorded from -70 to 220 milliseconds after AE for deployment events.

Fifteen (15) GM EDRs in our dataset could be downloaded using the version 2.8 CDR tool, which reported PDOF. Of these 15 cases, thirteen (13) cases were frontal impact tests, and the remaining two were side impact tests. In frontal barrier collisions such as the NCAP frontal test, there is very limited lateral acceleration and test vehicles are not instrumented with laterally oriented accelerometers. Therefore, a time history of PDOF could not be computed from the crash test instrumentation. For the side impact tests, the PDOF time histories computed from the

EDR ΔV were compared with PDOF computed by integrating crash test accelerometer channels located at the vehicle center of gravity (CG).

Two Ford EDRs that recorded dual axis ΔV information were also available. These modules do not provide an estimate of PDOF. However, these Ford EDRs also contain the ΔV time history recorded every 10 milliseconds from 0 to 250 milliseconds after AE.

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 U.S. Approximately 5,000 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 2009, NASS/CDS had recovered the data from over 4,000 EDRs in passenger vehicles involved in real-world crashes.

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, 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.

The ΔV_{max} algorithm is one proposed way to produce a characteristic PDOF for a collision event. However, other algorithms, summarized in Table 1, could also be used. The maximum longitudinal ΔV could be used with the lateral ΔV at that same time to compute PDOF ($\Delta V_{max,x}$). Conversely, the maximum lateral ΔV could be used with the longitudinal ΔV at that same time. Finally, the PDOF at all time points recorded by the EDR can be averaged. Estimates of PDOF using these algorithms were compared using the EDR recorded ΔV to assess the viability of each.

Table 1. PDOF Estimate Algorithms

Algorithm Name	Formulation
ΔV_{max}	Maximum ΔV_x and Maximum ΔV_y
$\Delta V_{max,x}$	Maximum ΔV_x and ΔV_y at maximum ΔV_x
$\Delta V_{max,y}$	Maximum ΔV_y and ΔV_x at maximum ΔV_y
Average PDOF(t)	Average PDOF over entire event

RESULTS

Staged Crash Tests

The PDOF estimation algorithms were evaluated using EDR data from 15 GM vehicles and 2 Ford vehicles subjected to NCAP crash tests. The 15 GM EDRs contained dual-axes ΔV data that could be read with the Bosch CDR Tool version 2.8, which reports PDOF. Table 2

summarizes the PDOF estimates in the staged crash tests. In all cases, the EDR estimated PDOF included in the CDR and computed using the maximum longitudinal and lateral ΔV algorithm are similar. The CDR report appears to have rounded the PDOF to the nearest 5 degrees. If the estimated PDOF computed using the maximum longitudinal and lateral ΔV are rounded to the nearest 5 degrees, they exactly match those reported by the CDR report. PDOF was also estimated by average the time-history of the PDOF for the event. This estimate also yielded similar results to the ΔV_{max} algorithm, even in side impact.

Table 2. Comparison of PDOF Estimates for Staged Crash Tests with Dual-Axes EDRs

Test No.	Make	Model	Year	Module	Test Type	PDOF Estimates (degrees)		
						EDR	**ΔV_{max}**	**PDOF(t)**
5250	Pontiac	G6	2005	Epsilon2005	Frontal	0	-0.94	-0.35
5256	Pontiac	G6	2005	Epsilon2005	Side	-75	-77.19	-76.73
5325	Chevrolet	Cobalt	2005	Epsilon2005	Side	-80	-79.22	-79.14
5326	Chevrolet	Cobalt	2005	Epsilon2005	Frontal	0	-1.95	-0.11
5547	Chevrolet	Impala	2006	SDMC2006	Frontal	0	-2.09	-1.27
5567	Chevrolet	Hummer H3	2006	SDMDS2005	Frontal	0	0	0
5569	Cadillac	DTS	2006	SDMC2006	Frontal	0	1.04	0
5578	Chevrolet	Monte Carlo	2006	SDMC2006	Frontal	0	1.06	-0.09
5589	Buick	Lucerne	2006	SDMC2006	Frontal	5	3.12	0.98
5602	Chevrolet	HHR	2006	Epsilon2006	Frontal	0	0	0
5741	Buick	Lucerne	2006	SDMC2006	Frontal	0	1.5	0.34
5830	Pontiac	G6	2006	Epsilon2006	Frontal	0	1.37	1.13
5844	Saturn	Aura	2007	Epsilon2006	Frontal	0	0.91	-0.13
5859	Pontiac	Solstice	2007	Epsilon2006	Frontal	0	0	0
5877	Chevrolet	Silverado	2007	SDMC2006	Frontal	0	0	0
6734	Ford	Mustang	2010	FordRC6_2010	Side	-	-79.7	-80.8
6743	Ford	Fusion	2010	FordRC6_2010	Side	-	-74.1	-74.0

Four EDRs, two GM and two Ford modules, were available from side impact tests. Figure 4 shows the computed PDOF from the EDR and crash test change in velocity. In the first 10 to 20 milliseconds of the events, there is high frequency oscillation in the velocity measurements and both ΔV_x and ΔV_y are close to zero, which manifests itself as the spikes in the crash test PDOF estimates observed near the beginning of the event. The PDOF estimates then maintain a relatively constant value for the remainder of the events.

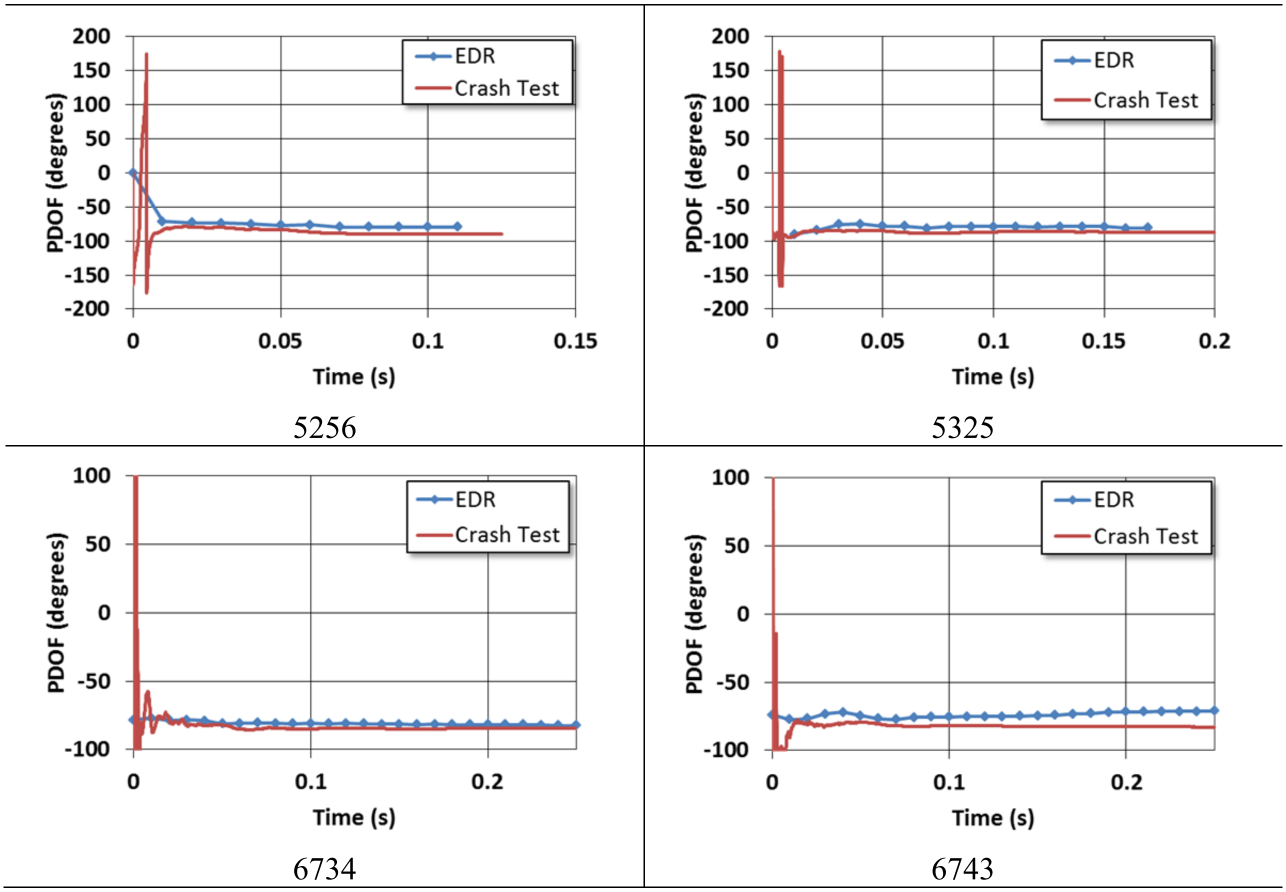

Figure 4. EDR and Crash Test Estimated PDOF.

Table 3 summarizes the PDOF estimates for the two GM and two Ford EDRs obtained from NCAP side impact tests. Comparing the average PDOF over the entire event, the EDRs were with 10% of crash test instrumentation. Crash test instrumentation was placed at the vehicle CG. Many EDRs are located near the vehicle CG, but some are offset (e.g. under the right front passenger seat). Therefore, one source of error may be rotational effects. It is estimated that approximately 6% of the kinetic energy in NCAP side impact crash tests is due to rotational effects, which are not accounted for in this linear PDOF calculation (Johnson & Gabler, 2011).

Table 3. Summary of EDR and Crash Test Instrumentation PDOF Estimates in Side Impact NCAP Tests.

Test	Make	Module	Event Recorded	EDR ΔV_{max}	EDR PDOF(t) Average	Crash Test Average PDOF	% Error
5256	GM	Epsilon2005	Deployment	-77.2	-76.7	-85.1	10%
5325	GM	Epsilon2005	Non-Deployment	-79.2	-79.8	-85.6	7%
6734	Ford	FordRC6_2010	Locked Side Event	-79.7	-80.8	-82.8	2%
6743	Ford	FordRC6_2010	Locked Side Event	-74.1	-74.0	-82.4	10%

These limited cases suggest that the EDR can provide an estimate of PDOF for a crash event. For these side impact tests, using a time average of the PDOF and the ΔV_{max} algorithm does not

yield different PDOF estimates. It should be noted that computation of PDOF in real world crashes may be more challenging than in staged crash tests. Real-world collisions can involve longer impacts and offset collisions which can introduce additional rotational effects.

PDOF Estimates in Real-World Collisions

Of 4,188 GM EDRs from NASS/CDS 2000-2009 cases, 125 had dual-axes ΔV with a locked deployment event. Of these, 82 were from single event collisions. From the 277 Ford EDRs from NASS/CDS 2000-2009, 18 had dual-axes ΔV with a locked deployment event. Of these, 9 were from single event collisions. In total, 91 real-world collisions were examined. Figure 5 shows a histogram of NASS/CDS estimated PDOF for selected cases. Three cases had an unknown PDOF.

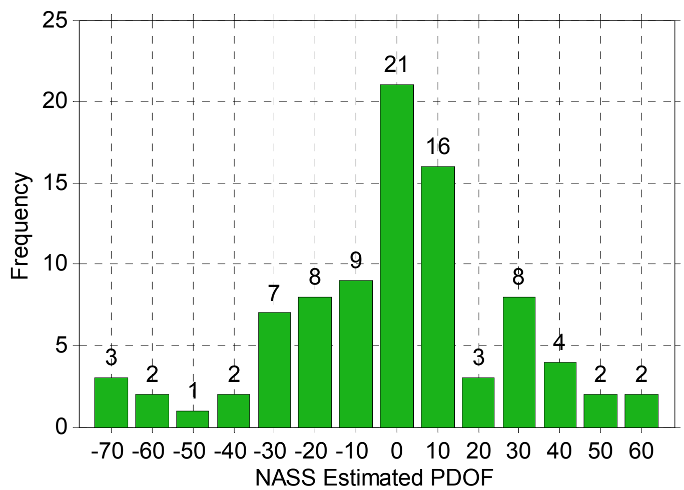

Figure 5. Histogram of NASS/CDS Estimated PDOF.

Figure 6 shows the EDR estimated and ΔV_{max} estimated PDOF for GM EDRs. Of the 82 EDRs in the dataset, 3 modules could not be read by the earlier versions of the CDR software such as version 2.8. As in the NCAP EDRs, all PDOF values estimated using the ΔV_{max} algorithm were equal to the EDR estimate when rounded to the nearest 5 degrees. This supports the theory that the PDOF reported on earlier CDR reports was obtained by the ΔV_{max} algorithm.

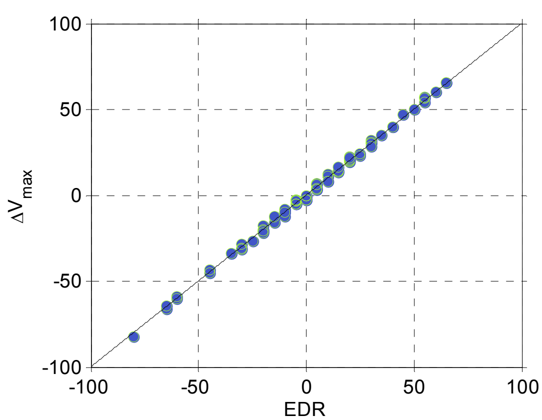

Figure 6. EDR and ΔV_{max} Estimated PDOF for NASS/CDS Cases.

Figure 7 compares the PDOF estimates from the ΔV_{max} and other algorithms. The $\Delta V_{max,y}$ algorithm is most different from the ΔV_{max} algorithm for low-PDOF collisions, i.e. PDOF close to zero degrees. In these collisions, there is very little lateral acceleration. Therefore, the maximum lateral ΔV can occur at times before or after the main collision event. Conversely, the $\Delta V_{max,x}$ method is most different from the ΔV_{max} method at oblique PDOF collisions. The average PDOF as a function of time is also similar to the ΔV_{max} algorithm. Because the $\Delta V_{max,x}$ and $\Delta V_{max,x}$ algorithms appear to be dependent on PDOF, ΔV_{max} or the average PDOF algorithm seem better suited for consistent PDOF estimation. Regardless of the algorithm, all PDOF estimates were within 15° of each other (dotted lines). This difference is likely less than the errors introduced by rotational effects or other inaccuracies.

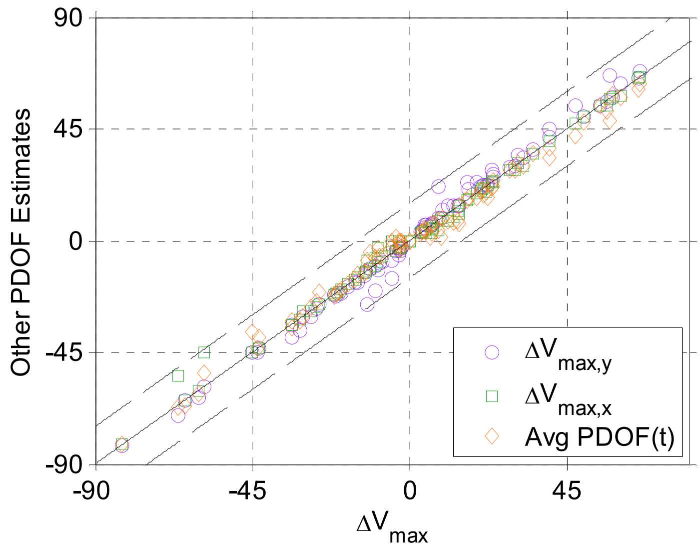

Figure 7. Comparison of ΔV_{max} and Other PDOF Estimation Algorithms.

Figure 8 compares the NASS/CDS estimated PDOF and the PDOF estimated by the EDR using the ΔV_{max} algorithm. The estimates are separated by the object struck in the collisions. Vehicle to vehicle collisions comprised 80 of the 91 cases, followed by impacts will trees or poles (7 cases) and with barriers (4 cases). There is a wide degree of scatter for vehicle to vehicle collisions. The sample size is too small to make substantive conclusions, but in impacts into trees and poles the PDOF estimates of the investigator were, in general, consistent with the EDR. PDOF is determined by the investigator by inspecting damage to the vehicle(s). The damage from a tree, pole, or other narrow object leaves a characteristic deep pocket damage pattern which is readily identifiable. The damage from a barrier, such as metal or concrete guardrail which are designed to redirect a vehicle back onto the road, may leave a more scraping damage pattern, from which PDOF estimation may be difficult or not possible. Because there is no benchmark source for the "true" PDOF in these real world crashes, the assessment in this study should not be interpreted as assessing the accuracy of either method.

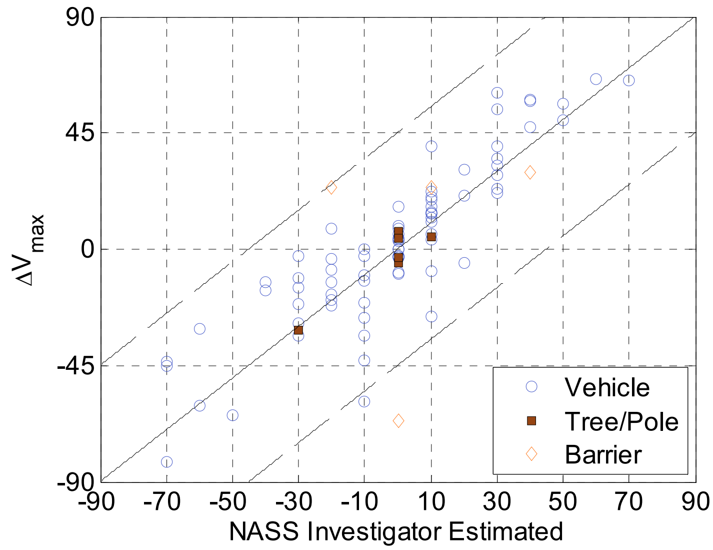

Figure 8. Comparison of NASS/CDS Investigator Estimated PDOF and EDR Estimated PDOF (ΔV_{max}) by Object Struck.

Case Study: Difficulties in Assessing PDOF

One case where the NASS/CDS investigator was not consistent with the EDR PDOF was 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 Figure 9. The investigator recorded the PDOF of the single impact as zero degrees while the EDR estimated the PDOF as -66°.

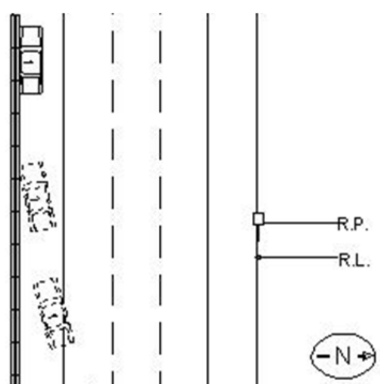

Figure 9. Scene Diagram for NASS/CDS case 2006-73-170.

The damage to the vehicle was primarily to the left side of the car, shown in photographs in Figure 10. Analyzing the damage for this vehicle may be difficult, as the 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 milliseconds 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 milliseconds 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.

Figure 10. Vehicle Damage in NASS/CDS Case 2006-73-170.

Figure 11 shows the PDOF as computed using the ΔV 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° and a second with a PDOF of approximately -71°. Using the ΔV_{max} algorithm the PDOF was estimated as -66° and the average PDOF was -67°. In this case, as in all real-world cases, it is impossible to assess what the "true" PDOF is from the available information. However, this case illustrates both the difficulty in examining damage on vehicles and assigning a characteristic PDOF to some events.

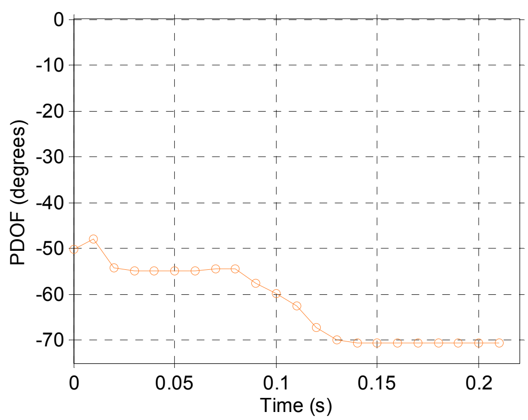

Figure 11. PDOF Computed from EDR Data for NASS/CDS Case 2006-73-170.

Using PDOF as a Surrogate for Damage Side

Figure 12 shows the distribution of general area of damage (GAD) and PDOF in serious injury crashes from the National Automotive Sampling System / Crashworthiness Data System database (NASS/CDS) year 2008 for passenger vehicles not involved in a rollover. Serious injury here is defined as the driver sustaining a maximum abbreviated injury score (AIS) of 3 or greater (MAIS3+). The smaller bars show the proportion of cases with a PDOF of a given values, stacked by reported damage side. For example, at a PDOF of 40˚, there were almost an equal number of crashes with damage side of front and right. 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 +/- 45˚.

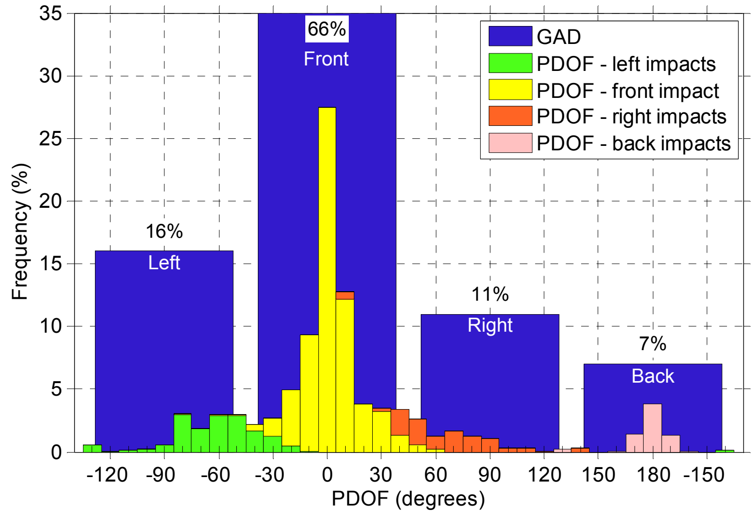

Figure 12. Distribution of Seriously Injured (MAIS3+) Drivers by General Area of Damage (GAD) and Principal Direction of Force (PDOF) from NASS/CDS 2008.

Similarly, Figure 13 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 +/- 45°), cases with frontal damage had PDOFs ranging from -80° to 60°. ACN 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° and 60° for right side damage and -60° and -30° for left side damage.

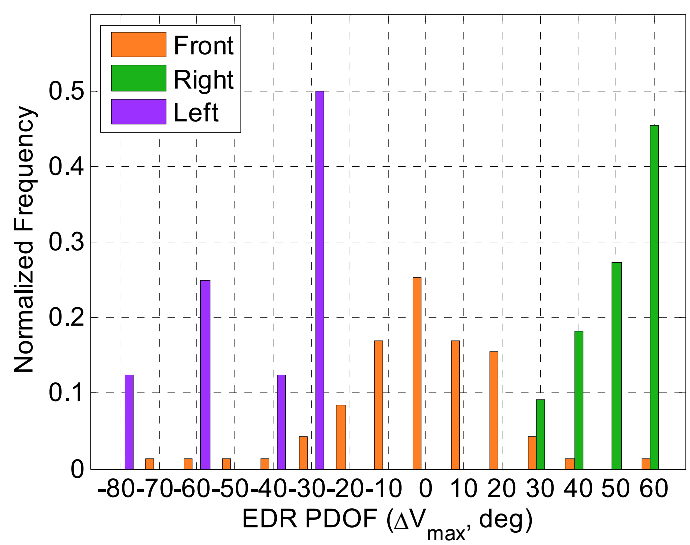

Figure 13. Histogram of EDR PDOF Estimate by Damage Side.

Effect of using PDOF as a Surrogate for Damage Side in Injury Prediction

In the sample of NASS/CDS cases with EDRs, the damage side estimated from the PDOF and the actual damage side matched in most cases. Using conventions from previous studies (+/- 45˚ as frontal, 45˚to 135˚ as right, +/- 135˚ as rear, and -135˚ to -45˚ as left), we can compare the accuracy of using PDOF as a surrogate for damage side (Bahouth, et al., 2004; Kononen, et al., 2011). Using the PDOF estimated by the investigator to predict damage side, only 18 of the 91 cases (20%) cases did not match. Using the PDOF estimated by the EDR, the estimated damage side did not match the actual damage side in only 12 cases (13%). Using the Kononen injury risk function, a frontal collision with a ΔV of 40 mph has a 9% probability that at least one occupant that 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.

Because the number of cases examined in this study is small, it is difficult to assess what the overall impact using PDOF as a surrogate for damage side has on injury risk predictions for the entire fleet. The injury risk function developed by Kononen was developed using PDOF to place cases into 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 estimation can vary depending on algorithm used to compute PDOF from ΔV and based on the sensor accuracy. 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 algorithms were developed using the PDOF estimated by the crash investigator, not that estimated by the PDOF, which will ultimately be the source of PDOF predictions in ACN 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 is available only for a limited number of cases.

CONCLUSIONS

This study assessed the accuracy of four different algorithms for PDOF estimation in 17 staged crash tests, and in a set of 91 real-world collisions to assess the evaluation of PDOF in the field. This study has important implications for advanced ACN algorithms which use PDOF as a surrogate for vehicle damage side. The findings of the study are summarized below:

- The algorithm used to compute PDOF in earlier versions of the Bosch CDR tool appears to be computed using arctan ($\Delta V_{max,y} / \Delta V_{max,x}$)
- In side impact crash tests, such as those performed for the NCAP, PDOF remains relatively constant. In the four cases examined, the EDR was within 10% of the PDOF estimated by crash test instrumentation located at the vehicle CG

- In a set of 91 real-world collisions of sufficient severity to deploy the airbags, the ΔV_{max}, $\Delta V_{max,x}$, $\Delta V_{max,y}$, and average PDOF algorithms yielded estimates within 15° of each other in all cases
- In collisions that were complex, i.e. that involved vehicle rotation or sliding, the NASS/CDS investigator determined PDOF and EDR PDOF may not be consistent
- Care must be taken when interpreting the meaning of PDOF with respect to damage side Using PDOF as a surrogate for damage side may not be valid for collisions between 30° and 60°. In this range of PDOF, there is a possibility that the general area of damage could either be the front or side planes of the car. An incorrect choice of damage side for a given PDOF will likewise result in an incorrect computation of injury risk. Crashes with PDOF near the thresholds between front-side or side-rear may be especially sensitive to the accuracy of PDOF estimates.

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