PRELIMINARY EVALUATION OF NASS-CDS SIDE CRASH DELTA-V ESTIMATES USING EVENT DATA RECORDERS

Nicholas S. Johnson
Hampton C. Gabler
Virginia Polytechnic Institute and State University
United States of America
Dinesh Sharma
National Highway Traffic Safety Administration
United States of America
Paper Number 13-0240

ABSTRACT

The severity of a planar crash is most commonly defined by the change in vehicle velocity, or delta-V (ΔV). In the National Automotive Sampling System – Crashworthiness Data System (NASS-CDS), ΔV is computed from post-crash vehicle damage using a CRASH3 – based computer program called WinSMASH. Prior studies have investigated the accuracy of NASS-CDS ΔV in real world frontal crashes. Those studies compared the WinSMASH ΔV estimates in NASS-CDS to the ΔV obtained from the crashed vehicles' Event Data Recorders (EDRs). In those studies, the EDRs only measured/recorded ΔV in the longitudinal direction. Accordingly, the accuracy of WinSMASH ΔV in side crashes has been assessed only through comparison with controlled crash tests, not real world crashes. Many newer vehicles are now equipped with EDRs that record both longitudinal and lateral ΔV. The objective of this study is to use these newer EDRs to compare WinSMASH ΔV estimations to EDR ΔVs for real-world side crashes in the NASS-CDS.

This preliminary study examines 22 side impact crashes from the NASS-CDS. All struck vehicles were cars and all striking vehicles were either cars or light trucks and vans (LTVs). EDR measurements of side impact ΔV were used to evaluate the accuracy of WinSMASH ΔV estimates for these real world side crashes. WinSMASH systematically overestimated ΔV for the examined crashes. Overestimation for crashes involving cars struck by cars appeared greater than for those involving cars struck by LTVs. Observed systematic ΔV error varied by the area of the vehicle which was impacted.

INTRODUCTION

Planar crash severity is most commonly defined by delta-V (ΔV), which is the change in a vehicle's velocity vector during a crash. ΔV is the single best and most widely used correlate for occupant injury in automobile crashes (Gabauer and Gabler 2008). All ΔV estimates contained in the United States' (U.S.) National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) are generated using a CRASH3-derived program called WinSMASH (Sharma et al. 2007; NHTSA 1981). The accuracy of WinSMASH ΔV estimates for real-world crashes have previously been examined by comparison with ΔV from Event Data Recorders (EDRs) of crashed vehicles (Hampton and Gabler 2010; Niehoff and Gabler 2006). Historically, most EDRs in the U.S. vehicle fleet have recorded only longitudinal ΔV as most U.S. vehicles have had only frontal air bags. Consequently, WinSMASH has been validated against real-world data for frontal crash reconstructions only. Prior validation for side-impact crashes has used only staged crash tests (Prasad 1987; Johnson 2011; Johnson, Hampton and Gabler 2009), which are not real world crashes. However, some EDRs from vehicles equipped with side air bags record biaxial (i.e. both longitudinal and lateral) ΔV. As side air bags have become more common in the U.S. fleet, it has become feasible to assess WinSMASH ΔV accuracy against real-world data for side crashes as has been done previously for frontal crashes.

OBJECTIVE

This study will use biaxial ΔV data from newer EDRs to assess WinSMASH ΔV accuracy for real-world side crashes.

METHODS

The NASS-CDS reconstructs crashed vehicle ΔV using WinSMASH whenever possible. Conveniently, it also obtains EDR data for these vehicles whenever possible with the consent of the vehicle owner. In this analysis, we selected single-event side impact crashes from the NASS-CDS for which a) WinSMASH ΔV had been coded and b) biaxial EDR data was available. For these crashes, we compared the

WinSMASH-estimated resultant ΔV with the EDR-recorded resultant ΔV to assess the accuracy of WinSMASH. Although crashes can involve multiple events, only single-event crashes were used because this eliminates any ambiguity as to which impact the EDR data corresponds to. Additionally, only EDRs from crashes where the air bags actually deployed were used. Air bag deployment prevents the crash record from being overwritten with data from subsequent events which may not be the event of interest.

We also used this biaxial EDR data to assess the accuracy of NASS-CDS estimates of Principal Direction of Force. Principal Direction of Force, or PDOF, is the orientation of the net crash impulse relative to the vehicle and is a key parameter in WinSMASH reconstructions. In the NASS-CDS, PDOF is visually estimated by crash investigators using various observations such as the vehicle deformation pattern and collision trajectories. Having both longitudinal and lateral ΔV from an EDR allows for computation of the actual PDOF in a crash, to which the NASS estimates can be compared.

Extraction of Resultant ΔV, PDOF from EDRs

Biaxial EDRs sense both longitudinal and lateral accelerations during a crash and process them to obtain longitudinal and lateral ΔV histories. Acceleration from each axis is measured and processed separately to obtain the ΔV history for that axis. In this analysis, we examined the maximum resultant EDR ΔV. To obtain this, resultant ΔV was first calculated at each time increment in the record using the longitudinal and lateral ΔV. The maximum of these resultant ΔVs was used as the resultant EDR ΔV for that crash. PDOF was then calculated as the arctangent of the longitudinal and lateral components of this ΔV.

Many older EDRs record only about 70 – 80 ms of ΔV data after the recording algorithm is triggered, which is shorter than most crash pulses. Because of this, older EDRs sometimes underestimate actual ΔV (Niehoff and Gabler 2006). However, newer biaxial EDRs typically record 200 – 300 ms of crash data, with some portion of that being pre-algorithm-trigger. Newer EDRs thus typically record the entire crash pulse. In this analysis, any records with resultant acceleration greater than 1 g between the last and second-to-last time steps were manually inspected for completeness, regardless of record duration. Most EDRs do not record acceleration, but only measure it to compute ΔV. Consequently, acceleration was calculated from the change in resultant ΔV between the final and penultimate data points.

Comparison of WinSMASH ΔV and PDOF to Values Obtained from EDRs

For each case examined, we compared 1) the WinSMASH-estimated resultant ΔV to the resultant EDR ΔV, and 2) the investigator's estimate of PDOF to the EDR-derived PDOF. We also examined WinSMASH ΔV and PDOF estimate accuracy with respect to a number of other parameters, such as vehicle bodystyle and area of the vehicle struck, to determine whether there was any correlation. WinSMASH was never intended to be a forensic reconstruction tool, but rather a standard benchmark that is accurate on average. The magnitude of the ΔV error in individual reconstructions is therefore of less importance than the *systematic* error over many cases. For ΔV, systematic error was computed as the slope of a linear regression of WinSMASH ΔV versus actual ΔV with the intercept fixed at zero. On a cross-plot of estimated ΔV versus actual ΔV, the amount by which the slope of such a regression deviates from unity gives an indication of the amount of systematic error in the estimated values (e.g. a slope of 1.050 would indicate a 5% overestimation).

Statistical testing was performed using SAS v9.2 (SAS; Cary, NC, United States). The NASS-CDS uses a stratified, clustered and weighted sample design allowing for nationally representative estimates to be made from the data. However, no attempt was made in this study to perform statistical testing using the NASS weights, as the sample size was insufficient. Therefore, this analysis is only representative of the population of crashes recorded in the NASS-CDS, and is not representative of all U.S. crashes nationally.

Sample Summary

Table 1.
Data Set Composition

Total Crashes:	**22**
Struck Vehicle Make:	
Ford	1
General Motors	21
Struck Vehicle Bodystyle:	
Cars	22
Striking Vehicle Bodystyle:	
Cars	8
LTVs	14

Table 1 gives a summary of the final dataset used in this analysis. The dataset consists of 22 single-impact crashes coded in the NASS-CDS (case years 2006 – 2010) for which both WinSMASH ΔV and biaxial EDR data (locked, air bag-deployment events) were available. Only crashes where cars were struck in the side by another vehicle were retained for this analysis. Struck-LTV crashes (2 cases: 2010-12-154 and 2010-49-65) and crashes involving fixed objects (1 case: 2006-50-46) were not available in sufficient numbers for a meaningful analysis of those crash configurations, so were excluded. Side impacts were identified by the General Area of Damage (GAD) coded in NASS. GAD is defined as part of the Collision Deformation Classification (CDC) code (SAE 1980); all cases in the sample have a GAD of "L" or "R" which stands for left or right side of the vehicle, respectively.

One case – NASS case 2007-80-045 – was excluded from the final sample for having an incomplete ΔV record. The EDR in this case came from a 1990 Honda Prelude and recorded only a 78 ms window of ΔV. Additionally, this EDR was unusual in that it provided a record of acceleration in addition to a record of ΔV. The recorded acceleration clearly indicated that the crash was not complete by the end of the recording. All other examined cases reported either 220 ms or 250 ms of ΔV data with some amount of that being pre-trigger ΔV, so pulse truncation is unlikely in the retained sample.

RESULTS

WinSMASH ΔV Accuracy

Figure 1 compares WinSMASH-estimated ΔV to EDR-measured ΔV for the dataset. WinSMASH appears to systematically over-predict ΔV in the examined side crashes by about 3.5%. Random error (RMS error about the regression line) is about 5.5 km/h. There was insufficient evidence to reject the assumption of normally distributed data; a paired t-test did not indicate that the ΔV over-prediction was significant (p=0.1360, PROC TTEST). This is due at least in part to the small sample size.

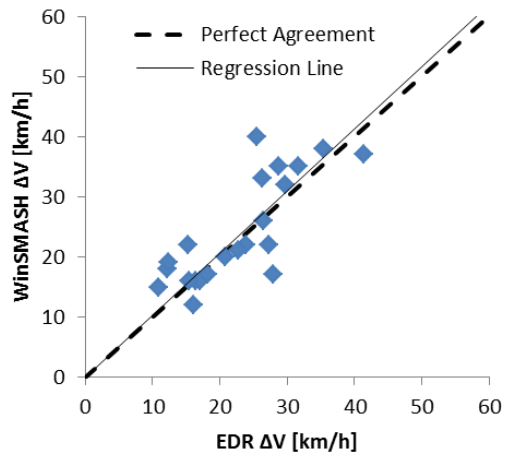

Figure 1. WinSMASH ΔV vs. EDR ΔV. Regression equation: y = 1.0347x. RMS_{err} about regression line: 5.490 km/h.

Effect of Striking Vehicle Body Type

Figure 2 and Figure 3 compare WinSMASH ΔV to EDR ΔV for cars struck by cars and cars struck by LTVs respectively. Cars are defined as NASS body type codes 1 – 11, 13 and 17 while LTVs are codes 14 – 16, 19 – 22, 30 – 33, 39 – 42 and 45. All vehicles in the sample fell into one of these two categories. WinSMASH ΔV for cars struck by other cars appears to be systematically higher than EDR ΔV by about 8.2%. For cars struck by LTVs, WinSMASH appears to have no systematic error. Observed random error was higher for striking LTVs than for striking cars (6.17 km/h vs. 4.09 km/h RMS error), but then there were more striking LTVs in the sample. The assumption of normally distributed data could not be rejected for either striking body type. An independent sample t-test did not find the difference in WinSMASH ΔV error between striking body types to be statistically significant (p=0.4434, equal sample variances, PROC TTEST).

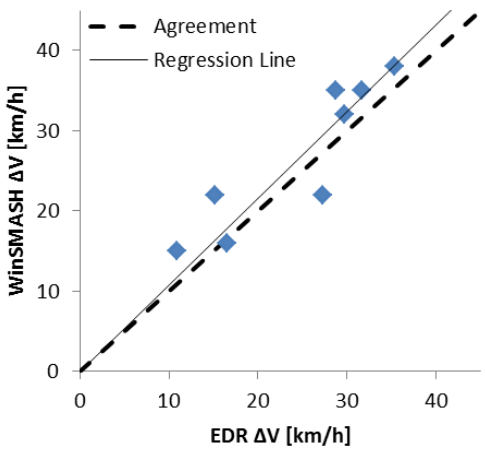

Figure 2. WinSMASH ΔV vs. EDR ΔV for cars struck by cars. Regression equation: y = 1.0824x. RMS_{err}: 4.090 km/h.

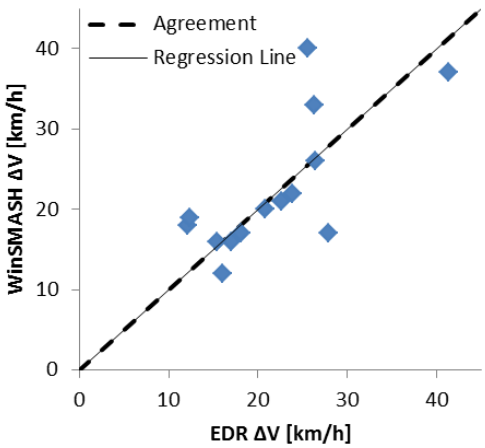

Figure 3. WinSMASH ΔV vs. EDR ΔV for cars struck by LTVs. Regression equation: y = 1.0006x. RMS_{err}: 6.170 km/h.

Effect of Impacted Vehicle Region

Figure 4 shows the Specific Horizontal Location (SHL) codes defined by the CDC standard (SAE 1980) and used by NASS-CDS to describe the particular horizontal area of the vehicle which was damaged in an impact. Figure 5 shows WinSMASH ΔV error broken down by SHL. WinSMASH appears to underestimate ΔV for crashes involving damage to F, while P and especially D appear to be overestimated. Note that the sample contained no B impacts. One-way ANOVA indicates that the mean errors for each SHL are not universally equal (p = 0.0079, PROC GLM).

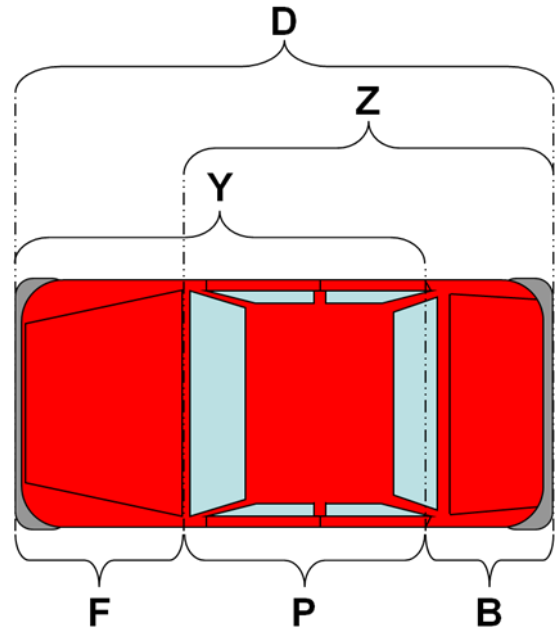

Figure 4. Specific Horizontal Location (SHL) codes defined by SAE standard J224 and used in NASS-CDS.

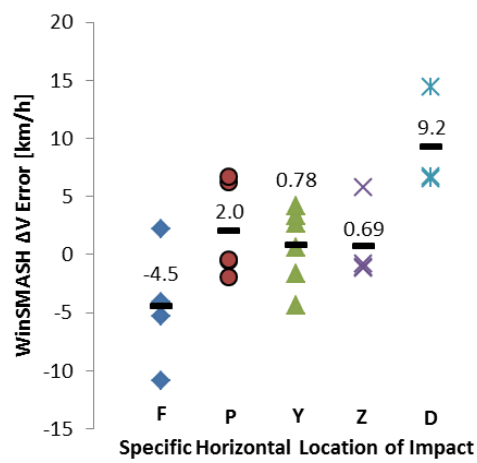

Figure 5. WinSMASH ΔV error vs. SHL of impact. Black bars indicate the mean ΔV error for each SHL value.

Effects of WinSMASH Calculation Type

WinSMASH can perform different types of reconstruction calculations depending upon what information is available for a case. The type of reconstruction performed for a case is coded by the DVBASIS variable in NASS-CDS. "Standard" and "Missing Vehicle" reconstructions (Sharma et al.

2007) are represented in the cases studied here. Figure 6 shows a small difference in ΔV error between Standard and Missing Vehicle reconstructions, but one-way ANOVA found it to be insignificant. Note that there were only 3 cases of the Missing Vehicle type.

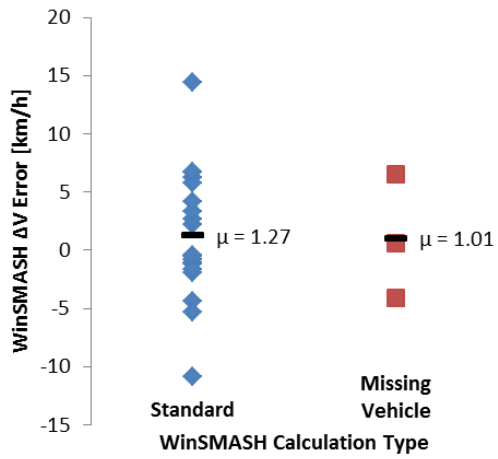

Figure 6. WinSMASH ΔV error vs. WinSMASH calculation type. Black bars indicate the mean ΔV error for each calculation type.

Investigator PDOF Accuracy

Figure 7 shows discrepancy in NASS investigator estimates of PDOF with respect to the PDOF computed from EDR data. Mean PDOF discrepancy was -4.5 °; this was not found to be significantly different from zero (p=0.1584, paired-sample t-test, normality not rejected for the sample). Also, note that NASS only codes PDOF to the nearest 10 °. Smith and Noga (1982) gave 95% confidence limits on the accuracy of field-recorded PDOF as ±20 °. Observed standard deviation in PDOF discrepancy here was 14.5 ° which equates to 95% confidence limits of ±28.3° assuming normally distributed error (1.96*standard deviation).

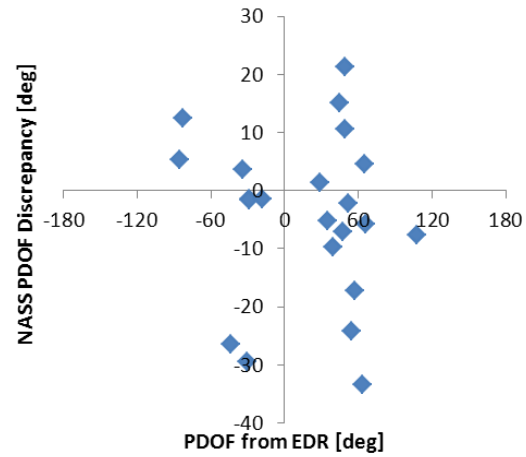

Figure 7. Discrepancy in NASS PDOF vs. EDR-derived PDOF. Mean NASS PDOF discrepancy: -4.515 °. Positive values are clockwise from the front of the vehicle when viewed from overhead, negative values are counterclockwise.

Effect of PDOF Discrepancy on WinSMASH ΔV Accuracy

Figure 8 shows a cross plot of WinSMASH ΔV error magnitude against PDOF discrepancy magnitude. There appears to be no correlation between PDOF discrepancy and WinSMASH ΔV error; the miniscule R^2 value for the regression ($R^2 < 0.0001$) indicates that it predicts virtually none of the observed variance in the data.

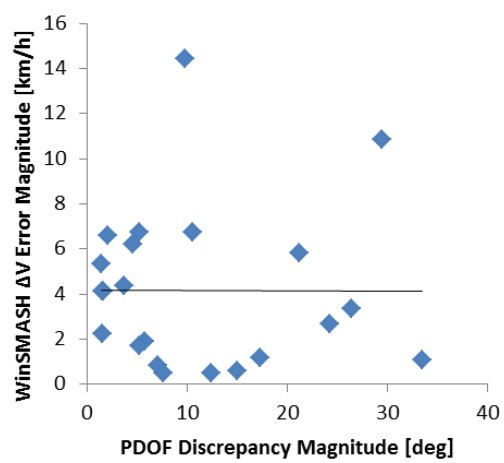

Figure 8. WinSMASH ΔV error magnitude vs. PDOF discrepancy magnitude. Regression equation: $y = -0.0021x + 4.1967$, $R^2 < 0.0001$.

DISCUSSION

WinSMASH ΔV estimates do not include the effects of restitution, but EDR measurements of ΔV do. Hence, if WinSMASH were reconstructing collisions accurately it would systematically underestimate the ΔV given by EDRs, probably by about 10% on average (Ishikawa 1994, Johnson and Gabler 2011).

Figure 1, Figure 2 and Figure 3 all show that WinSMASH *over*estimates EDR ΔV by about 8% for cars struck by cars, and shows no overestimation (and no underestimation) for cars struck by LTVs. Johnson and Gabler (2011) examined WinSMASH ΔV accuracy for NHTSA side crash tests. In that analysis, test instrumentation made it possible to determine when restitution began and to obtain the vehicle's actual ΔV up to that point. That study found that for NHTSA side crash tests, WinSMASH overestimated pre-restitution ΔV – the precise ΔV that WinSMASH models – by about 19% for struck cars. Nineteen percent overestimation minus about 10% ΔV gain from restitution gives 9% overestimation compared to the total ΔV including restitution. This aligns with the 8% overestimation observed here for cars struck by cars. Unfortunately, EDRs do not record sufficient data to determine pre-restitution ΔV. Thus, a direct comparison with pre-restitution ΔV equivalent to the Johnson and Gabler (2011) study was not possible here.

WinSMASH uses "vehicle stiffness" parameters to estimate the energy dissipated in crashes from measurements of residual vehicle damage. Different stiffness parameters are used for damage to the front, side and rear of individual vehicles. All side crash stiffnesses used by WinSMASH are derived from damage in NHTSA side crash tests. These stiffnesses may not represent crashes with damage to areas different from the tests from which they are derived, as vehicle side structure is not homogenous. NHTSA side impact tests are Y (SHL) impacts verging on P, so the observed underestimation of ΔV for F crashes (Figure 4, Figure 5) may be due to the stiffer vehicle structures in this region absorbing more energy for a given amount of crush than do the softer structures of the P region (passenger compartment). The geometry of the striking vehicle itself also influences which areas of the impacted vehicle are engaged. LTVs tend to be taller and wider than cars, and may or may not have greater ground clearance. Given collisions of otherwise identical configuration, striking LTVs can engage different or additional structures compared to striking cars. This could account for the differences between Figure 2 and Figure 3.

WinSMASH calculation type (Figure 6) does not appear to make any significant difference in the systematic ΔV error. However, only three cases used a reconstruction type other than Standard. A larger sample is necessary to draw any conclusions about the possible effects of calculation type.

PDOF and ΔV

In our sample, NASS PDOF estimates for side crashes (Figure 7) showed relatively little systematic discrepancy with EDR-derived values. Average observed discrepancy was -4.5 °, which could indicate that NASS investigator PDOFs tend to be slightly counterclockwise from the real value on average. However, it is far more likely that this is simply an artifact of the small sample size. Additionally, NASS only codes PDOF to the nearest 10 °; the observed magnitude of systematic discrepancy is thus within the measurement precision for PDOF. EDR-derived estimates of PDOF are also known to have a root mean square error of 4.4 ° and to differ from values obtained from crash test instrumentation by as much as 10 ° (Kusano, Kusano and Gabler 2012).

Based on the observed standard deviation in PDOF discrepancy, 95% confidence limits for side crash NASS PDOF are ±28.3 °. This is roughly similar to the 95% confidence limits of ±20 ° quoted by Smith and Noga (1982) for field measurements of PDOF. The way in which Smith and Noga arrived at their estimate is somewhat different than the approach used here, and recall again that NASS PDOF estimates are only precise to the nearest 10 °.

Figure 8 shows that there is no correlation between the magnitude of PDOF error and the magnitude of WinSMASH ΔV error. In the WinSMASH calculations, the relationship between PDOF error and ΔV error depends on other parameters describing the crash configuration, so this is perhaps unsurprising. This also indicates that the effects of PDOF error are being washed out by some other sources of error.

Limitations

EDR measurements do not account for the effects of rotation. This could potentially skew their ΔV measurements, but any such skew would not be systematic and it would probably not be very large in comparison to the measured ΔVs. EDRs are not generally mounted far from the vehicle center of gravity, which would tend to reduce the effects of

rotation on ΔV measurements. Also, typical rotation rates in NHTSA side crash tests are a relatively slow 90 °/s (Johnson 2011). The crashes in this sample are much less severe than the typical NHTSA side crash test, and most of them have SHL values which suggest crash impulse moment arms that are not any larger than those of side crash tests. It therefore seems logical that rotation rates in these crashes would tend to be lower than the already low values observed in NHTSA side crash tests. Additionally, EDR-derived PDOF estimates, which are computed from biaxial ΔV measurements, have been observed to have a root mean square error of only 4.4 ° (Kusano, Kusano and Gabler 2012).

The findings of this study are not nationally representative, but pertain only to the analysis sample. The limited sample size precludes the use of statistical techniques necessary to perform significance tests with clustered, stratified and weighted NASS-CDS data. Also, small sample size is a limitation in its own right. The small sample size examined here is a result of the limited number of NASS CDS crashes for which EDR data is available, compounded by the additional requirements for biaxial EDR data and a single-event crash. The NASS CDS has only collected EDR data since 2000 and at first, NASS investigators could only read EDRs from Ford and General Motors. This is reflected in the near-total proportion of General Motors vehicles in the dataset. While the lack of makes other than General Motors could be seen as a limitation, it is unlikely to have a significant effect. WinSMASH vehicle stiffness parameters are derived from tests of individual vehicles, so any characteristics particular to a given manufacturer are already accounted for. In any case, as more vehicles equipped with side air bags are added to the NASS-CDS, the available sample size will increase fairly quickly. NASS investigators can now read EDRs used by many vehicle manufacturers, so the number of represented makes and models will likely increase as well.

CONCLUSIONS

WinSMASH appears to overestimate struck vehicle ΔV for cars in real-world side crashes. This overestimation appears to be greater in cases where the striking vehicle was a car than in cases where it was an LTV. However, this observation only applies when cars are the struck vehicle. The analysis did not examine crashes where the struck vehicle was an LTV, nor did it examine fixed-object crashes of any type. It seems likely that the side impact stiffness parameters used by WinSMASH do not represent crashes which differ substantially from NHTSA side impact crash tests.

NASS field estimates of PDOF do not appear to exhibit any systematic discrepancy. The amount of random PDOF discrepancy observed here is consistent with the findings of prior studies. PDOF discrepancy magnitude showed no correlation with WinSMASH ΔV magnitude, which indicates that its effect is being washed out by other sources of discrepancy.

REFERENCES

Gabauer DJ and Gabler HC (2008), “Comparison of Roadside Crash Injury Metrics using Event Data Recorders,” *Accident Analysis and Prevention*, vol. 40, issue 2, pp 548-558.

Hampton CE and Gabler HC (2010), “Evaluation of the Accuracy of NASS/CDS Delta-V Estimates from the Enhanced WinSMASH Algorithm,” Proceedings of the 54th Annual AAAM Conference.

Ishikawa H (1994), “Impact Center and restitution Coefficients for Accident Reconstruction,” SAE 940564, Society of Automotive Engineers.

Johnson N (2011), “Assessment of Crash Energy – Based Side Impact Reconstruction Accuracy,” Master of Science thesis, Virginia Polytechnic Institute and State University, pp. 32.

Johnson N, Hampton CE and Gabler HC (2009), “Evaluation of the Accuracy of Side Impact Crash Test Reconstructions,” *Biomedical Sciences Instrumentation 45*: pp. 250-255.

Johnson N and Gabler HC (2011), “Accuracy of a Damage-Based Reconstruction Method in NHTSA Side Crash Tests,” Traffic Injury Prevention, 13:1, pp.72-80.

Kusano KD, Kusano SM and Gabler HC (2012), "Automated Crash Notification Algorithms: Evaluation of In-Vehicle Principal Direction of Force (PDOF) Estimations." *Transportation Research Part C*, DOI 10.1016/j.trc.2012.09.005 (published online 28-November 2012).

NHTSA (1981), *CRASH3 (Calspan Reconstruction of Accident Speeds on the Highway) User’s Guide and Technical Manual*, Accident Investigation Division, N.C.S.A., National Highway Traffic Safety Administration, report no. HS-805 732.

Niehoff P and Gabler HC (2006), “The Accuracy of WinSMASH Delta-V Estimates: The Influence of Vehicle Type, Stiffness, and Impact Mode,” Proceedings of the 50th Annual AAAM Conference.

Prasad AK (1987), “CRASH3 Damage Model Reformulation”, Department of Transportation Report No. VRTC-87-0053, Vol. I & II

SAE, “Collision Deformation Classification,” SAE Surface Vehicle Standard J224. Society of Automotive Engineers, Warrendale, PA, U.S.A. 1980.

Sharma D, Stern S, Brophy J, Choi E (2007), “An overview of NHTSA’s crash reconstruction software WinSMASH,” Proceedings of the 20th International Technical Conference on Enhanced Safety of Vehicles, paper no. 07-0211.