

THE ACCURACY OF WINSMASH DELTA-V ESTIMATES: THE INFLUENCE OF VEHICLE TYPE, STIFFNESS, AND IMPACT MODE

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ABSTRACT

The objective of this paper is to investigate the accuracy of WinSmash delta-V estimates as a function of crash mode, vehicle body type, and vehicle stiffness. The accuracy of WinSmash delta-V estimates was evaluated for 121 NASS/CDS 2000-2003 cases for which direct measurements of delta-V had been retrieved from an Event Data Recorder on the case vehicle. WinSmash was found to underestimate delta-V by 23% on average. WinSmash was found to be most accurate in crashes involving full frontal engagement of the vehicle structure. When using categorical stiffness coefficients, the accuracy of delta-V estimates was found to be a strong function of vehicle type. WinSmash underestimated delta-V for pickup trucks by only 3%, but underestimated delta-V for front-wheel drive cars by 31%. The use of vehicle-specific stiffness coefficients improved the accuracy of the longitudinal delta-V estimate. The single most important factor in improving WinSmash accuracy was the inclusion of restitution. After adjusting for restitution, WinSmash underestimated delta-V in frontal crashes by only 1% on average.

THE WINSMASH COMPUTER CODE estimates vehicle change in velocity, or delta-V, based on post-crash measurements of vehicle deformation. Delta-V is a crucial component of accident reconstruction, and is widely used as a measure of crash severity in crash statistics databases, e.g. the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS).

Computation of delta-V using WinSmash and other derivatives of the CRASH3 code is not always successful or accurate. Smith and Noga (1982) reconstructed 27 vehicle-to-vehicle

crash tests using CRASH3, and compared the results with the delta-V measured by crash test instrumentation. Their study concluded that CRASH3 underestimated delta-V by approximately 10% on average, and exhibited a fair amount of scatter surrounding that average. O'Neill et al (1996) compared CRASH3 delta-V estimates with impact speed in 41 frontal offset barrier crash tests, and found that CRASH3 produced a delta-V estimate that was approximately 33% less than the impact speed of the collision. Nolan et al (1998) confirmed this finding using SMASH, a CRASH3 derivative, and observed that the tendency to underestimate delta-V in frontal offset crash tests varied with vehicle type. Stucki and Fessahaie (1998) examined WinSmash performance in staged collisions with varying degrees of offset, and concluded that decreased vehicle frontal overlap led to greater delta-V underestimates. Lenard et al (1998) investigated the accuracy of CRASH3 with European cars. In 64 km/hr frontal offset crash tests, this study found that frontal offset impacts resulted in an average computed delta-V that was 7 km/hr lower than the actual delta-V.

The installation of Event Data Recorders (EDRs) in many production vehicles provides an alternative method to crash testing for evaluation of CRASH3 which may better capture the many complexities of a real-world crash. Current EDRs record either vehicle acceleration or change in velocity as a function of time during the crash event. These direct measurements of delta-V can be used to evaluate the accuracy of WinSmash or CRASH3 delta-V estimates.

In a study of 65 real-world crashed vehicles, Gabler et al (2004) compared the delta-V measured by Event Data Recorders with the delta-V estimated by WinSmash, and found that WinSmash underestimates longitudinal delta-V by 25% on average. The number of cases in the study was too small however to explore the reasons for this inaccuracy. In this paper, this issue is revisited with an expanded EDR data set to determine the reasons for WinSmash inaccuracy.

OBJECTIVE

The objective of this paper is to investigate the accuracy of WinSmash as a function of crash mode, vehicle body type, and vehicle stiffness.

METHODS

In this study, EDR measurements were used to evaluate the accuracy of WinSmash delta-V estimates. Our dataset was extracted from NASS/CDS 2000-2003 cases for which EDR data had been

retrieved by crash investigators. NASS/CDS is a national sample of 4,000 to 5,000 crashes investigated each year by the National Highway Traffic Safety Administration (NHTSA) at 27 locations throughout the United States. To date, the majority of cases in NASS/CDS with associated EDR data are General Motors (GM) vehicles. The dataset used in this study was comprised of only GM passenger vehicles of model years range from 1995 to 2003. The GM EDRs used in this study could record only longitudinal delta-V vs. time during the crash event. NASS investigators used WinSmash version 2.42 or earlier to compute the delta-V for the cases included in our analysis.

This study used a subset of the NASS/CDS EDR cases for a comparison between WinSmash and EDRs. Several criteria were used to select the cases for examination. First, only cases in which NASS/CDS investigators were able to estimate delta-V using WinSmash were used. Approximately, one-half of all cases in NASS/CDS have an unknown delta-V. Second, only cases which were severe enough to deploy the frontal airbag were included. Deployment of the airbag locks in the EDR data so that it can not be overwritten by subsequent events. Third, only collisions which were composed of a single crash event were included. In crashes with multiple events, it can be difficult to ensure that the EDR recorded the event which was reconstructed by NASS investigators using WinSmash. Finally, any case in which the EDR either obviously malfunctioned or did not record the entire event was excluded from our comparison. Our final dataset contained 121 cases meeting these requirements. The resulting dataset is not, nor should it be interpreted to be, a nationally representative sample of crashes.

The following section evaluates the accuracy of WinSmash delta-V estimates by comparison with EDR direct measurements of delta-V. In an earlier study, the authors found that, in staged crash tests, the delta-V measurements recorded by EDRs delta-Vs are six percent lower than the true delta-V (Niehoff et al, 2005b). The study was based upon 37 crash tests of GM, Ford, and Toyota passenger vehicles equipped with EDRs. The dataset was composed of 25 full frontal rigid barrier tests, 10 frontal offset tests using a deformable barrier, one vehicle-to-vehicle angled frontal crash test and one side impact test. The discussion which follows focuses on the accuracy of WinSmash, but the results may be applicable to other energy-based crash reconstruction codes which were derived from CRASH3.

RESULTS

OVERALL ACCURACY OF WINSMASH – Figure 1 presents a comparison of WinSmash delta-V vs. EDR delta-V for all cases in our dataset. Our EDR dataset was composed of a broad

spectrum of collision configurations, and vehicle types. Vehicles ranged from compact sedans to full-sized pickup trucks and vans. Collision types were primarily full-frontal or offset-frontal crashes, with varying principal directions of force (PDOF). Eighteen of the crashes were side impacts that deployed the airbag.

In Figure 1, symbols falling on the dashed line drawn diagonally across the plot are cases where the EDR and WinSmash delta-V perfectly matched. Symbols falling below the dashed line represent cases in which WinSmash underestimated delta-V. A least squares curve fit to the data is shown as a solid line in the figure. Based on the least squares fit ($R^2 = 0.60$), WinSmash underestimated longitudinal delta-V by approximately 23 percent, on average, for these deployment cases. There was significant scatter surrounding WinSmash delta-V estimates. The error in WinSmash delta-Vs was substantially higher than 23 percent in several individual cases. It should be noted that, because EDRs underestimate true delta-V by 6 percent on average, WinSmash likely underestimates the true delta-V by an amount even greater than 23% on average.

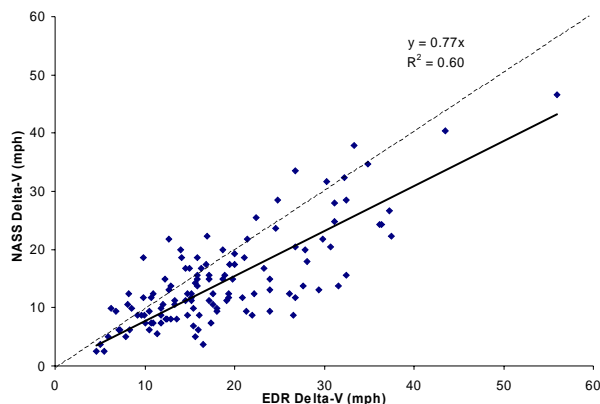


Figure 1. Comparison between EDR measured delta-Vs and NASS calculated delta-Vs

ACCURACY VERSUS FRONTAL OVERLAP – Previous research has shown that the error in WinSmash and SMASH delta-V is related to the amount of frontal overlap of the vehicle with its collision partner in a frontal crash [Nolan et al, 1998; Stucki and Fessahaie, 1998]. WinSmash and CRASH3 frontal stiffness coefficients are derived from full frontal rigid barrier crash tests. WinSmash extends these results to crashes which involve only partial overlap of the front structure by assuming that the frontal stiffness is uniform across the width of the car. By this reasoning, WinSmash should be most accurate in crashes which are most similar to full frontal crash tests, i.e, crashes in which there is full frontal engagement of the vehicle. Likewise, WinSmash should be less

accurate in crash configurations which diverge from full frontal engagement, e.g. for offset crashes.

To investigate this hypothesis, the dataset was divided into two subsets: those vehicles with less than 50% frontal overlap, and those vehicles with frontal overlap ranging from 50% to full frontal structural engagement. In both sets, delta-Vs were compared to EDR measured delta-Vs as shown in Figure 2.

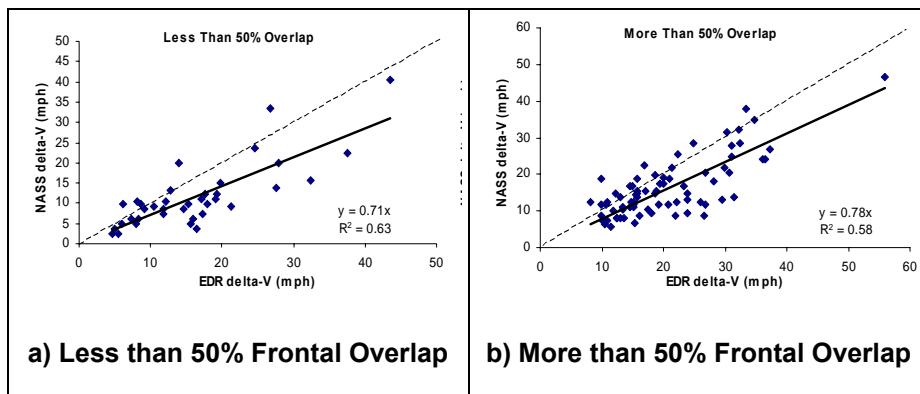


Figure 2. A comparison of WinSmash delta-V estimates in collisions, grouped by percent overlap

As seen in Figure 2, the performance of WinSmash delta-V estimates suffers when overlap decreases. Using the slope of the best-fit line as a quantitative assessment, the value decreases from 0.78 when more than 50 percent of the vehicle is engaged, to 0.71 for crashes with lower overlap. In addition, WinSmash was found to underestimate EDR measurements in 82 percent of impacts with less than 50 percent EDR overlap, and 75 percent of impacts with more overlap.

This finding is consistent with earlier studies that observed that CRASH3, SMASH, and WinSmash underestimated delta-V by a substantial amount in frontal offset crash tests [O’Neill et al, 1996; Nolan et al, 1998, Stucki and Fessahaie, 1998]. While more complete frontal structure engagement resulted in better delta-V predictions, full frontal engagement did not greatly reduce WinSmash error. Delta-V reconstruction for collisions with more than 50 percent overlap was only slightly better than the delta-V accuracy of all cases studied. This indicates that while WinSmash underestimates delta-V in offset collisions, the degree of frontal overlap is not the primary reason for underestimated delta-Vs.

ACCURACY VERSUS DELTA-V MAGNITUDE – Smith and Noga (1982) reported that CRASH3 tends to underestimate delta-V at low speeds and is unbiased at higher speeds. Because little crash test data exists at lower speeds, stiffness coefficient computations are based primarily on crush results from higher speed

crash tests at 25 to 40 mph. As a substitute for low speed crash test data, the stiffness computation assumes that there is no residual crush at some arbitrary speed, typically 7.5 mph (Prasad, 1990). Little is known about the accuracy or influence of this low speed, zero crush assumption.

EDR measurements of delta-V in NASS/CDS cases allow the accuracy of WinSmash in lower-speed and higher speed collisions to be compared. In this section, two groups of NASS cases will be compared: those cases with EDR measured delta-Vs of less than 15 mph, and those cases with higher delta-Vs. Forty-seven (47) cases were in the lower-speed group, and seventy-four (74) were in the higher-speed group.

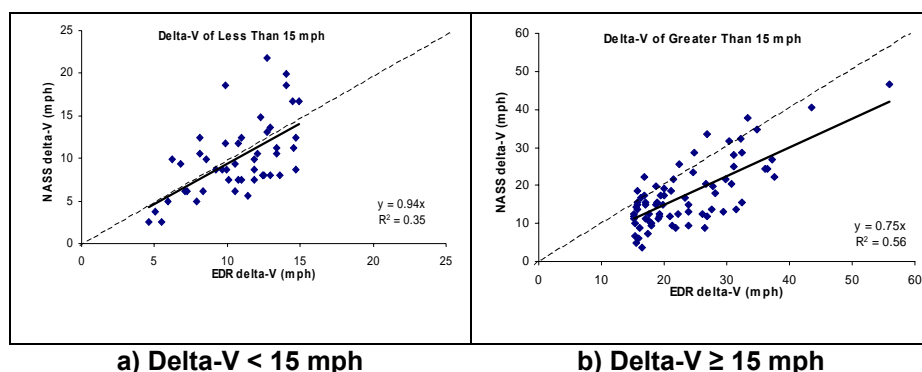


Figure 3. A comparison of WinSmash delta-V estimates in collisions, grouped by EDR measured delta-V

As shown in Figure 3, the least squares fit for cases with EDR delta-V below 15 mph resulted in $R^2 = 0.35$ suggesting that there is only a weak correlation between EDR delta-V and longitudinal delta-V estimated by WinSmash at these lower speeds. This indicates that at these speeds WinSmash is not a good predictor of true longitudinal delta-V. When the lower delta-V cases were removed from the dataset, WinSmash is noted to still underestimate EDR delta-V by 25% on average. Unlike the findings of Smith and Noga, we did not observe greater accuracy of WinSmash for higher delta-V cases.

ACCURACY VERSUS BODY TYPE – NASS/CDS
 computes delta-V using categorical stiffness coefficients, i.e., average stiffness values for a particular vehicle body type category. Both CRASH3 and WinSmash version 2.42 employ nine stiffness groups corresponding to different body types as shown in Table 1. Every passenger car or truck is categorized into one of these nine groups [NHTSA, 1986].

When categorical stiffness coefficients are used, Nolan et al (1998) observed that the accuracy of SMASH, a WinSmash precursor code, varied by vehicle body type. Delta-V computed

using categorical stiffness coefficients was 33% lower than impact speed for cars, 22% lower for utility vehicles, and 10% lower for passenger vans. In offset crash tests, the error in SMASH delta-V for Ford Ranger pickups was approximately half the error observed for mid-sized passenger cars. These findings however were limited to offset crash tests. This section will revisit this issue and extend the analysis to all crash modes.

Table 1. CRASH3 Stiffness Coefficient Categories

WinSmash Stiffness Category	Vehicle Body Type
1	Mini-cars
2	Subcompact
3	Compact
4	Intermediate
5	Full Size
6	Luxury
7	Vans and four-wheel drive
8	Pickup Trucks
9	Front-wheel drive

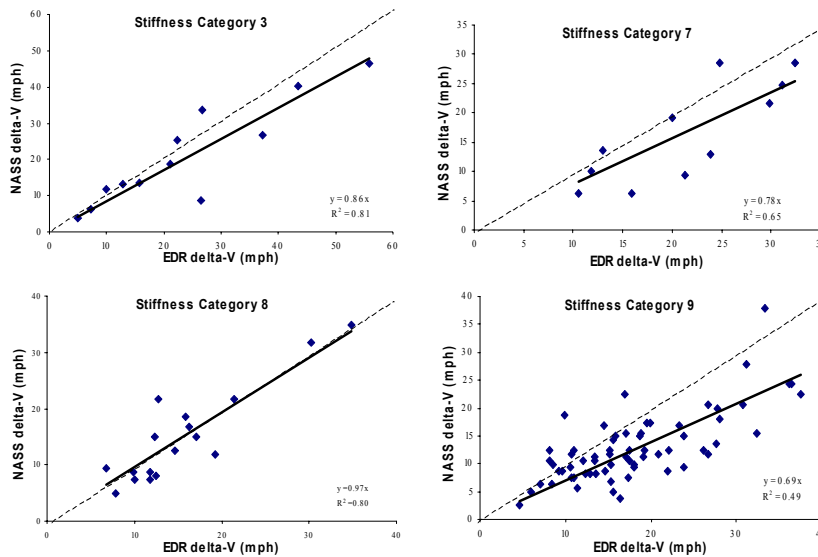


Figure 4. Comparison of WinSmash delta-V estimates in collisions, grouped by stiffness categories

There were sufficient numbers of EDR cases in four of the stiffness categories to allow analysis of delta-V accuracy by body type: compact cars (category 3), vans and four-wheel drive vehicles (category 7), pickup trucks (category 8) and front-wheel cars

(category 9). Figure 4 presents the comparison between WinSmash estimated delta-Vs and EDR measured delta-Vs for each category. A summary of the comparisons by body type is shown in Table 2.

Table 2. A summary of WinSmash delta-V estimate performance grouped by stiffness category

Body Type	Stiffness Category	Number of Cases	Slope	R ²
All	All	121	0.77	0.60
Compact cars	3	12	0.86	0.81
Vans and four-wheel drive	7	11	0.78	0.65
Pickup trucks	8	17	0.97	0.8
Front-wheel cars	9	65	0.69	0.49

This comparison confirms that WinSmash delta-V estimates are more accurate for certain body types. Pickup truck delta-Vs estimated by WinSmash were only 3% lower, on average, than EDR measurements. On the other hand, WinSmash underestimates delta-V for front-wheel drive cars by 31% - substantially higher than the sample error as a whole. These differences are likely due to differences in accuracy in the categorical stiffness coefficients for each body type.

WINSMASH DELTA-V CONFIDENCE – NASS/CDS investigators are asked by NHTSA to subjectively rate their confidence in the accuracy of each reconstruction. This confidence level is assigned by crash investigators based on how well the collision type is modeled with an energy-based approach, or what type of model was used to obtain delta-V. It has been suggested that WinSmash delta-V underestimates are the result of including cases in which investigators have only limited confidence in the reconstruction. Figure 5 compares the accuracy of WinSmash for cases rated as high-confidence reconstructions with the cases rated as having only limited confidence.

Examining the results of this comparison leads to several conclusions. First, significantly more scatter is evident in the lower-confidence cases. R² was equal to 0.23 for the lower confidence cases which indicates that there is only a weak correlation between WinSmash and EDR delta-V for these cases. Limiting the analysis to only high confidence cases does not reduce the amount of WinSmash error. WinSmash still underestimates delta-V by 23% on average even when NASS/CDS cases are restricted to those reconstructed

with high confidence. However, removal of lower confidence cases reduced the scatter in the fit somewhat. R^2 improved from 0.58 when all cases were included to 0.65 when only high confidence cases were included.

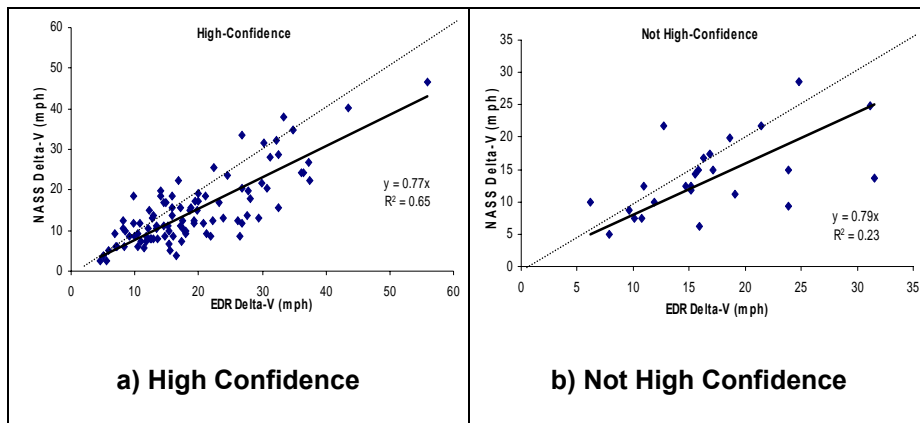


Figure 5. Comparison between NASS/CDS high-confidence delta-Vs and lower confidence delta-Vs

CATEGORICAL VERSUS VEHICLE-SPECIFIC STIFFNESS COEFFICIENTS

Much of the error observed in WinSmash delta-V computation may be the result of using categorical rather than vehicle-specific stiffness coefficients. Even within a given body type category, there may be a wide variation in vehicle stiffness from vehicle model to model. Using an average stiffness value for an entire body type category may lead to inaccurate computations for some vehicles. In this section, vehicle-specific coefficients were calculated for a large number of vehicle models and compared with the corresponding categorical stiffness value used in WinSmash.

METHOD USED TO CALCULATE STIFFNESS

COEFFICIENTS – The method used to calculate these values was originally developed by Prasad (1990). The crash tests used in the calculation were all frontal-rigid barrier tests from the NHTSA vehicle crash test database (NHTSA, 2005). Impact speeds in the tests ranged from 25 to 35 mph. For each test, the NHTSA crash test database contained vehicle geometrical properties (width and curb weight), crash test conditions (impact type and speed), and post-impact vehicle crush measurements at six points across the front of the vehicle. For each vehicle, the stiffness coefficients d_0 and d_1 , (the y-intercept and slope, respectively) of that relationship were computed. The vehicle-specific stiffness coefficients used in this study and a detailed description of the method of calculation is presented by Niehoff (2005a).

COMPARISON OF ABSORBED ENERGY USING DIFFERENT STIFFNESS COEFFICIENTS – A critical assumption in energy-based accident reconstruction is that the energy dissipated in a collision can be approximated through vehicle crush measurements. The method used to estimate this absorbed energy requires the use of the previously discussed stiffness coefficients. These coefficients have a significant effect on the calculation of absorbed energy, which is then used to approximate delta-V.

This section will compare the calculation of absorbed energy in vehicles involved in frontal crashes using both the vehicle-specific and categorical stiffness coefficients. The dataset used in this comparison consisted of the post-crush measurements from seventy-three (73) vehicles as recorded in NASS/CDS. EDR data was not used for this analysis.

Figure 6 compares the calculation of absorbed energy using both the categorical and vehicle-specific stiffness coefficients. The horizontal axis represents the absorbed energy as calculated with the categorical coefficients, while the vertical axis represents energy calculated with vehicle-specific values. The diagonal dotted line represents a hypothetical perfect agreement between the two. Most data points are above the dashed line, indicating that on average the absorbed energy calculated with vehicle-specific coefficients is greater than absorbed energy computed using categorical stiffness coefficients.

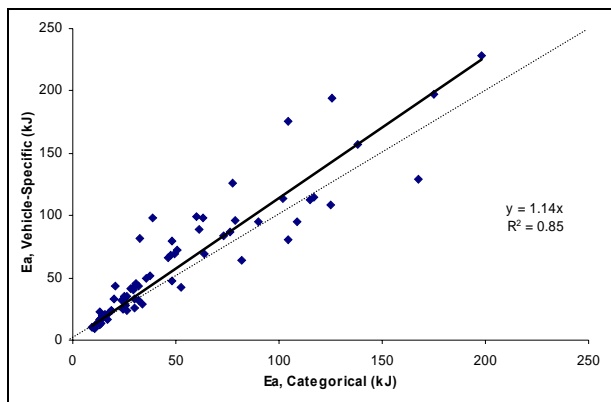


Figure 6. Comparison of E_a using categorical and vehicle-specific stiffness coefficients

In this study, absorbed energy was calculated to be 14% higher, on average, when using vehicle-specific coefficients than when using categorical stiffness coefficients. For frontal collisions, this dataset suggests that the use of categorical stiffness coefficients tends to underestimate a vehicle’s absorbed energy.

COMPARISON OF DELTA-V WHEN COMPUTED WITH VEHICLE-SPECIFIC VERSUS CATEGORICAL STIFFNESS COEFFICIENTS – WinSmash allows the user to input either vehicle-

specific or categorical stiffness coefficients. Results from previous studies suggest delta-Vs calculated using categorical stiffness coefficients were lower than those calculated using vehicle-specific stiffness coefficients [Nolan et al, 1998]. To quantify this possible explanation for WinSmash inaccuracy, delta-Vs from twenty-five (25) NASS/CDS collisions were recalculated using the previously derived vehicle-specific coefficients. The results were compared to both the delta-Vs calculated with categorical coefficients, as well as the EDR measured delta-Vs.

WinSmash version 2.42 was used to re-calculate delta-Vs for twenty-five (25) vehicle-to-vehicle collisions. The only alteration made in this recalculation was the use of vehicle-specific stiffness coefficients in place of the categorical values. All other input data was obtained from the NASS/CDS database. In order to verify that the only variables being changed were the stiffness coefficients, the categorical WinSmash estimates were recalculated and verified against values in the NASS/CDS database. Niehoff (2005a) presents the detailed results of this calculation including the original delta-V using categorical stiffness coefficients, re-calculated delta-V using vehicle-specific stiffness coefficients and the EDR measured delta-V if available.

Frontal stiffness coefficients were used in the delta-V calculation of the cases because the primary damage plane was frontal in all cases. However, both the lateral and longitudinal delta-Vs were re-calculated during this process. The lateral delta-V was not included in the comparison because the EDRs in this study did not record lateral delta-V. Because principal direction of force was not changed, the ratio of longitudinal to lateral delta-V also did not change as a result of the recalculation.

Figure 7 illustrates the differences between the re-calculated delta-Vs and their original values. As expected, nearly all re-calculated delta-Vs were greater in magnitude than the originals. This is due to predominantly higher stiffness coefficients, which resulted in a greater calculated absorbed energy and resulting delta-V. A best-fit line indicated the re-calculated values to be six percent higher on average than the original delta-Vs.

Figure 8 provides a comparison of three data sets. EDR measured delta-Vs were plotted on the x-axis, and both the original and re-calculated WinSmash delta-Vs were plotted on the y-axis. Only vehicles from the comparison displayed in Figure 7 that had corresponding EDR delta-Vs were included in Figure 8. Best-fit lines were included for the categorical and vehicle-specific derived values, as well as a diagonal line that indicates perfect agreement. The presence of EDR data in this comparison provides a baseline with which to evaluate both the categorical and vehicle specific methods of calculating delta-V.

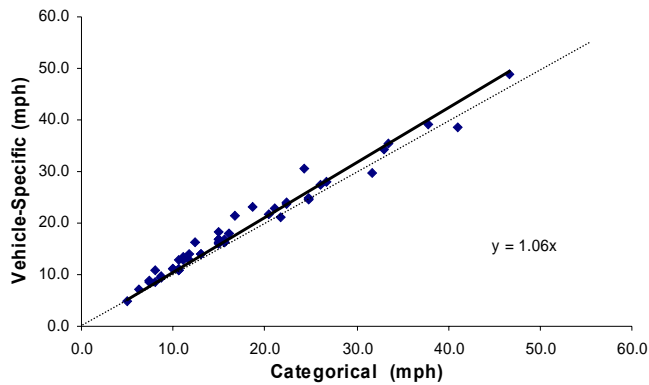


Figure 7. Delta-V calculated with Vehicle-specific stiffness coefficients vs. original WinSmash delta-Vs computed with categorical stiffness coefficients

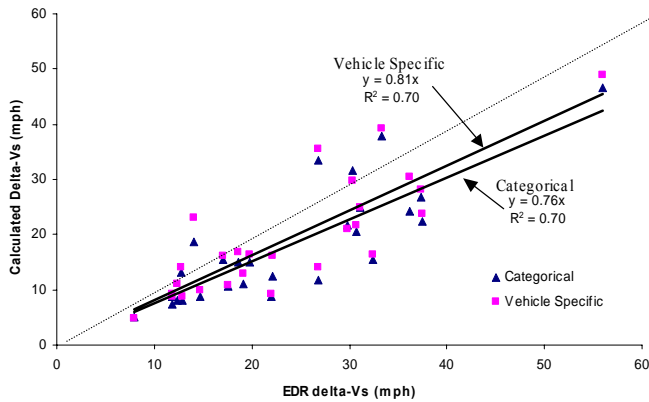


Figure 8. NASS and re-calculated delta-Vs vs. EDR measured delta-Vs

As shown in Figure 8, the use of vehicle-specific stiffness coefficients improves the accuracy of the longitudinal delta-V estimate. When vehicle-specific stiffness coefficients are used for reconstruction, WinSmash underestimates delta-V by 19%. In contrast, when categorical stiffness coefficients were used with this dataset, WinSmash underestimated delta-V by 24%. Both methods of calculating delta-V resulted in underestimates of the true delta-V on average, however the use of vehicle-specific stiffness coefficients in this dataset reduced the amount of average underestimation by approximately five percent. The R^2 value is the same for both methods, which suggests that the use of vehicle-specific stiffness coefficients resulted in no improvement in data scatter about the best fit line.

The error associated with categorical stiffness coefficients could potentially be reduced by simply computing improved estimates of categorical stiffness. Niehoff (2005) has investigated

this possibility, but still finds that vehicle-specific coefficients give more accurate estimates of delta-V.

INFLUENCE OF VEHICLE RESTITUTION – WinSmash assumes that collisions are purely plastic. In a real world crash, however, plastic deformation is followed by a small amount of elastic restitution of energy during unloading. In a frontal barrier crash test, like that shown in Figure 9, elastic restitution of energy resulted in a vehicle rebound velocity away from the barrier.

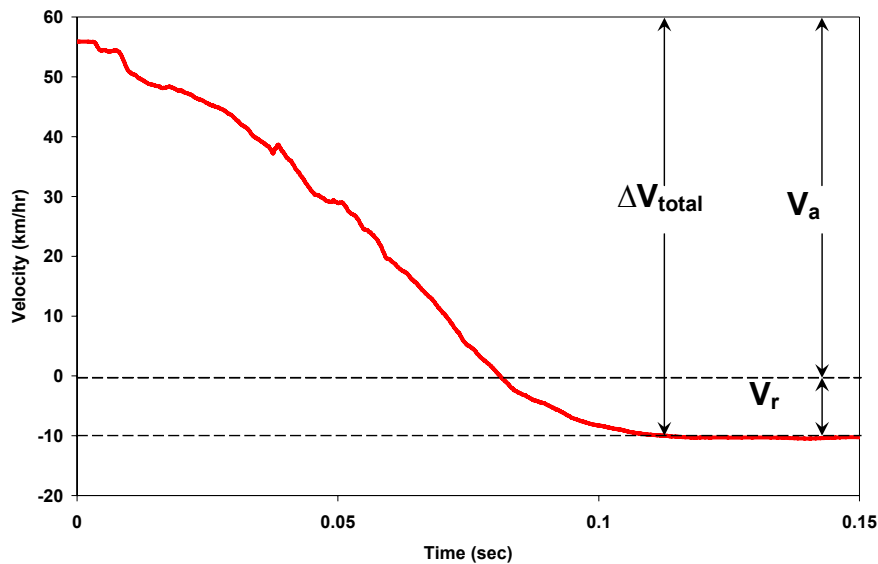


Figure 9. Frontal Barrier Crash Test of a 2006 Honda Ridgeline (NHTSA Test 5383)

The total delta-V is the sum of the approach velocity, V_a , and the rebound velocity, V_r , i.e., $\Delta V_{total} = V_a + V_r$. By assuming zero restitution, WinSmash underestimates delta-V by the amount of this rebound velocity. The objective of this section is to determine the extent of WinSmash delta-V error which results from assuming zero restitution. Restitution can be included in a collision calculation through the use of a restitution coefficient as shown below:

$$\Delta V_{total} = \Delta V_{plastic} (1 + \epsilon)$$

$$\text{Where } \epsilon = V_r / V_a$$

In the relationship shown above, $\Delta V_{plastic}$ is the delta-V computed by WinSmash. Restitution coefficients were computed for forty-seven (47) vehicles based on NHTSA full frontal barrier crash tests. In a vehicle-to-vehicle crash, both vehicles return elastic energy while rebounding from the collision, and require the computation of a combined restitution coefficient which is a function of both vehicles' restitution and stiffness. We used the method

developed by Prasad (1990) to compute a combined restitution coefficient in the event of a vehicle-to-vehicle crash. The resulting restitution coefficients were applied to 50 vehicles to calculate a corrected delta-V. Twenty-seven (27) of these vehicles also had associated EDR data.

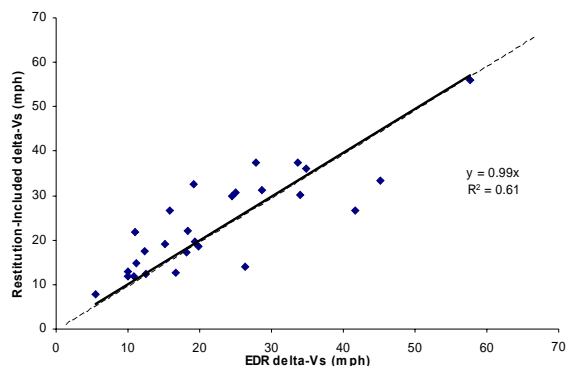


Figure 10. Restitution-corrected WinSmash delta-V versus EDR delta-V measurements

Figure 10 shows the comparison of EDR delta-V with the restitution-corrected delta-V. The resulting delta-V estimates are in substantially better agreement with EDR delta-V measurements. For this dataset, the restitution-corrected delta-V estimates are on average only 1% below EDR delta-V.

LIMITATIONS

Several limitations associated with this study are discussed below:

1. The results of this study analyzed NASS/CDS delta-V estimates produced by WinSmash versions 2.42 or earlier. Our conclusions should be revisited when using future versions of WinSmash.
2. The study uses the EDR recorded delta-V as a surrogate for true delta-V. In staged crash tests, however, EDRs have been found to underestimate true delta-V by 6% on average.
3. The analysis of EDR delta-V was restricted to GM vehicles. The conclusions are not expected to vary by vehicle manufacturer, but this assumption could not be verified with the current dataset. Furthermore, because current GM EDRs only record longitudinal delta-V, our findings only apply to WinSmash estimates of longitudinal delta-V.
4. The average values of WinSmash error reported in this paper apply only to the EDR data set used in this study. The dataset was not designed to be, nor should it be interpreted, as a nationally representative sample.

5. The analysis of WinSmash accuracy using vehicle-specific stiffness coefficients and energy restitution used a dataset composed entirely of frontal crashes. As a result, the findings from these analyses are only applicable to frontal collisions.
6. Full frontal rigid barrier crash tests were used to calculate vehicle stiffness coefficients and restitution coefficients. These tests may not be representative of many real-world collisions for several reasons. Real-world frontal collisions are typically offset, which results in partial engagement of the front bumper. Incompatible bumper heights between vehicles also result in less than complete frontal structure engagement. These additional complications may not be well modeled with vehicle specific stiffness and restitution coefficients derived from full frontal barrier crash tests.
7. Several assumptions were made when incorporating vehicle restitution coefficients into the delta-V calculation process. It was assumed that a single restitution coefficient could be used to model the elastic response of a vehicle's structure, however it is known that restitution is a function of crash type and delta-V. For example, a collision involving two incompatible vehicles will result in override, which would affect the rebound velocity and structural restitution. Also, at low speeds such as 5mph, most vehicle structures are completely elastic. Therefore, it is likely that the use of a restitution coefficient offers only an approximation of rebound velocity.
8. Because only a limited number of crash tests were available for each vehicle model, all crash tests for each vehicle model nameplate were aggregated during the calculation of vehicle specific stiffness and restitution coefficients. An improved approach, given a larger set of crash tests, would be to compute a separate set of stiffness coefficients for each version of a particular vehicle model.

CONCLUSIONS

A comparison of WinSmash and EDR delta-Vs showed that WinSmash underestimates delta-V by 23% on average. This conclusion is consistent with previous studies, which also found that WinSmash and CRASH3 underestimate delta-V. These previous studies have suggested that this error is due to (a) the degree of overlap in frontal offset collisions, (b) inaccuracies in low-speed delta-V estimates, and (c) the use of categorical stiffness coefficients rather than vehicle-specific stiffness coefficients. These three factors were investigated as part of this study. Conclusions from this study are:

- WinSmash was found to underestimate longitudinal delta-V more for lower frontal overlap cases than for higher overlap cases. WinSmash underestimated longitudinal delta-V by 29% for frontal overlap lower than 50%, but only 22% for cases in which overlap exceeded 50%.
- Little correlation was observed between WinSmash and EDR delta-V for cases with EDR delta-V below 15 mph.
- WinSmash accuracy was shown to be a function of vehicle body type when using categorical stiffness coefficients. WinSmash delta-V estimates were most accurate for the pickup truck and compact car categories. WinSmash only underestimated delta-V by 3% for pickups and 14% for compact cars on average. Least accurate were delta-V estimates for front-wheel drive vehicles, which were underestimated by 31%.
- Restricting the analysis to NASS/CDS cases reconstructed with high confidence had little effect on WinSmash error. For these high confidence cases, WinSmash underestimated longitudinal delta-V by 23%.
- The use of vehicle-specific stiffness coefficients improved the accuracy of the longitudinal delta-V estimate. When vehicle-specific stiffness coefficients were used for reconstruction, WinSmash underestimated delta-V by 19% - a notable improvement over delta-V computed using categorical stiffness coefficients.
- The use of restitution adjustments greatly reduced WinSmash error to only 1% of true delta-V. The inclusion of restitution was found to be the single most important factor in improving WinSmash accuracy.

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