EVALUATION OF WINSMASH ACCURACY IN NHTSA SIDE CRASH TEST RECONSTRUCTIONS

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ABSTRACT

Several researchers have raised anecdotal concerns that NASS/CDS may overestimate ΔV in side crashes. NASS/CDS investigators use the WinSmash code, a successor to CRASH3, to perform the estimations The objective of this study was to determine the accuracy of WinSmash reconstruction of ΔV in side crash tests. The actual ΔV and absorbed crash energy were computed for a suite of 73 NHTSA side crash tests using crash test instrumentation. Multiple accelerometers on both the striking and struck vehicle were used to calculate full planar motion histories, vehicle rotation, and center-of-gravity ΔV at maximum crush and at vehicle separation. The same crash tests were then reconstructed using WinSmash and post-test crush measurements. This paper compares the WinSmash ΔV with the actual ΔV at maximum crush and ΔV at separation. The paper concludes that WinSmash over-predicts ΔV at separation in side crash tests by 11% on average.

INTRODUCTION

In 2008, a total of 23,888 individuals lost their lives in passenger vehicles involved in accidents in the United States (FARS 2008). Of these, 5,265, or just over 22%, died in vehicles which were struck in the side. Research aimed at understanding side impact crashes and mitigating their toll on society relies heavily on data provided by the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS), an in-depth crash investigation program sponsored by the U.S. National Highway Traffic Safety Administration (NHTSA).

One of the most important data elements recorded in the NASS/CDS is the vehicle change in velocity, or ΔV. ΔV is the vector change in velocity experienced by a vehicle during a collision, and is widely used as a measure of collision severity in crash safety research (Bahouth et al.2004; Gabauer and Gabler, 2008). The ΔV information in NASS/CDS is used by NHTSA to determine research needs, regulatory priorities, design crash test procedures (e.g., test speed), and to determine countermeasure effectiveness.

The WinSmash crash reconstruction code is used to compute the ΔV estimates in the NASS/CDS. However, the reconstruction accuracy of the current WinSmash version has not previously been examined for side impacts. Given the importance of side impact crash modes and the widespread use of NASS/CDS data, an assessment of the program's reconstruction accuracy is warranted.

OBJECTIVE

The objective of this study was to determine the accuracy of WinSmash reconstructions of side crash tests.

APPROACH

Crash tests provide a wealth of controlled crash response data against which to evaluate WinSmash. Knowing the WinSmash accuracy in reconstructing crash tests, we can infer WinSmash accuracy in reconstructing real-world side crashes. For this study, WinSmash was compared to NHTSA side impact crash tests conducted for both FMVSS No. 214 and the NHTSA New Car Assessment Program. The actual ΔV for the struck vehicle was determined from test instrumentation for each test, and this ΔV was compared to the WinSmash-reconstructed ΔV of the same test.

NHTSA Side Crash Tests

Figure 1 shows the crash configuration used in the Side NCAP and FMVSS 214D side crash tests run by the NHTSA. In this test, a stationary test vehicle has a Moving Deformable Barrier (MDB) towed into it at either 33.5 mph (FMVSS 214D) or 38.5 mph (Side NCAP) in a crabbed configuration. This means that the MDB wheels are all angled at 27 degrees with respect to the MDB body; this gives the MDB face a lateral velocity with respect to the struck vehicle at impact and simulates a collision where both vehicles are moving.

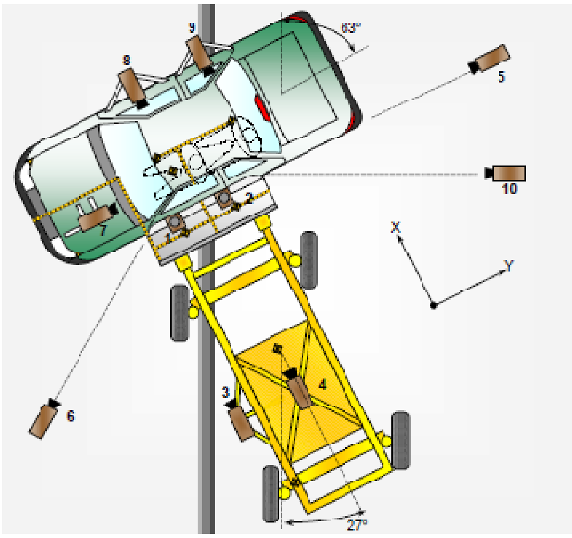

Figure 1. Crash configuration used in NHTSA side tests. Reproduced from NHTSA (2006).

WinSmash Reconstructions

All WinSmash reconstructions performed in this study were of the "standard" type. For a standard reconstruction, WinSmash requires measurements of the damage to both involved vehicle. These "damage profiles" take the form of 6 equally spaced measurements of crush depth (relative to the original vehicle outline) all taken at the same height above ground. For real-world crashes, both the length of the damaged region, i.e., the damage length, and the height at which measurements are determined using investigator judgment. For NHTSA side crash tests such as those examined here, 6-point damage profiles are generated for the struck vehicle and recorded in the test documentation. Detailed crush measurements are also made for the MDB face, but a 6-point damage profile is not recorded. For the reconstructions in this study, a 6-point damage profile was generated for the Moving Deformable Barrier (MDB) damage profile by linearly interpolated from the MDB crush measurements recorded at mid-bumper height.

Most vehicle specifications and contact configuration parameters used in WinSmash reconstructions were obtained from the crash test records and/or testing protocols. The vehicle radius of gyration is specified by the NHTSA testing protocols for the MDB, however this parameter is seldom known for actual vehicles, in crash tests or in real-world crashes. All reconstructions in this study used the WinSmash default method of estimation (Sharma et al. 2007) shown in equation 1 to estimate the struck vehicle radius of gyration.

$$radius\ of\ gyration = 0.3 * (length) \quad (1).$$

Vehicle Center of Gravity (CG) location was not recorded directly in the test reports, but was calculated from the recorded wheelbase and front/rear tire weight distribution and assumed to lie on the vehicle centerline.

When reconstructing a crash, WinSmash requires that the investigator estimate Principal Direction of Force (PDOF) and damage offset. PDOF is the direction of the crash impulse relative to the vehicle. Damage offset describes the location of the point of application of the crash impulse relative to the vehicle center of gravity (CG). Errors in estimations of these parameters, which are largely unavoidable, will introduce some amount of error into all WinSmash reconstructions. In order to eliminate this confounding effect from the analysis, the PDOF and damage offset used here were both calculated from the crash test data itself. PDOF was simply calculated as the direction of the vehicle's ΔV at maximum crush.

Damage offset was determined by calculating the crash impulse moment arm required to generate the observed vehicle yaw rate at maximum crush, assuming the estimated value of radius of gyration (resultant crash impulse being calculated from observed ΔV). Using the calculated PDOF, the longitudinal position of the point of impulse application was then calculated, assuming some lateral depth for the application point. In this analysis, the lateral depth of the damage profile centroid was chosen for this purpose, based on the work of Ishikawa (1994).

WinSmash assumes that restitution in all crashes is negligible. In effect, WinSmash therefore only calculates ΔV up to the point of common interface velocity or maximum crush. The difference between maximum crush ΔV and total ΔV at separation of the vehicles is dependent upon the amount of restitution that actually occurs in the test. In order to separate the effect of the restitution assumption from other effects, WinSmash ΔV was compared to the crash test ΔV recorded at both the time of common velocity and the time of separation.

Because the MDB face in side crash tests absorbs some energy, its deformation must be accounted for in WinSmash reconstructions of crash tests. This analysis used a stiffness value computed by Struble et al. (2001) from frontal barrier tests of the NHTSA MDB face (Table 1). Struble originally presented this stiffness in a format used by CRASH3, the predecessor to WinSmash. The second value in Table 1 was converted using the relationships $A = d_0 * d_1$ and $B = {d_1}^2$ developed by Prasad (1990) and presented by Sharma et al. (2007).

Table 1.
MDB face stiffness reported by Struble et al. (2001), used in WinSmash reconstructions.

CRASH3 Format (original)		WinSmash Format (used here)	
$A\ [N/cm]$	$B\ [N/cm^2]$	$d_0\ [\sqrt{N}]$	$d_1\ [\sqrt{N}/cm]$
502.8	127.4	44.555	11.285

Stiffness parameters for the struck vehicle were selected by WinSmash automatically, based on the year, make, model, bodystyle and damaged side (front/side/rear). WinSmash first attempts to find a vehicle-specific stiffness coefficient in its integrated library for the exact vehicle specified. If an exact match cannot be found, WinSmash applies a categorical stiffness coefficient instead.

Processing of Crash Test Data

NHTSA side crash tests, being crabbed, can involve substantial rotation. To capture both rotational and translational motion, NHTSA tests record bi-axial acceleration for both vehicles (MDB and test vehicle) at multiple locations. Using a technique presented by Marine and Werner (1998), the full planar motion history of both the MDB and the struck vehicle was first calculated. By determining the time at which the MDB protruded the farthest into the struck vehicle, the time of maximum crush could be determined and the maximum crush ΔV at that time recorded. Separation ΔV was then simply taken at the time when the struck vehicle achieved its maximum velocity. Total absorbed energy was calculated by subtracting the rotational and linear kinetic energy for each vehicle at maximum crush from the kinetic energy of the MDB at the start of the test (the vehicle is initially stationary) (equation 2).

$$E_{abs\ total} = KE_{MDB-0} - (KE_{MDB\ max\ crush} + KE_{Veh\ max\ crush})$$

$$KE_{MDB-0} = \frac{1}{2} * m_{MDB} * V_{0\_MDB}{}^2$$

$$KE_{MDB\ max\ crush} = \left(\frac{1}{2} * m_{MDB} * V_{MDB\ max\ crush}{}^2\right) + \left(\frac{1}{2} * I_{MDB} * \omega_{MDB\ max\ crush}{}^2\right)$$

$$KE_{Veh\ max\ crush} = \left(\frac{1}{2} * m_{Veh} * V_{Veh\ max\ crush}{}^2\right) + \left(\frac{1}{2} * I_{Veh} * \omega_{Veh\ max\ crush}{}^2\right) \quad (2).$$

In the tests examined in this study, rotation accounted for 6.3% of the total kinetic energy of the struck vehicle at maximum crush non average, and 8.6% of the MDB kinetic energy at the same time on average.

All tests were checked for problems using multiple techniques. Any tests with problems that could not be corrected were discarded from the analysis. Data quality checks included the following:

- **<u>Visual Inspection of Data</u>** Visual inspection of plots of the data for each case eliminated obvious problems such as corrupted accelerometer channels, or typographical errors in crush measurements.

- **<u>Momentum Conservation</u>** From momentum conservation, the ratio of the resultant ΔV for the MDB and vehicle to the inverse ratio of their masses should be nearly equal (equation 3):

$$\left\|\frac{\Delta V_1}{\Delta V_2}\right\| = \frac{m_2}{m_1} \quad (3).$$

  Marine and Werner (1998) used two biaxial accelerometers to compute a motion history. The MDBs in NHTSA tests have exactly this number, but the struck vehicles often have more biaxial accelerometers. There is no guarantee however that all of these accelerometers recorded useful data. Thus, the vehicle ΔV was computed using each possible pairing of accelerometers. The results for the accelerometer pairing which most closely obeyed momentum conservation at common velocity were retained. If the best ratio of the resultant ΔVs differed from the inverse ratio of the masses by more than 5%, the case was excluded from further analysis.

- **<u>Sequence of Events</u>** Any cases in which the time of vehicle separation occurred before the calculated time of maximum crush were discarded.

- **<u>PDOF Colinearity</u>** The calculated PDOFs for the vehicle and MDB were checked for colinearity. In theory, the test vehicle and MDB should both change velocity along the same line, but in opposite directions. Knowing the velocity change of each vehicle, and its orientation at maximum crush, the agreement with theory was tested. Maximum crush was chosen since, being earlier in the collision than separation, it is less affected by cumulative errors in the velocity integration. WinSmash itself allows for 10 degrees difference between vehicle PDOFs. Any tests in which the observed MDB PDOF and vehicle PDOF differed by more than this amount were excluded from the analysis. For purposes of the WinSmash reconstruction, the MDB PDOF was set to be precisely collinear with the measured struck vehicle PDOF, rather than use the measured MDB PDOF. The magnitude of the difference between the measured MDB PDOF and the value used in WinSmash was 4.13 degrees on average, with a minimum of 0.08 degrees and a maximum of 9.82 degrees.

Statistics

All comparisons between WinSmash – predicted values and measured values were visualized using a cross plot displaying the data points and a linear regression line fit to the data using a fixed intercept of zero. This has the virtue of concisely describing both systemic error and random error about the mean. Rigorous tests on the statistical significance of all comparisons were carried out in SAS 9.2 using Student's Paired T-test ('PROC TTEST' using the 'PAIRED' keyword) or the Wilcoxon Signed Rank Sum test (part of the output of 'PROC UNIVARIATE'), which is the non-parametric equivalent of the Paired T-test. Whenever a significance level is stated, the test used to determine it is given as well. The test used, Student's or Wilcoxon, is indicative of whether or not PROC UNIVARIATE found the difference to be normally distributed.

RESULTS

Table 2 summarizes the data set used in this study. Test included both FMVSS 214-D compliance tests (33.5 mph nominal impact speed) and Side NCAP tests (38.5 mph nominal impact speed) from 1994 to 2006.

Table 2. Summary of dataset composition.

Dataset Composition	
Total Tests:	73
Vehicle Type:	
Cars	66
LTVs	7
Nominal Impact Speed:	
33.5 mph (FMVSS)	31
38.5 mph (NCAP)	42
Stiffness Type:	
Vehicle Specific	69
Categorical	4

Figure 2 shows a plot of WinSmash-estimated resultant vehicle ΔV versus the value measured from tests at separation. WinSmash was observed to over-predict resultant ΔV by 11% systemically (see regression equation), with a great deal of case-to-case variability. The observed difference between the WinSmash ΔV and the measured ΔV was found to be significant at 95% confidence (p-value < 0.0001) using Student's Paired T-test.

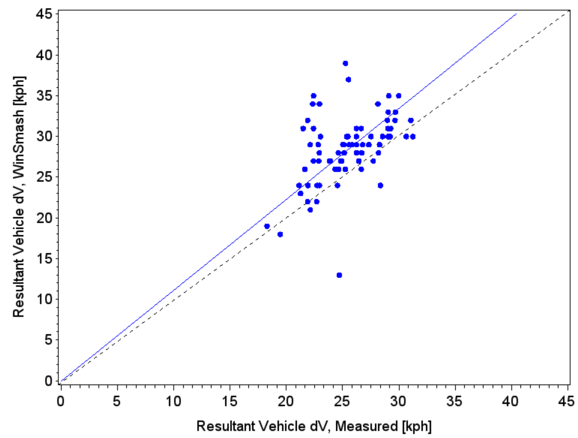

Figure 2. Resultant vehicle ΔV at separation, WinSmash predictions versus measured values. Regression equation: y = 1.114x

Figure 3 compares ΔV measured at separation to ΔV measured at maximum crush, and demonstrates the effect of restitution on the measured ΔV. NHTSA side tests appear to exhibit about 8% restitution on average. The observed difference in ΔV was found to be significant at 95% confidence (p-value <0.0001) using the Wilcoxon Signed Rank Sum test.

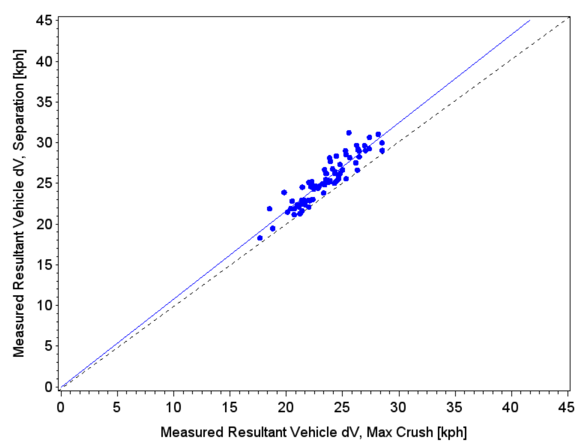

Figure 3. ΔV measured at separation versus ΔV measured at maximum crush. Regression equation: y = 1.081x

Figure 4 compares WinSmash ΔV to the ΔV measured at maximum crush. This comparison is not affected by WinSmash's assumption of zero restitution as is Figure 2. Notice that the difference between WinSmash ΔV and the measured ΔV has increased to 21%. The observed difference was found to be significant at the 95% confidence level (p-value < 0.0001) using Student's Paired T-test.

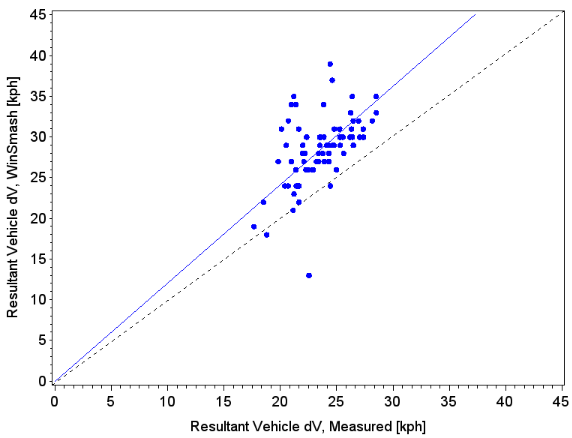

Figure 4. Resultant vehicle ΔV at maximum crush, WinSmash predictions versus measured values. Regression equation: y = 1.207x

Figure 5 compares WinSmash's estimate of the total amount of energy absorbed in the collision (the sum of energy absorbed by both vehicles) to the actual value calculated from the test data at maximum crush. This is a key comparison, as the WinSmash stiffness model predicts energy absorbed specifically at maximum crush and not at separation. The observed difference is consistent with over-prediction of ΔV, and was found to be significant at 95% confidence (p-value < 0.0001) using Student's Paired T-test.

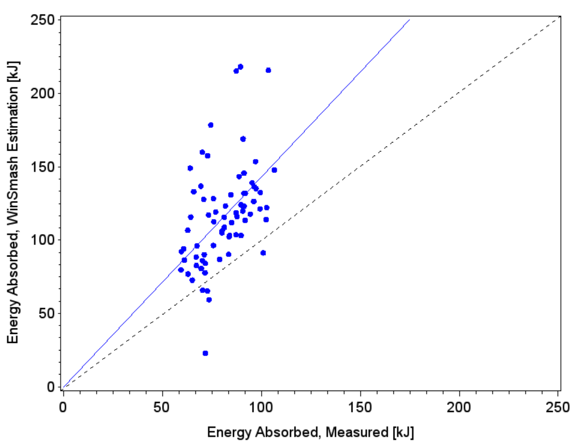

Figure 5. Total energy absorbed in test, WinSmash estimation versus measured value at maximum crush. Regression equation: y = 1.43x

Figure 6 compares the ΔV measured at maximum crush and the ΔV estimated by WinSmash when WinSmash is forced to use precisely the energy calculated from the test data at maximum crush. This comparison is not affected by either error due to restitution or inaccurate energy estimations. While the two ΔVs were still found to be significantly different at 95% confidence (p-value < 0.0001) using the Wilcoxon Signed Rank Sum test, the mean difference was only 0.45 km/h, or about 2% on average as shown in the regression equation. Note also the drastic reduction in case-to-case variability.

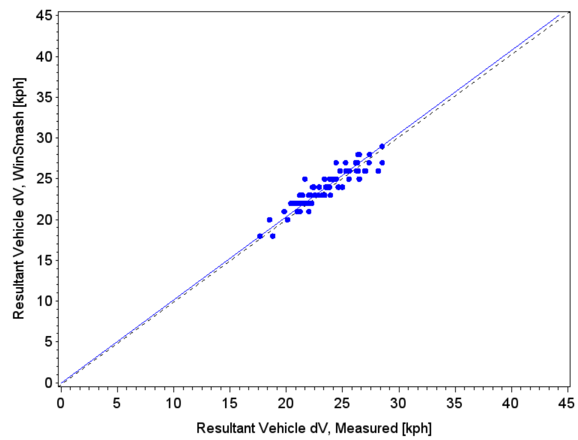

Figure 6. Resultant vehicle ΔV at maximum crush, WinSmash predictions using measured energy versus measured ΔV values. Regression equation: y = 1.018x

DISCUSSION

Figure 2 indicates that WinSmash over-predicts struck vehicle ΔV in NHTSA side crash tests by 11%. The accuracy of the WinSmash reconstruction model is strongly affected by investigator estimates of PDOF (Brach and Brach, 2005), but PDOF (and damage offset) error has been controlled for in this analysis. Vehicle specifications are all known with a high degree of certainty from the test documentation, except for radius of gyration. However, the damage offset parameter used in the WinSmash reconstructions was calculated using the estimated radius of gyration, so this is controlled for as well. This leaves WinSmash's restitution assumptions and estimations of absorbed energy as the most probable sources of error.

Figure 3 indicates that there is about 8% restitution on average in NTHSA side crash tests (the precise mean difference between maximum crush and separation is 1.9 km/h). If WinSmash were reconstructing the crash tests otherwise perfectly, an under-prediction of about 8% average would be expected due to ignoring restitution (ΔV always being higher at separation than at maximum crush). Figure 2 clearly demonstrates that the opposite is happening, which implies some other effect is present in these reconstructions. Figure 4 bears this out further. By comparing the WinSmash – reconstructed ΔV to the ΔV measured at maximum crush, restitution no longer factors into the comparison. The observed over-prediction of crash test ΔV then increases from 11% to 21%. The WinSmash assumption of zero restitution appears to partly mask the error due to some other influence.

This other influence is the accuracy of WinSmash's estimation of the amount of energy absorbed in collisions. Estimation of absorbed energy is central to the WinSmash crash reconstruction algorithm (Campbell, 1974; Sharma et al., 2007). WinSmash estimates the energy absorbed in a collision, at the time of maximum crush, based on the residual vehicle crush and a vehicle "stiffness". WinSmash then calculates ΔV from this energy estimate using momentum conservation principles (NHTSA, 1986; Prasad, 1990; Sharma et al., 2007). For side crashes, this stiffness is derived from NHTSA side crash tests using two important assumptions. Both assumptions affect the accuracy of WinSmash. First, WinSmash side stiffnesses are computed using an absorbed energy value calculated by applying 1-D momentum conservation. Second, the computation of WinSmsah side stiffness assumes that MDB damage accounts for only 5% of the total energy absorption.

1-D momentum conservation is the theoretical upper limit on absorbed energy in a collision between two bodies. This is because it constrains the crash impulse to act through both vehicle CGs, which results in the maximum potential ΔV for any given impact speed (Brach and Brach, 2005). For a fixed impact speed, collisions between two bodies where the crash impulse is not collinear with one or more CGs will result in a smaller ΔV, and thus a smaller change in kinetic energy. The vehicle CGs in NHTSA crash tests – and in many real-world crashes – are not in general collinear with the crash impulse, so the absorbed energy in such tests will invariably be less than what is predicted by 1-D momentum conservation. Figure 7, which compares the energy absorption predicted by 1-D momentum conservation to the value actually measured from the test data at maximum crush, confirms this for the tests used in this study.

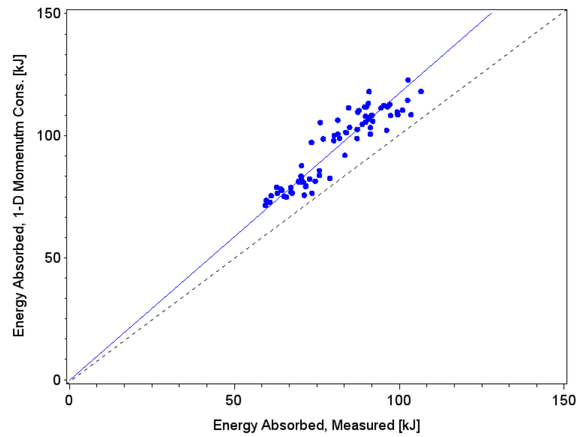

Figure 7 Total absorbed energy, 1-D momentum conservation versus measured at maximum crush. Regression equation: y = 1.173x

Additionally, WinSmash side stiffness computation assumes that the MDB accounts for 5% of the total absorbed energy. Prasad (1991) made this assumption out of necessity, as at the time little was known about the dynamic crush-energy relationship of the NHTSA MDB face. Since the Prasad (1991) paper, the NHTSA has conducted several frontal-barrier tests of the NHTSA MDB. Struble et al. (2001) used these tests to compute the MDB stiffness values used in this study. WinSmash continues to use side stiffness values computed assuming 5% energy absorption in the MDB. This may not be the case for the NHTSA side crash tests examined here. On average, WinSmash computes that the MDB absorbs 13.8% of the total absorbed energy, with a minimum of 2.49% and a maximum of 49.1%. Even compared with the WinSmash prediction of total absorbed energy which are likely high, the fraction of the energy absorbed by the MDB (using the MDB stiffness reported by Struble) is still almost three times the 5% assumed when calculating WinSmash side stiffnesses. These results suggest that, in the computation of WinSmash side stiffness values, both the total amount of energy absorbed in the crash, and the fraction absorbed by the struck vehicle are over-estimated.

Because WinSmash uses vehicle stiffnesses which likely correlate an artificially high amount of energy to a given amount of crush, WinSmash is likely over-estimating the amount of energy absorbed in the studied crash tests. Figure 5 confirms that this is occurring. For the tests examined, WinSmash over-predicts the amount of energy absorbed in the collision by 43% on average.

The vehicle crush measurements used in reconstructions also affect WinSmash's absorbed energy estimations, but it is far less likely that they would cause the observed systemic error. Errors in crush measurement would have to be systemically high. Any errors in post-test crush measurements would be more likely to randomly distributed given that they are recorded at different times and by different test houses. More convincingly, many of the crush profiles for the crash tests in this study were used to calculate the very stiffnesses which WinSmash used to reconstruct these selfsame tests, in which case it would be highly unlikely for these measurements to be systemically high.

Whichever the cause, Figure 6 shows that much of the observed error in the WinSmash-reconstructed ΔV is eliminated when the correct value for absorbed energy is used to reconstruct the test. The WinSmash ΔVs in Figure 6 were generated using a specially modified version of WinSmash which bypasses the crush/stiffness model and accepts a value for absorbed energy directly. Using this version of WinSmash, the tests were reconstructed with the amount of absorbed energy calculated from the crash test data at maximum crush. Not only does this eliminate almost all of the systemic over-prediction of ΔV, but the case-to-case variation is drastically reduced as well. Taken together, the results of Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6 indicate that, excluding other confounding factors such as PDOF, damage offset and restitution, WinSmash's ability to accurately reconstruct ΔV in NHTSA side crash tests is highly dependent on its ability to accurately estimate the amount of energy absorbed in the collision.

Limitations

One limitation of this study is the assumption that MDB absorbed energy is well described by the Struble et al. (2001) stiffness. Struble's calculations used the only source of crash test data available for the NHTSA MDB – rigid barrier tests. The MDB ΔVs in these tests were 44.9 km/h and 59.1 km/h (separation) and the average crush depths (across the entire MDB face at bumper level) were 24.3 cm and 32.2 cm respectively. These crush and ΔV values are substantially more severe than the values in the NHTSA side crash tests examined in this study. Mean MDB ΔV at separation was 31.4 km/h (minimum 24.4 km/h, maximum 41.2 km/h), and mean average crush depth was 8.12 cm (min 1.67 cm, maximum 17.8 cm). The crush patterns themselves are also radically different – the rigid barrier tests have essentially uniform crush across the entire height and depth of the barrier face, while the side crash tests produce damage almost exclusively at bumper level. There is also evidence that the MDB face may have actually crushed completely and bottomed out in the rigid barrier tests. Thus, the Struble et al (2001) MDB stiffness may not characterize energy absorption by the MDB face well at the lower crush values seen in NHTSA side crash tests. Our absorbed energy estimates could be improved if lower-severity MDB tests were available.

Another limitation of this study is that all comparisons were made at only two closing speeds, both of which represent the extreme of severity in real-world crashes. Whether the findings of this study are also true at lower, more representative impact speeds could not be evaluated.

Finally, there are the assumptions and approximations made to facilitate WinSmash reconstructions of the crash tests. PDOF can be a substantial source of error in the WinSmash reconstructions of real-world crashes (Brach and Brach, 2005; Smith and Noga, 1982). With crash tests however, PDOF can be readily computed and had no effect on our estimates of WinSmash error. However, reliance on an approximated radius of gyration for the struck vehicles could potentially have some effect on the fidelity of reconstructions, both directly and via its use in calculating damage offset. Our reconstructions are also dependent on the crush measurements recorded in the crash test reports. In particular, the overall length of the damaged region spanned by the 6-point crush profile is difficult to define consistently at times.

CONCLUSIONS

This study investigated the accuracy of WinSmash ΔV estimates in the reconstructions of 73 NHTSA side crash tests. WinSmash was found to over-predict struck vehicle resultant ΔV by 11% at time of separation, even when PDOF error and damage offset error are controlled for, with a great deal of case-to-case variability. This difference appears to be primarily due to WinSmash's overestimation of the energy absorbed by damage to the struck vehicle. The result was that WinSmash over-predicted ΔV by 21% at time of common velocity. When NHTSA side crash tests are reconstructed in WinSmash using the correct amount of absorbed energy, and PDOF and damage offset error are controlled for, there is no appreciable systemic error and random scatter in the data is greatly reduced as well. These results indicate that, given accurate input parameters, WinSmash is capable of accurately reconstructing side crash tests.

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