EVALUATION OF THE ACCURACY OF SIDE IMPACT CRASH TEST RECONSTRUCTIONS

Nicholas Johnson, Carolyn Hampton, Hampton C. Gabler
Virginia Tech – Wake Forest Center for Injury Biomechanics

ABSTRACT

Each year in the U.S., vehicle side crashes result in over 6,000 fatalities. Delta-V, the vehicle change in velocity, is a widely used measure of crash injury risk in real world crashes. However, delta-V is difficult to estimate accurately for side crashes using reconstruction codes such as CRASH3. Such codes are the source of a large portion of the delta-V values in crash databases, so their accuracy has a direct impact on injury risk prediction data. In this study, delta-V was first reconstructed for a series of 42 staged side impact crash tests using CRASH3. This reconstructed delta-V was then compared to the delta-V recorded by the crash test instrumentation to determine the accuracy of the reconstructed value.

Keywords: CRASH3, Crash Reconstruction, Delta-V, Side Impact, Injury Risk

INTRODUCTION

Each year in the U.S., vehicle side crashes result in over 6,000 fatalities. Databases such as the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) database, (maintained by the National Highway Transportation Safety Administration, NHTSA), are used almost universally in side impact research as a source of various data including delta-V, a widely used predictor of injury risk. Delta-V is defined as the change in velocity experienced by a vehicle during a crash. Many of the delta-V values in widely used crash databases are generated using accident reconstruction codes based on the CRASH3 algorithm.

CRASH3 estimates delta-V using momentum conservation principles and an estimate of the energy absorbed in the impact. The estimation of absorbed energy is made using vehicle damage and a vehicle "stiffness" for each vehicle involved. This stiffness is at the heart of the CRASH3 algorithm: it relates the energy absorbed by a vehicle at *max dynamic* crush to the amount of *static crush* (crush after the restitution of the vehicle structure, measured at the scene) observed on the vehicle. It is based on a correlation observed by Campbell (1974) that the quantity $\sqrt{2 \cdot E_{Absorbed} / W_{Damage}}$, where $E_{Absorbed}$ is the energy absorbed by the vehicle structure at max dynamic crush and W_{Damage} is the width of the damaged area, is linear versus static crush up to 35 [in] [1]. The CRASH3 vehicle stiffness takes the form of the slope and intercept (d_0 and d_1) of this correlation for a given vehicle [2, 3].

The accuracy of reconstructed delta-V values, when considered for large numbers of reconstructions, has a direct impact on the validity of injury risk predictions. As an example, consider Figure 1: the curve gives the probability of MAIS3+ injury versus delta-V for near-side impacts. The curve is based on 6550 cases from the NASS/CDS database for 1995 – 2006, and was derived using binary logistic regression. Simple inspection shows that if the (reconstructed) delta-V values associated with given injuries contain a systematic error, injury risk for a given delta-V can be distorted. Injury risk functions such as this are the basis for crash safety regulation, so the accuracy of delta-V reconstructions is very important.

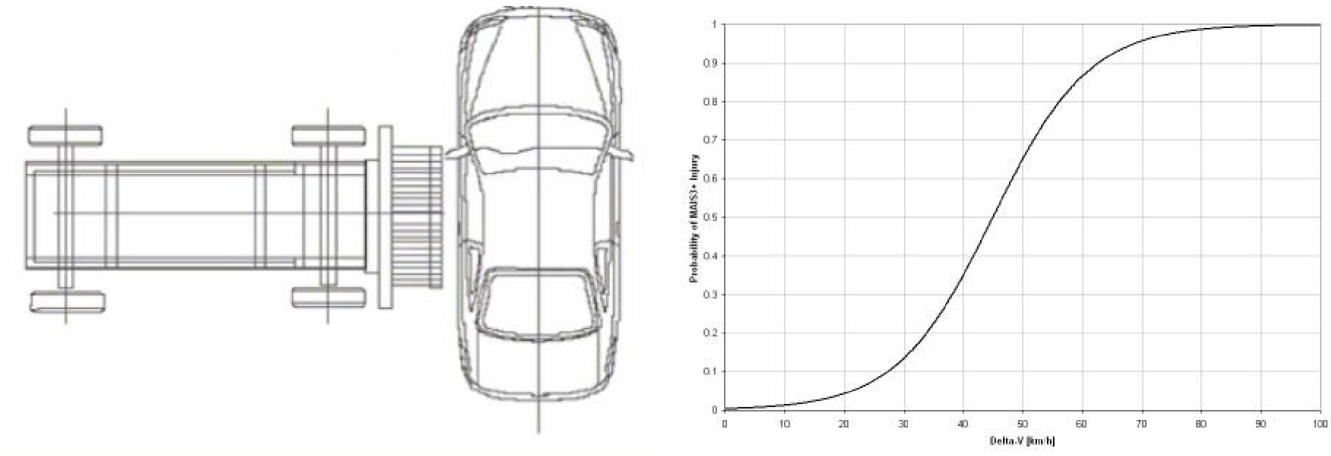

Figure 1: Schematic of IIHS side crash test and probability of MAIS3+ Injury in Near Side Crashes vs. Delta-V. Even relatively small biases in delta-V values can, if consistently present for a particular type of reconstruction, seriously affect injury risk predictions. This curve was derived from NASS data for 6550 near-side impacts in years 1995 through 2006 using binary logistic regression.

METHODS

The objective of this study was to gauge the accuracy of side-impact delta-V estimates made using the CRASH3 algorithm. The approach taken was to select side-impact crash tests where the delta-V for each vehicle could be determined with certainty, and to reconstruct them using the CRASH3 algorithm. In order to reconstruct a crash, CRASH3 requires input of the damage to both vehicles be entered as a post-crash crush profile. A CRASH3 crush profile consists of crush measurements taken at 6 evenly spaced intervals along the length of the damaged area. Crush measurements are taken in that single horizontal plane which is most representative of the entire damage profile [4, 5, 6]. CRASH3 computes the delta-V at the vehicles' centers of gravity at the time in the impact where the vehicles obtain a common velocity at the crush interface. This is not the same as total delta-V at the end of the collision, as it ignores the effects of restitution of the vehicle structure. This had important implications for the selection of test cases. In order for a side impact test to be useful for this study, enough crush information for both the striking and struck vehicles must have been recorded to construct a CRASH3 crush profile, and it must have been possible to determine when the two vehicles in the test achieved a common velocity in the crush interface (and the CG velocities at this time must obviously have been known as well).

Most side impact crash tests involve a test vehicle being struck in the side with a Moving Deformable Barrier (MDB), which simulates a striking vehicle. In side impact crash tests conducted by the Insurance Institute for Highway Safety (IIHS), the MDB strikes the test vehicle with only a longitudinal velocity component [8], meaning that there is very little rotation in IIHS tests (Figure 1). Additionally, as with most other impact types, what rotation does occur is typically seen late in the event (the implication being after common velocity). Thus, the point of common CG velocity in IIHS tests can be assumed to coincide with common interface velocity, with very little error introduced as a result. Other tests, e.g. side impact tests conducted by NHTSA, have a significant rotational component which would require compensation prior to studies such as presented here. For crush profiles, this study used CRASH3 standard damage profiles computed for a number of IIHS side impact tests by Arbelaez et al [9]. Of these, the stiffnesses for 42 vehicles were available, and are given in Table 1. These particular 42 IIHS side impact tests were the vehicles used in this study.

For each of the tests, the point where the MDB CG velocity and the test vehicle average velocity (averaged from two accelerometers at each end of the test vehicle) were equal was determined by inspection. This velocity and the time at which it occurred were recorded, and the true delta-V for each vehicle calculated as follows:

$$\Delta V_{MDB} = V_0 - V_{common} \tag{1}$$

$$\Delta V_{Vehicle} = V_{common} \tag{2}$$

Figure 2 illustrates this technique: the data corresponds specifically to IIHS test CES0420, but is typical of most IIHS side impact tests.

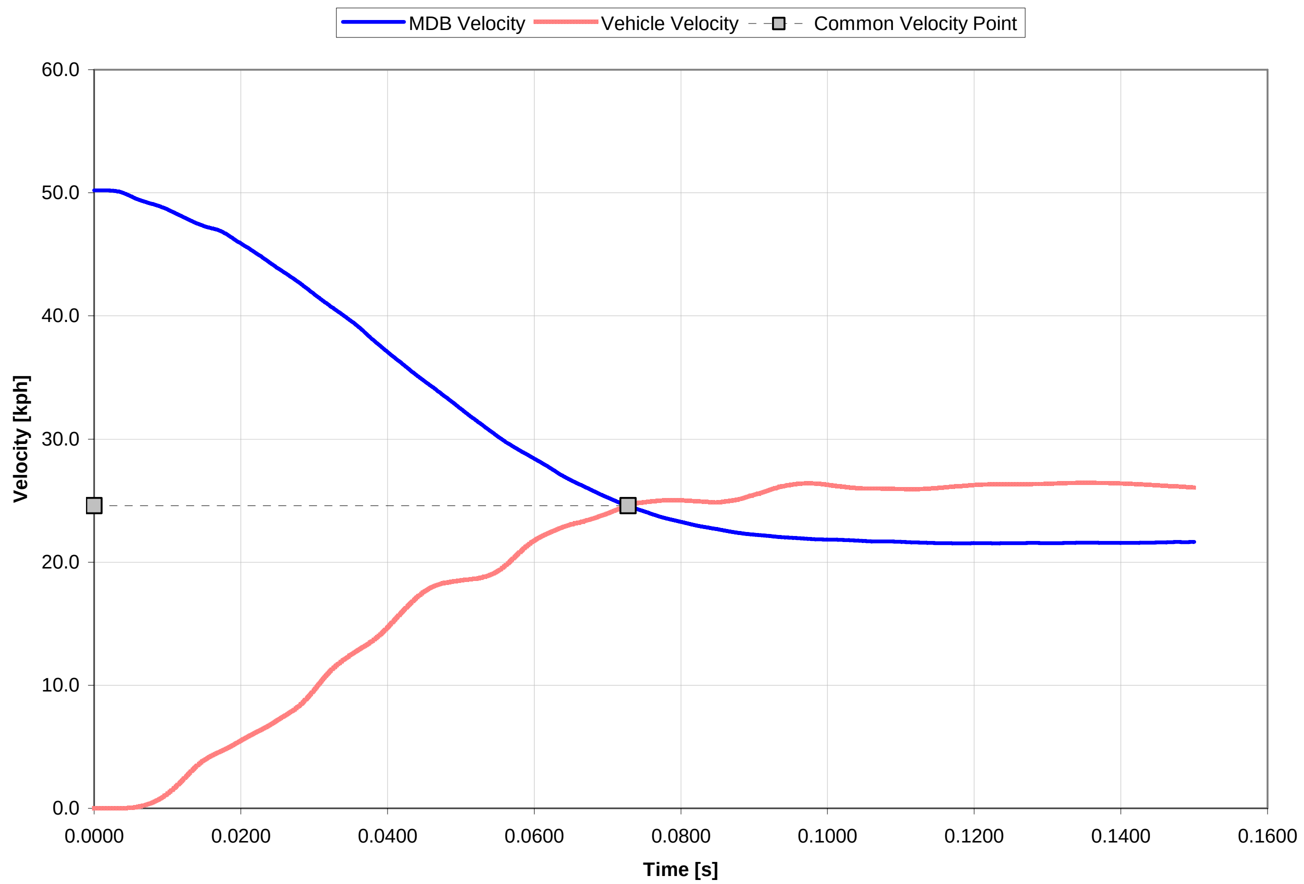

Figure 2: Velocity versus time for IIHS test CES0420. The point where the average vehicle velocity curve and MDB velocity curve intersect is the point of common velocity. This point and the corresponding value on the velocity axis, are marked by the gray squares on the plot.

A momentum conservation analysis was also run for each case, and the delta-V prediction from this used as a check for the delta-V observed from instrumentation.

The CRASH3 reconstructions were run using the damage profiles given in [9]. Vehicle specifications were taken from the IIHS crash test reports when available. The vehicle specifications for the IIHS MDB were determined primarily from the IIHS side impact test specifications in [8]. The MDB, which has a mass of 1500 [kg], was determined to have a stiffness of d_0 = 100.30 [sqrt(N)] and d_1 = 10.859 [sqrt(N)/cm] from NHTSA test 3836 using NASS standard protocol given in [3, 6]. Once the vehicle and MDB specifications were loaded, the damage profiles for the test vehicle and MDB face were entered from [9] and the reconstructions run. The difference between the reconstructed and observed delta-V values was calculated for each case. Finally, the probability of MAIS3+ injury was calculated using the curve in Figure 1, the formula for which is given by:

$$P_{MAIS3+F} = \frac{1}{1 + e^{5.594 - 0.1244*DV}} \tag{3}$$

RESULTS

Because this analysis focuses on side impact results, delta-V data for the MDB in each collision type is not reported, as the MDB experiences a frontal impact. Table 1 gives the tabulated delta-V results for the struck vehicle, as well as the injury risk corresponding to the observed and reconstructed delta-V based on eq. (3). Also reported is the delta-V predicted by conservation of linear momentum.

Table 1: The 42 IIHS side impact tests used in this study and the corresponding results for each vehicle. The standard deviation of the average difference between simulated and observed delta-V (**Diff.**) is 3.384 [kph].

Reconstruction Results (all velocities in [kph], d_0 in [sqrt(N)], d_1 in [sqrt(N)/cm])									
IIHS Test #	**Year/Make/Model**	**d_0**	**d_1**	**ΔV_{act}**	**ΔV_{mom}**	**ΔV_{CR3}**	**Diff.**	**P_{MAIS3+} Act.**	**P_{MAIS3+} CR3**
CES0422	*2004 Kia Spectra*	63.3	9.587	23.5	25.2	37	13.5	6.48%	27.1%
CES0419	*2004 Nissan Sentra*	63.3	7.536	24.1	26.1	32	7.87	6.96%	16.6%
CES0423	*2005 Dodge Neon*	63.3	8.276	23.7	26.0	32	8.28	6.64%	16.6%
CES0417	*2005 Ford Focus*	63.3	8.188	24.4	25.8	31	6.64	7.15%	15.0%
CES0426	*2005 Saturn Ion*	63.3	12.018	24.2	25.6	38	13.9	7.00%	29.6%
CES0427	*2005 Saturn Ion*	63.3	12.018	24.2	25.7	36	11.8	7.02%	24.7%
CES0420	*2005 Toyota Corolla*	63.3	9.522	24.6	26.2	36	11.4	7.33%	24.7%
CES0421	*2005 Toyota Corolla*	63.3	9.522	24.6	26.3	36	11.4	7.32%	24.7%
CES0410	*2004 Acura TL*	63.3	9.376	19.1	22.7	30	10.9	3.83%	13.4%
CES0403	*2004 Chevrolet Malibu*	63.3	8.415	22.5	23.8	29	6.49	5.76%	12.1%
CES0404	*2004 Chevrolet Malibu*	63.3	8.415	23.3	23.8	29	5.71	6.32%	12.1%
CES0313	*2004 Dodge Stratus*	63.3	8.799	20.7	24.1	30	9.35	4.63%	13.4%
CES0319	*2004 Honda Accord*	63.3	7.881	22.2	23.9	28	5.79	5.56%	10.8%
CES0320	*2004 Honda Accord*	63.3	7.881	22.2	24.1	30	7.78	5.57%	13.4%
CES0317	*2004 Hyundai Sonata*	63.3	10.361	21.6	23.6	36	14.4	5.18%	24.7%
CES0406	*2004 Jaguar X-Type*	63.3	9.931	19.8	22.5	32	12.2	4.17%	16.6%
CES0414	*2004 Lexus ES-330*	63.3	9.481	19.8	23.1	28	8.21	4.18%	10.8%
CES0415	*2004 Lexus ES-330*	63.3	9.481	21.0	23.2	28	6.99	4.83%	10.8%
CES0401	*2004 Mazda 6*	63.3	9.644	22.9	24.1	37	14.1	6.02%	27.1%
CES0402	*2004/05 Mitsubishi Galant*	63.3	13.739	21.4	23.2	37	15.6	5.04%	27.1%
CES0418	*2004/05 Mitsubishi Galant*	63.3	13.739	21.6	23.2	38	16.4	5.15%	29.6%
CES0412	*2004 Saab 9-3*	63.3	12.7	21.1	23.9	35	13.9	4.86%	22.4%
CES0409	*2004 Saab 9-5*	63.3	9.552	19.6	22.9	31	11.4	4.07%	15.0%
CES0318	*2004 Suzuki Verona*	63.3	8.373	21.8	23.3	30	8.20	5.30%	13.4%

CES0315	*2004 Toyota Camry*	63.3	9.637	21.8	23.9	34	12.2	5.32%	20.4%
CES0316	*2004 Toyota Camry*	63.3	9.637	21.7	24.0	33	11.3	5.25%	18.4%
CES0405	*2005 Nissan Altima*	63.3	6.987	21.9	24.0	27	5.14	5.34%	9.66%
CES0408	*2005 Subaru Legacy*	63.3	13.908	22.1	23.5	35	13.0	5.46%	22.4%
CES0411	*2005 Subaru Legacy*	63.3	13.908	22.0	23.6	36	14.0	5.42%	24.7%
CES0310	*2003 Ford Escape*	63.3	11.714	21.7	23.3	31	9.26	5.27%	15.0%
CES0311	*2003 Ford Escape*	63.3	11.714	21.8	23.2	31	9.25	5.27%	15.0%
CES0307	*2003 Honda CR-V*	63.3	11.966	22.8	23.4	33	10.2	5.99%	18.4%
CES0308	*2003 Honda Element*	63.3	12.32	20.9	22.9	31	10.1	4.78%	15.0%
CES0304	*2003 Hyundai Santa Fe*	63.3	10.378	20.3	21.7	26	5.69	4.45%	8.63%
CES0303	*2003 Mitsubishi Outlander*	63.3	11.72	21.2	23.2	34	12.8	4.94%	20.4%
CES0301	*2003 Saturn VUE*	63.3	14.998	21.4	23.0	35	13.6	5.08%	22.4%
CES0312	*2003 Subaru Forester*	63.3	12.57	22.0	24.1	33	11.0	5.42%	18.4%
CES0305	*2003 Suzuki Grand Vitara*	63.3	6.53	22.5	23.6	23	0.487	5.77%	6.11%
CES0302	*2003 Toyota RAV-4*	63.3	10.152	22.6	24.3	30	7.42	5.82%	13.4%
CES0407	*2004 Toyota RAV-4*	63.3	10.152	22.6	24.0	29	6.35	5.86%	12.1%
CES0424	*2005 Ford Escape*	63.3	11.714	22.0	22.8	30	8.02	5.42%	13.4%
CES0425	*2005 Honda CR-V*	63.3	11.966	21.8	23.0	30	8.24	5.28%	13.4%
Average	**---**	**---**	**---**	**22.1**	**23.9**	**32.1**	**10.0**	**5.50%**	**16.8%**

DISCUSSION

In IIHS crash tests, the CRASH3 algorithm, using side-impact stiffnesses given in Table 1, over-predicts struck vehicle delta-V by 10.0 [kph] on average, with a standard deviation of 3.384 [kph]. This is an average over-prediction of 45.4%. The fact that the mean difference is greater than 2 standard deviations makes these results statistically significant to a high degree of probability. Inspection of _ reveals that for each vehicle, the delta-V predicted by linear momentum conservation is slightly greater than the observed delta-V, with only a 34.3% difference between the average reconstructed delta-V and that predicted by momentum conservation. The most likely explanation for this is that, while the momentum analysis accounts for no rotation of the vehicles, the vehicles do rotate slightly during the tests and this is reflected in the observed delta-V (and also in the CRASH3 reconstruction). Again, IIHS tests were chosen specifically for their small rotational component, so that ignoring it would not introduce significant error into the results. This error is bounded by the discrepancy between the average observed delta-V and average delta-V from momentum conservation – i.e., 1.8 [kph]. Although, in the interest of brevity, the delta-V for the MDB was not reported in the tables above, it is useful to note that the MDB delta-V was over-predicted by 7.17 [kph] on average with 3.68 [kph] standard deviation: not quite as severe an over-prediction as the struck vehicles, but still fairly large.

The fact that delta-V for both vehicles (struck and MDB) are consistently over-predicted in the data indicates that CRASH3 is overestimating the net amount of energy absorbed in the collision. There are two factors that affect the energy estimation; the crush profile and the vehicle stiffness. In order to account for the observed discrepancy between actual absorbed energy and the predicted amount, the error in the vehicle crush measurements would have to be enormous. This leaves only vehicle stiffness, which if inaccurate, could easily account for the observed over-prediction.

LIMITATIONS

The vehicle side stiffnesses used in this study were generated based on NHTSA side impact tests, which use a distinctly different MDB geometry than IIHS tests. The lateral velocity component in these tests can also impart a shearing component to an impact, meaning that energy is dissipated in ways other than direct crush. Additionally, the inhomogeneity of vehicle side structure means that the observed stiffness may depend heavily on impact location. Considering that a CRASH3 stiffness is a correlation between dissipated energy and delta-V, it is very reasonable to assume that if that energy is dissipated in different ways, then the correlation may be inaccurate. In more direct terms, CRASH3 vehicle side stiffnesses may only be applicable to collisions similar to the crash tests with which they were measured. Since the stiffnesses in this study were all derived from NHTSA side impact tests, while the cases they were applied to were exclusively IIHS side impact tests, it may very well be that the stiffnesses used do not accurately characterize the collisions that were examined.

CONCLUSIONS

In IIHS side impact crash tests, the CRASH3 crash reconstruction algorithm was found to overpredict delta-V by 45% on average. Use of these delta-V values to predict injury severity would also overpredict injury risk at these impact conditions. Because this study only examined one impact speed and one side crash configuration, it is not known how these results generalize to other side crashes. However, further investigation is vital, as errors in delta-V have critical implications for injury risk prediction in side crashes.

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