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A Supplemental Analysis of Selected Two-Vehicle Front-to-Rear Collisions from the NASS/CDS

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A Supplemental Analysis of Selected Two-Vehicle Front-to-Rear Collisions from the NASS/CDS

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ABSTRACT

The National Automotive Sampling System/Crashworthiness Database System (NASS/CDS) is a well-known digital repository containing statistics on hundreds of thousands of vehicle crashes that occurred over the past 30 years. Many of the NASS crashes contain estimates of *Delta-v* calculated using WinSMASH, a common software reconstruction package. Recent work indicates that WinSMASH typically underestimates *Delta-v* in frontal impacts, and that inclusion of restitution significantly improves the estimate of *Delta-v* to within 1% of the value recorded on EDR-equipped vehicles [1]. Prior experiments have shown that in front-to-rear collisions, restitution is a strong inverse function of closing velocity (the difference between the respective pre-impact speeds in the bullet and target vehicles) [2], with calculated restitutions ranging from 0.265 down to 0.0 for closing speeds varying from 11.4 mph to as high as 36 mph. This work uses front-to-rear impact data from the NASS/CDS to examine the effect of coefficient of restitution on calculated *Delta-v* values for both the bullet and target vehicles. The WinSMASH-based values of *Delta-v* and dissipated energy contained in the NASS/CDS were compared to *Delta-v* values computed using traditional analytical (energy and momentum) equations. With restitution set equal to zero, the mean value of the calculated values of *Delta-v* (for bullet and target vehicles) ranged between −1.76 and 1.47 percent of the values contained in the NASS/CDS. However, including values of restitution computed iteratively using pre-impact closing velocity increased the computed values of *Delta-v* for both bullet and target vehicles by an average of 10.38 - 13.17 percent over those provided (in the absence of restitution) by the NASS/CDS. In addition, it was found that small errors in reported values of vehicle mass or dissipated energy (2% - 10%) produced similar or smaller percentage variations in calculated *Delta-v* values for both the bullet and target vehicles.

1. INTRODUCTION

As roads and highways become more congested with traffic, the problem of front-to-rear vehicle impacts continues to persist. Such impacts often occur in stop-and-go traffic, which means that impact speeds and/or total amounts of property damage may be quite low. Front-to-rear impacts are quite common: using state statistics reported by the National Highway Transportation Safety Administration (NHTSA), the percentage of vehicle "involvements" classified as rear impacts hovers between 21 and 25 percent of all accidents reported [3]. The severity of such impacts - especially in the context of injury - is often quantified by the *Delta-v* values of each vehicle, which are the respective changes in vehicle velocities induced by the impact [4,5]. This work therefore focuses on factors related to the determination of *Delta-v*.

In rigid barrier impact tests involving a single vehicle, it has been established that *Delta-v*, and hence the change in vehicle kinetic energy, is directly related to the amount of energy dissipated as the vehicle is crushed, assuming the "no-damage" impact speed has been exceeded [6,7,8]. However, in the absence of any other information, the amount of crush damage (and hence dissipated energy) measured using standard approaches on a particular vehicle involved in a straight-line front-to-rear two-vehicle impact cannot alone be used to accurately estimate either its own change in kinetic energy or impact-induced *Delta-v* [4]. Figure 1 clearly shows the lack of correlation between dissipated energy (measured using standard crush techniques) and *Delta-v* for both striking (bullet) and struck (target) vehicles (when taken individually) in well-documented front-to rear collisions selected from the National Automotive Sampling System/Crashworthiness Database System (NASS/CDS), discussed in detail in Section 2. Because the magnitude of the impact-induced *Delta-v* of a vehicle involved in this type of collision cannot be deduced by considering its damage alone, additional parameters of

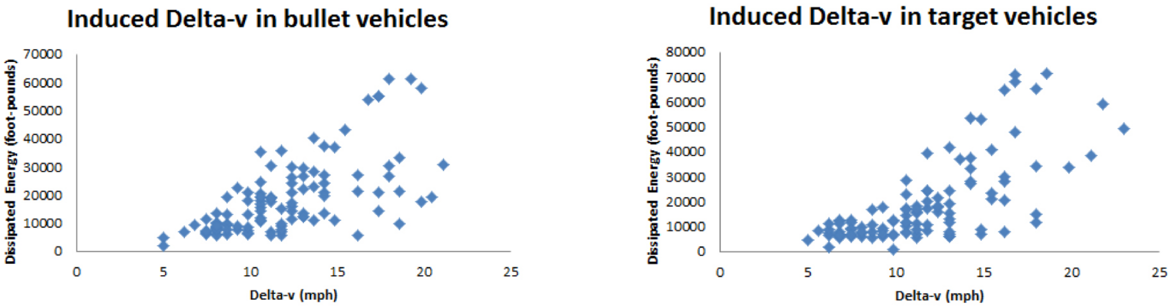

Figure 1. Two-vehicle front-to-rear crash data taken from NASS database show only a weak relationship between Delta-v and vehicle crush (as indicated by dissipated energy) measured on the front bumpers of individual bullet (striking) and the rear bumpers of target (struck) vehicles. The respective linear trend-line fit of the data on these plots (not shown) resulted in correlation values (R^2) of less than 0.5 in both cases.

both vehicles must be taken into account in order to include a vehicle's damage in the estimation of its *Delta-v*. These include total mass of each vehicle, total crush energy for both vehicles in the collision, and restitution. A review and discussion of these methods comprise the bulk of this paper.

2. BACKGROUND

Over the past four decades, a number of studies pertaining to the determination of impact-induced *Delta-v* values using vehicle impact damage have been performed. Many of these relate to the National Automotive Sampling System/ Crashworthiness Database System (NASS/CDS), a collection of thousands of vehicle crashes documented by accident investigators and administered by the NHTSA. A substantial portion of the collisions in the database contain estimates of *Delta-v* obtained using simulation software such as WinSMASH in conjunction with six-point crush measurements taken of each vehicle [8,9]. The crush measurements are converted into an equivalent dissipated energy via a series of empirical equations and coefficients using an approach first suggested by Campbell [7]. Since the impact force-displacement relationship varies with location (e.g. bumper versus rear quarter panel) and vehicle type, it is the selected applicable coefficients that establish the direct relationship between crush and dissipated energy. In versions of WinSMASH used prior to 2007, categorical stiffness values were used that corresponded to large groups of vehicles, including compact cars, vans and four-wheel drive vehicles, pickup trucks, and front-wheel drive cars [10]. This approach did not account for differences in stiffness present among different vehicle models in the same category, and *Delta-v* values computed using these categorical stiffness values tended to underestimate the respective changes in velocity in each vehicle by 23% on average [1]. More recent versions of WinSMASH feature updated categorical coefficients that better reflect the physical material behavior of vehicles produced in the 1990's and 2000's. Furthermore, the program has been augmented with stiffness values specific to individual vehicle models to allow a more accurate calculation of *Delta-v* [10]. An assessment of these improved values was conducted for EDR (electronic data recorder) equipped vehicles involved in accidents contained within the NASS/CDS database; the improved simulation software still resulted in computed *Delta-v* values that underestimated the EDR values by about 16% on average [10]. One cause of this overall underestimation is related to the assumption within WinSMASH that the coefficient of restitution (*e*) is zero (corresponding to a perfectly plastic collision where there is no post-impact vehicle separation). Prior to this more recent Hampton study, Niehoff and Gabler found that modifying WinSMASH to account for restitution reduced the underestimation of *Delta-v* to only 1% in frontal collisions [1]. This particular study used NHTSA data taken from 47 vehicles subjected to full-frontal barrier crash tests, and obtained pertinent combined vehicle-vehicle restitutions using the method described in Prasad [8]. Of course, since restitution tends to increase as collision severity decreases, underestimation of *Delta-v* was found to be highest in minor collisions, while the WinSMASH-computed *Delta-v* values matched experimental values in high-impact collisions where the coefficient of restitution approached zero [10].

The works cited above show that the benefits and limitations of using WinSMASH for computing *Delta-v* values in documented front-to-rear impacts are known and well-characterized. As an alternative, using classical equations such as conservation of momentum, conservation of energy, and restitution to calculate the impact-induced *Delta-v* values in a straight-line front-to-rear impact can be of benefit to the crash analyst, as it allows the sensitivity of the calculated *Delta-v* values to changes in parameters such as vehicle mass, restitution, and dissipated energy to be easily assessed. Such an approach can be useful to analysts who are attempting to determine the severity of a particular impact in the absence of detailed incident data. However, before such sensitivities can be evaluated, the ability of the classical equations to produce results that mirror the estimates of *Delta-v* provided by WinSMASH must be confirmed.

3. METHODS

Brach, Cipriani and Anderson, among others, have all used a “rigid body” approach to calculate impact-induced speed changes in front-to-rear impacts [2,11,12,13]. According to Newton's Second Law of Motion, an object's change of speed (acceleration) directly depends on the forces applied to it. Therefore, the forces and motions (dynamics) that occur in any linear (near-straight-line) impact between two vehicles are governed by three equations commonly studied in sophomore-level engineering courses, which include Conservation of Momentum (Eq. 1); Conservation of Energy (Eq. 2); and Restitution (Eq. 3).

$$m_1 v_1 + m_2 v_2 = m_1 v_1' + m_2 v_2' + \sum_{i=1}^{n} F_i \Delta t_i \tag{1}$$

$$\frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 = \frac{1}{2} m_1 v_1^{2'} + \frac{1}{2} m_2 v_2^{2'} + U_{diss} \tag{2}$$

$$e = \frac{v_2' - v_1'}{v_1 - v_2} \tag{3}$$

In each of the equations, m_1 and m_2 represent the mass of the vehicles; v_1 and v_2 represent vehicle velocities; the subscripts 1 and 2 represent the bullet (striking) and target (struck) vehicles; and the unprimed and primed (‘) velocity notations respectively indicate values immediately before and immediately after the impact. In this context, the impact-induced changes in velocity of the bullet and target vehicles are respectively defined as *Delta-*$v_b = v_1' - v_1$ and *Delta-*$v_t = v_2' - v_2$. A special case of the front-to-rear collision is one where the pre-impact speed of the struck vehicle (v_2) is zero. Assuming all other parameters can be determined or estimated, this means that Eqs. 1, 2, 3 can be solved for the three remaining unknown velocities without requiring any other prior knowledge of vehicle speeds.

Conservation of Momentum (Eq. 1) is a fundamental equation that is a mathematical restatement of Newton's Second Law of Motion ($F = ma$). Note that the final term in the momentum equation, $\sum_{i=1}^{n} F_i \Delta t_i$, represents external forces *(F)* applied to either vehicle for the duration of the impact *(Δt)*. Such external forces are not present in typical front-to-rear impacts, unless the wheels are locked and restricted from rolling. In many cases, the bullet vehicle either rolls or accelerates into the target. If it is known that the driver of the bullet vehicle was braking just prior to impact (or to assess the effect of such braking) the product of the frictional drag force and the impact duration (typically 0.125 - 0.15 seconds [12]) can be included. Even if the driver of a struck vehicle is applying his or her brakes prior to the impact, the physics of the impact makes it unlikely for the driver to maintain foot pressure on the brake pedal during the impact and ensuing forward acceleration [13]. In this work, unless the struck vehicle was parked, it was assumed that all external friction force affecting the collision was zero. This parallels the assumptions of the WinSMASH-based algorithms, which don't take pre-impact braking of either vehicle into account. While the presence of tire-related drag typically results in lower *Delta-v* values, specific effects can be explored through a sensitivity analysis by varying the size of the impulse term in Eq. 1 and then solving the complete system.

Conservation of Energy (Eq. 2) is also a fundamental, well-known equation typically studied by sophomore-level engineering students. The final term in Eq. 2 stands for dissipated energy, and is related to energy “lost” during the collision. Dissipated energy is a quantity that can, in part, be linked to the visible permanent damage in the vehicle, with less damage corresponding to lower values of dissipated energy. However, the dissipated energy term is also linked to other factors not related to visible permanent damage. This includes internal friction in the material that causes irreversible energy dissipation even when the applied force is not sufficient to cause permanent deformation. Therefore, the value of U_{diss} will not be zero even when no residual vehicle crush is measured.

The **Coefficient of Restitution** shown in Eq. 3, e, represents the ratio of the post-impact vehicle-velocity-difference to the pre-impact vehicle-velocity-difference between the two vehicles. The value of e can range from 0 to 1. A “zero” value of e indicates a collision where the two vehicles “lock together” (possess the same velocity) post-impact, with no rebound. The coefficient of restitution is a complicated parameter, which depends upon the geometrical and material parameters for both vehicles at the specific location where both vehicles come together during the impact. Restitution has also been found experimentally to be an inverse function of closing speed between a striking and struck vehicle [2]. For a given impact, a best-fit value for restitution (e) as a function of closing velocity (typically v_1 expressed in units of m/s if the struck vehicle is not moving prior to impact) can be obtained by solving the following equation

$$e = 0.47477 - 0.26139\log(v_1) + \cdots$$

$$+0.03382\log(v_1)^2 - 0.1139\log(v_1)^3 \tag{4}$$

simultaneously with Eqs. 1, 2, 3. Equation 4 is a fit of experimental data corresponding to closing speeds up to 6.8 m/s (15.2 mph), for which the predicted value of e is 0.215. Extrapolation of Eq. 4 results in positive values of e for closing speeds as high as 16.55 m/s (approximately 37 mph), above which the value of *e* is taken to be zero.

Low-speed, low damage collisions tend to produce higher rebound (and hence higher values of *e*). As mentioned previously, it is well known that the WinSMASH algorithm does not take restitution into account when calculating *Delta-v* [1,14]. For this reason, it is expected that WinSMASH-computed values of *Delta-v* will track well with those computed via a simultaneous solution of Eqs. 1, 2, 3, 4 for higher speed, higher damage front-to-rear impacts for fully (or substantially) plastic collisions (impacts where the coefficient of restitution is close to zero). However, using Eqs. 1, 2, 3, 4 to simultaneously obtain values of both restitution and *Delta-v* is expected to yield *Delta-v* values that are larger in magnitude than those provided by the NASS database for both bullet and target vehicles.

4. NUMERICAL STUDY

The differences between *Delta-v* values for front-to-rear impacts obtained via the WinSMASH algorithms used by NASS/CDS and those calculated using the classical methods (Eqs. 1, 2, 3, 4) were evaluated for both target and bullet vehicles. In this study, NASS/CDS data from both 2004 and 2010 were used to allow *Delta-v* values computed using the WinSmash 2008 release to be compared with those obtained using earlier versions of the software. Hampton and Gabler indicate that the 2008 release of the software incorporated vehicle-specific stiffness values that weren't used in prior versions of the software [10]. Furthermore, the categorical stiffness values included in the new software release were updated in order to better reflect the physical stiffness characteristics of modern vehicles. The improved parameters incorporated in the updated software were found to "…reduce the underestimation of *Delta-v* from 23% to 13% on average…" In the previous Hampton and Gabler study, the WinSmash-computed *Delta-v* values were compared with crash data taken from 478 EDR-equipped General Motors vehicles contained in the 2000-2008 NASS/CDS database that were involved in frontal-type collisions [15].

For this study, front-to-rear impacts from the 2004 and 2010 NASS/CDS were chosen that met the following criteria, based on information contained in the database:

- Involved only longitudinal components of velocity.
- Involved two vehicles only.
- Damage to both vehicles involved in the collision were photo-documented.
- Six-point vehicle crush measurements were made on both vehicles.
- Dissipated energy and *Delta-v* values were provided for both target and bullet vehicles.
- Dissipated energy value for any one vehicle did not exceed 100000 Joules (73756 foot-pounds).
- The respective crush measured for each target and bullet vehicle was used by WinSMASH to calculate corresponding *Delta-v* values.
- NASS/CDS cases that used the "missing vehicle approach" to compute *Delta-v* values were not considered here.

Of the 769 cases from 2004 in the NASS/CDS database involving rear impact, only 42 met all the criteria stated above. Similarly, of the 795 cases from 2010 in the NASS/CDS database involving rear impact, only 64 met all the criteria stated above. NASS case numbers for all collisions analyzed herein are contained in the Appendix. Unlike the previous studies cited, post-impact *Delta-v* values from the NASS/CDS database for both bullet and target vehicles were compared with values calculated using the classical mechanics approach (Eqs. 1, 2, 3). Including Eq. 4 as part of the iterative solution allowed restitution (and its effect) to be estimated based on the pre-impact closing velocity calculated between the two vehicles. Furthermore, while the Hampton and Gabler study analyzed primarily GM vehicles containing EDRs, cases for this study were chosen based only on the criteria listed above, without any other limitations.

In order to calculate *Delta-v* values using the classical mechanics approach assuming a zero restitution value (Eqs. 1, 2, 3), vehicle masses and dissipated energy values had to be specified for each target and bullet vehicle, in order to ensure that the number of unknown quantities being estimated did not exceed the number of equations. Note that while MathCAD was used to directly solve Eqs. 1, 2, 3, any symbolic or spreadsheet solver can be used to obtain the results contained herein. Calculation of restitution in addition to the *Delta-v* values used the same approach, but required simultaneous solution of Eqs. 1, 2, 4. For both sets of calculations, the amount of energy dissipated in a given collision was obtained from the corresponding case in the NASS/CDS database, where it was set equal to the sum of the crush energies measured from the bullet and target vehicles. The vehicle mass values used in the calculations were similarly obtained from the NASS/CDS case being studied. Regardless of whether the correct vehicle curb weight was included in the NASS/CDS data, there is some uncertainly associated with the actual total pre-collision mass of each vehicle. This is because factors such as occupant and cargo weight must be added to the curb weight in order to get the most accurate net weight of each vehicle. While some of the NASS/CDS cases contained specific values for both cargo weight and weight of each vehicle occupant, other NASS/CDS files were less complete. Some of the less complete cases identified vehicle occupants by gender and age (which allowed population-based statistical estimates of their weights [16] to be used), while other cases only listed the total number of vehicle occupants. In cases where only number of occupants was provided, occupant gender was occasionally, but not always listed. The sensitivity of calculated *Delta-v* values (for both bullet and target vehicles) to variations in vehicle weights and dissipated energy is discussed in Section 6.

For the set of 42 collisions from the 2004 NASS/CDS database and the set of 64 collisions from the 2010 NASS/CDS database meeting the criteria described in the above bullets, the values of *Delta-*v_b magnitudes provided within the NASS/CDS database (computed using the WinSMASH software) consistently underestimated *Delta-*v_b values computed using the classical methods with Cipriani restitution (Eqs. 1, 2, 3, 4). As expected, this underestimation was generally most pronounced for lower values of *Delta-*v_b. Similarly, the values of *Delta-*v_t magnitudes provided by NASS consistently underestimated *Delta-*v_t values computed using Eqs. 1, 2, 3, 4. Again, this underestimation was also generally most pronounced for collisions with lower values of *Delta-*v_t. Mean and standard deviation values of the WinSMASH underestimation are presented as percentages in the second and third columns of Table 1. The small differences among these mean values are inconsequential when compared to the data scatter indicated by the calculated standard deviations, hence no significance is assigned to the variation in mean values presented in the left-most column of data. These data show that for the front-to-rear impacts considered here, the NASS/CDS-calculated values of *Delta-v* provide a similar underestimation of *Delta-v* values calculated using the classical equations augmented by restitution regardless of which version of WinSMASH was used. This is not surprising, given that the dissipated energy values used in Eq. 2 are based on the respective categorical and/or vehicle-specific stiffness used within WinSMASH to calculate the NASS/CDS Delta-v values in the 2004 and 2010 databases.

Figure 2 shows that the underestimation of the NASS/CDS values generally becomes less pronounced as the severity of the impact (indicated by *Delta-v*) increases. This is an expected result; as impacts become more severe, vehicle deformation increases, and restitution tends towards zero. Hence, the NASS/CDS values of *Delta-v* calculated for the higher speed impacts are similar in value to those calculated using Eqs. 1, 2, 3, 4, where iterative estimation of restitution indicates values approaching zero. Perfect agreement between the two *Delta-v* calculation methods would cause all of the data to lie on the thicker line in each plot.

In order to directly compare the WinSMASH calculations contained in the NASS/CDS database with the calculations performed using the classical mechanics approach, each of the *Delta-v* values shown on the ordinates of Fig. 2 was recalculated using only Eqs. 1, 2, 3, with restitution (e) set to zero. As the WinSMASH software assumes zero restitution, it was predicted that there would be better agreement between *Delta-v* values computed assuming a restitution of zero, and those contained within the NASS/CDS cases described previously. This prediction was confirmed for both *Delta-*v_b and *Delta-*v_t for the conforming cases found in the NASS/CDS 2004 and 2010 databases. Expressed as percentages, the classical calculation (with $e = 0$) respectively underestimated the 2004 and 2010 NASS/CDS-computed values of *Delta-*v_b magnitudes by 1.47% and 1.23%, and actually overestimated the 2004 and 2010 values of *Delta-*v_t respectively by 1.76% and 0.53%. Once again, however, the standard deviation of these differences, expressed in terms of percentages, far exceeded the small differences among the mean values. These data are plotted in Fig.3. Each of the graphs show that there is excellent agreement in *Delta-v* values calculated by both versions of WinSMASH and Eqs. 1, 2, 3 when restitution is set to zero. The lines fit to each plot show both correlation (R^2) and slope attaining values that are close to 1.00.

5. DISCUSSION

A. Restitution

As discussed by Niehoff and Gabler, it would be quite simple to improve the accuracy of the *Delta-v* values provided by the NASS/CDS, since the effect of restitution on calculated velocity can be determined using the following equation (for both bullet and target vehicles):

$$\Delta v_{total} = \Delta v_{e=0}(1+e) \tag{5}$$

where Δv = *Delta-V* for either the target or bullet vehicles [1]. This simple relationship is shown graphically in Fig. 4, where the percentage increase in the magnitude of *Delta-v* is linearly related to the coefficient of restitution determined during the simultaneous solution of Eqs. 1, 2, 3, 4.

While it would be convenient to simply "improve" the *Delta-v* values provided by the NASS/CDS using Eq. 5, this cannot be easily done because the database does not include an estimate of restitution, nor can restitution be calculated using the values provided in the database. NASS/CDS specifically includes only *Delta-v* values, and provides estimates of pre-impact speeds for neither the target nor bullet vehicles. The Cipriani approach for estimating restitution depends upon closing velocity (i.e. the difference between the pre-impact speeds of the bullet and target) hence it cannot be calculated based on the information provided by NASS/CDS alone. In contrast, the "classical approach" used (Eqs. 1, 2, 3, 4) fixes the pre-impact speed of the target vehicle, and then solves simultaneously for the pre-impact speed of the bullet vehicle, the post-impact speed of both vehicles, and restitution, with the pre-impact speed of the bullet vehicle "standing in" for the closing velocity in Eq. 4. Hence at this time, only the classical solution approach allows calculation of *Delta-v* values that account for the effect of restitution for the two-vehicle front-to-rear collisions considered herein.

Table 1. Comparison of how much NASS/CDS-calculated values of Delta-v for both bullet and target vehicles underestimate values of Delta-v calculated using classical mechanics approach and restitution estimated based on closing speed (left) and restitution set to zero (right). Negative values in table indicate over estimation.

	Mean Under Estimation of Calculated vs. NASS/CDS *Delta-v* values (%)	Standard Deviation (%)	Mean Under Estimation of Calculated vs NASS/CDS *Delta-v* values (%): *e* = 0	Standard Deviation (%)
2010 (bullet)	11.84	6.78	1.23	3.09
2004 (bullet)	13.17	5.44	1.47	2.27
2010 (target)	10.38	6.91	-0.53	3.69
2004 (target)	10.59	5.40	-1.76	5.31

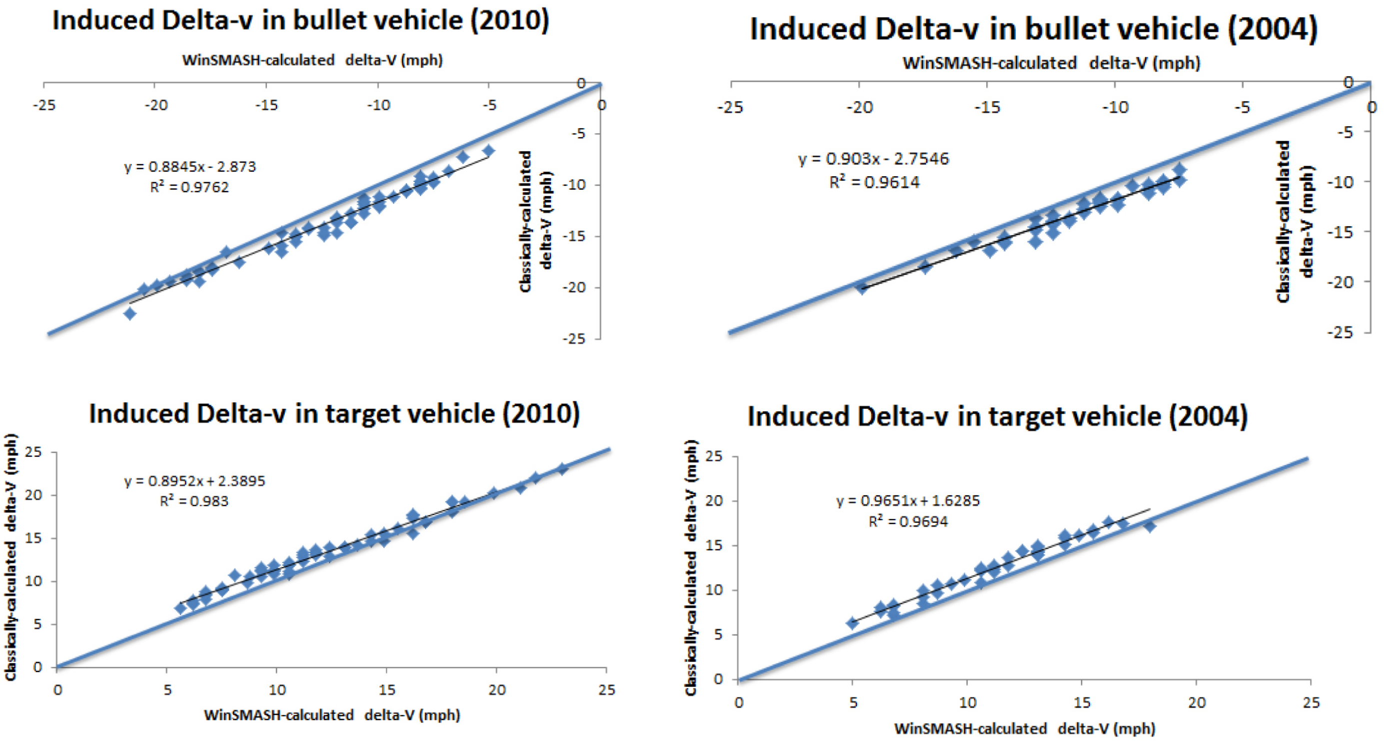

Figure 2. WinSMASH-calculated Delta-v underestimates the magnitude of Delta-v calculated using classical equations (energy, momentum and restitution) for both bullet (top) and target (bottom) vehicles. Exemplar cases taken from 2010 (left) and 2004 (right) NASS/CDS databases. Perfectly-corresponding values would be located along thick diagonal line

B. Pre-Impact Speed of Target Vehicle

In the above numerical study, Eqs. 1, 2, 3, 4 were used to solve for four unknown parameters for each NASS/CDS case analyzed: pre-impact bullet vehicle velocity; pre- and post-impact target vehicle velocities, and restitution. As mentioned previously, pre-impact target vehicle velocity was set to a specific value (here zero). This reflects typical conditions in a front-to-rear impact where a bullet vehicle strikes a slow-moving or stationary target. As Eqs. 1, 2, 3, 4 can only be used to solve for the four unknown parameters listed above, repeating the solution for various fixed values of the pre-impact velocity of the target allows its effect to be studied.

C. Energy

Solution of Eqs. 1, 2, 3, 4 for three velocities and restitution (as described herein) requires prior knowledge of total impact crush energy. In the above numerical study incorporating the NASS/CDS cases shown in the Appendix, the bullet and target crush energies included for each collision were summed, and "plugged in" to Eq. 2 as dissipated energy (U_{diss}).

In cases where crush measurements cannot be made on vehicles involved in a front-to-rear impact, appropriate exemplars from the NASS/CDS can be used to establish an estimated range for the energy dissipated by each vehicle in a subject collision. For instance, a range for the energy dissipated by the subject 1990 Honda Accord bullet vehicle

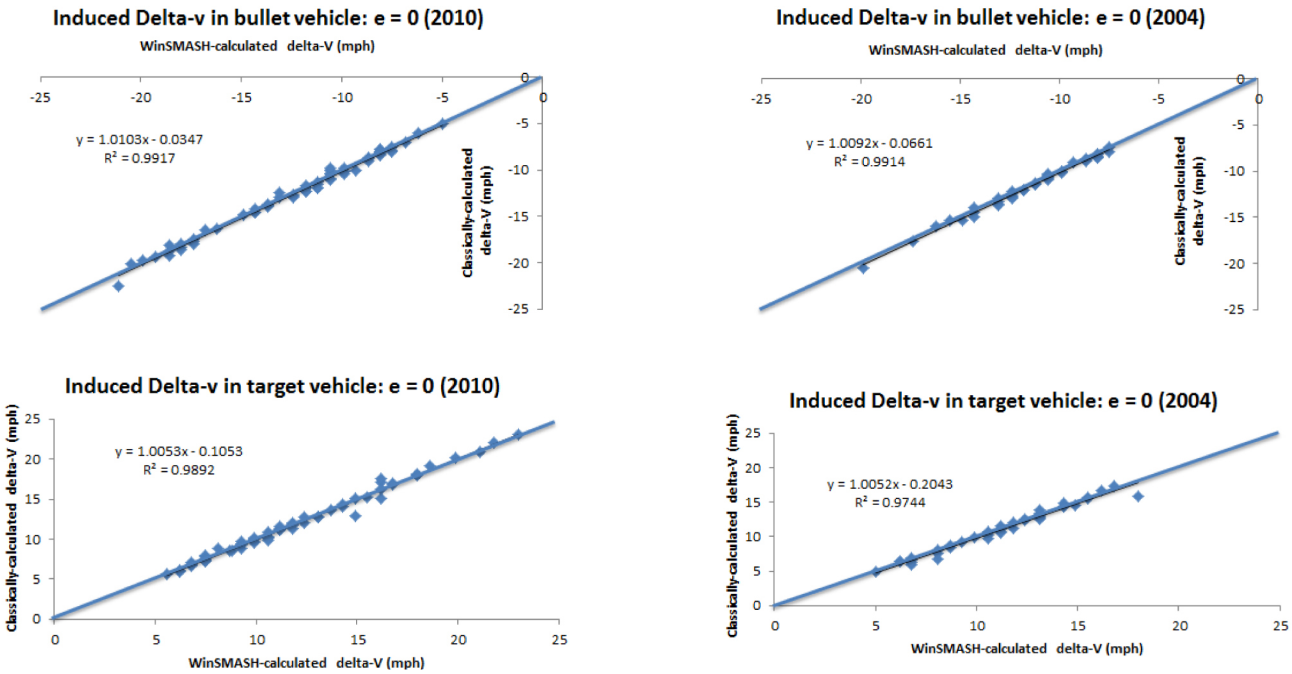

Figure 3. WinSMASH-calculated Delta-v generally agrees with magnitude of Delta-v calculated using classical equations (energy and momentum) for both bullet (top) and target (bottom) vehicles when an assumption of zero restitution is incorporated into the classical calculations. Exemplar cases taken from 2010 (left) and 2004 (right) NASS/CDS databases. Perfectly-corresponding values would be located along thick diagonal line

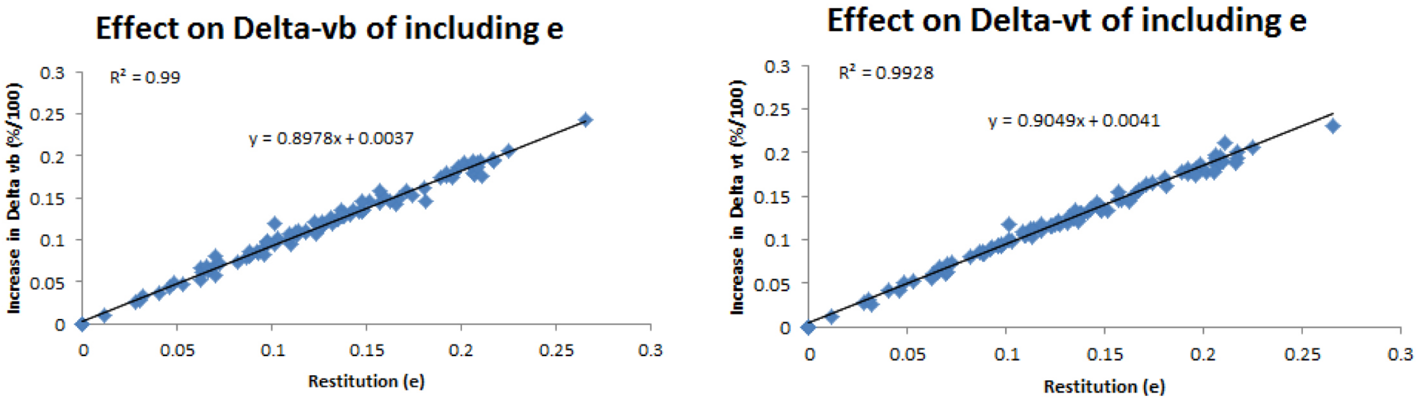

Figure 4. Using values of Delta-v and restitution calculated via Eqs. 1, 2, 3, 4, the percentage increase in Delta-v over the baseline (e=0) Delta-v value is directly proportional to restitution.

shown in the lower right of Fig. 5 can be estimated by using the NASS/CDS crush energies assigned to similarly damaged series 1990 - 1993 Honda Accords. A similar approach can be used to estimate a range for the energy dissipated by the subject target vehicle. Using a "variation of parameter" approach, Eqs. 1, 2, 3, 4 can be solved repeatedly using different values for U_{diss} established by the NASS exemplars. Instead of solving for single values of pre- and post-impact speeds and restitution, using a range of dissipated energies based on a range of appropriate bullet and target exemplars from the NASS/CDS will establish ranges for those values. The effect of changes in dissipated energy on calculated impact speed is contained in Section 6.

6. SENSITIVITY ANALYSIS

Many of the more recent papers cited herein are concerned with the *accuracy* of the various approaches used to compute *Delta-v*. There is general recognition that providing better input values (in this case dissipated energy, mass, restitution) to any computational algorithm yields more accurate results. However, at some point, spending time and computational resources on improving the accuracy of such input parameters may not pay off in terms of substantially more precise estimates of *Delta-v*. This can be illustrated through a limited sensitivity analysis, which explores how calculation of *Delta-v* varies as individual input parameters are perturbed.

1990 Accord, U = 12311 J
NASS/CDS 1997-043-116

1991 Accord, U = 12604 J
NASS/CDS 1999-049-206

1991 Accord, U = 10631 J
NASS/CDS 2002-079-004

1993 Accord, U = 10764 J
NASS/CDS 2005-074-054

1993 Accord, U = 13316 J
NASS/CDS 2003-002-050

1990 Accord, subject vehicle with unknown crush

Figure 5. Five exemplar 1990 - 93 Honda Accord vehicles from the NASS/CDS, plus a subject 1990 Honda Accord (lower right). The range of crush energies taken from the NASS/CDS exemplars can be used to estimate a range for the energy dissipated by the front of the subject Accord.

A. Weight

When analyzing a front-to-rear collision, there is always some uncertainty associated with estimation of the weight of each vehicle and its contents. While VIN analysis and industry data can certainly provide nominal values for the curb weight of each vehicle, the weight of cargo as well as the vehicle occupants is going to be more challenging to determine precisely, especially if the information is not obtained immediately at the time of the impact. The difficulty in obtaining pertinent data is reflected by the values stored in the NASS/CDS database, which contains many cases with incomplete or inconsistent information. While some of the case files contain details about each occupant (e.g. gender, weight, age), others only include partial demographic or physical information, and may not even contain the total number of people in the vehicle at the time of impact. Assuming some partial information is available, it is possible to estimate total occupant weight by using sources such as age/weight charts published by the CDC (Centers for Disease Control and Prevention) [16]. However, estimates based on statistical charts provide inexact information. Another source of uncertainty stems from vehicle cargo, as it will typically not be possible to get an exact weight of the items contained in each vehicle at the time of the impact. Once again, this uncertainty is manifested by the NASS/CDS database. While cargo weight is listed in certain NASS/CDS records, such values are often based on estimates of the driver and/or an investigator, rather than an actual measurement. Finally, unless measured immediately after impact, it is generally impossible to determine the amount of fuel in each gas tank (as well as the amount of other fluids in each vehicle). The uncertainty introduced by fuel and fluid levels is not insignificant - for instance, one gallon of gas weighs about 6.1 pounds, and fuel tank capacities exceed 25 gallons in many vehicles.

Since it is likely that the estimated total weight of each vehicle (including its occupants and contents) may differ from the true values by tens or even hundreds of pounds, it is necessary to understand how sensitive calculated values of *Delta-v* are to this discrepancy. This was accomplished using Eq. 1, 2, 3, 4 for both bullet and target vehicles via two baseline cases. Both baselines assumed nominal vehicle weights of 3220 lbs (100 slugs), and varied them individually by +/− 10% (which approximately corresponds to +/− two people) and +/− 2% (which approximately corresponds to +/− 10 gallons of fuel). In the analysis, total dissipated energy was set at 10000 ft-lbs and 25000 ft-lbs, simulating impacts resulting in two different levels of physical damage. A summary of sensitivities of calculated values of *Delta-v* to variations from nominal weight is contained in Table 2. On a percentage basis, it appears that small uncertainties in weight are slightly attenuated as they propagate through to the calculated *Delta-v* values. Note that perturbations in vehicle mass also changed the estimated value of coefficient restitution as well as the *Delta-v* values, since the entire system comprising Eqs. 1, 2, 3, 4 had to be re-solved using the new mass values.

Table 2. The effect of small imprecisions in reported total mass (vehicle plus contents and occupants) affects the precision of vehicle Delta-v values calculated for both bullet and target vehicles. Nominal total mass of each vehicle was set at 100 slugs, and two damage levels (as indicated by dissipated energy) were considered.

Dissipated Energy [ft-lbs]	*e*	*m* (bullet) [slugs]	*m* (target) [slugs]	*Delta-v* bullet [mph] (% variation)	*Delta-v* target [mph] (% variation)
10000	0.223	Nominal (100)	Nominal (100)	-8.6	8.6
	0.233	Nominal	+10%	-8.8 (2%)	8.1 (6%)
	0.224	Nominal	-10%	-8.4 (2%)	9.3 (8%)
	0.233	+10%	Nominal	-8.0 (7%)	8.9 (4%)
	0.224	-10%	Nominal	-9.3 (8%)	8.3 (4%)
	0.230	Nominal	+2%	-8.6 (0%)	8.5 (1%)
	0.228	Nominal	-2%	-8.7 (1%)	8.7 (1%)
	0.230	+2%	Nominal	-8.4 (2%)	8.7 (1%)
	0.228	-2%	Nominal	-8.7 (1%)	8.6 (0%)
25000	0.137	Nominal (100)	Nominal (100)	-12.4	12.4
	0.142	Nominal	+10%	-12.9 (4%)	11.6 (6%)
	0.131	Nominal	-10%	-11.9 (4%)	13.3 (7%)
	0.142	+10%	Nominal	-11.6 (6%)	12.7 (2%)
	0.131	-10%	Nominal	-13.3 (7%)	12.0 (3%)
	0.138	Nominal	+2%	-12.5 (1%)	12.2 (2%)
	0.136	Nominal	-2%	-12.3 (1%)	12.6 (2%)
	0.138	+2%	Nominal	-12.2 (2%)	12.5 (1%)
	0.136	-2%	Nominal	-12.6 (2%)	12.3 (1%)

Table 3. The effect of small imprecisions in total dissipated energy affects the precision of vehicle Delta-v values calculated for both bullet and target vehicles. Nominal total mass of each vehicle was set at 100 slugs, and two damage levels (as indicated by dissipated energy) were considered.

Dissipated Energy [ft-lbs]	*e*	*m* (bullet) [slugs]	*m* (target) [slugs]	*Delta-v* bullet [mph] (% variation)	*Delta-v* target [mph] (% variation)
Nominal (10000)	0.229	Nominal (100)	Nominal (100)	-8.6	8.6
+2%	0.227			-8.6 (0%)	8.7 (1%)
-2%	0.231			-8.6 (0%)	8.5 (1%)
+10%	0.220			-9.0 (5%)	8.9 (4%)
-10%	0.238			-8.2 (5%)	8.2 (5%)
Nominal (25000)	0.137			-12.4	12.4
+2%	0.134			-12.5 (1%)	12.5 (1%)
-2%	0.139			-12.3 (1%)	12.3 (1%)
+10%	0.126			-12.8 (3%)	12.8 (3%)
-10%	0.148			-12.0 (3%)	11.9 (4%)

B. Energy

Recent work by Brach [17] has shown that variations in physical crush measurements as well as stiffness parameters can have a dramatic effect on the calculated values of both dissipated energy and *Delta-v*. In that work, the authors took dissipated energy values from 11 actual NHTSA crash tests, and selected a variation range of +/− 2σ (representing a 95% confidence interval) to set the upper and lower bound values, ranging from 134540 - 813292 Joules (99232 - 599853 foot-pounds) used to evaluate the effect on calculated *Delta-v*. High values of dissipated energy were obtained because of the nature of the collisions evaluated (head-on impacts at relative speed of 80 mph). Here, we've chosen to reference front-to-rear collisions from the NASS/CDS database whose total dissipated energies were 100000 Joules (73756 foot-pounds) or less. Furthermore, in order to illuminate exactly how sensitive *Delta-v* computations are to smaller imprecisions in dissipated energy value, nominal values for dissipated energy were set at 10000 and 25000 foot-pounds, and were varied by +/− 2% and +/− 10%. Results are summarized in Table 3. The same nominal value for vehicle mass (100 slugs) was used here as was assumed for the computations summarized in Table 2. Results show that 10% imprecisions in dissipated energy only cause variations of up to 5% in the calculated *Delta-v* values, indicating that on a percentage basis, *Delta-v* values are less sensitive to uncertainties in the stated value of dissipated energy than they are to mass uncertainties.

7. SUMMARY/CONCLUSIONS

The determination of *Delta-v* in a front-to-rear impact has long been considered an important measure of collision severity. The work presented herein has showed that for impacts that dissipate low amounts of energy (below 25000 foot-pounds), small percentage variations in estimated parameters such as total vehicle weight, as well as dissipated energy, cause similar or smaller changes, on a percentage basis, to the computed magnitudes of *Delta-v*. The results of this sensitivity analysis suggest that small amount of uncertainty in these estimate parameters may be acceptable, with the caveat that the estimated values of *Delta-v* will reflect similar levels of precision. However, the systematic underestimation of *Delta-v* reported when calculating it using either WinSMASH or directly through Eqs. 1, 2, 3 can be reduced or eliminated entirely for low-speed front-to-rear impacts by incorporating an appropriate non-zero coefficient of restitution in the calculations. Although the approximately 10-13% average increase in calculated *Delta-v* obtained here mirrors the results obtained by Hampton and Gabler [10]; and Niehoff and Gabler [1], further confirmation using a data-set incorporating both measured and computed values of *Delta-v* is desirable.

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APPENDIX

Table A1. NASS/CDS case numbers used for numerical study (*www.nhtsa.gov/NASS*)

2004-02-130	2004-82-141	2010-48-118
2004-03-033	2010-02-062	2010-48-182
2004-04-077	2010-02-094	2010-48-184
2004-04-095	2010-02-111	2010-48-206
2004-08-122	2010-04-023	2010-48-221
2004-08-130	2010-05-121	2010-48-230
2004-08-226	2010-08-018	2010-48-247
2004-11-095	2010-08-080	2010-48-257
2004-11-111	2010-08-104	2010-73-106
2004-12-093	2010-08-178	2010-73-122
2004-12-108	2010-09-080	2010-75-022
2004-12-170	2010-12-066	2010-75-096
2004-12-179	2010-12-072	2010-75-143
2004-13-031	2010-12-113	2010-75-193
2004-13-126	2010-12-133	2010-76-003
2004-13-144	2010-12-134	2010-76-047
2004-43-048	2010-12-146	2010-79-022
2004-43-102	2010-12-200	2010-79-137
2004-43-104	2010-12-222	2010-81-042
2004-43-177	2010-12-226	2010-81-082
2004-43-192	2010-13-005	2010-82-016
2004-43-281	2010-13-060	2010-82-025
2004-43-293	2010-13-098	2010-82-028
2004-43-321	2010-13-131	2010-82-116
2004-47-084	2010-13-142	
2004-50-073	2010-13-168	
2004-50-110	2010-13-198	
2004-73-211	2010-13-207	
2004-74-073	2010-41-062	
2004-74-091	2010-41-118	
2004-74-212	2010-43-033	
2004-74-269	2010-43-099	
2004-75-003	2010-43-118	
2004-75-090	2010-43-133	
2004-76-007	2010-43-183	
2004-76-050	2010-43-207	
2004-81-008	2010-48-014	
2004-81-047	2010-48-030	
2004-81-120	2010-48-042	
2004-82-102	2010-48-109	
2004-82-112	2010-48-115	

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