SAE International

Uncertainty of CRASH3 ΔV and Energy Loss for Frontal Collisions

2012-01-0608
Published
04/16/2012

R. Matthew Brach, Raymond M. Brach and Andrew Louderback
Brach Engineering

doi:10.4271/2012-01-0608

ABSTRACT

This research investigates the uncertainty in the calculation of the change in velocity, ΔV, and the crush energy, E_C, due to variations in the computed values of crush stiffness coefficients, A and B (d_0 and d_1), and due to variations in the measurements of the residual crush, C_i, $i = 1,\ldots 6$, using the CRASH3 damage algorithm. An understanding of the nature of such uncertainties is of particular importance as both the ΔV and E_C are frequently used as inputs to reconstruction methods and become variations in the reconstruction process. These variations lead to uncertainties in the results of the reconstruction which are generally the preimpact speed of one or both of the vehicles involved in the collision. This paper consists of three parts. The first investigates the uncertainty associated with the calculation of the stiffness coefficients A and B (d_0 and d_1). The second part looks at the uncertainty of the CRASH3 process of calculating the velocity change, ΔV, of both vehicles and the energy loss, E_C, of the system. The third part examines the effect of such variations on the reconstruction of vehicle speeds in frontal collisions.

The magnitudes of the uncertainty of the manual measurements of residual crush values C_i, $i = 1,\ldots 6$, are determined from results presented in the literature. The uncertainty of the stiffness coefficients, A and B (d_0 and d_1), were determined by accessing six different light vehicle models for which experimental data from multiple NHTSA frontal barrier tests was available. The stiffness coefficients were computed for each set of test data for each vehicle model. These values, with a minimum of six frontal barrier tests per vehicle, give an average and standard deviation for each coefficient for each vehicle model. These values then provide the variation of the stiffness coefficients for these vehicle models. These variations then are used in the CRASH3 damage algorithm, through the use of Monte Carlo analysis, to calculate the uncertainty in the ΔV and E_C for each of the six vehicle models colliding with a fixed, rigid barrier. Comparison of the results of the analyses shows that the uncertainty in ΔV and E_C due to the experimentally-determined stiffness coefficients is considerably more significant than the uncertainty due to the variation in the measurements of the residual crush.

The paper then examines the use of these results in the reconstruction of two in-line collisions. Here the uncertainties in ΔV and E_C become variations in the reconstruction process. The results of this section present a range of values for the preimpact speed of one of the crash vehicles based on the range of values for the crush energy loss determined in the first part of the paper.

INTRODUCTION

The CRASH3 damage algorithm [1], established initially in the 1970's, has been the subject of numerous papers that have examined various aspects of the method (see for example [2, 3, 4, 5]). It has also been used for several decades in various software programs available for use in the field of accident reconstruction [6, 7, 8, 9, 10]. Other papers have considered specific aspects of the method such as the nonlinear nature of the crush stiffness of vehicles [11, 12] while another looks to refine the methodology with increased number of measurements of the residual crush [13].

Several papers consider the accuracy of the CRASH3 damage algorithm method relative to tests [14, 15, 16]. These papers generally raised the question, relevant at the time, of the appropriateness of different stiffness "categories" for classes of vehicles. In particular, Smith and Noga [14] look at the sensitivity (i.e. uncertainty) of the velocity changes, ΔV_1 and ΔV_2 relative to variations in the stiffness coefficients A and B and in the crush measurement values of C_1 through C_6. The uncertainty of the energy loss due to variations of the crush measurements and stiffness coefficients is affected by ΔV being a function of the square root of the energy loss, E_C, and that this functional relationship reduces the uncertainty of ΔV relative to E_C. More recently, [17, 18] it has been shown that the energy loss, E_C, is more accurately portrayed as the work done by the normal component of the contact impulse and eliminates the need for the CRASH3 tangential correction factor and visual estimation of the PDOF (Principal Direction of Force). This approach relates the damage-only energy loss directly to a common crush surface using planar impact mechanics (impulse and momentum) and can provide a more accurate reconstruction of vehicle speed, particularly when restitution is a factor [17, 31].

This investigation examines the uncertainties of frontal crashes associated with CRASH3 using NHTSA New Car Assessment Program (NCAP) and FMVSS frontal barrier crash test results of contemporary vehicles. Specifically, in the time since Smith and Noga evaluated the sensitivity, testing programs that produce experimental rigid barrier data for the majority of light vehicles in North America, relatively rare at the time that paper was published, have become commonplace. The comparatively large amount of experimental crash data permits variations in values of the stiffness coefficients d_0 and d_1 (A and B) [4] from multiple tests of identical vehicles to be examined, providing new insights into uncertainty.

Partial motivation for examination of the variations related to the measurements of residual crush comes from recent literature that deals with a variety of techniques used to measure the residual crush with increased accuracy relative to manual measurements (see for example [19, 20, 21]). Such papers describe techniques for measuring residual crush with high accuracy using photogrammetry in contrast to the traditional, manual measurements (by way of tape measure and plumb bobs, dedicated fixtures and jigs, etc.). A question arises as to whether the increased accuracy of these more sophisticated measurement methods (that presumably reduce the variation in the crush measurements) actually reduces the uncertainty in the calculation of the ΔV and E_C generated by the CRASH3 damage algorithm. This topic is addressed in this paper.

BACKGROUND

An early study [2] of data from frontal, fixed rigid barrier tests at speeds above about 20 mph (32 km/h) noted a nearly linear relationship between test speed and the amount of residual crush. At closing speeds higher than about 30 mph (48 km/h) restitution generally has been considered small [29], and the energy lost in a barrier collision is close to the entire kinetic energy of approach. Because kinetic energy is proportional to the square of speed, the trend noted in the early study implies that the square root of the kinetic energy loss is approximately linearly proportional to the residual crush. Assuming that crush energy equals the kinetic energy loss, the crush energy, E_C, per unit width, w, of a crushed vehicle can then be expressed as a linear function of crush, C [4]:

$$\sqrt{\frac{2E_C}{w}} = d_0 + d_1 C \tag{1}$$

where the residual crush, C, is measured in a direction normal (perpendicular) to, and from, the nominal undeformed vehicle surface. The constants d_0 and d_1 are called the crush stiffness coefficients and are determined using data from staged barrier impact tests. These coefficients differ from vehicle to vehicle and between the front, side, and rear of each vehicle. They can also be different for different regions along a vehicle, although this is usually not taken into account. This is primarily because most existing crush-based reconstruction methods do not accommodate such variations and available test data generally do not determine the stiffness coefficients by regions of a given side of a vehicle.

Vehicles do not always collide head-on into flat rigid barriers, so the above relationship between energy (and speed) and residual crush is not generally applicable for accident reconstructions unless it can be adapted to nonuniform crush profiles and vehicle-to-vehicle collisions. This relationship was exploited and a method was developed [1] for the National Highway Traffic Safety Administration called CRASH3 (Calspan Reconstruction of Accident Speeds on the Highway, version 3). CRASH3 was developed for collisions of light vehicles. The measurement process of residual crush is intended to follow a specific protocol [22]. The protocol typically uses a series of six lateral crush measurements spaced equally over a deformed surface of a damaged vehicle at a uniform height from the ground at a level corresponding to where vehicles are designed to resist and develop controlled crush forces. This is usually at the bumper height for front and rear collisions. In the theoretical development, crush is usually assumed to be uniform from top to bottom of the deformed vehicle surface. This is rarely the case in practice, particularly for damage to the side of the vehicle.

Residual crush measurements are made over the full lateral extent (beginning to end) of damage. This includes direct contact damage and induced damage. Induced damage is residual deformation that occurs not due to direct vehicle-to-vehicle contact, but because of contact forces at adjacent areas. If the profile of the initial undeformed body shape is curved (such as looking at a bumper from above), it is important to measure each crush value from the corresponding curved, original, undeformed surface of the vehicle.

CRASH3 was originally formulated to be used with four, or even two, measurements for reasonably uniform damage profiles. The development presented here uses six measurements at equal lateral intervals as this is generally how the test data are reported. Figure 1 illustrates a series of six crush measurements made along damage of extent w of the front of a vehicle where C_1 - C_6 are the measured distances from the undeformed, as manufactured, surface of the vehicle to the point of the crushed surface.

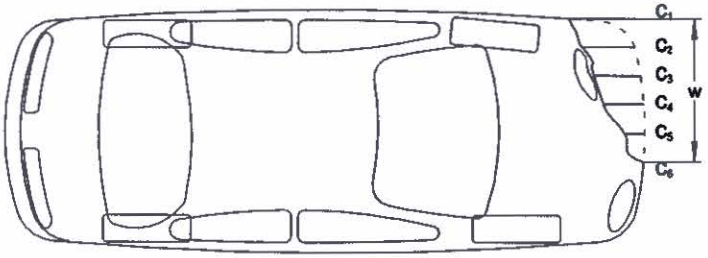


Figure 1. Example of the front six-point crush measurements protocol.

Prasad [4, 23, 24] shows that if the crush profile is approximated by linear segments of crush between the six equally spaced points, and Eq. 1 is at least approximately true, then the crush energy can be computed from:

$$E_C = d_0^2 K_1 + d_0 d_1 K_2 + d_1^2 K_3 \tag{2}$$

where

$$K_1 = w/2 \tag{3}$$

$$K_2 = w\left[C_1 + 2(C_2 + C_3 + C_4 + C_5) + C_6\right]/10 \tag{4}$$

and

$$\begin{aligned} K_3 = w\,[&C_1^2 + 2(C_2^2 + C_3^2 + C_4^2 + C_5^2) + C_6^2 + \\ &C_1C_2 + C_2C_3 + C_3C_4 + C_4C_5 + C_5C_6]/30 \end{aligned} \tag{5}$$

Equations 2, 3, 4, 5 form the CRASH3 crush energy, or damage-only, algorithm.

Crush stiffness coefficients can alternatively be expressed as constants A and B [1] determined directly from d_0 and d_1, using:

$$A = d_0 d_1 \text{ and } B = d_1^2 \tag{6}$$

Different techniques exist for measuring C_i, $i = 1,\ldots 6$. If the damaged vehicle is available for inspection, the measurements can be made manually through the use of a dedicated jig, plum bob and tape measure or electronically through the use of a total station or coordinate measuring machine. Photogrammetry can also be used to measure crush if a sufficient set of pictures of the damaged vehicle is available. More recently, three-dimensional laser scanners have been used for measuring crush profiles.

Computing Crush Stiffness Coefficients

One of the most common methods used to determine the crush stiffness coefficients, d_0 and d_1, for the front of a vehicle is from residual crush measurements of a vehicle crashed into a fixed rigid barrier at a known speed. This section describes one method that can be used to calculate the crush stiffness coefficients from six measurements of the residual crush of a tested vehicle.

The first task in calculating the coefficients is to select a threshold speed below which no measurable residual crush occurs; that is, a speed for which $C = 0$ for Eq. 1. Note that this does not necessarily mean that no damage to the vehicle is visible, but rather no significant residual crush occurs. Often this speed is chosen to lie in the range of 5 to 7 mph (8.0 to 11.3 km/h). Once the kinetic energy and the crush width, w, are known, then with C set equal to zero (for no residual crush), Eq. 1 is used to solve for d_0. The coefficient d_1 can then be calculated from experimental barrier data (known energy loss, crush width, and six measurements of the residual crush) using a modified form of Eq. 1:

$$d_1 = \frac{1}{C_{avg}}\left(\sqrt{\frac{2E_C}{w}} - d_0\right) \tag{7}$$

where C_{avg} is computed with the six equally spaced measurements of the residual crush, using the weighted average (weighted according to Eq. 4):

$$C_{avg} = \left[C_1 + 2\left(C_2 + C_3 + C_4 + C_5\right) + C_6\right]/10 \tag{8}$$

Computing Velocity Change, ΔV

Once the stiffness coefficients are known and the six crush values are measured for vehicles involved in a collision, E_C can be computed using Eq. 2. Then the velocity change, ΔV_i, i=1, 2, of each vehicle of a two-vehicle collision can be calculated based on four simplifying assumptions. These are:

1. The crush energy, E_C, is equal to the impact kinetic energy loss, T_L.

2. The collision is perfectly inelastic; i.e., there is no rebound or restitution of the vehicles at and perpendicular to the crush surface ($e = 0$).

3. Relative sliding velocity of the vehicles along (tangent to) the crush surface ends (becomes zero) before or at the time the vehicles separate.

4. Forces external to the colliding vehicles (including tire ground forces) are negligibly small compared to intervehicular forces.

With these assumptions, ΔV can be calculated directly from E_C according to the original CRASH3 formulation:

$$m_i \Delta V_i = \sqrt{2 m_e E_c} \qquad i = 1, 2 \tag{9}$$

where

$$m_e = \frac{\gamma_1 m_1 \gamma_2 m_2}{\gamma_1 m_1 + \gamma_2 m_2} \tag{10}$$

$$\gamma_i = \frac{k_i^2}{k_i^2 + h_i^2} \tag{11}$$

The quantity k_i is the yaw radius of gyration of vehicle i, and h_i is the perpendicular distance between the center of mass of vehicle i and the principal direction of force (PDOF). Since the analysis of this paper deals with frontal barrier impacts with a zero degree impact angle and zero offset ($h_1 = 0 \rightarrow \gamma_1 = 1$) involving only one vehicle, the calculation of ΔV can be further simplified by assuming that the barrier experiences no velocity change ($m_2 = \infty$) and the vehicle experiences no rotation before or after impact. With these assumptions, ΔV is computed using Eq. 9 with $m_e = m_1$.

It is important to note that the above approach (use of Eq. 9, 10 and 11) has significant limitations when applied to oblique collisions [17, 18, 29]. All applications in this paper are to direct frontal collisions with no tangential impulse.

TERMINOLOGY

Throughout this paper, the terms "variation" and "uncertainty" are intended to have specific meanings. If an independent variable, x, is a random variable, a function (formula) $y = f(x)$ is also a random variable. The statistical distribution of x is considered to be a *variation* that causes *uncertainty* in y. That is, a variation in an independent variable leads to, or causes, uncertainty in the calculation of the dependent variable.

For example, variations in crush measurements, C_i, $i = 1,\ldots 6$, lead to uncertainty in the calculation of the crush energy, E_C (see Eq. 2, 3, 4, 5). However, when the crush energy is used, in turn, to reconstruct a vehicle's preimpact speed, the (input) distribution of E_C is then considered to be a variation in the determination of the uncertainty of the vehicle's speed.

STIFFNESS COEFFICIENTS FROM BARRIER CRASH TESTS

This research studies experimental data taken from the NHTSA Vehicle Crash Test database [25]. Frontal barrier impact test data for vehicles of various makes and models, but of consistent model year runs, were selected. Vehicle model generations included in this investigation are:

- 1996-1999 Ford Taurus
- 2003-2007 Honda Accord
- 1995-2004 Toyota Tacoma
- 1997-2004 Ford F-150
- 1985-1994 Chevrolet Astro
- 2001-2007 Chrysler Town & Country

These vehicles were chosen because they represent a diverse group of manufacturers and body styles and because each has a relatively high number of NTSHA frontal barrier crash tests. Each vehicle chosen has at least six frontal barrier impact test reports that contain all of the necessary information to compute stiffness coefficients.

Variations in Stiffness Coefficients

The NHTSA test reports provided the test mass, vehicle preimpact speed, length of the damaged region, and six equally spaced, frontal residual crush measurements. Some of the reports provided the change in velocity which was used to calculate the coefficient of restitution for that test. When the restitution was available, it was used in the calculation of the stiffness coefficients. (Table A13 in the Appendix contains a list of these restitution values.) In the cases where the rebound velocity is not included in the test report, the stiffness coefficients were calculated with the assumption that the coefficient of restitution was zero. It was also assumed during this research that the zero residual crush speed of the vehicles was 7 mph (11.27 km/h). The data taken from the reports are shown in Tables A1, A2, A3, A4, A5, A6 of the Appendix.

The experimental data were then used to calculate the frontal crush stiffness coefficients d_0 and d_1 for each test vehicle using the Vehicle-to-Barrier Coefficients spreadsheet in

VCRware [10]. The values for the mean and standard deviation for each model run were then calculated from the applicable tests. Tables A7, A8, A9, A10, A11, A12 of the Appendix show tabular values of d_0 and d_1 listed by vehicle and test number. The sample average and standard deviation for each stiffness coefficient are listed at the bottom of each table. Figures A1 and A2 visually display the histograms of the coefficients using dot plots. In addition, the linearity of the relationship between the test speed and residual crush was evaluated for each vehicle model. These data are shown in Figure A3.

Values of d_0 and d_1 averaged from a given vehicle's data can be found in a different way. This is by using least-square fitting of the crush energy-crush line (see, for example, Figure A3) to the crash test data. The stiffness coefficients are the intercept and the slope of the regression line. The results are essentially the same as using the data directly to compute means of d_0 and d_1.

Variation in Crush Measurements

Appropriate statistical variations of the residual crush measurements are needed to undertake a statistical uncertainty analysis. NHTSA does not make repeated measurements of crush for each C_i from a test vehicle; only one set of measurements is reported. Therefore, each individual crush measurement reported by NHTSA was considered here to represent the mean for each C_i. A representative value for the standard deviation of 2.5% of the mean crush is used, obtained from previous studies of manual crush measurements [19, 26].

Despite the fact that the values of C_i, $i = 1,\ldots 6$ are used from each test to compute d_0 and d_1, it is assumed that these variables are statistically independent. This is because the variations in the measured values of C_i in a Monte Carlo simulation are intended to represent measurements made by a reconstructionist on a vehicle involved in a crash, not measurements made from a vehicle in a barrier test(s) to determine d_0 and d_1.

Uncertainty in ΔV and E_C

The values of the mean and standard deviation for d_0 and d_1 and the mean and standard deviation of the crush measurements were then used as input parameters (variations) in a Monte Carlo simulation [27] to determine the uncertainty of E_C and ΔV for a collision of each vehicle model into a fixed rigid barrier. This analysis was done using a spreadsheet from *VCRware* [10] that calculates both E_C and ΔV based on the CRASH3 damage algorithm. Separate simulations were carried out, one with statistical variations of d_0 and d_1 and another with statistical variations of C_i, $i = 1,\ldots 6$. All the variations were defined in the Monte Carlo analysis as normally distributed random variables using the corresponding mean and standard deviation as described previously. A single, constant vehicle weight was used corresponding to the average of the weights of the vehicles crashed in the barrier tests for each vehicle model. The crush profile used in the analysis was the average of the crush profiles from the tests (see Tables A1, A2, A3, A4, A5, A6). While not associated with a specific test, these average residual crush values are representative of the crush expected for a barrier collision for the appropriate vehicle model and facilitate the comparative evaluation of uncertainties which is the goal of the analysis.

Although the width of the damaged region, w, is generally determined by field measurement, it was treated as a constant in the analysis. This approach was used since the entire width of the vehicle is generally involved in a frontal barrier test and the undeformed overall width of the test vehicle is typically used for the crush width in any subsequent calculations. However, for the sake of this study, a separate Monte Carlo analysis was also carried out to evaluate the uncertainty of E_C and ΔV for variations of w.

Results

The distributions obtained for ΔV and E_C from Monte Carlo simulations were computed using 10,000 trials for each vehicle model. The parameters d_0 and d_1 are considered random and uncorrelated. Although d_1 is computed using d_0, other research [28] has shown that these two parameters are weakly correlated and the effects of the correlation are small. The mean and standard deviations of ΔV and E_C are listed in Tables 1 and 2.

Histograms representing the distribution of E_C when varying either the d_0 and d_1 values and/or the C_i values are presented for each model run in Figures A4, A5, A6, A7, A8, A9, A10, A11, A12, A13, A14, A15 of the Appendix. Table 3 presents the means and standard deviations of ΔV and E_C for normally distributed variations of the crush width w, using a standard deviation of 2.5% of the measured value (consistent with the variation of the C_i's). These values were calculated with d_0 and d_1 and with C_i, $i = 1,\ldots 6$ held constant at their mean and measured values, respectively. Table 4 presents the results of Monte Carlo simulations run for combined variations in the d_0 and d_1 values and the C_i values. Table 5 presents the results of Monte Carlo simulations run in which variations only in d_1 are considered.

Comparison of the results in Tables 1, 2, 4 and 5 shows that variations of d_0 and d_1 have, by far, the largest effect on the uncertainty (via the standard deviations) of the crush energy loss, E_C, and the uncertainty (via the standard deviations) of the speed changes, ΔV. These data show that the variation of

Table 1. E_C and ΔV Distribution Statistics from varying d_0 and d_1 using Monte Carlo Simulations

Vehicle	E_C - AVG [J]	E_C - σ [J]	ΔV - AVG [m/s]	ΔV - σ [m/s]
Taurus	170,759.9	41,461.4	13.91	1.71
Accord	180,101.2	36,088.0	14.66	1.48
Tacoma	151,804.9	35,752.2	13.83	1.65
F-150	215,295.8	30,347.0	14.03	0.99
Astro	230,100.5	30,976.4	14.75	1.00
T & C	257,132.9	64,254.0	15.32	1.94

Table 2. EC and ΔV Distribution Statistics from varying C_i, $i = 1,\dots 6$ using Monte Carlo Simulations

Vehicle	E_C - AVG [J]	E_C - σ [J]	ΔV – AVG [m/s]	ΔV – σ [m/s]
Taurus	167,885.9	2,868.8	13.90	0.12
Accord	177,972.8	3,197.9	14.65	0.13
Tacoma	149,348.5	2,492.1	13.81	0.12
F-150	214,308.8	3,634.1	14.04	0.12
Astro	229,233.0	3,952.6	14.76	0.13
T & C	252,500.1	4,480.4	15.30	0.14

Table 3. E_C and ΔV Distribution Statistics from varying w alone using Monte Carlo Simulations

Vehicle	E_C – AVG [J]	E_C - σ [J]	ΔV – AVG [m/s]	ΔV – σ [m/s]
Taurus	167,800.2	4,189.6	13.89	0.17
Accord	177,876.9	4,473.9	14.65	0.18
Tacoma	149,282.7	3,754.6	13.81	0.17
F-150	214,234.5	5,391.3	14.03	0.18
Astro	229,231.3	5,717.7	14.76	0.18
T & C	252,428.5	6,332.7	15.30	0.19

Table 4. E_C and ΔV Distribution Statistics from varying d_0 and d_1 and C_i, $i = 1,\dots 6$ using Monte Carlo Simulations

Vehicle	E_C – AVG [J]	E_C - σ [J]	ΔV – AVG [m/s]	ΔV – σ [m/s]
Taurus	170,759.9	41,461.4	13.91	1.71
Accord	180,052.5	36,137.9	14.66	1.48
Tacoma	151,493.3	35,900.5	13.81	1.65
F-150	215,720.4	30,321.0	14.05	0.99
Astro	230,503.9	30,920.9	14.77	0.99
T & C	255,994.4	64,839.8	15.28	1.96

the values of d_0 and d_1 from the available barrier test accounts for the majority of the uncertainty in E_C and ΔV in comparison to variations in residual crush measurements (and variation in crush width, *w*). Thus, as the efforts to increase the accuracy (and precision) of the measurement of the residual crush are a welcome advancement (improvement in measurements technique and methodology are always desirable), the effect on the improvement of the model to predict E_C and ΔV is limited. Focus should perhaps shift to improving the process of acquiring the test data that affects the computation of the stiffness coefficients d_0 and d_1. Future research into this topic could include a thorough audit of the data provided in the test reports to check for accuracy in the documentation of the data related to the calculation of d_0 and d_1. In addition, the procedures used to acquire that data, particularly the measurement of the residual crush, should be examined.

Table 5. E_C and ΔV Distribution Statistics from varying d_1 only using Monte Carlo Simulations

Vehicle	E_C- AVG [J]	E_C- σ [J]	ΔV - AVG [m/s]	$\Delta V - \sigma$ [m/s]
Taurus	170,509.8	41,581.7	13.90	1.72
Accord	179,806.3	35,787.3	14.65	1.47
Tacoma	151,594.7	35,419.7	13.82	1.63
F-150	215,694.4	30,097.5	14.05	0.98
Astro	229,749.7	30,629.9	14.74	0.99
T & C	255,549.1	63,359.7	15.27	1.92

Table 6. Impact Speed Distribution, varying d_0, d_1 and the C_i's, Ford Taurus

	ΔV [km/h]
Mean	-48.27
σ	8.83
Mean ± 2σ	-30.61, - 65.93

Table 7. Test Parameters, NHTSA Test 5657

Vehicle	Mass [kg]	Impact Speed [km/h]	ΔV [km/h]
2001 Honda Civic	1552.8	71.0	81.6
2005 Chrysler T&C	2273.0	49.1	55.8

APPLICATION TO RECONSTRUCTIONS

The implications of the uncertainties found above for ΔV and E_C can be further investigated by using them as variations in the reconstruction of a collision. Two such cases are examined here. Case 1 involves a speed reconstruction of a hypothetical crash using a modified version of the central impact equations (Low-Speed Front-to-Rear Impact of Vehicles spreadsheet in *VCRware* [10]). The modification allows the user to specify as input the system kinetic energy loss, E_C, of the crash. With one of the vehicle's initial velocities known (such as from EDR data [30]), this modification permits reconstruction of the other vehicle's initial velocity. Case 2 is based on a head-on collision test conducted by NHTSA [25] using the energy loss and speed change from the CRASH3 damage algorithm and Planar Impact Mechanics [29]. The result of Case 1 is a distribution of the reconstructed unknown preimpact speed using the CRASH3 damage algorithm. These values reflect the effect of the variations of d_0 and d_1 computed from available barrier tests and the C_i's due to measurement variations on the variation of the reconstructed speed of a vehicle.

In Case 1, a 1997 Toyota Tacoma traveling at 50.0 km/h (31 mph) collided head-on with a 1996 Ford Taurus. The speed of the Taurus is to be reconstructed. Figure A16 of the Appendix shows the spreadsheet containing the various vehicle inputs. A Monte Carlo simulation was run for 10,000 trials of the specified total system kinetic energy loss with a mean value of 318,637.1 J and a standard deviation of 54,844.7 J. The mean value corresponds to the system energy loss that would result if the Toyota Tacoma and the Taurus were traveling towards each other at the same speed of 50 km/h (31 mph). The standard deviation was the value determined for the Taurus and the Tacoma when varying d_0, d_1 and the C_i's, shown in Table 4 as 41461.4 J and 35900.5 J, respectively, where $54844.7 = (41461.4^2 + 35900.5^2)^{1/2}$.

The Monte Carlo simulation used a set of 10,000 trials to produce a histogram of the impact speed of the Taurus. The statistical distribution is presented in Table 6, and a histogram representing the distribution is presented in Figure A17. The results show that the total uncertainty in crush energy based on variations in the crush stiffness coefficients and measurement of the residual crush is higher than previously understood.

In Case 2, a central head-on collision test performed by NHTSA is reconstructed [Ref 25, Test #5657]. In this test, a 2001 Honda Civic (Vehicle 1) and a 2005 Chrysler Town & Country (Vehicle 2) were collided head-on with 0% offset. In this test, the Honda Civic was the target vehicle and the Chrysler Town & Country was the bullet vehicle. The various measurements and results of this test are presented in Tables 7 and 8.

Table 8. Crush Measurements, NHTSA Test 5657

Vehicle	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	W [cm]
2001 Honda Civic	57.9	68.0	72.5	76.5	78.0	78.1	172
2005 Chrysler T&C	35.2	50.3	55.7	58.6	38.3	35.5	200

Table 9. Statistical Data by Test Number, Honda Civic

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
3456	87.0	8.5
3458	87.4	8.4
3610	85.9	8.2
4172	87.2	9.1
4613	87.0	8.6
4659	86.5	4.2
4682	87.0	7.2
4830	84.4	11.6
5175	92.7	7.0
5176	91.1	7.0
5178	91.1	9.3
Average	87.9	8.1
STDEV	2.5	1.8
(±σ)%	5.8	45.6
(±2σ)%	11.6	91.1

Table 10. Frontal Impact Energy Loss Ranges

Vehicle	$E_{C,L}$ [J]	$E_{C,U}$ [J]
Honda Civic	134,540.2	813,291.7
Chrysler T & C	134,404.5	434,430.2

Table 9 shows the crush stiffness coefficient statistical data gathered for the model run of the Honda Civic using the same procedure as previously outlined for the other vehicles.

Rather than performing a Monte Carlo simulation, upper and lower bounds were used in this example to represent a range of values of crush energy loss. Crush energy loss was computed from the CRASH3 damage algorithm using d_0, d_1 and C_i values that were two standard deviations greater than and less than the average or measured values, respectively. This produced two values of crush energy loss per vehicle representing the 95% confidence interval (±2σ), shown in Table 10.

By handling the uncertainty in the follow-on calculations (for preimpact speed for example) using upper and lower bounds, as opposed to Monte Carlo analysis, any indication of likelihood of the actual result within the calculated upper and lower bounds is lost.

This analysis considers two different scenarios in which the preimpact speed is known (or can be reasonably calculated) for only either one vehicle or the other, and the physical evidence is limited to the residual crush measurements of the two vehicles. This type of reconstruction is typical for collisions in which neither vehicle has EDR data to provide impact speed and ΔV but circumstances allow for a reasonable approximation of one of the vehicle's speed at impact, e.g. an assumed acceleration from a known stopped position to its position at impact. In both scenarios, the coefficient of restitution is calculated from the test data: $e = 0.144$. In general, this value will not be known for an actual collision. A fixed (accurate) value is used here as a best-case scenario. In an actual application, a suitable range would be used for the coefficient of restitution that would contribute to the uncertainty of the reconstructed preimpact speeds of the vehicles.

In the first scenario, the preimpact speed of the Chrysler Town & Country is known or calculated to be 49.1 km/h (30.5 mph) while the preimpact speed of the Honda Civic is

Table 7. Planar Impact Analysis Results, Honda Civic

	E_T [J]	$E_{C,1}$ [J]	$E_{C,2}$ [J]	v_1 [km/h]	V_1 [km/h]	v_2 [km/h]	V_2 [km/h]	ΔV_1 [km/h]	ΔV_2 [km/h]
Lower Bound	345,252.4	134,540.20	210,712.2	50.4	17.2	49.1	2.9	67.6	46.2
Upper Bound	956,827.6	813,291.7	143,535.9	116.6	4.0	49.1	27.8	112.6	76.9

Table 8. Planar Impact Analysis Results, Chrysler Town & Country

	E_T [J]	$E_{C,1}$ [J]	$E_{C,2}$ [J]	v_1 [km/h]	V_1 [km/h]	v_2 [km/h]	V_2 [km/h]	ΔV_1 [km/h]	ΔV_2 [km/h]
Lower Bound	434,252.2	299,847.7	134,404.5	71.0	4.9	40.7	11.1	75.9	51.8
Upper Bound	697,591.8	263,161.6	434,430.2	71.0	25.2	70.6	4.9	96.2	65.7

unknown. The Planar Impact Mechanics spreadsheet in *VCRware* [10] is able to compute the postimpact velocities of both vehicles and the crush energy loss for a given set of preimpact speeds, collision geometry and vehicle parameters (mass, etc.). Using Equations 12 and 13, the kinetic energy loss for the Honda Civic, $E_{C,1}$, can be computed based on the energy loss of the system, E_T, and the energy loss of the Chrysler Town & Country, $E_{C,2}$.

$$E_{C,1} = E_T - E_{C,2} \tag{12}$$

$$E_{C,2} = \frac{1}{2} m_2 (V_2^2 - v_2^2) \tag{13}$$

In Equations 12 and 13, E_T is the energy loss of the system, $E_{C,i}$ is the energy loss in crush for vehicle i ($i = 1, 2$); speeds shown in lower case, v_1, are preimpact speeds (in this case for Vehicle 1), and speeds shown in upper case, V_2, are postimpact speeds (in this case for Vehicle 2). In this analysis, the Goal Seek utility in Microsoft Excel was used to find $v1$ that resulted in the lower and upper bounds of the energy loss (Table 10) for the Honda Civic. The results of this analysis produced two values for v_1 presented below in Table 7.

The second scenario considers what the range of postimpact speed for the Chrysler Town & Country is when the preimpact speed of the Honda Civic is known or calculated to be 71.0 km/h (44.1 mph). A similar analysis was performed to determine the value of v_2 that resulted in crush energy bounds in Table 10 for the Chrysler Town & Country. The results of the analysis produced two values for v_2 presented in Table 8.

These results show that, in a reasonable reconstruction application, the variations in the stiffness coefficients, d_0 and d_1, and the measurements of the residual crush, the C_i values, produce significant uncertainty range in the preimpact speed of one of the vehicles. In the first scenario, the range of preimpact speed for the Honda Civic is 66 km/h (41 mph). In the second scenario, the range of preimpact speed is 30 km/h (18½ mph). In some circumstances, reconstructed vehicle preimpact speed results with such wide ranges may not be useful. Note also that the range of uncertainty will increase if variation for restitution is included.

DISCUSSION

The results of this study show that for frontal colisions, on average, in each of the vehicle model runs examined, the variations in the crush stiffness coefficients will result in uncertainty in crush energy loss and speed change that are much greater than the uncertainty resulting from variations in the measurements of residual crush. Assuming that the vehicles examined in this study constitute an accurate representation of all vehicles subjected to the same NHTSA tests, these results show that the accuracy of the CRASH3 damage algorithm in computing crush energy loss is limited by the accuracy of the crush stiffness coefficients and not by the accuracy of the crush measurements. This is not to say that the accuracy of crush measurements is unimportant during an accident reconstruction, but that the level of uncertainty associated with the CRASH3 algorithm should not be reported to be equal to that of the crush measurements. Note that previous studies have found that the accuracy of crush measurements can be surprisingly high [32].

Variation in Crush Measurements

The main focus of the present study is to examine the variations in crush stiffness coefficients and how they compare to variations in crush measurements in order to better understand their effect on the uncertainty of the CRASH3 method. This comparison required choosing variations in crush measurements that represent those of hands-on measurements as closely as possible. Two studies

[14, 19] provide information regarding this variation. While the data reported by Randles [19] show that the standard deviation in several manual measurements of the same vehicles is approximately 1.5 cm (0.6 in), research by Smith and Noga [14] suggests a much higher standard deviation of approximately 3.8 cm (1.5 in). The former is used throughout the present study since a standard deviation of 3.8 cm (1.5 in) represents a 95% confidence range of ±15.2 cm (6.0 in). This range does not make physical sense when applied to some crush measurements from the NHTSA database [25] since the range is, in some cases, larger than the crush measurement itself.

It is also important to note that while the results produced in Table 3 demonstrate greater amounts of uncertainty in crush energy than those in Table 2, this study remains justified in holding the crush width constant throughout the analysis. All tests reports [25] used in this research are of frontal barrier impacts where the preimpact speeds are large enough such that the entire frontal width of the vehicle is damaged. As a result, w is not measured manually because it is known to be the undamaged width of the vehicle and it will not have any associated variation.

Continuing Crush Research

In their study published in 1982, Smith and Noga [14] note that the CRASH3 damage method would benefit in terms of its accuracy if vehicle specific impact tests were available to determine crush stiffness coefficients. At the time crush stiffness coefficients were only available for front, side, and rear impacts based largely on vehicle class. An investigation similar to that of this paper was performed based on a 10% variation in the coefficients A and B. The present study serves to assess the reasonableness of this variation and what effect vehicle specific crush stiffness coefficient data has on the method. Tables 9 and 10 present the statistical distributions of the crush stiffness coefficients, d_0 and d_1, for each vehicle model and the 95% confidence interval. These tables show that the actual variations in the crush stiffness coefficient can be as high as 60% of the mean value, much larger than the assumed 10% variation in [14].

Table 9. Variations in d_0 per Vehicle Model

	Mean [$N^{0.5}$]	σ [$N^{0.5}$]	(±2σ)%
Taurus	95.9	0.9	3.8
Accord	94.4	2.0	8.5
Tacoma	95.1	5.2	21.9
F-150	105.3	2.5	9.5
Astro	102.5	4.1	16.0
Town & Country	102.7	3.4	13.2

Table 10. Variations in d_1 per Vehicle Model

	Mean [$N^{0.5}$/cm]	σ [$N^{0.5}$/cm]	(±2σ)%
Taurus	9.1	1.4	61.5
Accord	8.2	1.0	48.8
Tacoma	8.5	1.3	61.2
F-150	6.7	0.6	35.8
Astro	7.9	0.7	35.4
Town & Country	8.4	1.3	61.9

Crush Energy and Event Data Recorders (EDR)

Without additional information (such as postimpact motion, preimpact motion, etc.) and an impact model that accounts for vehicle rotations (such as planar impact mechanics), the results of the CRASH3 damage-only method (ΔV_1, ΔV_2, and E_C) are insufficient to reconstruct the individual preimpact speeds of the two vehicles involved in some types of collisions [30]. Only the closing speed can be determined. Where one or both vehicles have an EDR that records the ΔV and the preimpact speed of one of the vehicles, the use of the CRASH3 damage method may not be necessary and the uncertainty associated with the calculation of the ΔV_S and crush energy is not an issue.

However, not all EDR's record the preimpact speed of the vehicle. If the preimpact speed of at least one of the vehicles is not known from an EDR (or cannot be otherwise estimated), planar impact mechanics alone cannot solve for the initial speeds of the vehicles involved, even if the ΔV_S are known. Under such circumstances, the energy loss due to vehicle crush (from both vehicles) would provide speeds that would satisfy the ΔV_S [30]. In this case, the computation of E_C would include the uncertainty due to variation of d_0 and d_1 as outlined in this paper.

REFERENCES

1. NHTSA, CRASH3 Technical Manual, US Department of Transportation, 1986. Available for download as a PDF file at: http://www-nass.nhtsa.dot.gov/NASS/MANUALS/Crash3Man.pdf

2. Campbell, K., "Energy Basis for Collision Severity," SAE Technical Paper 740565, 1974, doi:10.4271/740565.

3. Strother, C., Woolley, R., and James, M., "A Comparison Between NHTSA Crash Test Data and CRASH3 Frontal Stiffness Coefficients," SAE Technical Paper 900101, 1990, doi:10.4271/900101.

4. Prasad, A., "CRASH3 Damage Algorithm Reformulation for Front and Rear Collisions," SAE Technical Paper 900098, 1990, doi:10.4271/900098.

5. Neptune, J., Flynn, J., Underwood, H., and Chavez, P., "Impact Analysis Based Upon the CRASH3 Damage Algorithm," SAE Technical Paper 950358, 1995, doi: 10.4271/950358.

6. m-Crash, McHenry Software, Inc., Cary, NC. http://www.mchenrysoftware.com/mcrash.htm

7. EDCRASH, Engineering Dynamics Corporation, Beaverton, OR. http://www.edccorp.com/products/edcrash3.html

8. WinCRASH, AR Software by Trantech, Edmonds, WA. http://www.arsoftware.com/sw.htm

9. Crush, Rec-Tec, Rockledge, FL. http://www.rec-tec.com/Manual-PDF/RTCRS.pdf

10. *VCRware*, Brach Engineering, LLC, Granger, IN. http://www.brachengineering.com/about_vcrware.htm

11. Varat, M., Husher, S., and Kerkhoff, J., "An Analysis of Trends of Vehicle Frontal Impact Stiffness," SAE Technical Paper 940914, 1994, doi:10.4271/940914.

12. Woolley, R., "Non-Linear Damage Analysis in Accident Reconstruction," SAE Technical Paper 2001-01-0504, 2001, doi:10.4271/2001-01-0504.

13. Singh, J., "The Effect of Residual Damage Interpolation Mesh Fineness on Calculated Side Impact Stiffness Coefficients," SAE Technical Paper 2005-01-1205, 2005, doi:10.4271/2005-01-1205.

14. Smith, R. and Noga, J., "Accuracy and Sensitivity of CRASH," SAE Technical Paper 821169, 1982, doi: 10.4271/821169.

15. Woolley, R., Warner, C., and Tagg, M., "Inaccuracies in the CRASHS Program," SAE Technical Paper 850255, 1985, doi:10.4271/850255.

16. Strother, C., Woolley, R., James, M., and Warner, C., "Crush Energy in Accident Reconstruction," SAE Technical Paper 860371, 1986, doi:10.4271/860371.

17. Brach, R. and Brach, R., "Crush Energy and Planar Impact Mechanics for Accident Reconstruction," SAE Technical Paper 980025, 1998, doi:10.4271/980025.

18. Brach, R., Welsh, K., and Brach, R., "Residual Crush Energy Partitioning, Normal and Tangential Energy Losses," SAE Technical Paper 2007-01-0737, 2007, doi: 10.4271/2007-01-0737.

19. Randles, B., Jones, B., Welcher, J., Szabo, T. et al., "The Accuracy of Photogrammetry vs. Hands-on Measurement Techniques used in Accident Reconstruction," SAE Technical Paper 2010-01-0065, 2010, doi: 10.4271/2010-01-0065.

20. Fenton, S., Johnson, W., LaRocque, J., Rose, N. et al., "Using Digital Photogrammetry to Determine Vehicle Crush and Equivalent Barrier Speed (EBS)," SAE Technical Paper 1999-01-0439, 1999, doi:10.4271/1999-01-0439.

21. O'Shields, L., Kress, T., Hungerford, J., and Aikens, C., "Determination and Verification of Equivalent Barrier Speeds (EBS) Using PhotoModeler as a Measurement Tool," SAE Technical Paper 2004-01-1208, 2004, doi: 10.4271/2004-01-1208.

22. Tumbas, N. and Smith, R., "Measuring Protocol for Quantifying Vehicle Damage from an Energy Basis Point of View," SAE Technical Paper 880072, 1988, doi: 10.4271/880072.

23. Prasad, A., "Energy Absorbed by Vehicle Structures in Side-Impacts," SAE Technical Paper 910599, 1991, doi: 10.4271/910599.

24. Prasad, A., "Energy Absorbing Properties of Vehicle Structures and Their Use in Estimating Impact Severity in Automobile Collision," SAE Technical Paper 925209, 1992.

25. NHTSA Vehicle Crash Test Database: http://www.nhtsa.gov/Research/Databases+and+Software

26. Smith, R. A. and Noga, J. T. "Accuracy and Sensitivity of CRASH," Technical Report DOT-HS-806-152, January 1982.

27. RiskAMP Monte Carlo Simulation Engine, Structured Data LLC, www.riskamp.com.

28. Fleck, G. and Daily, J., "Sensitivity of Monte Carlo Modeling in Crash Reconstruction," *SAE Int. J. Passeng. Cars - Mech. Syst.* 3(1):100-112, 2010, doi: 10.4271/2010-01-0071.

29. Brach, R.M. and Brach, M., "Vehicle Accident Analysis and Reconstruction Methods, Second Edition," SAE International, Warrendale, PA, ISBN 978-0-7680-3437-0, 2011, doi:10.4271/R-397.

30. Brach, R., "The Use of EDR Data in Vehicle Accident Reconstructions", *Collision Magazine*, Volume 6, Issue 2, Fall 2011.

31. Brach, R., Welsh, K., and Brach, R., "Residual Crush Energy Partitioning, Normal and Tangential Energy Losses," SAE Technical Paper 2007-01-0737, 2007, doi: 10.4271/2007-01-0737.

32. Bartlett, W., Wright, W., Masory, O., Brach, R. et al., "Evaluating the Uncertainty in Various Measurement Tasks Common to Accident Reconstruction," SAE Technical Paper 2002-01-0546, 2002, doi:10.4271/2002-01-0546.

CONTACT INFORMATION

R. Matthew Brach
Brach Engineering, LLC
Granger, IN 46530-8501
matt_brach@brachengineering.com

APPENDIX

Graphs and Tables

Table A1. Ford Taurus NHTSA Frontal Barrier Impact Test Data

Test No.	Model Year	Test Mass [kg]	Impact Speed [km/h]	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	w [cm]
2312	1996	1764.0	56.5	35.1	40.5	41.0	42.8	41.0	37.4	185.0
2450	1996	1749.5	46.8	31.8	35.6	38.9	39.4	36.1	36.8	185.0
2671	1996	1714.0	48.9	25.5	38.0	40.2	40.2	37.1	27.5	185.0
2748	1998	1738.0	56.2	30.5	37.5	40.0	40.5	43.0	31.0	185.0
2832	1998	1737.6	47.2	17.4	27.9	28.7	30.0	31.4	23.4	185.0
2905	1998	1666.1	47.2	19.7	27.1	29.3	30.7	30.8	27.5	185.0
2913	1999	1731.4	56.3	50.5	49.4	51.4	50.2	48.0	48.3	185.0
3093	1999	1776.0	47.2	26.7	31.0	32.5	33.2	34.0	25.3	185.0
3102	1999	1765.8	47.5	29.0	40.8	40.4	37.8	33.0	26.5	185.0
Average		1738.0	50.4	29.6	36.4	38.0	38.3	37.2	31.5	185.0

Table A2. Honda Accord NHTSA Frontal Barrier Impact Test Data

Test No.	Model Year	Test Mass [kg]	Impact Speed [km/h]	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	w [cm]
4457	2003	1586.5	56.5	22.2	48.4	51.7	53.4	51.1	28.6	182.0
4485	2003	1571.0	55.8	27.5	35.5	45.2	40.3	32.4	30.7	182.0
4686	2003	1706.9	47.6	18.1	44.0	48.6	48.8	46.8	25.0	182.0
5104	2004	1673.0	39.8	20.1	26.2	27.2	27.2	25.7	18.2	182.0
5145	2004	1654.4	56.5	34.0	53.9	56.2	56.5	62.9	42.5	182.0
5526	2005	1757.6	56.5	33.3	50.5	56.4	57.4	50.4	28.6	182.0
Average		1658.2	52.1	25.9	43.1	47.6	47.3	44.9	28.9	182.0

Table A3. Toyota Tacoma NHTSA Frontal Barrier Impact Test Data

Test No.	Model Year	Test Mass [kg]	Impact Speed [km/h]	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	w [cm]
2296	1995	1447.0	56.6	44.4	45.2	45.8	45.1	44.6	42.3	169.0
2442	1996	1449.0	47.6	27.9	31.5	33.0	34.5	33.5	30.7	169.0
2542	1997	1575.0	56.3	36.5	40.8	41.5	40.5	41.2	37.6	169.0
2767	1998	1913.5	55.7	42.0	49.0	41.5	40.0	52.5	49.5	169.0
2992	1999	1814.4	56.3	45.2	48.0	49.5	49.5	48.0	39.9	169.0
3115	1999	1431.5	40.3	24.8	29.2	30.2	29.0	28.4	21.5	169.0
3119	1999	1432.4	48.2	33.2	39.6	39.6	40.0	40.4	34.6	169.0
3128	1999	1505.4	47.9	32.4	38.0	38.5	38.4	37.4	30.6	169.0
3146	1999	1517.3	40.3	24.0	30.0	32.5	32.3	30.3	25.1	169.0
Average		1565.1	49.9	34.5	39.0	39.1	38.8	39.6	34.6	169.0

Table A4. Ford F-150 NHTSA Frontal Barrier Impact Test Data

Test No.	Model Year	Test Mass [kg]	Impact Speed [km/h]	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	w [cm]
2437	1997	2136.0	47.2	40.9	41.9	48.0	49.8	41.1	34.0	192.0
2452	1997	2055.0	55.7	51.0	60.2	66.4	68.5	59.0	48.5	192.0
2747	1998	2072.0	56.2	60.0	64.5	70.5	72.5	62.5	52.5	192.0
3046	1999	2062.0	55.8	61.5	73.9	75.9	78.6	73.2	62.5	192.0
3494	2001	2270.5	56.2	56.7	64.6	70.5	67.9	62.3	48.4	192.0
3833	2001	2292.5	40.0	32.5	39.4	40.6	42.6	39.0	30.8	192.0
3902	2001	2292.1	47.9	45.0	53.2	60.0	60.0	52.5	40.0	192.0
4320	2001	2220.8	40.2	31.3	37.5	44.7	45.8	38.3	31.0	192.0
Average		2175.1	49.9	47.4	54.4	59.6	60.7	53.5	43.5	192.0

Table A5. Chevrolet Astro NHTSA Frontal Barrier Impact Test Data

Test No.	Model Year	Test Mass [kg]	Impact Speed [km/h]	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	w [cm]
800	1985	1855.0	56.0	44.5	49.8	55.9	55.9	51.1	45.7	196.0
1677	1992	2084.0	56.3	46.2	53.6	54.9	54.5	50.8	43.4	196.0
1692	1992	2188.0	47.5	39.8	44.5	46.0	46.5	42.9	37.6	196.0
1979	1993	2132.0	56.2	49.5	53.0	55.5	55.5	45.4	44.8	196.0
2046	1994	2359.0	47.2	45.5	49.0	49.8	48.8	46.5	40.6	196.0
2071	1994	2009.0	47.3	37.1	43.9	44.5	44.2	44.2	38.1	196.0
Average		2104.5	51.8	43.8	49.0	51.1	50.9	46.8	41.7	196.0

Table A6. Chrysler Town & Country NHTSA Frontal Barrier Impact Test Data

Test No.	Model Year	Test Mass [kg]	Impact Speed [km/h]	C_1 [cm]	C_2 [cm]	C_3 [cm]	C_4 [cm]	C_5 [cm]	C_6 [cm]	w [cm]
3659	2001	1950.0	55.6	31.5	39.6	41.3	42.6	44.6	36.9	200.0
4146	2001	2069.2	48.0	23.6	45.0	44.9	44.5	43.8	26.1	200.0
4936	2005	2229.0	56.5	45.5	58.1	60.2	57.8	54.7	48.8	200.0
5266	2005	2134.7	56.5	39.4	51.4	59.9	63.8	58.0	46.8	200.0
5713	2005	2353.9	56.4	34.4	48.4	48.3	40.0	29.7	23.3	200.0
5760	2005	2202.6	56.2	37.9	54.3	57.7	56.1	51.3	41.2	200.0
Average		2156.6	54.9	35.4	49.5	52.1	50.8	47.0	37.2	200.0

Table A7. Ford Taurus Frontal Crush Stiffness Coefficients

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
2312	96.60	9.63
2450	96.20	8.24
2671	95.30	7.45
2748	95.90	9.97
2832	95.90	11.04
2905	93.90	10.57
2913	95.70	6.77
3093	97.00	9.86
3102	96.70	8.66
Average	95.91	9.13
STDEV	0.92	1.44

Table A8. Honda Accord Frontal Crush Stiffness Coefficients

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
4457	92.40	8.07
4485	91.90	9.96
4686	95.80	7.35
5104	94.90	8.79
5145	94.30	7.08
5526	97.20	7.95
Average	94.42	8.20
STDEV	2.02	1.05

Table A9. Toyota Tacoma Frontal Crush Stiffness Coefficients

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
2296	91.60	6.98
2442	91.60	11.28
2542	95.50	9.47
2767	105.30	9.10
2992	102.50	7.29
3115	91.10	8.39
3119	91.10	7.73
3128	93.40	8.26
3146	93.80	8.08
Average	95.10	8.51
STDEV	5.24	1.31

Table A10. Ford F-150 Frontal Crush Stiffness Coefficients

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
2437	104.40	7.62
2452	102.40	6.66
2747	102.80	6.28
3046	102.60	5.58
3494	107.60	6.75
3833	108.10	7.13
3902	108.10	6.55
4320	106.40	6.95
Average	105.30	6.69
STDEV	2.53	0.60

Table A11. Chevrolet Astro Frontal Crush Stiffness Coefficients

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
800	96.30	7.44
1677	102.00	7.87
1692	104.60	7.70
1979	103.20	8.02
2046	108.60	7.29
2071	100.20	9.16
Average	102.48	7.91
STDEV	4.15	0.67

Table A12. Chrysler Town & Country Frontal Crush Stiffness Coefficients

Test No.	d_0 [$N^{0.5}$]	d_1 [$N^{0.5}$/cm]
3659	97.70	8.62
4146	100.50	8.04
4936	104.50	7.55
5266	102.20	7.44
5713	107.40	11.04
5760	103.80	7.99
Average	102.68	8.45
STDEV	3.37	1.34

Table A13. Restitution Coefficients for Select Tests

Test No.	Vehicle	Test Mass	Impact Speed [km/h]	ΔV [km/h]	e
2671	1996 Ford Taurus	1714.0	48.9	59.5	0.217
2913	1999 Ford Taurus	1731.4	56.3	66.5	0.181
5104	2004 Honda Accord	1673.0	39.8	44.6	0.121
2296	1995 Toyota Tacoma	1447.0	56.6	69.4	0.226
2992	1999 Toyota Tacoma	1814.4	56.3	62.1	0.104
3659	2001 Dodge Caravan	1950.0	55.6	63.3	0.138
5266	2005 Chrysler T & C	2134.7	56.5	66.1	0.170

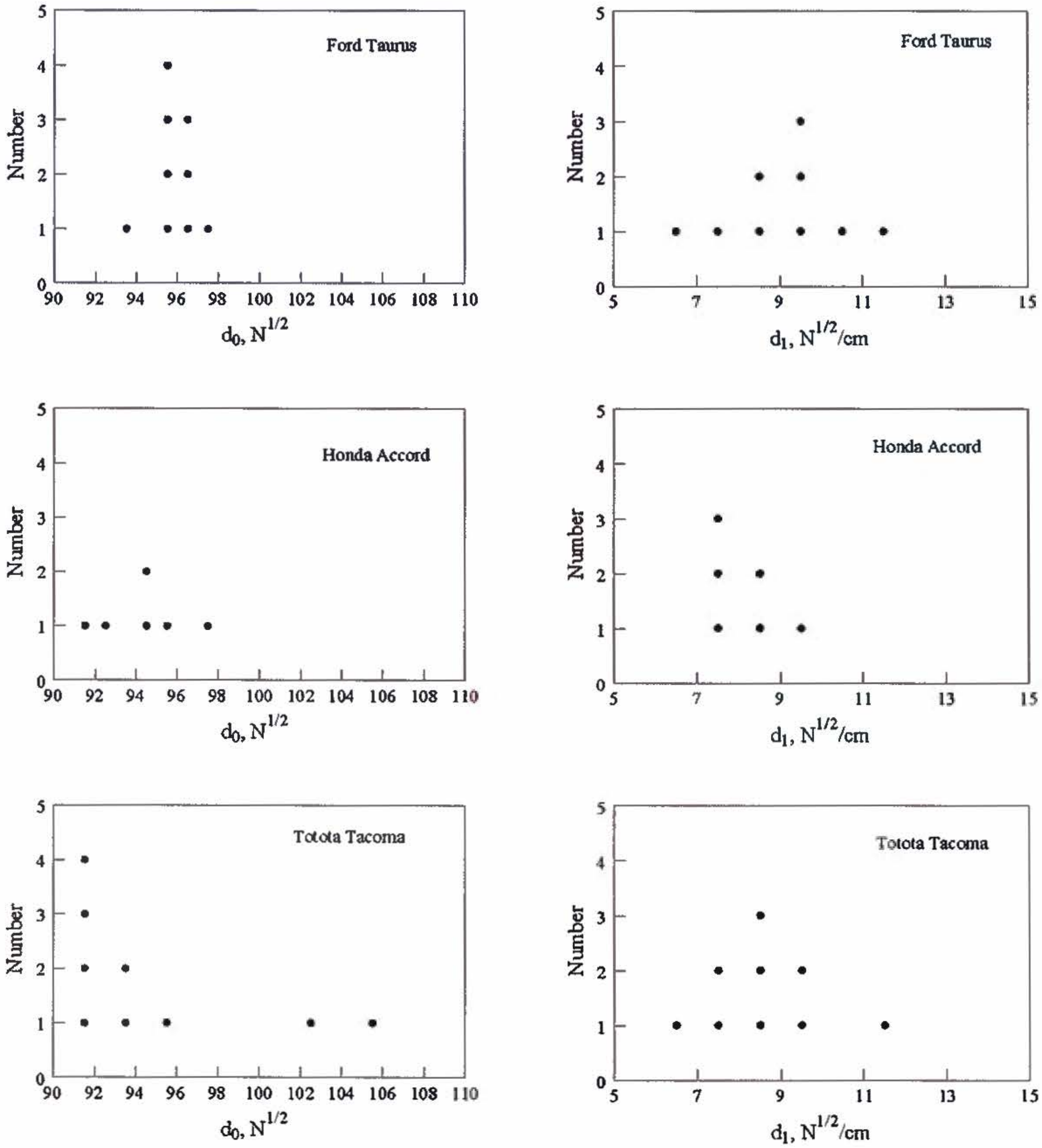


Figure A1. Distributions of Values of d_0 and d_1 of Ford Taurus, Honda Accord and Toyota Tacoma in the Form of Dot Plots.

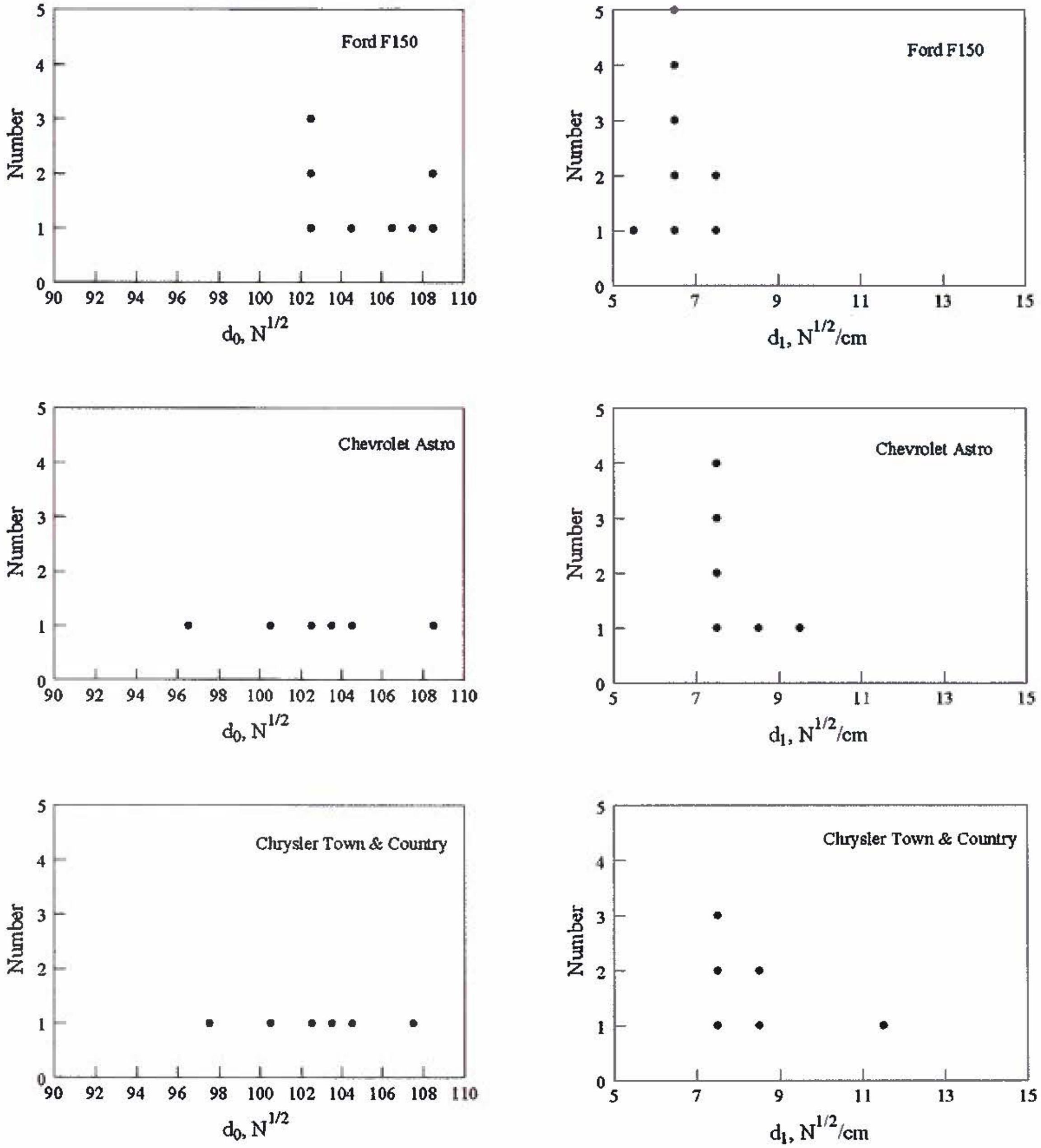


Figure A2. Distributions of Values of d_0 and d_1 of Ford F 150, Chevrolet Astro and Chrysler Town and Country in the Form of Dot Plots.

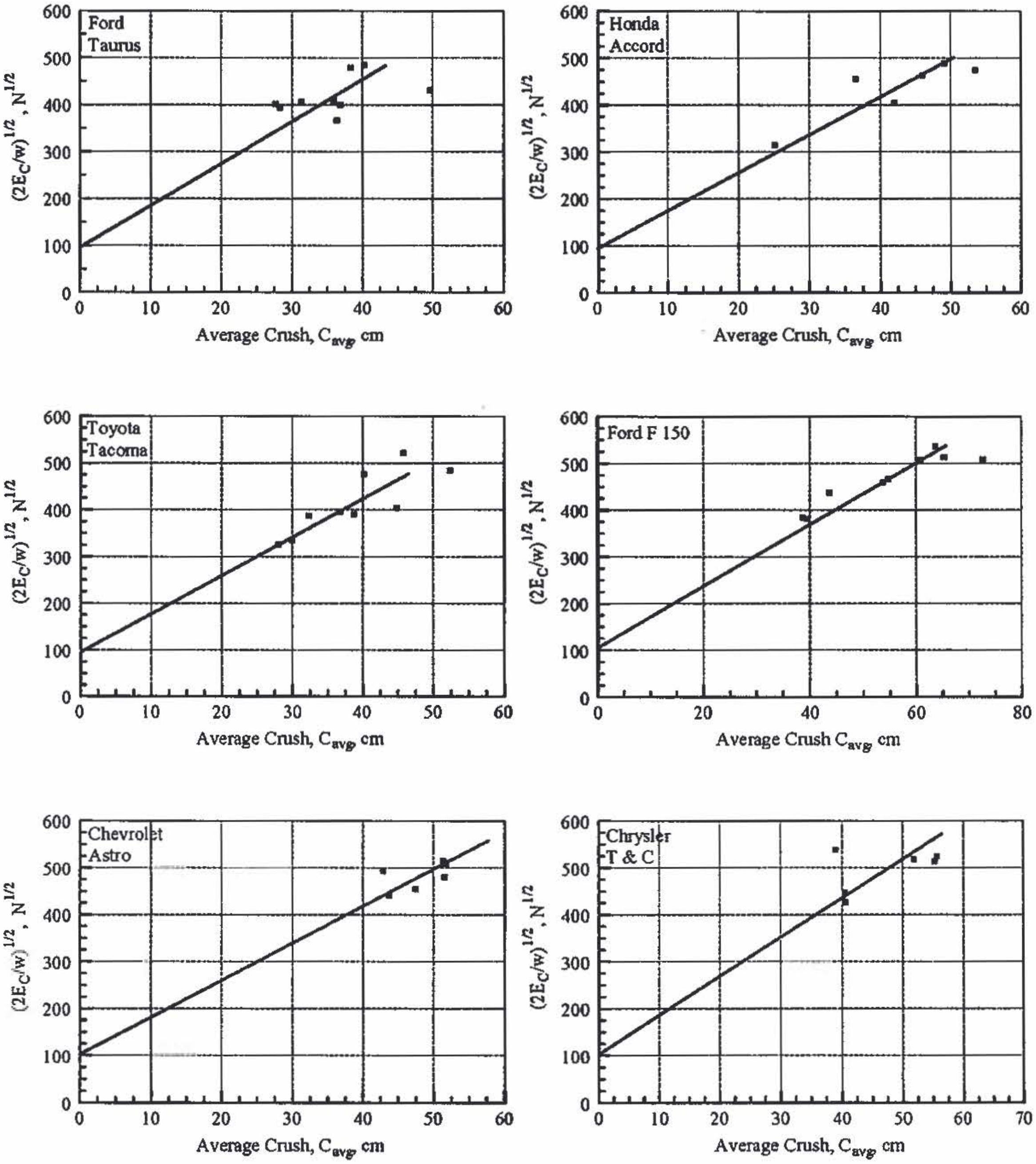


Figure A3. Plot of $(2E_C/w)^{1/2}$ versus Average Crush for each Vehicle Model

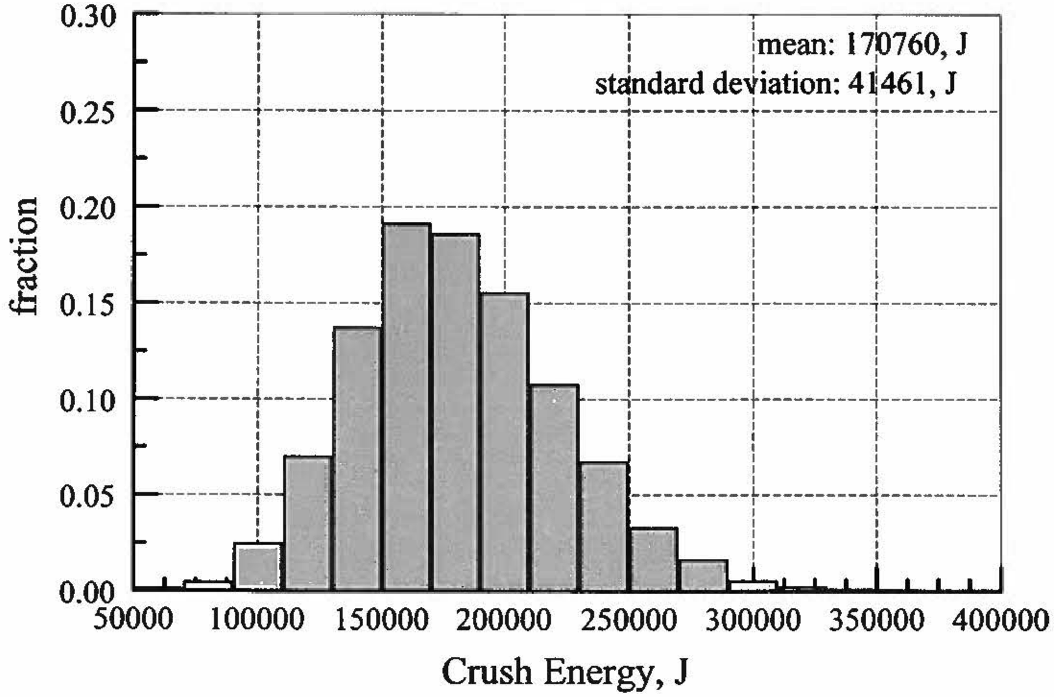


Figure A4. Crush Energy Loss Distribution, Varying d_0 and d_1, Ford Taurus

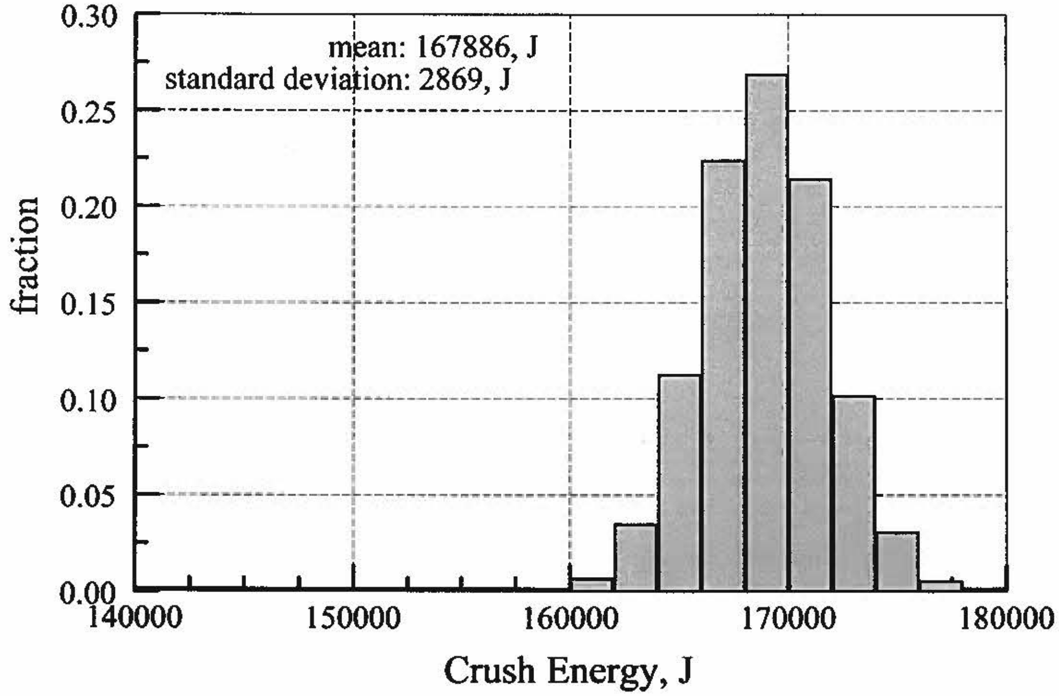


Figure A5. Crush Energy Loss Distribution, Varying $C_{1\text{-}6}$, Ford Taurus

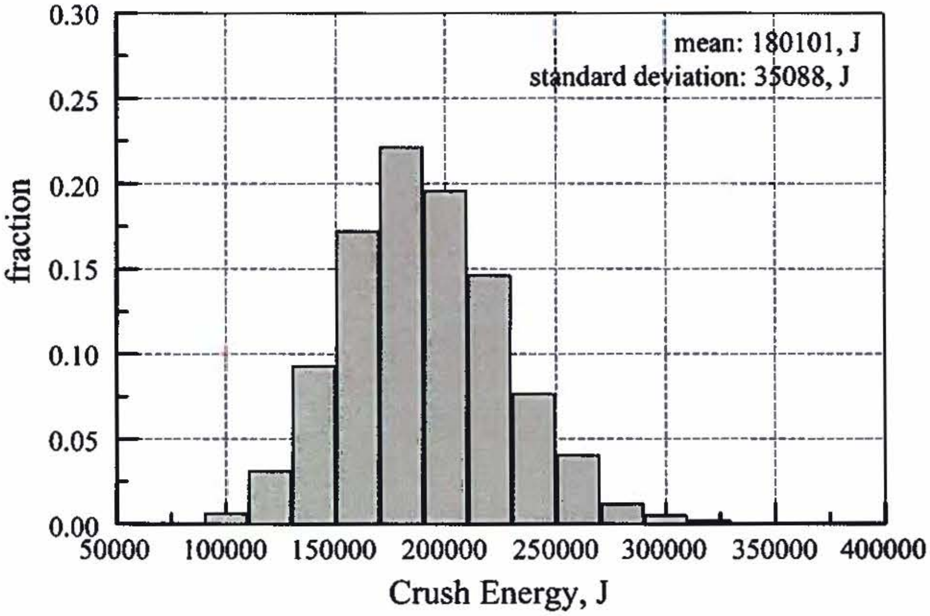


Figure A6. Crush Energy Loss Distribution, Varying d_0 and d_1, Honda Accord

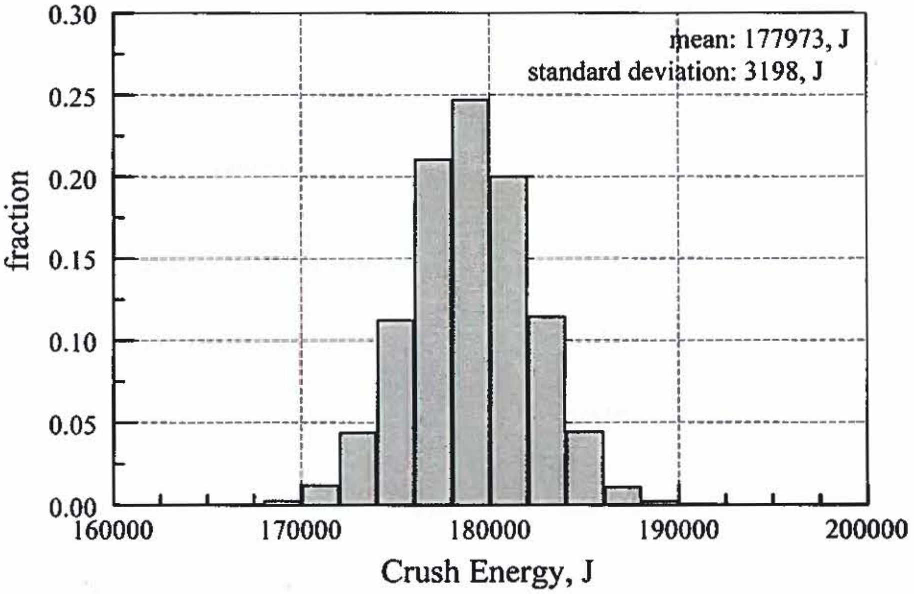


Figure A7. Crush Energy Loss Distribution, Varying C_{1-6}, Honda Accord

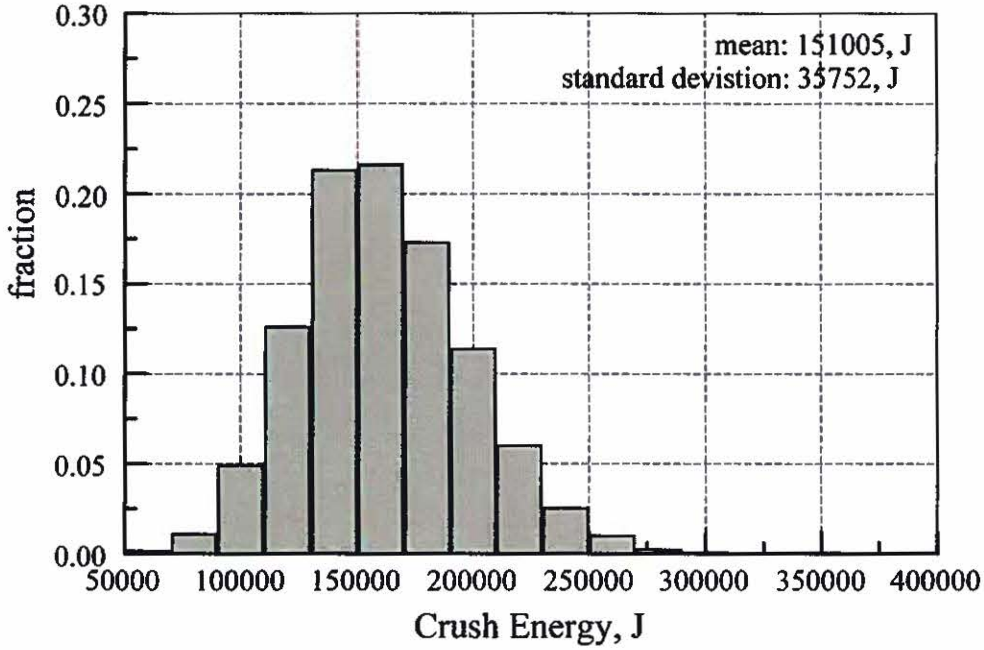


Figure A8. Crush Energy Loss Distribution, Varying d_0 and d_1, Toyota Tacoma

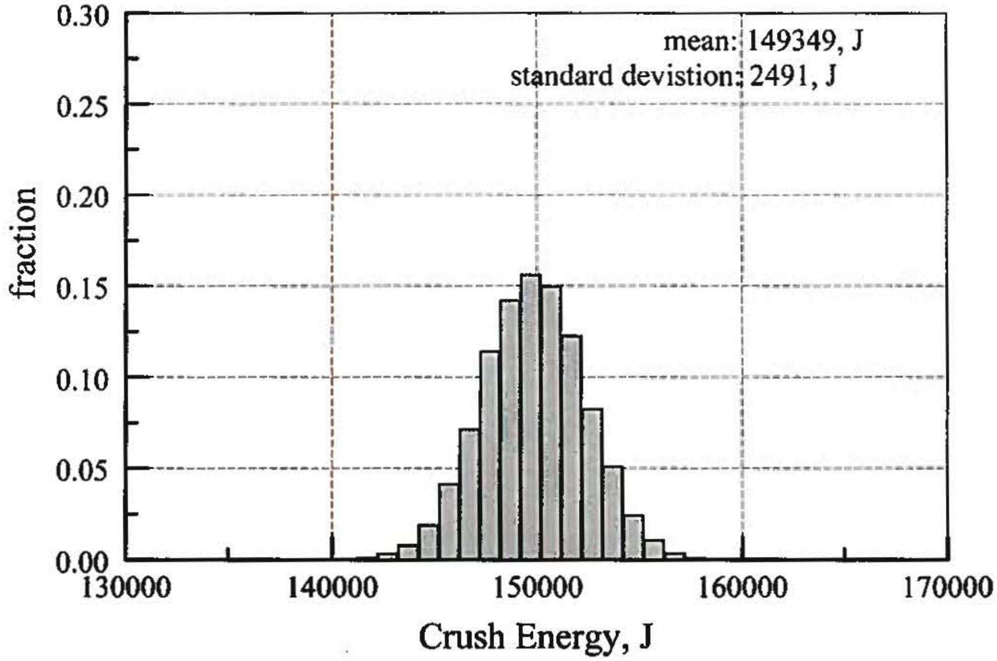


Figure A9. Crush Energy Loss Distribution, Varying C_{1-6}, Toyota Tacoma

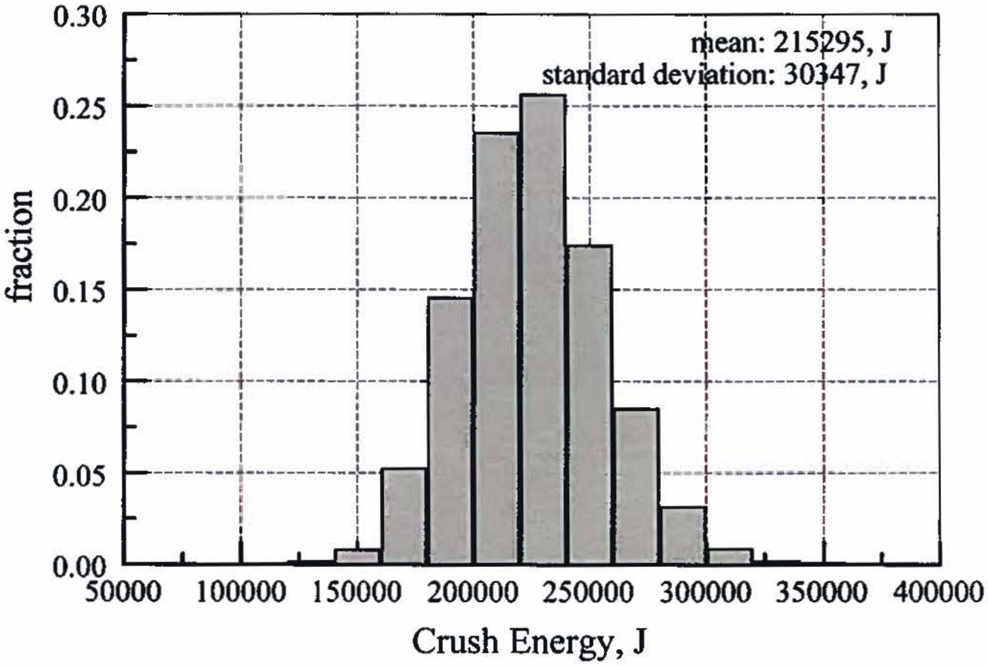


Figure A10. Crush Energy Loss Distribution, Varying d_0 and d_1, Ford F-150

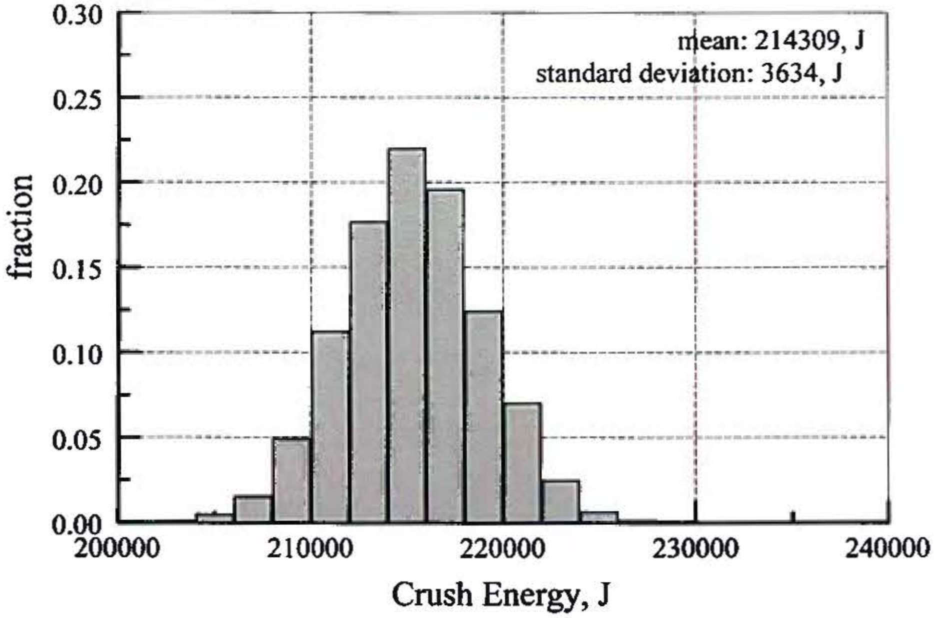


Figure A11. Crush Energy Loss Distribution, Varying C_{1-6}, Ford F-150

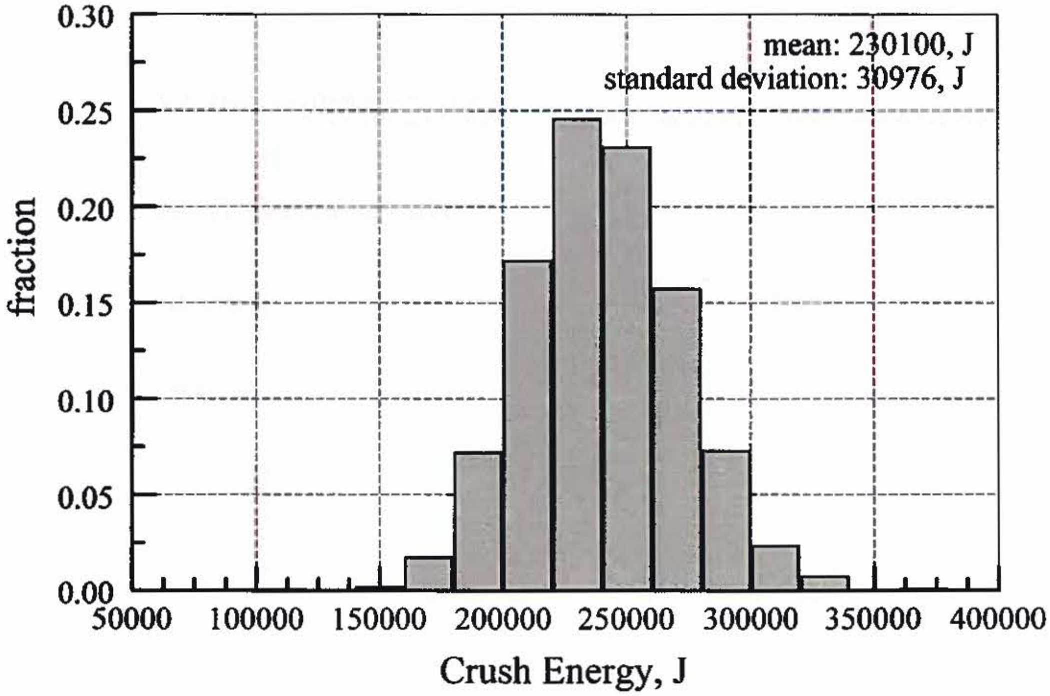


Figure A12. Crush Energy Loss Distribution, Varying d_0 and d_1, Chevrolet Astro

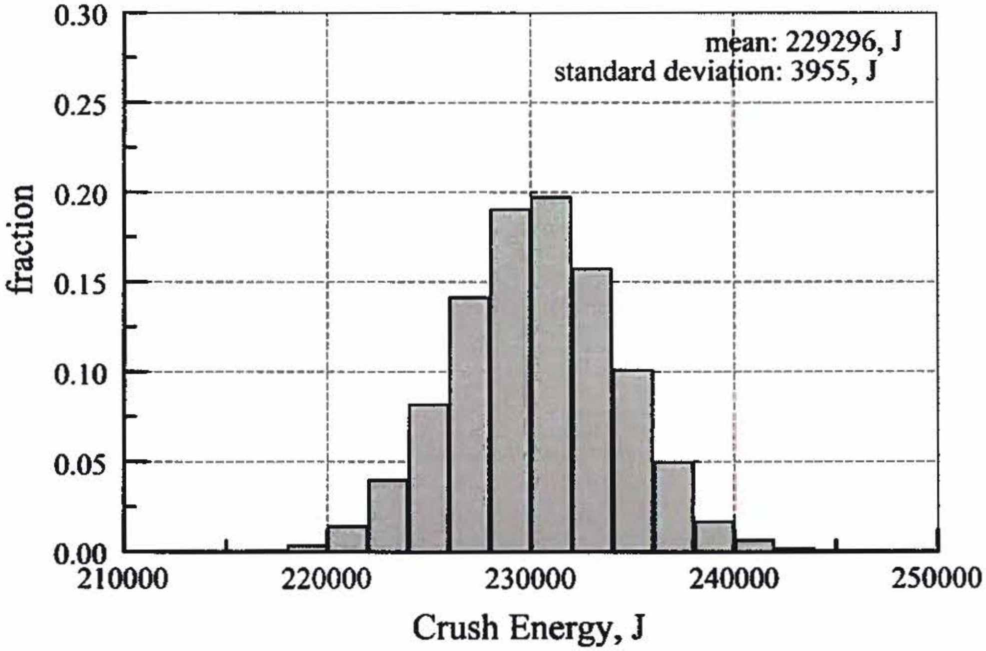


Figure A13. Crush Energy Loss Distribution, Varying C_{1-6}, Chevrolet Astro

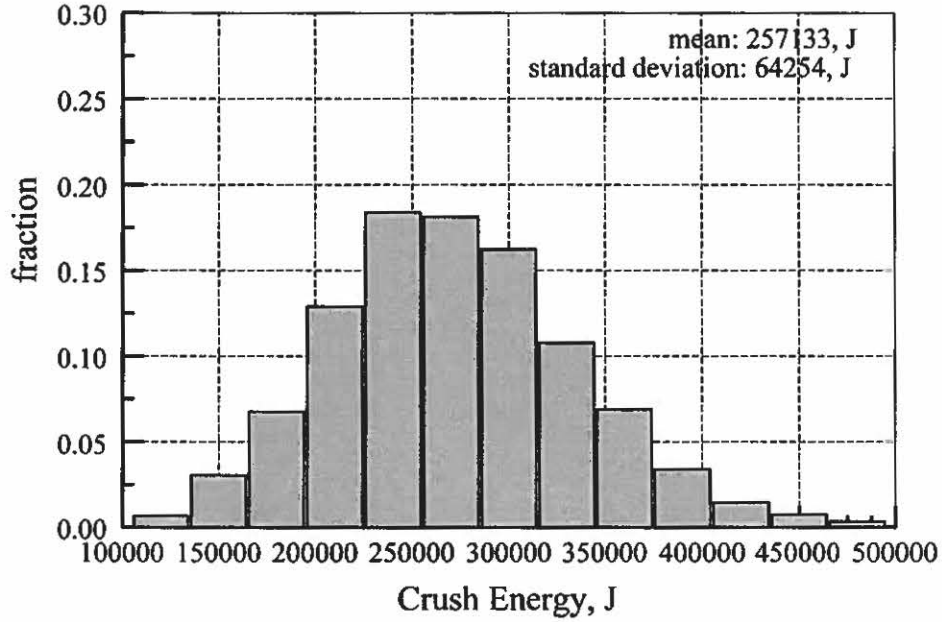


Figure A14. Crush Energy Loss Distribution, Varying d_0 and d_1, Chrysler Town & Country

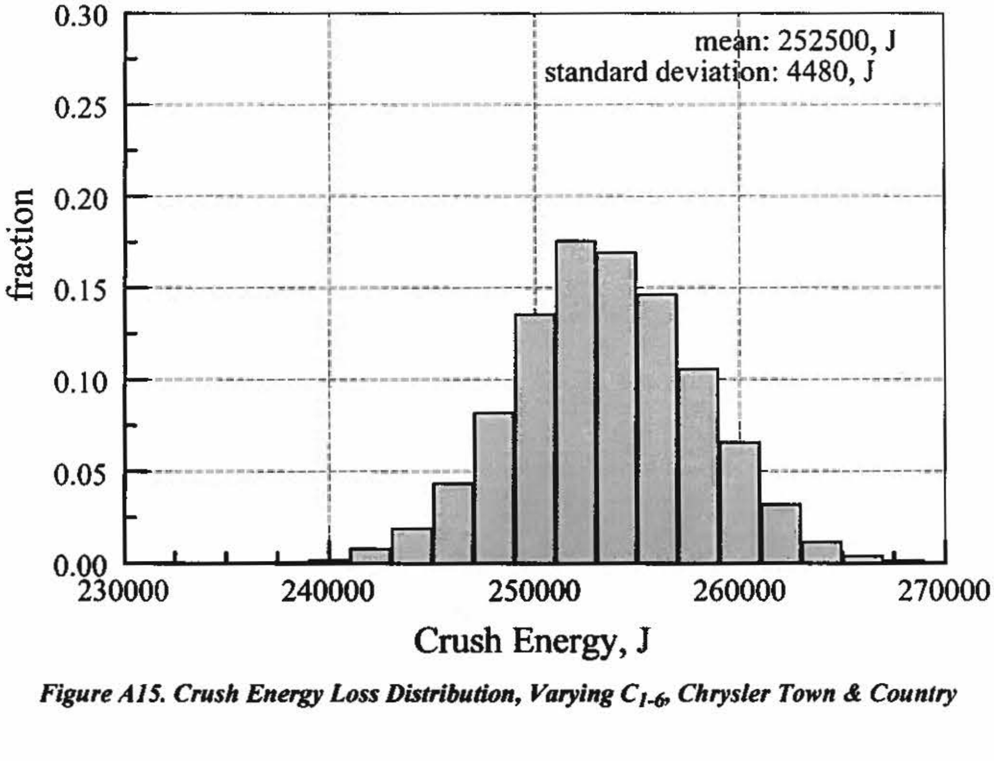
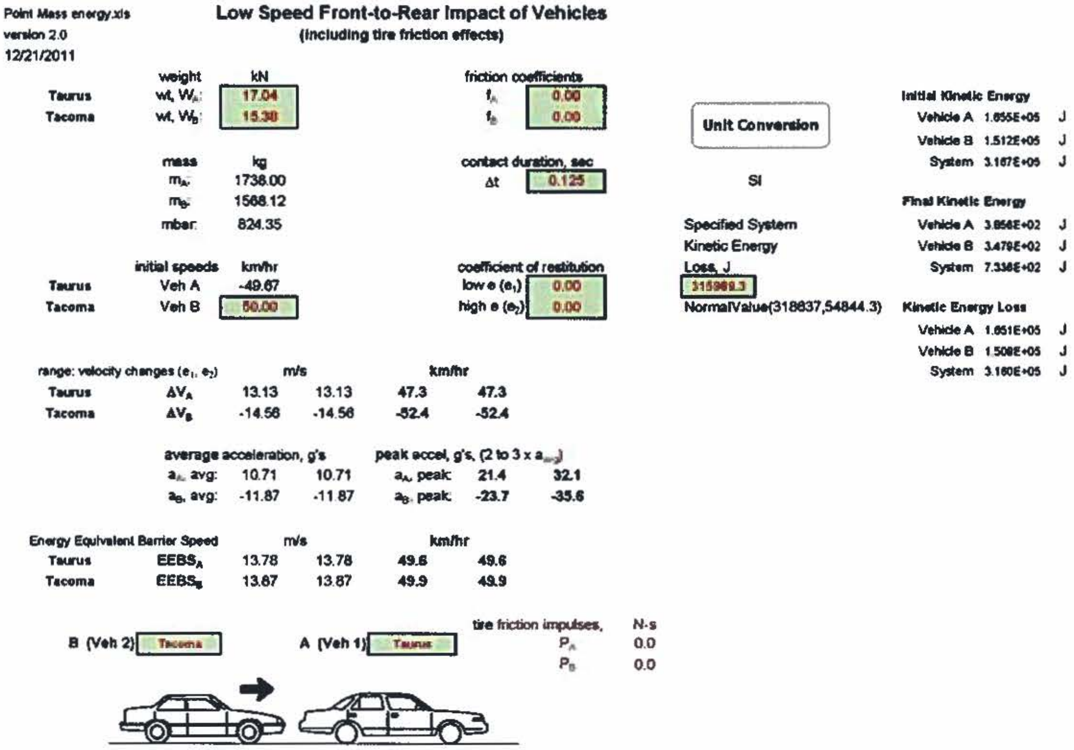


Figure A15. Crush Energy Loss Distribution, Varying C_{1-6}, Chrysler Town & Country



Point Mass energy.xls
version 2.0
12/21/2011

Low Speed Front-to-Rear Impact of Vehicles
(including tire friction effects)

	weight	kN
Taurus	wt, W_A:	17.04
Tacoma	wt, W_B:	15.38

friction coefficients	
f_A	0.00
f_B	0.00

mass	kg
m_A:	1738.00
m_B:	1568.12
mbar:	824.35

contact duration, sec
Δt 0.125

	initial speeds	km/hr
Taurus	Veh A	-49.67
Tacoma	Veh B	50.00

coefficient of restitution	
low e (e_1)	0.00
high e (e_2)	0.00

Unit Conversion

SI

Specified System
Kinetic Energy
Loss, J
315969.3
NormalValue(318837,54844.3)

Initial Kinetic Energy		
Vehicle A	1.655E+05	J
Vehicle B	1.512E+05	J
System	3.167E+05	J

Final Kinetic Energy		
Vehicle A	3.856E+02	J
Vehicle B	3.479E+02	J
System	7.336E+02	J

Kinetic Energy Loss		
Vehicle A	1.651E+05	J
Vehicle B	1.508E+05	J
System	3.160E+05	J

range: velocity changes (e_1, e_2)		m/s		km/hr	
Taurus	ΔV_A	13.13	13.13	47.3	47.3
Tacoma	ΔV_B	-14.56	-14.56	-52.4	-52.4

average acceleration, g's			peak accel, g's, (2 to 3 x a_{avg})		
a_A, avg:	10.71	10.71	a_A, peak:	21.4	32.1
a_B, avg:	-11.87	-11.87	a_B, peak:	-23.7	-35.6

Energy Equivalent Barrier Speed		m/s		km/hr	
Taurus	$EEBS_A$	13.78	13.78	49.6	49.6
Tacoma	$EEBS_B$	13.87	13.87	49.9	49.9

tire friction impulses,	N·s
P_A	0.0
P_B	0.0

B (Veh 2) Tacoma
A (Veh 1) Taurus

Figure A16. Planar Impact Mechanics Vehicle Inputs

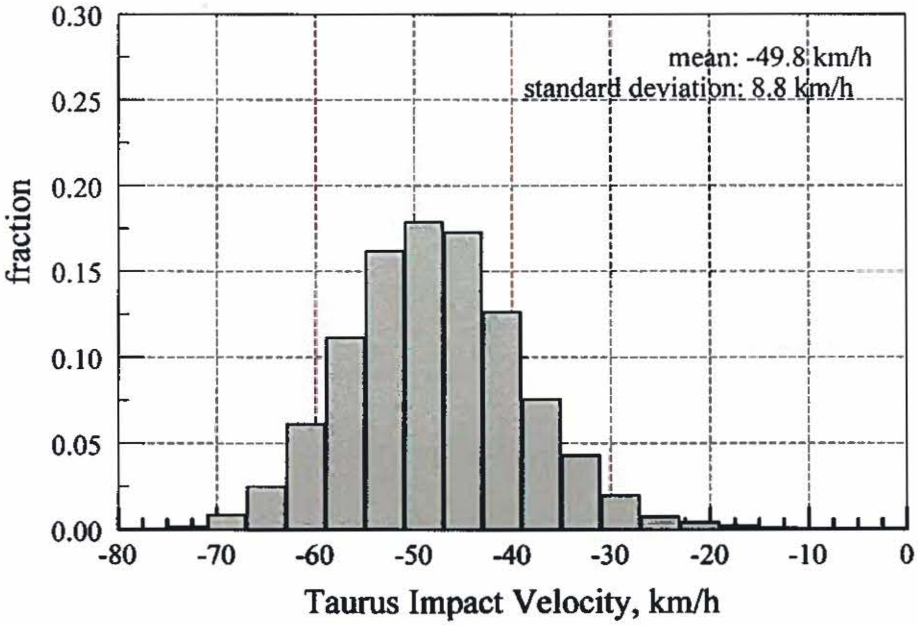


Figure A17. Impact Velocity Distribution of Ford Taurus Varying d_0 and d_1, (Toyota Tacoma - Taurus Collision)

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

SAE Customer Service:
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org
Printed in USA

SAE International