A Comparison of Equations for Estimating Speed Based on Maximum Static Deformation for Frontal Narrow-Object Impacts

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INTRODUCTION

Passenger vehicle frontal impacts with narrow fixed objects such as utility poles and trees are a common event. Such impacts represent a large segment of fixed-object crashes that are routinely investigated by accident reconstructionists.

Narrow object crash testing is occasionally conducted in a laboratory setting. The data from many, if not most, of these tests are not within the public domain and therefore, are not available to most crash reconstructionists. Additionally, an overwhelming percentage of these crashes employ the use of rigid pole barriers. In these pole impact crash tests, the assumption is often made that the vehicle absorbs all the crash energy during impact. This type of testing may be appropriate when the aim of such testing is the evaluation of vehicle crashworthiness; however, as is often the case, poles, and to a lesser extent, trees struck in the real world often fracture and/or move. Such fracture and movement is an indication that poles and trees absorb some amount of the crash energy. This form of energy absorption should be considered in the analysis of these crashes. Additionally, and to the extent possible, any post-impact energy possessed by the vehicle should also be considered.

Several equations for estimating vehicle speeds in frontal impacts with narrow objects such as utility poles, which are based upon maximum residual frontal crush, have been presented in the literature (1). This paper compares these methods as well as a relatively newer method known as the Vomhof method. Eight full-scale crash tests were conducted at known speeds. Maximum static crush was measured as required by each of the equations. Computations were performed and the results were then compared to the known impact speed.

The equations were also applied to a narrow object real-world crash, which involved a model year 2006 vehicle, in which the data from the vehicle's Event Data Recorder (EDR) was obtained. The results of this crash were consistent with the results from the crash tests that involved older vehicles.

DISCUSSION

CRASH TESTING

The crash testing utilized in this study occurred on four separate occasions at four different locations. The first crash test was a 1979 Dodge 100 pickup truck that was crashed into a pole at 38.2 mi/hr by the Southwestern Association of Technical Accident Investigators on July 14, 2000. The maximum crush depth in this test was 35.8 inches. This test was reported in the Accident Reconstruction Journal, issue number 60.

The second was a low-speed crash at 16.7 mi/hr into a wooden utility pole that was conducted as part of a conference hosted by the Illinois Association of Technical Accident Investigators (IATAI) in 2002 in Rockford, Illinois. The vehicle used in the IATAI test was a 1995 Ford Contour and was driven into the pole. The deepest static crush sustained by the vehicle measured 14 inches. The pole did not fracture, but was displaced rearward approximately 4 inches.

The third series of crash tests were performed in 2003 in Atlantic City, New Jersey as part of the annual Joint Conference undertaken by the New Jersey Association of Accident Reconstructionists (NJAAR), the New York Statewide Traffic Accident Reconstruction Society (NYSTARS), the National Association of Traffic Accident Reconstructionists and Investigators (NATARI), the Maryland Association of Traffic Accident Investigators (MATAI), and the National Association of Professional Accident Reconstruction Specialists (NAPARS). In these tests, vehicles were delivered to wooden utility poles by a pulley system. The vehicles employed were a 1978 Oldsmobile Cutlass, a 1986 Chevrolet Celebrity, and a 1989 Ford Escort. The vehicles sustained 25.2, 21.6, and 16.8 inches of crush, respectively. The impact speeds for the test vehicles were 28.0, 30.5 and 29.0 mi/hr respectively. In the tests that involved the Oldsmobile and the Ford, the utility pole fractured completely. In the Chevrolet test the pole did not fracture, but was displaced approximately 6 inches.

The fourth series of crash tests were performed as part of the University of North Florida's (IPTM) 2007 Special Problems that was held in Jacksonville, Florida. The vehicles employed were a 1996 Mercury Sable, a 1999 Mercury Sable and a 1998 Ford Taurus. The test speed for the 1996 Sable was 46 to 47 mi/hr and the maximum deformation was 20.4 inches. The test speed for the 1999 Sable was 43 to 44 mi/hr and the maximum deformation was 14.4 inches. The test speed for the 1998 Taurus was 48 to 49 mi/hr and the maximum deformation was 15.6 inches. The poles were completely fractured and the bases were displaced in all three tests.

THE EQUATIONS

Eight equations were examined. A brief description of each is presented. A common element shared by many of the equations is that they essentially follow the Campbell form of the Speed Vs. Residual Crush curve.

NTSB

This method was introduced in a 1981 National Transportation Safety Board (NTSB) report that addressed impacts with trees (2). It is not known to what extent, if any, the NTSB still employs this method. The equation is as follows:

$$V = BP_0 + BP_1(CRM) \quad \text{Eq. 1}$$

Where V = EBS in mi/hr; BP_0 = speed at which no crush is expected; BP_1 = slope of speed versus crush (change in impact speed to change in crush.); CRM = Maximum Crush (in).

A published table provided values for BP_0 and BP_1. The variables are based on the weight of the vehicle.

NTSB Values for BP_0 & BP_1		
Vehicle Wgt. (lbs)	BP_0 (mph)	BP_1 (mph/in)
1950-2450	3.04	.641
2451-2950	2.46	.648
2951-3450	4.04	.600
3451-3950	4.84	.516
3951-4450	4.33	.467

MORGAN AND IVEY

This equation, named for its authors, was presented in an SAE paper in 1987 (3). The equation is:

$$V = D\sqrt{(395 - .062W)(1 + \Delta E)} \quad \text{Eq. 2}$$

Where V = EBS in ft/sec; D = maximum crush in ft.; W = vehicle weight in lbs. ; ΔE = the increase or decrease in energy absorbed in crushing the vehicle due to impacting the pole, relative to that absorbed in an impact with a class 4-40 pole. Use ΔE of +.25 for class 3; 0 for class 4; and -.25 for class 5 poles. The .25 for a class 3 pole means that 25% more energy is required in an impact with a class 3 compared to a class 4 pole. The class of the pole is generally determined by the circumference of the pole measured at a standard height of 6 feet from the base or butt. Sometimes the circumference at the top of the pole is used to determine the class designation. The circumference for the same class of pole can vary somewhat from one species of wood to another. Irrespective of the species, wooden utility poles of a given class and length are designed to have approximately the same load-carrying capabilities (4). The class of pole may be determined by looking for the manufacturer's brand, which is usually found approximately 4 to 5 feet above ground level. For example, the brand "4-40" means that the utility pole is a class 4 pole that is 40-feet long (overall).

The model from which the equation was developed considers that the vehicle's impact velocity is weight dependant. The equation allows for an adjustment based on the classification of the pole. An inherent assumption of this method is that all the change in the kinetic energy of the vehicle is absorbed in crushing the vehicle. Energy absorbed by the earth during impact or the pole prior to fracture is neglected. The authors caution on the use of this method in cases where the pole approaches fracture.

Morgan and Ivey conducted a computerized study wherein the change in velocity of vehicles weighing between 1500 and 5000 pounds traveling between 20 to 60 mi/hr were examined. They proffer that a vehicle within the weight range mentioned above that strikes a class 4-40 wooden utility pole at less than 30 mi/hr will be stopped at impact. They presented graphs that depict failure boundaries related to vehicle change in velocity. The graphs were derived from a single 60 mi/hr crash test.

NYSTROM AND KOST

Nystrom and Kost published their equation in a 1992 SAE paper (5). Using 19 staged frontal pole barrier crash tests, they evaluated methods for relating pre-impact speed to residual crush.

The diameter of the poles used in the tests ranged from 8 to 12 inches and collision offset distance from bumper center to contact center varied from 0 to 14 inches. The Nystrom and Kost equation is expressed as follows:

$$V = 5 + [\,.964 - (.0000351W)]\,(CRM) \quad \text{Eq. 3}$$

Where V = EBS in mi/hr; CRM = maximum crush (in) and W is the vehicle weight in lbs. The constant of 5 is equivalent to BP_0 (speed below which no crush is observed). The expression contained within the brackets is a representation of BP_1, which is the slope of the speed versus the crush relation in units of mi/hr/inch.

The Nystrom and Kost paper indicates that the nineteen tests they used to develop their formula involved rigid pole barriers. This implies that the pole barriers did not fracture or move. Typically, such barriers are constructed of steel.

THE CRAIG EQUATIONS

Victor Craig, the editor of the Accident Reconstruction Journal, has written extensively on the topic of narrow object impacts (1,6,7,8). The following equations are attributed to him largely due to the work he has done in this area and which he reported as early as 1993. Craig examined the previously mentioned equations and compared their results to a generalization which suggests that the depth of maximum static crush is approximately equivalent to the impact speed of the vehicle. The initial equation is:

$S = C_{max}$ Eq. 4

Where C_{max} = maximum crush measured in inches and S is the vehicle's EBS in mi/hr.

A benefit to the generalized rule of thumb equation is that it is easy to use in the field, giving the crash investigator a preliminary indication of the vehicle's EBS.

Craig used a linear regression approach to modify and further refine the accuracy of the rule of thumb equation. The equations consider the maximum depth of crush and the vehicle size. Craig examined 49 frontal pole barrier crash tests in the development of the following equations.

Small FWD where $C_{max} \leq 1$ ft.

$EBS = .47C_{max} + 4.0$ Eq. 5

Small FWD where $C_{max} > 1$ ft.

$EBS = 1.30C_{max} - 6.0$ Eq. 6

Mid and Full FWD & RWD where $C_{max} \leq 1.5$ ft.

$EBS = .54C_{max} + 4.0$ Eq. 7

Mid and Full FWD & RWD where $C_{max} > 1.5$ ft.

$EBS = 1.18C_{max} - 7.0$ Eq. 8

Average Standard Pickup

$EBS = .84C_{max} + 4.0$ Eq. 9

As in Equation 4, C_{max} in Equations 5 through 9 are measured in inches. Craig defines small cars as having a total length of less than 15 feet or weighing under 3000 pounds (8).

Craig points out that in cases where the pole fractures and/or the vehicle spins off following the impact, these equations may render impact speeds that are substantially less than the true impact speed.

The crash tests used by Craig and those who preceded his work employed automobiles whose model years ranged from the early 1980s to the early 1990s. Craig looked at NHTSA full barrier crash tests involving some mid 1990s model year vehicles and noticed that at similar speeds the later model vehicles typically crushed less. This suggests that the late model vehicles had stiffer frontal characteristics. In this regard, the Craig equations can be said to render conservative results.

THE VOMHOF CF METHOD

The Vomhof CF method has been discussed as early as 1991 and was first published in 1992 as part of the Expert Autostats® database. Two papers on the subject were formally presented in 1998 (9,10). The equation, in its general form, is very familiar to automobile crash investigators and reconstructionists as the minimum speed equation. The major difference is that instead of the *f* variable representing the drag factor in the classic sense, the Vomhof version employs a "crush factor" that is represented by the variable CF. In the equation, CF is analogous to the drag factor. The equation appears as follows:

$$V = \sqrt{30dCF} \quad \text{Eq. 10}$$

Where V (mi/hr) is the Kinetic Energy Equivalent Speed (The authors of the Vomhof CF Method identify the speed calculated through this method as a Kinetic Energy Equivalent Speed. This is more commonly referred to as an Equivalent Barrier Speed (EBS), and for consistency with the other formulas, that is how we will identify it); d = depth of crush in feet; and CF is the crush factor, which Vomhof indicates is a value of 21 for frontal impacts. Vomhof reports that the CF equation was derived and validated from examining over 1000 accidents. It is understood that less than ten of the real-world accidents examined involved utility poles. Some of the NHTSA crash tests that Vomhof examined in refining the CF process involved rigid pole barrier impacts, however, the population of the tests overwhelmingly involved full barrier impacts. The beginning premise for the development of the CF equation appears to come from the early work of Baker (11). In his work, Baker included a table that listed values of acceleration and deceleration, which indicates a drag factor for a crash into a solid fixed object at -20.0 g. Vomhof sought to re-evaluate this quantity.

The CF factor was derived from examining mostly flat, rigid barrier crash tests. Impact speed and maximum crush was taken from the crash test data and were utilized in a manipulated version of the work-energy relationship to develop what is essentially an acceleration factor. The formula takes the slightly modified form as follows.

$$CF = \frac{V^2}{30d} \quad \text{Eq. 11}$$

Where V is the crash test approach speed in mi/hr and d is the depth of the maximum crush in feet.

Vomhof has suggested using 60% of the CF as a rule of thumb method to correct for narrow-object impacts, which he developed from empirical results from limited testing. The method is expressed in equation form as follows:

$$V = \sqrt{(30)CF(.60)d} \qquad \text{Eq. 12}$$

Since the CF value is generically represented as 21 for all vehicle fronts, the equation can be simplified further to the following:

$$V = 19.4\sqrt{d} \qquad \text{Eq. 13}$$

The variable d in the equation represents the crush depth in feet.

WOOD

In 1993, Wood et al. published a set of equations to estimate the EBS and closing speed for a vehicle involved in a collision with a narrow object. Citing Thornton in (12), Wood wrote that the specific energy absorption (SEA) per unit mass is proportional to the normalized crush distance in addition to material and geometric factors. Regarding cars as having uniform density shows for constant crushing force, F, and mass, M_k, that the SEA is (13),

$$SEA = \frac{E}{M_k} = \frac{FL}{M_k}\left(\frac{1}{1-\frac{d}{L}}\right) \qquad \text{Eq. 14}$$

Where d is the maximum crush depth, L is the overall length of the car and d/L is the normalized crush depth. (Note that equation 14 is not a function of maximum crush depth and it would not be used in a reconstruction based on maximum static deformation.) The analysis is based on the deceleration of a constant mass. Wood showed that equation 14 progressively diverges from the constant mass representation for moderate- and high-speed collisions. The divergence was typically 5% at 50 km/hr (31 m/hr) and increased to 25% at 100 km/hr (62 m/hr). To account for this divergence, Wood used a two-stage crush model to represent the car population. Let

$$\alpha = \frac{\overline{d}}{d_{\max}} \ln\left(\frac{1}{1-\frac{d_{\max}}{L}}\right). \qquad \text{Eq 15}$$

Equation 15 is used to determine which of equations 16 or 17 should be used to calculate the SEA. Equation 16 is used for alpha <0.05 and equation 17 is used for alpha > 0.05.

$$SEA_1\left(J/kg\right) = 537\left(\alpha + 0.0072\right) \qquad \text{Eq. 16}$$

$$SEA_2\left(J/kg\right) = 1191\left(\alpha - 0.0235\right) \qquad \text{Eq. 17}$$

In equation 15, $d_{\max}$ is the maximum crush depth and $\overline{d}$ is the mean crush depth, which Wood calculates with equations 18 and 19 [refer to Figure 1 (Idealized crush mechanism—from Wood, SAE 930894)]. The units for $d_{\max}$ and $\overline{d}$ may be any unit appropriate for distance, (eg. feet, meters, inches, millimeters).

$$\overline{d} = \frac{1}{W}\sum_{j=1}^{n} d_j W_j \qquad \text{Eq. 18}$$

$$W = \sum_{j=1}^{n} W_j \qquad \text{Eq. 19}[1]$$

In the case where six equally spaced crush measurements are taken, equations 18 and 19 reduce to equation 18a for calculating the mean crush depth.

$$\overline{d} = \frac{1}{10}\left(C_1 + 2C_2 + 2C_3 + 2C_4 + 2C_5 + C_6\right) \qquad \text{Eq. 18a}$$

Likewise, equation 18b may be used for four equally spaced crush measurements.

$$\overline{d} = \frac{1}{6}\left(C_1 + 2C_2 + 2C_3 + C_4\right) \qquad \text{Eq. 18b}$$

Once the SEA is calculated, equations 20 and 21 can be used to calculate the EBS and the collision closing speed (CCS) of the car for narrow object impacts.

$$EBS\left(km/hr\right) = 3.6\sqrt{2SEA} \qquad \text{Eq. 20}$$

$$CCS\left(km/hr\right) = \left(\frac{M_k}{M_t}\right) EBS\left(km/hr\right) \qquad \text{Eq. 21}$$

In equation 21, M_t is the total mass of the car and M_k is the curb mass of the car. Wood uses the ratio of the curb mass to the total mass of the car because he defines EBS as being the equivalent barrier approach speed of

[1] For a treatment on the Sigma notation used in equations 18 and 19 see http://www.mathcentre.ac.uk/resources/leaflets/firstaidkits/2_22.pdf

the empty car. "Physically, it relates the kinetic energy of approach (i.e. the total kinetic energy absorbed before taking restitution into consideration) to the mass of the vehicle structure." Wood's opinion is that all test data should be related to a consistent baseline mass which he considers should be the curb mass. The value of M_t should be adjusted as necessary for offset impacts using equation 22:

$$M_t^{'} = M_t \frac{k^2}{k^2 + h^2}, \qquad \text{Eq. 22}$$

where k is the radius of gyration of the car in the horizontal plane and h is the perpendicular distance between the principal direction of force (PDOF) and the center of gravity. As with equation 15, the units for h and k may be any unit of length, as long as they are the same. The radius of gyration may be calculated from the yaw moment of inertia, I, with equation 22a,

$$k = \sqrt{\frac{I}{m}} \qquad \text{Eq. 22a}$$

where I is the yaw moment of inertia, which may be obtained from commercial databases or regression equations, and m is the mass of the vehicle.

Wood used these equations on 19 staged pole impacts performed by NHTSA. He calculated the normalized maximum crush depths using published data on the car lengths, and the collision speeds were converted into EBSs using published curb mass data and equation 21. Correction was not made for the eccentric impacts. Wood then plotted actual EBS as a function of calculated EBS and found a high degree of linear correspondence of the form,

$$EBS_{actual} = b_0 EBS_{Calc} \qquad \text{Eq. 23}$$

He found the mean value of the slope, b_0, was 1.007 and the 95% confidence range was 0.961 to 1.053. His analysis inferred that a value of 1.0 for the slope may be used. Furthermore, the standard deviation of individual values about the regression line was 4.25 km/hr (1.18 m/hr), which gives a 95% confidence range of +/- 9 km/hr (5.59 m/hr). This statistical analysis means that speeds calculated with equation 21 may be reported as +/- 9 km/hr (5.59 m/hr) with 95% confidence. The reader should note that equation 23 is only used for statistical analysis and not for reconstruction purposes.

<u>BILINEAR EQUATION</u>

Chen, et al., described a bilinear set of equations that may be used for unibody passenger vehicles (14). This set of equations is based on a bilinear model, which considers that a vehicle is less stiff during the first 0.3 M (11.8 inches) of crush. After approximately 11.8 inches, the engine and suspension are engaged in the collision, thus increasing the stiffness of the vehicle. For maximum deformation less than 0.3 M, the equation is,

$$V = 6.4 + 41.3C_{\max} \qquad \text{Eq. 24}$$

For maximum deformations greater than 0.3 M, the equation is,

$$V = -1.74 + 68.5C_{\max} \qquad \text{Eq. 25}$$

Where V is in km/h and $C_{\max}$ is the maximum deformation in meters. These equations were derived from NHTSA tests, which included 20 single impact tests and 6 series of repeated tests. The authors note that in general, unibody vehicles such as passenger cars have different bilinear curves than those of pickup trucks or other types of vehicles. Therefore, results derived from passenger car tests or other unibody vehicles may not be suitable to be applied to body-on-frame vehicles (14).

The above equations may be manipulated to solve for speed in mi/hr as a function of maximum deformation in inches. For maximum deformation of less than 11.8 inches equation 24a should be used and for maximum deformation of greater than 11.8 inches equation 25a should be used.

$$V = 4.0 + .65C_{\max} \qquad \text{Eq. 24a}$$

$$V = -1.1 + 1.1C_{\max} \qquad \text{Eq. 25a}$$

COMPARING EQUATIONS

Using the crash tests mentioned at the beginning of this paper, a comparison of the various equations was tabulated in Table 1 of the Appendix. All of the data were adjusted to reflect energy dissipated in fracturing or moving the pole.

Break fracture energy (BFE) was estimated utilizing either of two methods described in (15) and (16). Depending on which of the two methods are employed, a typical 4-40 wooden utility pole BFE can account for approximately 23000 ft-lbs to nearly 67000 ft-lbs of additional energy that must be considered in the calculation of an impact speed estimate. As can be seen, the range of BFE is quite broad. Kent and Strother have suggested in their work that the BFE values obtained using the Mak equations may in fact overestimate the BFE. The Mak paper (16) does not explain how the BFE equations were derived, but they seem to have evolved from testing done by the Southwest Research Institute (SWRI) in the 1970's. The same SWRI testing has served as the basis for the scaled testing reported in the Kent and Strother study. The paper also suggests that the methodology may also have been developed specifically for use with the CRASH 3 algorithm.

In the case of the Atlantic City tests, the pole circumferences were closer in dimension to class 5 poles. In the two crashes where the poles fractured and the method described in (15) was used, consideration of BFE resulted in approximately 11,000 ft-lbs and 12,000 ft-lbs of additional energy for the Oldsmobile and Ford crashes respectively. The net effect was an increase in the equation-derived speed estimates by approximately 10 mi/hr to 12 mi/hr for the Oldsmobile and Ford respectively.

The equations based on deepest crush and which have been mentioned above can be used to determine EBS in crashes involving wooden utility poles, trees and narrow objects in general. The BFE methods stated above would be applicable to wooden utility poles; however, as Kent and Strother point out, their method may also be applicable to trees provided conditions as set forth in their study (15) are satisfied. The factor having the most affect on wood material properties, such as bending strength, is moisture content. The bending strength of a specimen, for example, increases by about 30 percent when the moisture content drops from 12 to 6 percent. A similar trend is observed in most material properties for wood: strength and elasticity values generally increase as the moisture content decreases (15).

In short, the lower the moisture content, the greater the strength properties. Wooden utility poles have a general moisture content of approximately 6% or less. Trees, being living objects, has greater moisture content, typically 20% or more. In general, trees would require less fracture energy than dried poles of the same size and wood species (15). Trees generally exceed poles with respect to their anchoring systems. Poles will tend to rotate along a lateral axis more readily than trees which are generally more rigid and tend to remain in place.

Energy dissipated moving the pole was estimated by using the collision force reported by the EDCRASH™ computer program and the distance the base of the pole moved during the collision. For the column reporting Wood's results, the actual closing speed is reported as well as the 95% confidence range. Chart 1 is a graphic representation of Table 1.

Table 2 in the Appendix shows the difference in mi/hr from what the equations predicted compared to the actual impact speed. Wood's column reflects the difference for the calculated closing speed as well as the 95% confidence range reported in the Wood paper.

A least squares regression of the form used by Wood (Eq. 23) was employed for each of the equations reported in this paper. Chart 2 through Chart 9 in the Appendix show the results of the regressions. Table 3 show the results of the statistical analysis performed for each regression. This table includes the Fisher F-statistic, the slope of the regression line, the R-squared value, the 95% confidence interval for the uncertainty in the slope, the standard error of values about the regression line, and the 95% confidence interval for actual speeds about the regression line.

The critical value for the Fisher F-statistic (99% certainty) was 11.3 for all equations except Morgan & Ivey, which had one less degree of freedom at v_2 (the late-model test was not applied to the Morgan & Ivey equation as explained in the next section of this paper). The critical value for Morgan & Ivey was 12.2. All F-statistics were many times higher than their respective critical value, which means that it is 99% certain that the data is not a random scatter of points and that the regression is justified.

The results of the statistical analysis show that the Vomhof CF method rendered the best results with a slope of 1.02 with a 95% confidence interval of 0.028. This means that a slope of one is appropriate for the Vomhof CF method. The 95% confidence interval for the speed was +/- 7.44 mi/hr. The Wood equation and the equation by Nystrom and Kost were close seconds to Vomhof. The slope for Wood was 1.06 +/- .031 with a 95% confidence interval for the estimated speed of 8.00 mi/hr. The slope for Nystrom and Kost was 1.06 +/- 0.028 with a 95% confidence interval for the estimated speed of 7.04 mi/hr. The R-squared values for all of these equations were greater than .91.

The previous four equations were followed by the bilinear and the Craig one inch equals one mi/hr. The slope for the bilinear equation was 1.08 +/- 0.029 and the 95% confidence interval for the estimated speed was 7.28 mi/hr. The Craig rule showed a slope of 1.09 +/- 0.030 with a 95% confidence interval for the estimated speed of 7.35 mi/hr.

For the reconstructionist who seeks the most conservative results, the Morgan and Ivey equation along with the Craig set of equations provide the best results. These equations consistently under-reported the speed (there was one exception for the Craig modified equation in which the speed was over-reported by 0.7 mi/hr) In most cases, the Craig set of equations provided results closer to the actual speed than the Morgan and Ivey equation.

APPLICATION OF EQUATIONS TO LATE-MODEL VEHICLES

All of the tests researched for this paper employed older vehicles. Can the results as seen in this paper be expected for late-model vehicles? This is an area of on-going research for the present authors. The method planned to answer this question is to compare these equations to real-world crashes in which EDR data is available. As of the writing of this paper, the authors have only one such crash, which involved a 2006 Cadillac XLR that struck the corner of a granite foundation. The granite foundation did not move, nor did it fracture. Therefore, all of the energy was assumed to have been dissipated in damaging the vehicle. The vehicle was found against the foundation, so restitution was considered to be negligible. The EDR pre-crash data, the maximum delta-V, and scene data suggest that the Cadillac struck the foundation at approximately 24 mi/hr. The last row of Table 1 shows the results of all of the equations, while the last row of Table 2 shows the difference of the individual equations from the 24 mi/hr speed reconstructed from the EDR and the scene data. The Morgan and Ivey equation could not be used in this collision because the corner of a building had been impacted rather than a wooden utility pole. Specifically, there was no data available for ΔE, which the reader should recall is a given pole's comparison to a class 4-40 pole.

An examination of the data for the late-model Cadillac XLR manifests that all of the equations performed consistent to the crash tests that involved older vehicles. While this is not sufficient evidence to make any conclusions, it is encouragement to collect more data so that a proper examination of the equations may be made with late-model vehicles.

CONCLUSION

Several equations for the determination of vehicle EBS with narrow objects such as poles and trees have been presented and discussed in general. Calculated speeds using the equations were compared to speeds derived from full-scale low- and moderate-speed crash tests in an attempt to compare and analyze their respective abilities to estimate impact speeds.

When analyzing any type of pole impact, specific information about the subject crash should be scrutinized with sound accident reconstruction judgment. This paper has presented a comparison of formulas based upon a limited number of controlled frontal pole impacts. The preliminary findings seem to indicate that reasonable impact speed estimates may indeed be possible using some of the methods and equations presented herein.

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Appendix

Data Tables

2002 IATAI Test								
Car	Weight (lbs)	Test Speed (mi/hr)	Cmax (in)	Distance Car Traveled After Impact (ft)	Post-impact drag factor	Pole Circumference at Force Application (in)	Distance Pole Moved (ft)	Pole Fractured?
1995 Contour	3210	16.7	14	2.0	.01	36	4.00	No

2003 Joint Conference Data								
Car	Weight (lbs)	Test Speed (mi/hr)	Cmax (in)	Distance Car Traveled After Impact (ft)	Post-impact drag factor	Pole Circumference at Force Application (in)	Distance Pole Moved (ft)	Pole Fractured?
1978 Cutlass	3075	28.0	25.2	4.8	.01	28.8	N/A	Yes
1986 Celebrity	2702	30.5	21.6	4.2	.01	29.9	0.5	No
1989 Escort	2430	29.0	16.8	15.9	.01	36.6	N/A	Yes

2007 IPTM Special Problems Data								
Car	Weight (lbs)	Test Speed (mi/hr)	Cmax (in)	Distance Car Traveled After Impact (ft)	Post-impact drag factor	Pole Circumference at Force Application (in)	Distance Pole Moved (ft)	Pole Fractured?
1996 Sable	3400	46 to 47	34.5	15	.40 to .50	30.5	4.00	Yes
1999 Sable	3100	43 to 44	30.5	42	.40 to .50	28	3.00	Yes
1998 Taurus	3200	48 to 49	27.5	127	.30 to .40	28.5	0.66	Yes

EQUATION RESULTS FOR ALL CRASH TESTS AND REAL-WORLD COLLISION									
Vehicle	Actual Speed (MPH)	NTSB	Morgan & Ivey	Nystrom & Kost	Craig Crush Depth = Speed	Craig Modified	Vomhof .60 CF	Wood	Bilinear
’78 Oldsmobile Cutlass	28.0	21.8	22.9	29.1	27.2	28.7	28.2	22.5 16.9 – 28.1	28.0
’86 Chevrolet Celebrity	30.5	20.5	22.2	26.7	24.8	22.2	28.8	28.3 22.7 – 33.8	25.4
’89 Ford Escort	29.0	18.4	19.2	23.2	20.7	19.9	26.0	31.2 25.6 – 36.8	21.1
’95 Ford Contour	16.7	12.4	16.5	11.6	14.0	11.6	21.0	16.8 11.2 – 22.4	14.2
’79 Dodge Pickup	38.2	25.9	27.5	35.2	35.8	34.1	33.3	35.0 29.4 – 40.6.	37.7
’06 Cadillac XLR	24.0	17.0	N/A	24.6	23.5	20.7	27.4	28.0 22.4 – 33.6	22.3
1999 Ford Taurus	48 – 49	41.2 – 45.6	40.9 – 45.3	43.0 – 47.2	41.9 – 46.2	40.9 – 45.3	44.8 – 48.8	41.8 – 46.2	42.0 – 46.3
1996 Mercury Sable	46 – 47	41.9 – 42.5	41.7 – 42.2	44.5 – 45.0	43.6 – 44.1	42.2 – 42.7	46.1 – 46.6	41.5 – 42.0	43.9 – 44.4
1999 Mercury Sable	43 – 44	39.8 – 41.3	39.5 – 41.0	41.5 – 43.0	40.4 – 41.9	39.5 – 41.0	43.3 – 44.8	40.2 – 41.7	40.5 – 42.0

Table 1

DIFFERENCE OF SPEEDS ESTIMATED BY THE DEEPEST CRUSH METHOD EQUATIONS TO ACTUAL IMPACT SPEED (M.P.H)									
Vehicle	Actual Speed (MPH)	NTSB	Morgan & Ivey	Nystrom & Kost	Craig Crush Depth = Speed	Craig Modified	Vomho f .60 CF	Wood	Bilinear
’78 Oldsmobile Cutlass	28.0	-6.2	-5.1	+1.1	-0.8	+0.7	+0.2	-5.5 -11.1 to +0.1	0.0
’86 Chevrolet Celebrity	30.5	-10	-8.3	-3.8	-5.7	-8.3	- 1.7	-2.2 -7.8 to +3.3	-5.1
’89 Ford Escort	29.0	-10.6	-9.8	-5.8	-8.3	-9.1	-3.0	+2.2 -3.4 to +7.8	-7.9
’95 Ford Contour	16.7	-4.3	-0.2	-5.1	-2.7	-5.1	+4.3	+0.1 -5.5 to +5.7	-2.5
’79 Dodge Pickup	38.2	-12.3	-10.7	-3.0	-2.4	-4.1	-4.9	-3.2 -8.8 to +2.4	-.5
’06 Cadillac XLR	24.0	-7.0	N/A	+0.6	-0.5	-3.3	+3.4	+4.0 -1.6 to +9.6	-1.7
1999 Ford Taurus	48 – 49	-6.83 to -3.43	-7.14 to -3.7	-5.0 to -1.8	-6.1 to -2.6	-7.1 to -3.7	-3.24 to -0.2	-6.2 to -2.8	-6.0 to -2.7
1996 Mercury Sable	46 – 47	-4.5 to -4.1	-4.3 to 3.2	-2.0 to -1.5	-2.9 to -2.4	-4.3 to -3.9	-0.38 to 0.13	-5.01 to -4.6	-2.6 to -2.2
1999 Mercury Sable	43 – 44	-2.7 to -3.2	-3.5 to 1.8	-1.46 to -0.98	-2.1 to -2.6	-3.0 to -3.5	0.34 to 0.77	-2.8 to -2.3	-2.0 to -2.5

Table 2

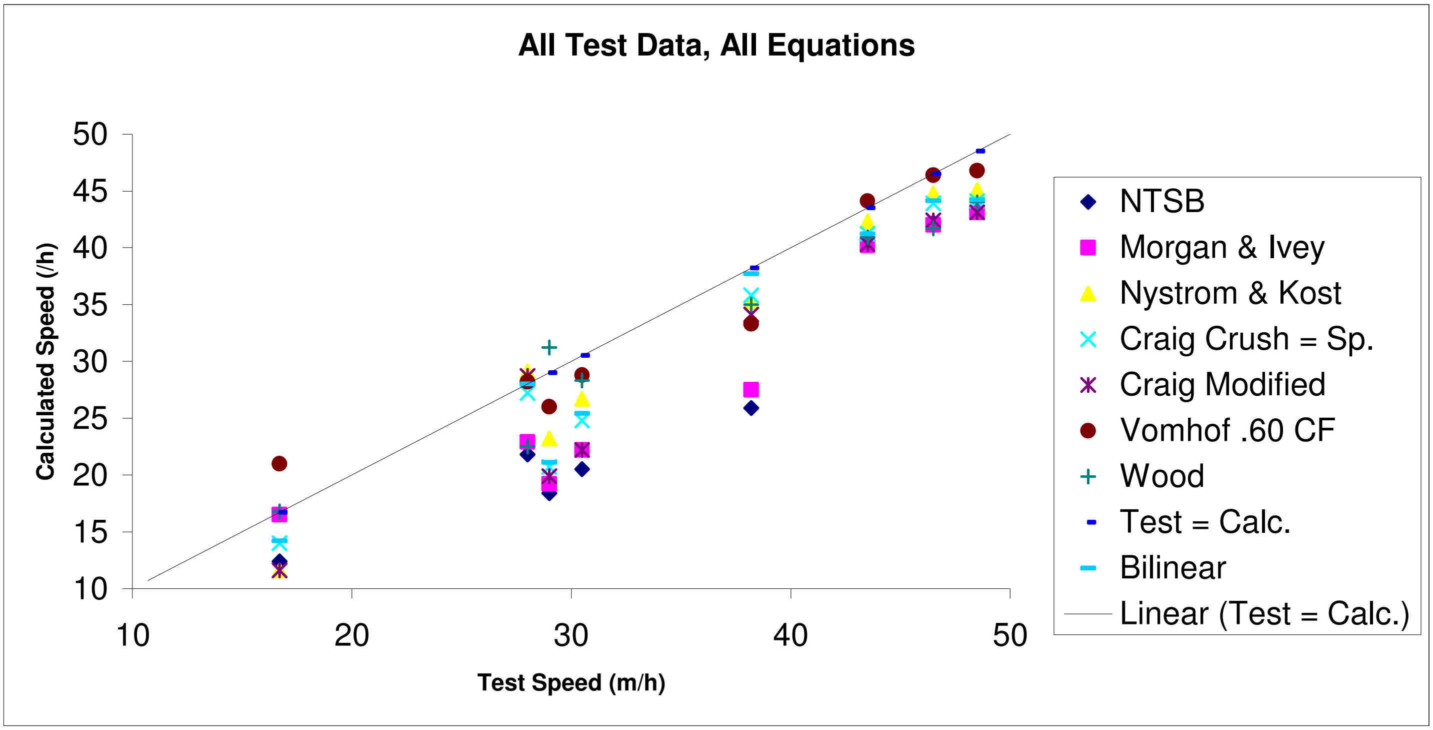

Chart 1

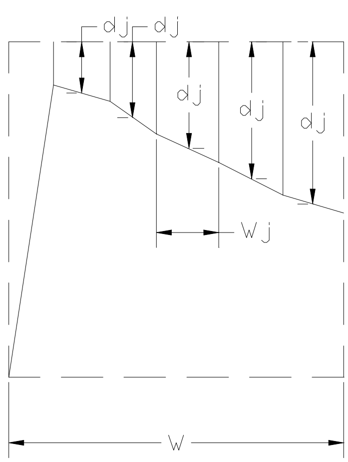

Figure 1 (Idealized crush mechanism—from Wood, SAE 930894)

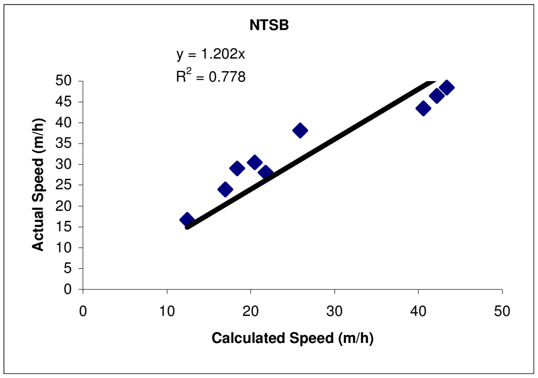

Chart 2

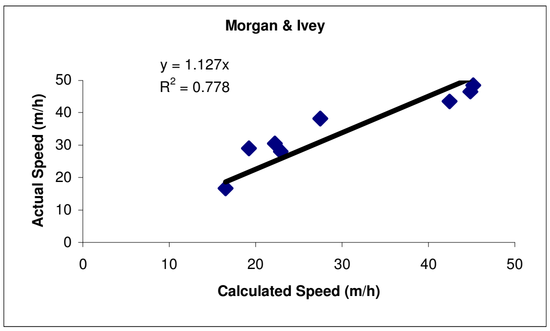

Chart 3

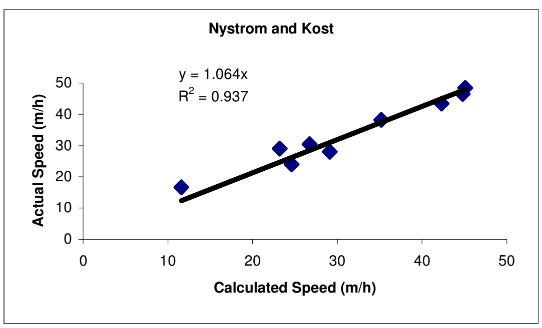

Chart 4

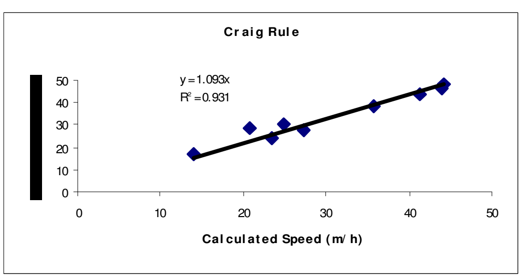

Chart 5

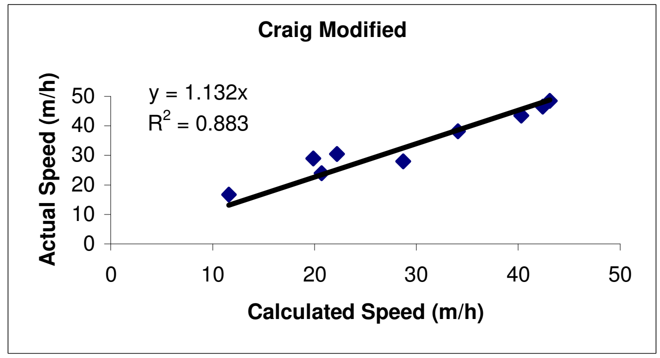

Chart 6

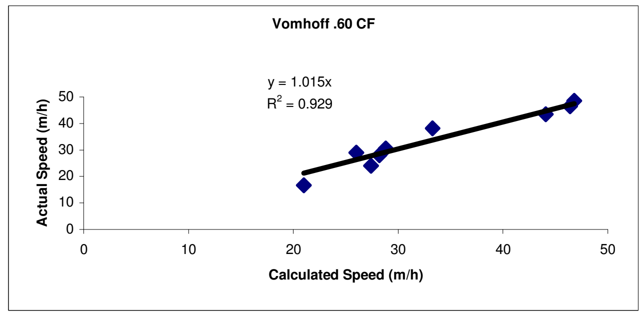

Chart 7

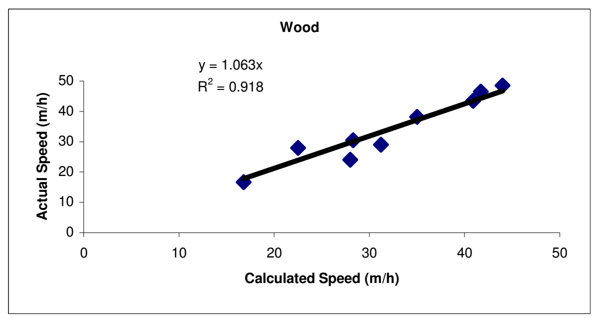

Chart 8

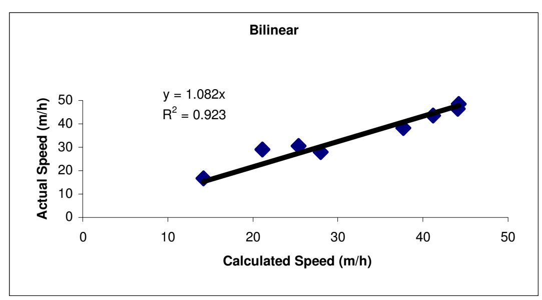

Chart 9

STATISTICAL ANALYSIS OF LEAST-SQUARES REGRESSION FOR ALL EQUATIONS						
Equation	**F-Statistic**	**Slope**	**R^2**	**95% CI of Slope**	**Standard Error (mi/hr)**	**95% CI of Actual Speed (mi/hr)**
NTSB	422	1.20	.778	.059	5.12	13.2
Morgan & Ivey	346	1.18	.844	.049	4.32	12.0
Nystrom & Kost	1497	1.06	.934	.028	2.74	7.04
Craig Crush Depth = Sp.	1371	1.09	.931	.030	2.86	7.35
Craig Modified	805	1.13	.883	.040	3.72	9.57
Vomhof .60CF	1340	1.02	.929	.028	2.89	7.44
Wood	1157	1.06	.918	.031	3.11	8.00
Bilinear	1400	1.08	.923	.029	2.83	7.28

Table 3

Crash Test Photos

Photo 1 – Results from Joint Conference 2003 crash tests. Oldsmobile impact speed: 28 mi/hr. Maximum crush = 25.2 inches.

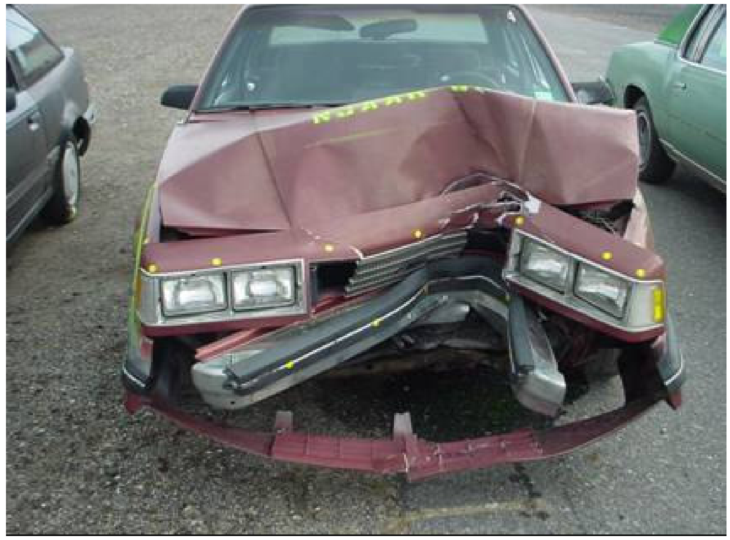

Photo 2 – Results from Joint Conference 2003 crash tests. Chevrolet impact speed = 30.5 mi/hr. Maximum crush = 21.6 inches.

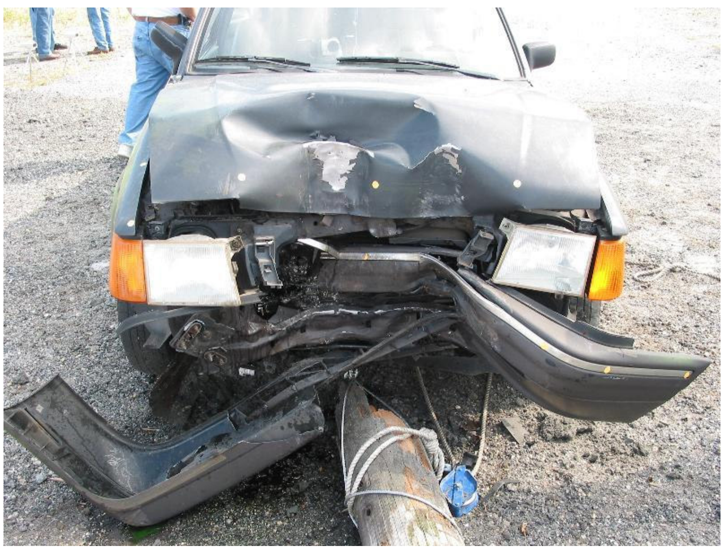

Photo 3 – Results from Joint Conference 2003 crash tests. Ford Impact speed = 29 mi/hr. Maximum crush = 16.8 inches.

Photo 4 – Results from IPTM Special Problems 2007 test. 1998 Ford Taurus. Impact speed 48 to 49 mi/hr. Maximum crush = 15.50 inches. Photo by Sergeant Greg Waters, N.Z Police: Serious Crash Unit (Waikato).

Photo 5 – Results from IPTM Special Problems 2007 test. 1999 Mercury Sable. Impact speed 43 to 43 mi/hr. Maximum crush = 14.75 inches. Photo by Sergeant Greg Waters, N.Z Police: Serious Crash Unit (Waikato).

Photo 6 – Results from IPTM Special Problems 2007 test. 1996 Mercury Sable. Impact speed 46 to 47 mi/hr. Maximum crush = 20.00 inches. Photo by Sergeant Greg Waters, N.Z Police: Serious Crash Unit (Waikato).