REVIEW OF CAR FRONTAL STIFFNESS EQUATIONS FOR ESTIMATING VEHICLE IMPACT VELOCITIES

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Paper Number 439

ABSTRACT

This paper reviews different force versus crush empirical equations for cars used in accident reconstruction over the past three decades. These equations are compared to numerous data obtained from various sources. A strategy for selecting the most appropriate equations to use for determining the frontal stiffness characteristics of a car for accident reconstruction, simulation modeling, and design purposes is also proposed. Estimates of error bands for a particular strategy chosen given available crash test data, are also provided.

INTRODUCTION

Estimates of vehicle speed changes during impacts are important for assessing the impact speed and hence crash severity of real world road accidents for research, insurance claims and litigation purposes. The term commonly used to define the speed change during an impact is Delta *V*. A method, essentially empirical, based on a vehicle's crush deformation and crush energy has been widely used to determine Delta *V*. Generally, for a frontal collinear car-to-car impact, from the crush profiles of the two cars involved, the crush energy can be calculated as

$$E_1 = \int_0^{w_{01}} \int_0^{C_1} F_1(C) dC dw \qquad (1).$$

$$E_2 = \int_0^{w_{02}} \int_0^{C_2} F_2(C) dC dw \qquad (2).$$

where *E* is the crush energy (J); *F*(*C*) represents the impact force per unit width of crush (N/m), *C* is the residual crush depth (m), w_{01}, w_{02} are the crush widths (m) and subscripts 1 and 2 refer to car 1 and car 2 [1]. Using the conservation of momentum, the conservation of energy, and assuming zero restitution, Robinette *et al* [2] provide the following equations for calculating Delta *V*:

$$\text{Delta}\, V_1 = \sqrt{\frac{2M_2(E_1+E_2)}{M_1(M_1+M_2)}};$$

$$\text{Delta}\, V_2 = \sqrt{\frac{2M_1(E_1+E_2)}{M_2(M_1+M_2)}} \qquad (3).$$

where M_1, M_2 are the mass of the respective vehicles(kg). Some commonly used crash reconstruction programs such as CRASH3, EDCRASH and PCCRASH make use of these type of equations for predicting pre and post crash impact speeds [3, 4].

Obviously, the accuracy of Delta *V* predicted using Equation 3 largely depends on the accuracy of the relationship between the vehicle's frontal impact force per unit crush width *F*(*C*) and the crush depth *C*. Numerous research and crash tests have been carried out in regards to the frontal crush resistance of a car. However, because of the wide diversity of vehicle frontal structures and their complex crush behaviour, *F*(*C*) must be empirically determined from full-scale crash tests.

As full-scale crash tests are expensive and need a lengthy time to prepare, only several car models have been tested at a limited range of impact speeds. Nevertheless, different trends of *F*(*C*) versus *C* were observed from this limited data [5-8]. For most car models, full-scale frontal crash tests were only conducted at 48.3 km/h (30 mph) for regulation compliance purposes and/or at 56.3 km/h (35 mph) for New Car Assessment Program (NCAP) tests. With regards to accident reconstructions involving cars that have one or two crash test data points, the common practice is to empirically assign a linear relationship between impact speed and residual crush depth, which is expressed as

$$\frac{V}{3.6} = b_0 + b_1 C \qquad (4).$$

where *C* is the residual crush depth (m), b_0 is the intercept or "zero crush" speed (m/s), b_1 is the slope of the speed-crush relationship (ms^{-1}/m) and *V* is the impact speed (Note that the term impact speed is used loosely here. In most reconstruction handbooks the symbol *V* is used for velocity and is expressed in m/s. In this paper *V* will be used to symbolize speed expressed in km/h). b_0 is usually set at 2.2 m/s (8 km/h or 5 mph) [5, 6, 9]. Thus, b_1 can be calculated from Equation 4 using the data (*V* and *C*) obtained from a single frontal crash test.

Campbell [1] originally proposed that if there is a linear relationship between impact speed and crush, the simplest characteristic for a vehicle's front structure that will reproduce the linear *V*-*C* relationship is a linear force-crush relationship. Hence

$$F(C) = A + BC \qquad (5).$$

where A and B are coefficients. Coefficients A and B can be determined as

$$A = \frac{Mb_0 b_1}{w_0} \quad (6).$$

$$B = \frac{Mb_1^2}{w_0} \quad (7).$$

where M is the vehicle mass (kg) and w_0 is the crush width (m) [1].

However, there are some concerns about this method for determining $F(C)$. One concern is that a single linear model type is used for all car models and used over the whole impact speed range. Vehicles do vary in their structures, within manufacturing tolerance, from one vehicle to the next that can result in significant differences in force versus crush values. Test set-ups can also vary from one crash to another. Another concern is that coefficients A and B are derived from only one crash test. The basic assumption here is that coefficients A and B hold for a particular vehicle over all speed ranges.

Hence it is not clear to what level of accuracy Delta V can be estimated. Variance is inevitable in crash tests due to various reasons. It is important for accident reconstructionists to quantify the error bands in regards to the accuracy of Equation 4. Over the past three decades, a wealth of crash test data has been made available from NCAP, regulatory and laboratory crash tests. This data provides the possibility to clearly assess the $F(C)$ equations used for Delta V estimations.

This paper reviews the different force versus crush equations proposed and various approaches used in accident reconstruction over the past three decades. These equations are then compared to numerous data obtained from various sources. A strategy for selecting the most appropriate equations to use for determining the frontal stiffness characteristics of a car for accident reconstruction, simulation modelling, and for design purposes is also proposed. Estimates of error bands for a particular strategy chosen given available crash test data, are also provided.

REVIEW OF CAR FRONTAL STIFFNESS MODELS

As mentioned above, because of the high expense of a crash test, only a limited number of car models have been crash tested over a range of impact speeds. Nevertheless, it was possible to estimate different frontal crush characteristics from this data.

Single Linear Equation

In the late 1960s, Emori [10] suggested that the impact force a car being subjected to in a head-on collision is directly proportional to the crush, somewhat similar to that of a spring force versus displacement. He also proposed that the frontal crush should be directly proportional to the impact velocity.

On the basis of Emori's work as well as a range of frontal fixed rigid barrier crash tests on 1971~1972 model full size GM cars and 1971~1974 model Chevrolet Vegas, Campbell [1] found a linear relationship between residual crush depth (C) and impact speed (V), as shown in Figures 1 and 2.

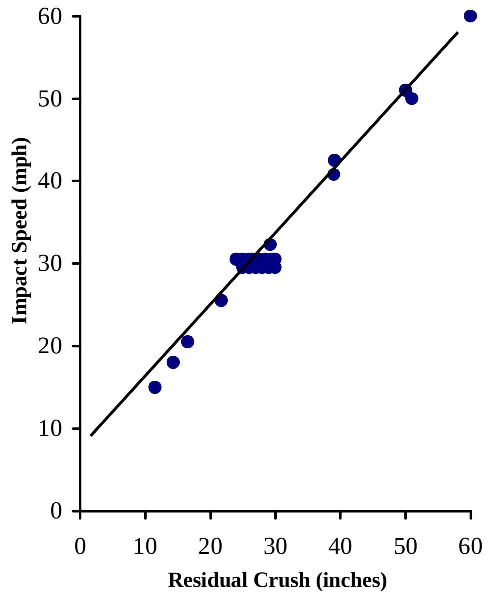

Figure 1. Impact speed vs residual crush for 1971~1972 model full size GM cars [1].

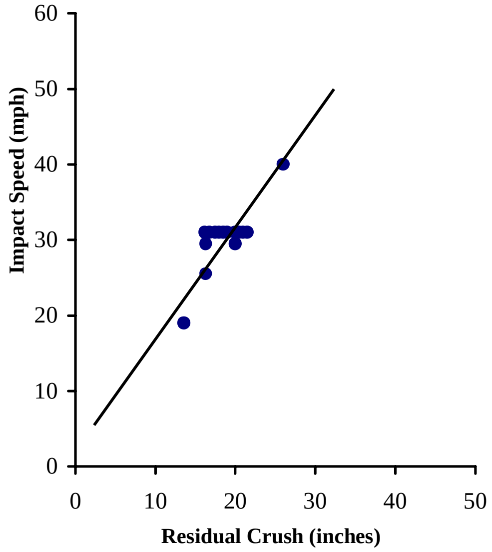

Figure 2. Impact speed vs residual crush for 1971~1974 model Chevrolet Vegas [1].

Campbell further proposed that this linear relationship between *V* and *C* could be transformed into a linear impact force-crush relationship, expressed as Equation 5. Crash test data indicated that the linear equation for *F*(*C*) was workable for estimating crush energy in frontal, oblique and off-set crashes. Campbell also gave the methods for determining coefficients *A* and *B* in the linear equation, as expressed in Equations 6 and 7. Campbell's findings have been extensively used for accident reconstructions and laid the theoretical foundation for some commonly used reconstruction programs, such as CRASH3 and EDCRASH [3, 4].

Since Campbell's "classical" work, numerous research papers have been published and crash tests have been carried out to investigate a vehicle's crush behaviour in relation to Equations 4 to 7. Frontal fixed rigid barrier impact tests on several car models (other than the ones tested by Emori [10] and Campbell [1]) also showed a linear *V-C* relationship, such as those proposed by Navin *et al* [6] when he analysed crash test data for 1974 to 1981 model Honda Civic cars (see Figure 3).

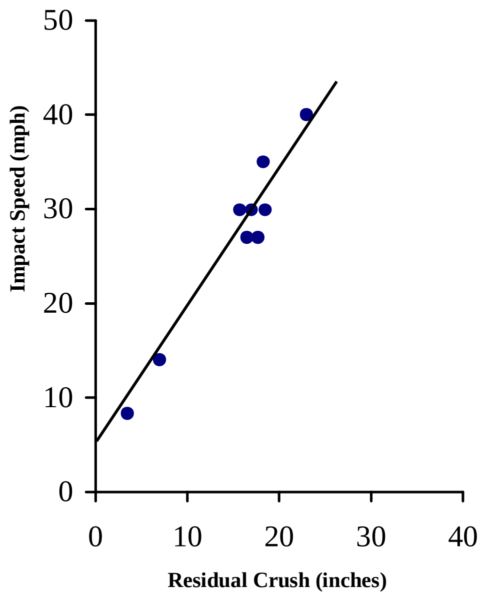

Figure 3. Impact speed vs crush for 1974~1981 model Honda Civic [6].

In order to account for the weight differences between different test vehicles, Varat *et al* [7] used an Energy of Approach Factor (*EAF*) to analyse crash test data. If the frontal structure of a vehicle behaves as a linear dissipator and zero restitution is assumed, the energy absorbed is

$$E = \frac{1}{2} k x^2 \qquad (8).$$

where E is the absorbed energy (J); k is the dissipator's linear force characteristic (N/m) and x is the crush distance (m). Energy absorbed per unit crush width is

$$\frac{E}{w_0} = \frac{1}{2}\left(\frac{k}{w_0}\right)x^2 \qquad (9).$$

Through some algebraic manipulation, we have

$$\sqrt{\frac{2E}{w_0}} = \sqrt{\frac{k}{w_0}} \cdot x \qquad (10).$$

Assigning $EAF = \sqrt{\frac{2E}{w_0}}$ and $B = \frac{k}{w_0}$, and considering that some initial elastic deformation energy is required before permanent crush results, the following equation is arrived at

$$EAF = EAF_0 + \sqrt{B} \cdot x \qquad (11).$$

where EAF_0 is the Onset Energy Factor and B represents the vehicle frontal impact coefficient which is a constant based on a vehicle's crush properties [7]. Note that for a car crashing into a rigid barrier, the crush energy E can also be equated to the car's kinetic energy just prior to impact such that $E = ½ M (V)^2$ (assuming zero rebound speed). As can be seen from Equation 11, the quantity *EAF* is theoretically linear to the residual crush depth. If a linear relationship exists between *EAF* and the residual crush depth from crash test data, it can be demonstrated the assumption that a vehicle behaves as a linear dissipator is acceptable, and using a linear force-crush equation to estimate crush energy is appropriate. Otherwise, if *EAF* is not linear in regards to crush depth, a linear force-crush equation may not be suitable for representing the vehicle crush behavior.

Varat *et al* [7] used Equation 11 to analyse a number of vehicle models where full frontal rigid barrier crash tests were carried out over a range of impact speeds. Eleven vehicle models were analysed. Varat concluded that two vehicle models showed a linear relationship between *EAF* and the residual crush up to 80 km/h (50 mph) (see Figure 4), and four vehicles exhibited a linear relationship up to 56 km/h (35 mph) (see Figure 5).

300
250
200
150
100
50
0
EAF
R^2 = 0.989
0 5 10 15 20 25 30 35 40
Crush (inches)

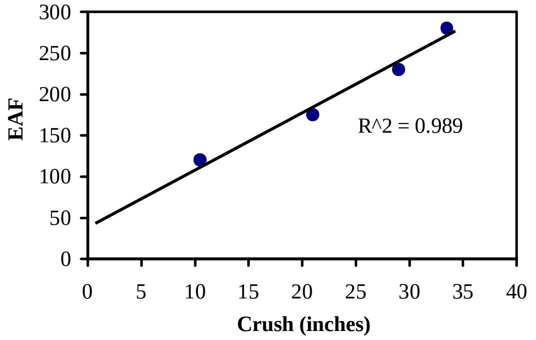

Figure 4. *EAF* vs crush for 1974 model Ford Pinto up to 50 mph [7].

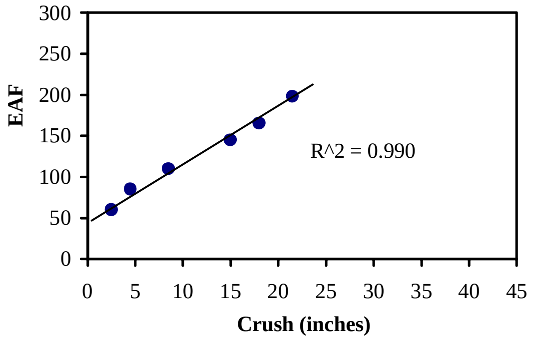

Figure 5. *EAF* vs crush for 1981~1985 model Ford Escort up to 35 mph [7].

Neptune [8] also observed that a linear relationship existed between *EAF* and residual crush up to 80km/h (50 mph) based on full overlap and partial overlap rigid barrier crashes for 1986 to 1991 model Ford Taurus cars (see Figure 6). He further stated that a review of available crash test data revealed that the linear relationship between impact force per unit crush width and crush depth was valid for full frontal collisions with rigid barriers up to a speed of 56 km/h.

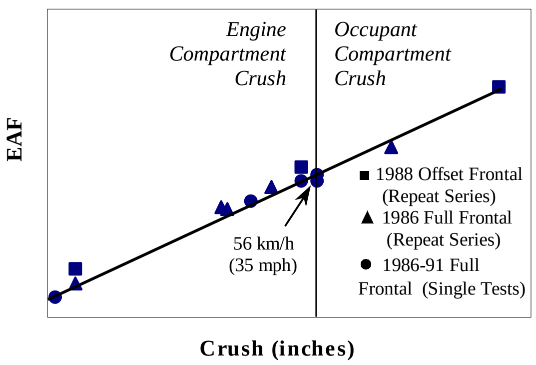

Figure 6. *EAF* vs crush for 1986~1991 model Ford Taurus [8].

Bi-Linear Equation

Some vehicles' crash test data also showed a non-linear trend. Strother *et al* [5], using *EAF* versus residual crush plots, found that a bi-linear equation was more suitable for 1980~1982 model GM Citation cars (see Figure 7).

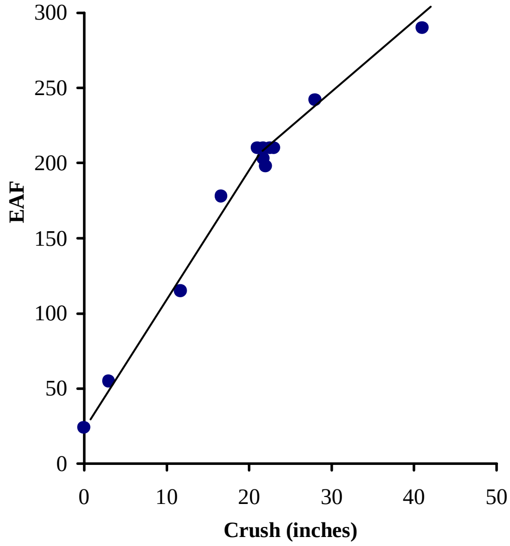

Figure 7. Energy Factor vs crush for 1980~1982 model Citation cars [5].

Neptune [8] also found that while a linear force-crush relationship could be demonstrated up to 56 km/h for 1981 to 1985 model Ford Escort cars, when the impact speed was greater than 56 km/h, the vehicle no longer displayed a linear relationship. The Escort dissipated less energy per unit crush above 56 km/h (see Figure 8). Neptune further concluded that in high severity collisions, the crush response characteristic of this vehicle could be divided into two regions, the engine compartment crush region and the occupant compartment crush region. Hence, the vehicle could be modelled as a bi-linear dissipator where the second dissipator (occupant compartment) does not compress until the first dissipator (engine compartment) bottoms out.

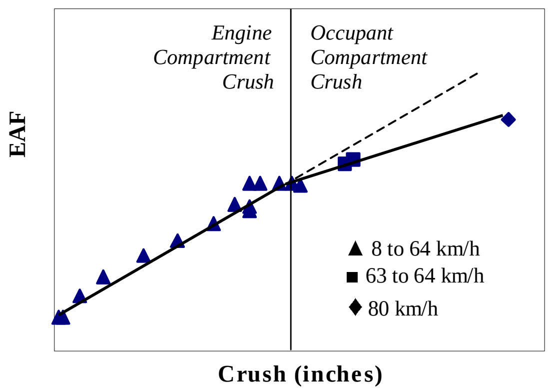

Figure 8. Energy factor vs crush for 1981~1985 model Ford Escort [10].

Varat [7] also drew similar conclusions in his research. For the six vehicle models that had a range of impact speeds up to 80 km/h, four vehicles displayed a bi-linear trend as shown in Figure 9.

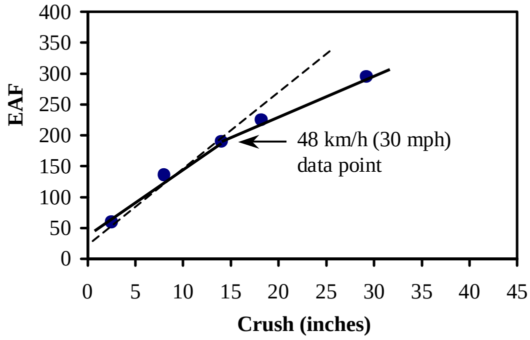

Figure 9. Comparison of a linear (dash) and a bi – linear (solid) model [7].

Constant Force Equation

Some crash test data also displayed a quadratic trend, e.g. full frontal barrier tests of 1974 model Plymouth Satellites as shown in Figure 10. Accordingly, Strother [5] proposed that a constant force value, expressed as $F/w_0 = D$, might be more suitable where F is the crush force.

Some researchers used sophisticated finite element models in conjunction with test results to develop a two-stage constant force relationship as shown in Figure 11. Wood *et al* [11] cited Sakuria's work and stated that a two-stage constant force-crush relationship with a transition as the deformation reaches the engine, could be used to represent vehicles' frontal crush characteristics. Futamata [12] and Toyama [13] confirmed Sakuria's two-stage force model by examining the pattern of energy absorbed by the various elements, such as side rails, suspension members and so on, in the course of crushing.

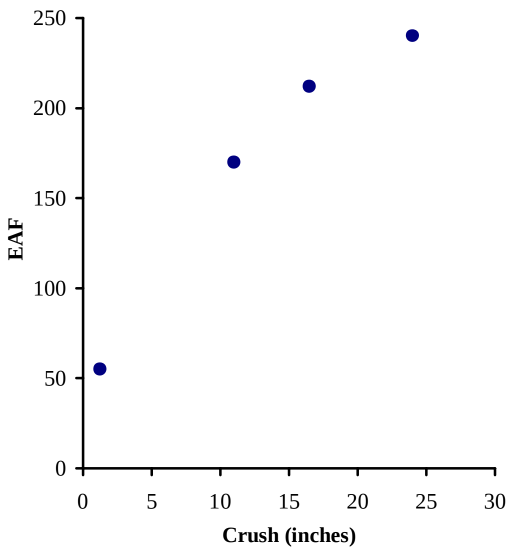

Figure 10. Energy Factor vs crush for 1974 model Plymouth Satellites [5].

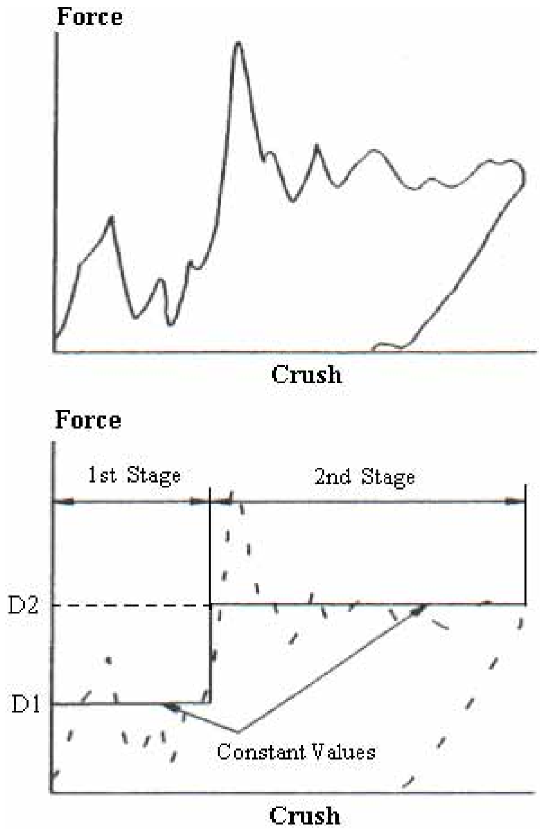

Figure 11. A two-stage constant force-crush relationship [11].

CRASH DATA

Most of the findings in the previous section were based on a limited number of crashes of vehicle models dating from 1960 through 1986. To extend these findings, as well as investigate the accuracy of equations adopted that describe a car's crush characteristics, data from over 1000 crash tests were collected. Vehicle models ranged over a large number of vehicle types and manufacturers and over a period starting from 1960 through to 2002.

Data Collection

Over the past three decades, a wealth of crash test data has been made available from NCAP, regulatory and laboratory crash tests. A literature and web search was carried out to collect as many frontal rigid barrier crash test results as possible. As a result, 1368 crash test points were collected from the database of the National Highway Traffic Safety Administration (NHTSA) [14], 50 crash tests were found from Australian NCAP [15], and 38 crash tests were obtained from some publications [6, 7, 9].

Data Analysis

As rebound velocities are not available for all tests, the *EAF* method was used where

$$EAF = \sqrt{\frac{2E}{w_0}} = \sqrt{\frac{M(V/3.6)^2}{w_0}} \qquad (12).$$

where the crush width w_0 was taken as the vehicle's overall width obtained from vehicle specification data sheets. Average crush depth was used in this analysis and was calculated based on a minimum of at least three crush measurements. However, in most cases, average crush was calculated from six measurements (C_1~C_6) [16, 17].

The data was first grouped according to the following body styles: passenger cars, vans, pickup trucks and four-wheel-drive vehicles (4WDs). Figures 12 through 15 show the plots of *EAF* versus average crush for these vehicles.

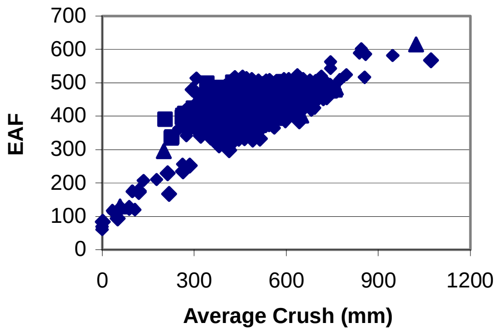

Figure 12. *EAF* vs crush for passenger cars.

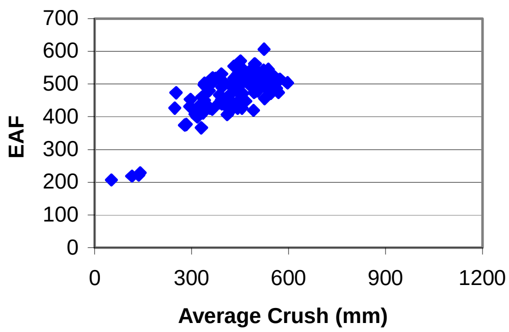

Figure 13. *EAF* vs crush for vans.

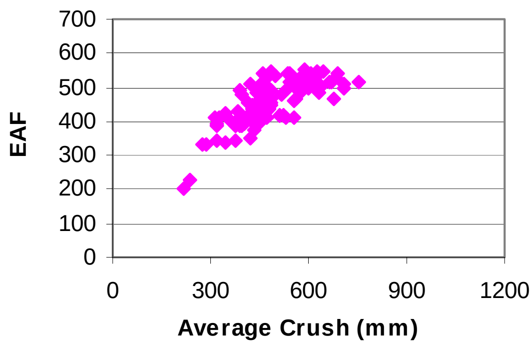

Figure 14. *EAF* vs crush for pickup trucks.

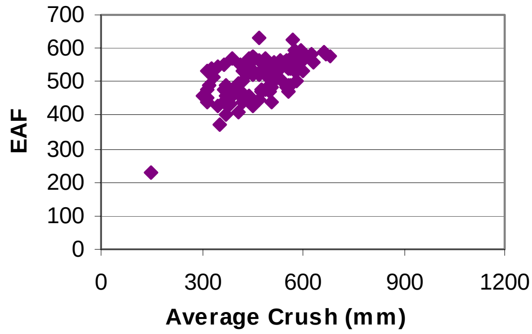

Figure 15. *EAF* vs crush for 4WDs.

As can be seen from Figure 12, an approximate bi-linear trend can be observed for all passenger cars. With regards to vans, pickup trucks and 4WDs, crash data over 56 km/h is not available, and there are only several crash tests available at low impact speeds. Nevertheless, a linear trend up to 56 km/h is evident as shown in Figures 13, 14 and 15.

Crash data of passenger cars was further grouped according to engine configurations. Data was segregated and graphed for cars with the same engine placement (transverse or inline), the same number of cylinders (4 cylinders, V6 cylinders, Straight 6 cylinders or V8 cylinders) and with similar engine capacity. Only the data for cars that were crash tested over a range of impact speeds are shown here. Where cars were only tested at two speeds (48 km/h and 56 km/h) data was omitted as these were effectively single point tests.

Figure 16 shows the data plotted for cars that have a 4-cylinder transverse engine with engine capacities ranging from 1.0 L to 1.9 L. All data is clearly located in the same narrow band that has a bi-linear trend. Similarly, data for cars with a 4-cylinder inline engine and for cars with a straight 6-cylinder transverse engine exhibit a bi-linear trend, as shown in Figures 17 and 18 respectively.

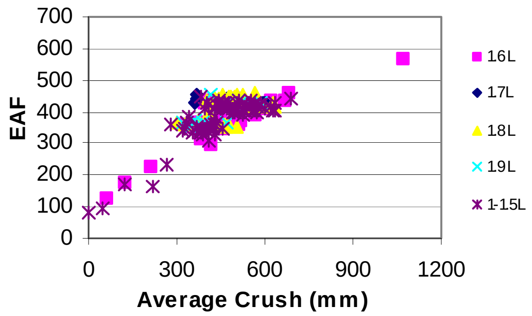

Figure 16. *EAF* vs crush for cars with a 4-cylinder transverse engine (1.0L~1.9L).

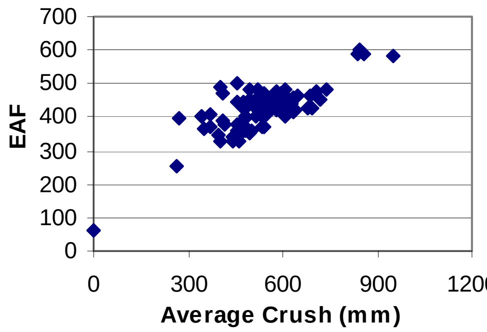

Figure 17. ***EAF* vs crush for cars with a 4-cylinder inline engine (1.3L~2.6L).**

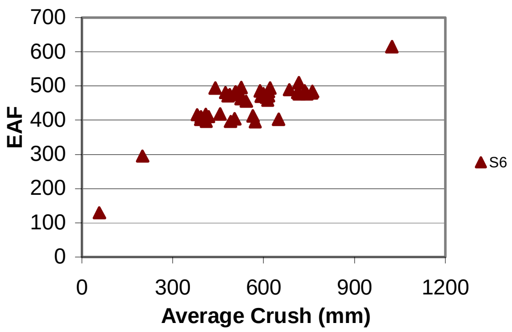

Figure 18. ***EAF* vs crush for cars with an S6-cylinder transverse engine (2.5L~3.8L).**

Figure 19 shows data for cars that have a V8-cylinder inline engine with engine capacities ranging from 4.9 L to 6.9 L. The maximum impact speed in this case is 57 km/h. Figure 20 shows data for cars that have a 2.5L 4-cylinder transverse engine where the maximum impact speed is 56.6 km/h. Both data plots indicate that a linear relationship exists between *EAF* and average crush.

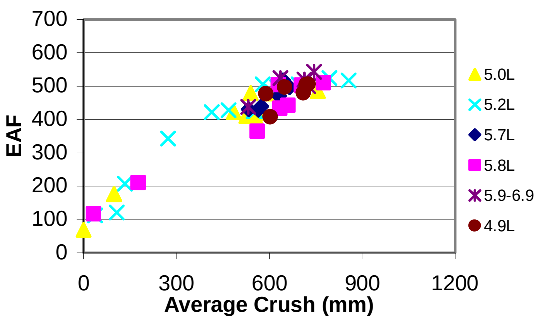

Figure 19. ***EAF* vs crush for cars with a V8-cylinder inline engine (4.9L~6.9L).**

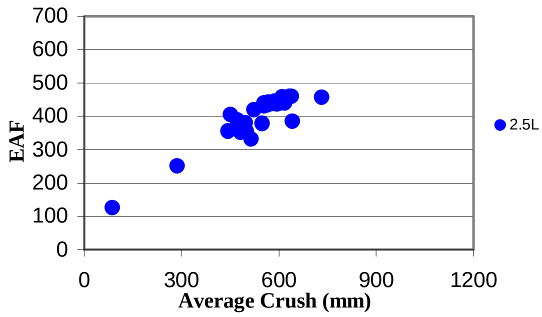

Figure 20. ***EAF* vs crush for cars with a 4-cylinder transverse engine (2.5L).**

DETERMINING *F*(*C*) MODELS

On the basis of the literature review and the data presented in Figures 12 to 20, a strategy for determining a vehicle's frontal crush force *F*(*C*) and the coefficients *A* and *B* in Equation 5 is proposed here.

When A Range Of Crash Test Points Are Available

The most accurate way to determine the *F*(*C*) of a given vehicle model is to conduct a series of full frontal rigid barrier crash tests at different speeds. Obviously, from a financial perspective, this is the most expensive method. If such crash test data is available, plot *EAF* versus residual crush, or plot the Energy of Crush Factor (*ECF*) versus residual crush, as outlined by Kerkhoff *et al* [18], if the rebound speed is available. *ECF* is expressed as

$$ECF = \sqrt{\frac{2E}{w_0}} = \sqrt{\frac{M(V^2 - V_R^2)}{w_0}} \qquad (13).$$

where V_R is the rebound speed (km/h) and *ECF* is the Energy of Crush Factor ($\sqrt{N}$).

- If the data plot is linear, Equation 5 can be used where the stiffness coefficients are

$$B = (slope)^2 \qquad (14).$$

$$A = EAF_0 \sqrt{B} \qquad (15).$$

where *slope* is the slope of the graphed line and EAF_0 is the intercept with the vertical axis [5].

An alternative is to use a *V-C* plot (e.g. Figures 1 and 2). The least squares method is recommended to obtain the best-fit line of the plotted data. b_1 and b_0 in Equation 4 is the slope of the straight line and the intercept of the line with y-axis respectively. The coefficients *A* and *B* can then be determined from Equations 6and7.

- If the data plot displays a bi-linear relationship, then the linear $F(C)$ equation (Equation 5) can be used in two stages. The same method as presented above can be used to determine the coefficients A_1 and B_1 for phase one and A_2 and B_2 for phase two.
- If the data plot shows a quadratic trend, the constant $F(C)$ equation can be used. In such cases, construct a plot of energy (E/w_0) versus residual crush. A true constant force model would appear as a straight line and the slope of the line is the constant crush force value [5].

When Only One Crash Test Data Point Is Available

Most cars only have a 48 km/h impact test and/or a 56 km/h NCAP crash test. In such cases where the relationship between the *EAF* and crush is not known, a bi-linear $F(C)$ model can be used.

The first stage of the bi-linear $F(C)$ model can be used up to 56 km/h. b_0 is usually set at 2.2 m/s (8 km/h or 5 mph) on the basis of some crash test data, and this has been commonly accepted in accident reconstruction literature [5,6,9]. If either a 48 km/h test or a 56 km/h test is available and the vehicle's crush profile is uniform, b_1 from Equation 4 is

$$b_1 = \frac{(V/3.6) - b_0}{C} \qquad (16).$$

If the crush profile is not uniform and is measured via 5 equal crush width zones (C_1~C_6) [16, 17], Neptune *et al* [19] propose that b_1 can be calculated such that

$$b_1 = -b_0\rho + \frac{\sqrt{(b_0\rho)^2 - 20\delta(b_0^2 - (V/3.6)^2)/3}}{2\delta/3} \qquad (17).$$

where: $\rho = C_1 + 2(C_2 + C_3 + C_4 + C_5) + C_6$

$$\delta = C_1^2 + 2(C_2^2 + C_3^2 + C_4^2 + C_5^2) + C_6^2 + C_1C_2 + C_2C_3 + C_3C_4 + C_4C_5 + C_5C_6$$

Coefficients *A* and *B* for the first linear phase can then be determined using Equations 6 and 7.

For the second stage of the bi-linear model, where impact speeds are over 56 km/h and up to 80 km/h, Varat [7] recommends setting a new intercept with the y-axis (b_0') at 6.7 m/s (24 km/h or 15 mph) according to crash test data he analysed. Using b_0'=6.7 m/s and the 48 km/h crash test point, b_1' can be obtained via Equation 16 or 17. Similarly, coefficients for the second phase linear equation can be determined using Equations 6 and 7.

ERROR BANDS

It should be noted that errors are inevitable using the strategy outlined in the previous section to determine $F(C)$ and its coefficients. This is particularly so when using only one crash test data point. Figure 21 shows a plot of impact speed versus crush for 1971~1974 model Chevrolet Vegas vehicles [1]. A linear *V-C* relationship can be derived from the range of test data as shown in Figure 21. Assuming that only one 48km/h (30 mph) crash test point is available and it happens to be the test with minimum crush depth, a linear *V-C* line for a 2.2 m/s (8 km/h or 5 mph) intercept (b_0) shown as Line 1 in Figure 21, can be plotted. Alternatively, another *V-C* line (Line 2) can be obtained if the crash test point happens to be the test with maximum crush depth. Obviously, if Line 1 or Line 2 is used to derive *A* and *B* and to predict Delta *V*, errors can be expected.

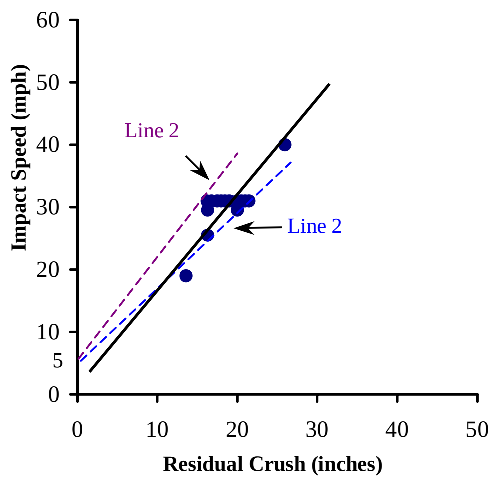

Figure 21. Impact speed versus crush for 1971~ 1974 model Chevrolet Vegas [1].

Crash test data also indicate that even for the same model car tested at the same impact speed, the test results differ, as shown in Figure 22. To illustrate the effect of test data variation (scatter) on the estimation of Delta *V*, an example is given here.

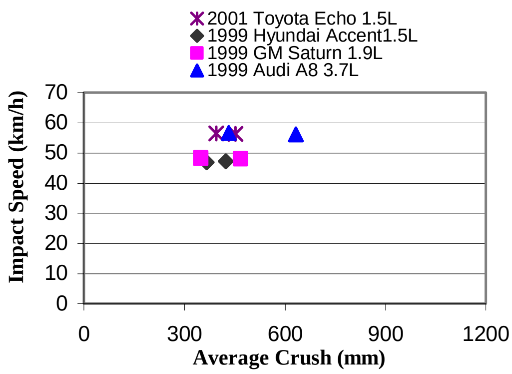

Figure 22. Comparison of average crush at the same impact speed.

Two data points were selected from the NHTSA database (Test Numbers 3127 and 3113) [14]. The crash data points represented results from full frontal crashes of 1999 model GM Saturn sedans into a rigid concrete barrier. This model car has a 1.9L 4-cylider transverse engine. The mass, crush width and average crush depth for the first crash (Test 3127) were assumed as known (M_1=1242 kg, w_{01}=1.685m and C=0.468 m), whereas the impact speed had to be determined. The second data point (Test 3113) was used to estimate the coefficients b_1, A and B in order to estimate the impact speed for the first "unknown" crash.

The mass of the car representing the second "known" data point was 1181 kg, its width was 1.682 m, its impact speed was 48.3 km/h and the average crush depth was 0.350 m. Using Equation 16 and b_0=2.2 m/s (8 km/h),

$$b_1 = \frac{(V/3.6) - b_0}{C} = \frac{(48.3/3.6) - 2.2}{0.350} = 32.0 \text{ (ms}^{-1}\text{/m)}$$

From Equations 6 and 7, the coefficients A and B are

$$A = \frac{Mb_0 b_1}{w_0} = \frac{1181 \times 2.2 \times 32.0}{1.682} = 49431 \text{ (N/m)}$$

$$B = \frac{Mb_1^2}{w_0} = \frac{1181 \times 32.0^2}{1.682} = 718992 \text{ (N/m}^2\text{)}$$

Using Equations 1 and 5, and assuming zero restitution, we have

$$E = \frac{1}{2} M (\text{Delta } V)^2 = \int_0^{w_0} \int_0^C F(C) dC dw$$
$$= \int_0^{w_0} \int_0^C (A + BC) dC dw$$
$$= \int_0^{w_0} (AC + \frac{1}{2} BC^2 + \text{G}) dw = w_0 (AC + \frac{1}{2} BC^2 + \text{G})$$

where $G = A^2/2B$ [1, 5]. Hence, Delta V can be determined such that

$$\text{Delta } V = \sqrt{\frac{2w_0(AC + \frac{1}{2}BC^2 + \frac{A^2}{2B})}{M}} \qquad (18).$$

Thus, the predicted Delta V of the car crashed representing the "unknown" first data point is

$$\text{Delta } V = \sqrt{\frac{2 \times 1.685 \times \left(49431 \times 0.468 + \frac{1}{2} \times 718992 \times 0.468 \times 0.468 + \frac{49431 \times 49431}{2 \times 718992}\right)}{1242}}$$

$$= 16.8 \text{ (m/s)} = 60.5 \text{ km/h}$$

However, the actual Delta V for the first data point was in fact 48.1 km/h. The predicted Delta V overestimates the actual Delta V by nearly 26%. Therefore, when using one crash test data point to predict Delta V, care must be exercised to evaluate the accuracy of the test data.

Figure 16 shows the data band for cars with a 4-cylinder transverse engine (1.0L~1.9L). A low $F(C)$ line, an average $F(C)$ line and a high $F(C)$ line is graphed in Figure 23. These $F(C)$ lines were also used respectively to estimate Delta V of the above 1999 model GM Saturn example. Figure 24 shows the comparison of the actual Delta V and predicted Delta V using the different $F(C)$ lines.

As can be seen, for a car with a 4-cylinder 1.0L to 1.9L transverse engine crashing into a rigid barrier, when the frontal crush is 0.468 m, the possible Delta V ranges from 41.2 km/h to 72.1 km/h and the average Delta V is 56.7 km/h. In other words, if a high $F(C)$ line was used from a single data point, the error could be as much as 50%. This data band as well as all other data plots for cars with different engine configurations can be used as a guidance for determining the possible Delta V range, particularly when the scatter of the crash test is uncertain or no crash test is available.

CONCLUSION

Theoretically, there is no unique frontal stiffness equation that can represent all vehicle models because of the wide diversity of vehicle frontal structures and their complex crush behaviour. In practice, unless the stiffness equation for a particular vehicle can be determined via a range of crash test data points, a linear stiffness equation can be used for impact speeds of up to 56 km/h and a bi-linear model can be adopted for high severity collisions for impact speeds ranging from 56 km/h to 80 km/h. In most cases, when using only one crash test point to determine the coefficients of the linear $F(C)$ equation to estimate Delta V, extreme care must be exercised when the crush versus speed scatter is uncertain. Determining the possible Delta V range is a useful guidance in Delta V estimations for crash reconstructions. This conclusion would be of particular interest to research centres relying on this methodology to estimate Delta V during the collection of real world data.

What is of particular importance is the need for frontal crash tests of common vehicles over a large range of speeds. National authorities should provide funding for tests because such data is being used in Civil and Criminal legal cases every day around the world. It is also essential for safety research and design of roadside barrier systems and impacts into structures.

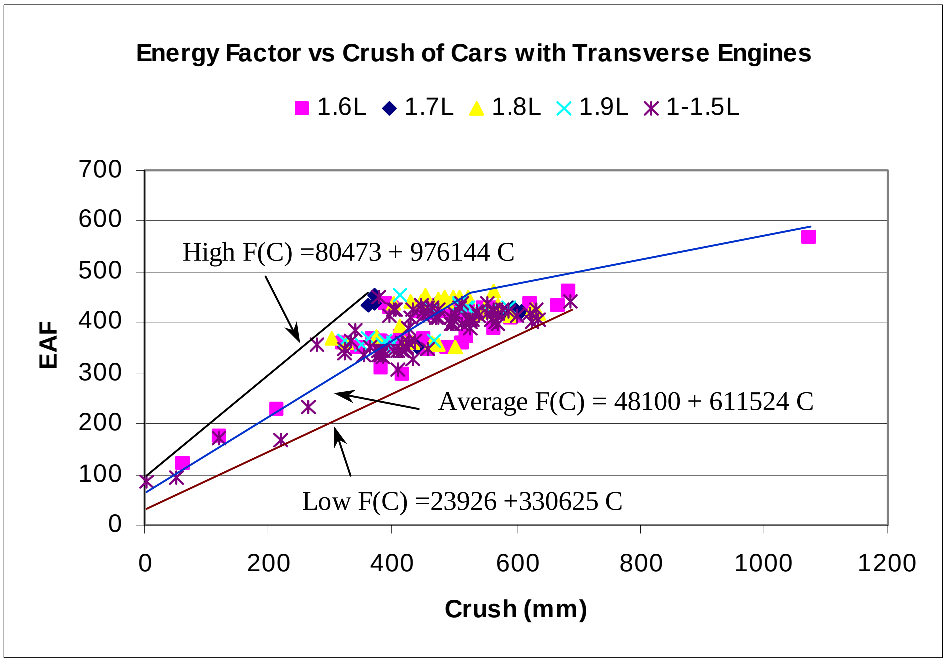

Figure 23. ***EAF*** **vs crush of cars with a 4-cylinder transverse engine (1.0L~1.9L) and its data band.**

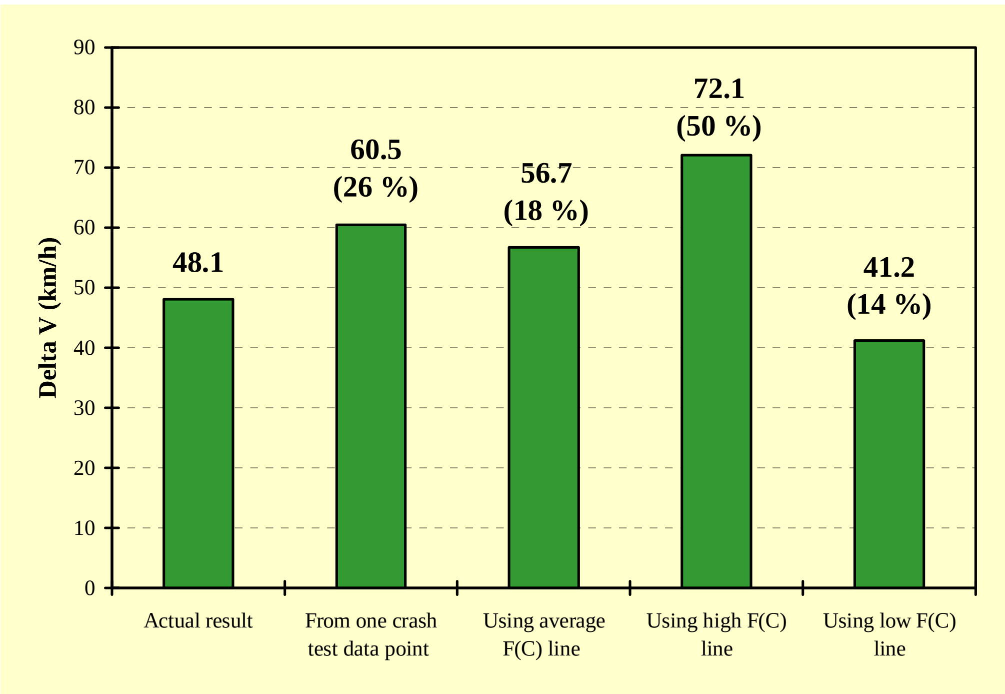

Figure 24. Comparison of the actual Delta *V* and predicted Delta *V* using different *F*(*C*) lines.

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