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16. Abstract

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With regard to accuracy, CRASH with one exception tends to underestimate delta-V at low values of delta-V and tends to be accurate at high delta-V. The number of tests at high delta-V are small. The exception to this general result is the oblique side-impact collision in which delta-V tends to be overestimated when the direction of force is inclined more than approximately 45 degrees to the side surface normal.

Typical errors estimated by available independent data indicate that the 95 percent confidence limits on individual calculations of delta-V ranges from approximately 9 to 25 percent. Errors of 10 percent in the force-deflection coefficients were observed to result in errors of 2-5 percent in delta-V calculation.

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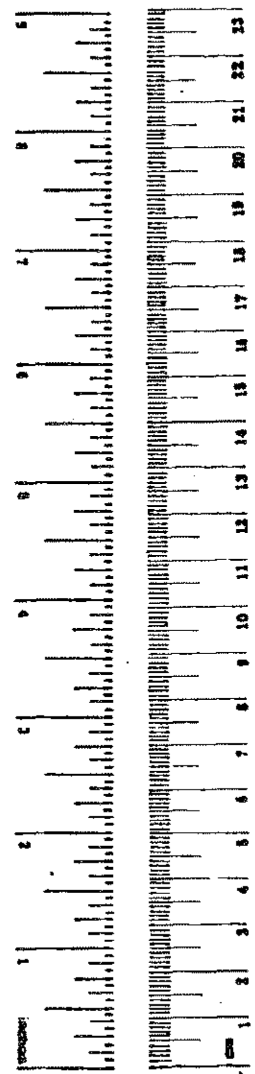
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

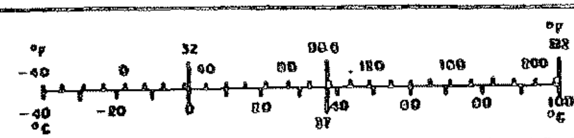
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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A	Coefficient in force-deflection relation, F=A+Bx (Eqn. 2)
B	Coefficient in force-deflection relation, F=A+Bx (Eqn. 2)
$C_1,\ldots C_6$	Deformation measurements in crush profile (Fig. 1)
D	Location of mid-point of damage length (Fig. 1)
E	Energy associated with work of deformation (Eqns. 3,4)
G	Parameter in energy Eqn. 4 ($G=A^2/2B$)
h	Moment-arm of average impact force about vertical axis through vehicle center-of-mass (Fig 2).
k	Radius of gyration about vertical axis through the vehicle center-of-mass
L	Length of damage profile (Fig. 1)
m	Vehicle mass
α	Angle between average impact force and the normal to damaged side (Fig. 2)
γ	Non-central impact parameter defined by Eqn. 6
ΔV	Delta-V, magnitude of velocity change experienced during impact (See Eqn. 1)
σ	Standard deviation of a normal distribution
2σ	95 percent confidence limits of a normal distribution.

ABSTRACT

The accuracy and sensitivity of the CRASH computer program in computing delta-V are examined. Accuracy is related to how well CRASH performs in comparison with results from 53 independent staged collisions. Sensitivity is related to how estimated field errors or imprecision results in imprecision in the computation of delta-V. The sensitivity to error in the coefficients of the force-deflection relationship is examined.

With regard to accuracy, CRASH with one exception tends to underestimate delta-V at low values of delta-V and tends to be accurate at high delta-V. The number of tests at high delta-V are small. The exception to this general result is the oblique side-impact collision in which delta-V tends to be overestimated when the direction of force is inclined more than approximately 45 degrees to the side surface normal.

Typical errors estimated by available independent data indicate that the 95 percent confidence limits on individual calculations of delta-V ranges from approximately 9 to 25 percent. Errors of 10 percent in the force-deflection coefficient were observed to result in errors of 2-5 percent in delta-V calculation.

INTRODUCTION

Beginning in the late 1970's, a method was introduced in the reporting of accident investigation results that attempted to measure the "severity" of a crash by estimating the velocity change experienced by the vehicle during the short duration impact. Generally speaking, the purpose of obtaining such a measure was to improve the ability to estimate the likelihood of injury once a crash occurred. It was known that parameters such as vehicle damage, seat belt use, seat position, and occupant age were important factors in predicting injury; however it was recognized from physical principles that a measure or surrogate measure for the acceleration or impact force was desirable. The delta-V or velocity change during impact is closely related to the impact force and it can be conveniently estimated in many impact types. To accomplish the reporting of delta-V, a simple computer code was developed that was generally applicable to head-on, side and rear impacts. The result has been called the CRASH computer program [1]*. CRASH was developed to provide "estimates" of delta-V rather than to provide a definitive alternative to laboratory measurement of accelerations. In this sense it best serves as a source for categorical classification of a large number of accident-involved vehicles into strata based on severity of impact. Any single or individual case must always be treated with caution and subjected to careful accident reconstruction before accepting CRASH results as one would accept careful instrumentation results obtained in staged collisions.

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* Numbers in brackets refer to references listed at the end of the report, p. 53

In its most common usage, the CRASH program algorithm computes the delta-V on the basis of estimates by the field investigator of the vehicle mass, deformation and direction of principal force. This is sometimes referred to as the "damage-only" option in the CRASH algorithm, in contrast to the "trajectory" option which computes the delta-V by more traditional concepts of vector algebra using the equation for conservation of linear momentum.*

The advantage of the "damage-only" option is that only data from observation and measurement of the vehicles are required to execute the program. In contrast, the "trajectory" option requires substantial scene evidence that is difficult to obtain in many accidents. The discussion herein is limited to the "damage-only" option because it is the one utilized most commonly in accident investigation work sponsored by the National Highway Traffic Safety Administration (NHTSA).

In the application of this methodology, two general sources of error are manifest. Herein, one is called "sensitivity," and the other, "accuracy." By "sensitivity" is meant a recognition that imperfect measurement of the field observations leads to error or imperfect estimation of the desired parameter, delta-V. In this presentation, a quantitative measure of sensitivity is

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* In cases where there is 10 degrees or less difference in the directions of the estimated impact speed vectors of two colliding vehicles, the trajectory option uses the damage data for delta-V estimation, because the small angle results in inordinately large errors when using vector algebra alone.

defined in terms of 95 percent confidence limits and results are presented that aid any analyst or investigator in understanding the degree to which field measurements contribute to error in delta-V. By "accuracy" is meant the measure of comparison between a predicted delta-V and the true delta-V, assuming no imperfection in field measurement is introduced. By utilizing a number of staged collision results, data are presented that illustrate the possible occurrence and magnitude of inaccuracy in the CRASH algorithm.

SENSITIVITY

Early in the field application of the CRASH algorithm, the question of the sensitivity of the computed delta-V to field measurement was examined. A controlled field experiment was executed [2], the approach to which is presented in Appendix B. It is sufficient here to note that the difference in delta-V resulting from 34 pairs of independent investigations of field data was obtained in this experiment. The 95 percent confidence limits on this error distribution were approximately ± 25 percent, and its mean was near zero. This was considered acceptable for the circumstances existing with field data collection involving detailed measurements of damaged vehicles. The 34 computations for delta-V were based on 21 actual cases involving single and two-vehicle crashes, and included head-on, side, and rear-end accidents. Nevertheless, this selection of cases and the results did not provide the breadth of accident type or range of severity in delta-V necessary to estimate the sensitivity that exists in a large unbiased selection of accidents obtained in an accident sampling program. This paper addresses the problem of estimating sensitivity from a selection of thousands of cases whose proportion or occurrence in the accident population is known.

First, the functional form for calculating delta-V and its relationship to field measurement must be examined. The delta-V for a vehicle in a two-vehicle crash is computed in the CRASH algorithm by the relation

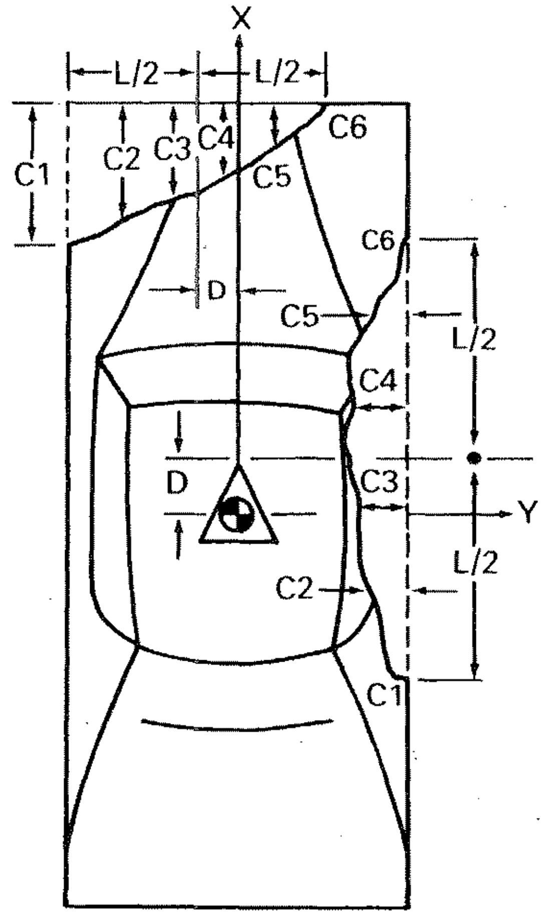
$$\Delta V_1 = \sqrt{\frac{2\gamma_1 (E_1 + E_2)}{m_1 \left(1 + \frac{\gamma_1 m_1}{\gamma_2 m_2}\right)}} \qquad (1)$$

where the subscript "1" indicates the vehicle for which delta-V is computed and "2" indicates the other crash-involved vehicle. (The relation is valid for certain single-vehicle impacts. For example, it is valid in a barrier crash for which $m_2 \rightarrow \infty$ and $E_2 = 0$.) In Eqn. (1), the variables are defined by:

E_1, E_2	energy absorbed in deformation of vehicles 1 and 2 respectively
m_1, m_2	masses of vehicles 1 and 2 respectively
γ_1, γ_2	non-central impact factor associated with the occurrence of impact force moments about the center-of-mass of vehicles 1 and 2 respectively.

The detailed derivation of this relation can be found in Reference [1]. It will not be reviewed further here, but it is important to review carefully the factors contributing to the computation of the energy of deformation, E, and the non-central impact factor, γ, because there are numerous ways in which field observations contribute to error in these terms.

Figure 1. Damage Dimensions



Frontal Damage: D >0 Right of Centerline
Side Damage: D>0 Fore of C.G.

Computation of Energy, E

The energy of deformation is computed under the assumption that the force-deflection characteristic of the vehicle is represented by a relation

$$F = A + Bx \tag{2}$$

where F is the force per unit width and the coefficients A, B depend upon the particular vehicle and area of damage. For practical purposes these coefficients have been grouped according to vehicle size categories (e.g., subcompact and intermediate) and according to area of damage (e.g., front, side and rear). The deformation itself, x, is not uniform, but is a "profile of damage", expressed generally by a series of six deformation measurements, whose location and orientation on the vehicle are described in Figure (1). The energy of deformation for a particular vehicle can be obtained by integrating the force-deflection relation, Eqn. (2), over the damage profile, assuming this profile is uniform in the vertical direction and the deformation is normal to the surface. Thus, for a force acting normal to the surface,

$$E_N = \int F \, dx \, d\ell \tag{3}$$

Where x is the deformation depth and ℓ is the length over which the damage occurs. Using the notation described in Figure (1) and the trapezoidal approximation to area within the profile, one obtains the following [1]:

$$E_N = \frac{L}{30}\Big[3A(C_1 + 2C_2 + 2C_3 + 2C_4 + 2C_5 + C_6) + \cdots$$
$$\cdots + B(C_1^2 + 2C_2^2 + 2C_3^2 + 2C_4^2 + 2C_5^2 + C_6^2 + \cdots \tag{4}$$
$$\cdots + C_1C_2 + C_2C_3 + C_3C_4 + C_4C_5 + C_5C_6) + 30G\Big]$$

where G is a constant of integration that represents physically the amount of energy absorbed in an impact with no residual crush. (It can be shown [3] that if residual crush is used in Eqn. (1), the constant of integration $G=A^2/2B$). The parameters A, B and G are obtained from independent crash testing of vehicles, while the parameters C_1, C_2.....C_6 and L are obtained by measuring observed vehicle damage.

Another important factor contributing to the estimation of the deformation energy, E, is the line of action of the forces causing the deformation. One assumption implicit in the result of Eqn. (4) is that the forces producing the deformation act normal to the surface. In actual impacts these forces are inclined generally to the surface normal by an angle, α. In Ref. [1] it was shown that the energy associated with deformation by a force inclined at the angle α from the normal is

$$E = (1 + \tan^2\alpha)\, E_N \tag{5}$$

where E_N is defined by Eqn. (4). The lines-of-action of the forces causing the deformation are in fact variable during the impact event and over the area of impact. An average direction must be estimated by the investigator based on observing the damage and impact orientation of both vehicles. This is called the direction of principal force.

Thus, the energy estimated from vehicle damage is dependent on the accuracy and measurement of a number of parameters that can be classified into two categories. One category, including the coefficients A, B and G, is composed of parameters assumed to be representative of the vehicle size and area of its damage. The investigator or field observer does not alter these values, but may place a vehicle into an inappropriate size class. The second category of parameters are those that depend directly on measurement or estimation by the investigator. Included in this category are the crush measurements, C_1, $C_2 \ldots C_6$, the length measurement, L, and the estimation of the direction of force, α, measured relative to the surface normal. In this discussion the influence of the coefficients A, B and G is treated under "accuracy" and the influence of the field measurements of deformation and force direction is treated under "sensitivity."

Computation of Non-Central Impact Factor, γ

The non-central impact factor, γ, is determined by the relation

$$\gamma = \frac{k^2}{k^2 + h^2} \qquad (6)$$

where

k= radius of gyration of the vehicle about a vertical axis through the center of mass.

h= moment arm of the line-of-action of the average force about a vertical axis through the vehicle's center-of-mass.

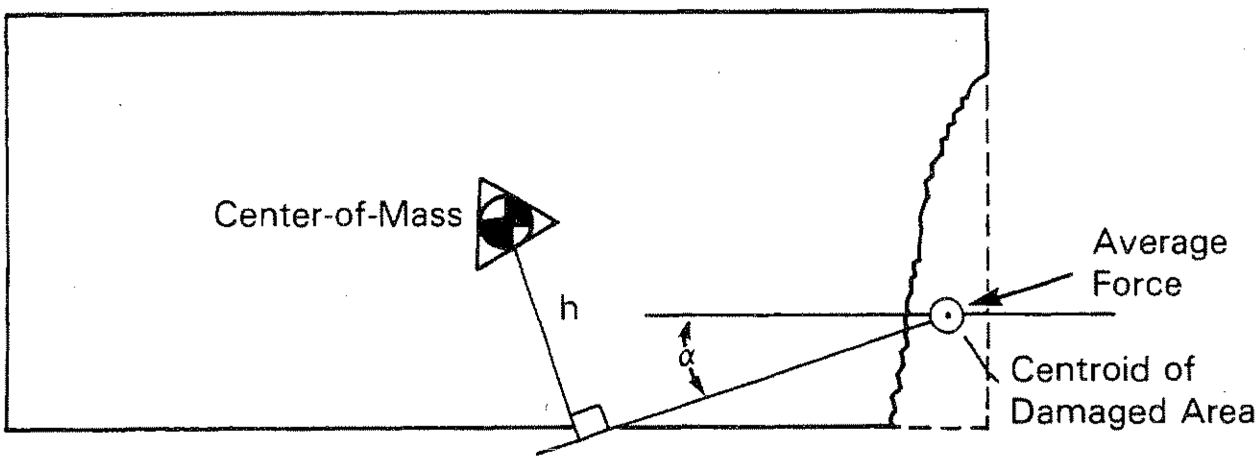
Although every vehicle has a unique radius of gyration, for practical reasons the CRASH algorithm assumes k is constant over a size class of vehicles, and values stored in the algorithm are used for the given vehicle size class in a manner similar to the coefficients A and B discussed under the estimation of the energy term E.

The moment arm, h, depends upon the shape and location of the damage profile and upon the line-of-action of the force vector. The force itself is assumed to act through the centroid of the damage area (See Figure 2). The moment arm is calculated by the CRASH algorithm using measured data entered into the program by the investigator and stored vehicle parameters.

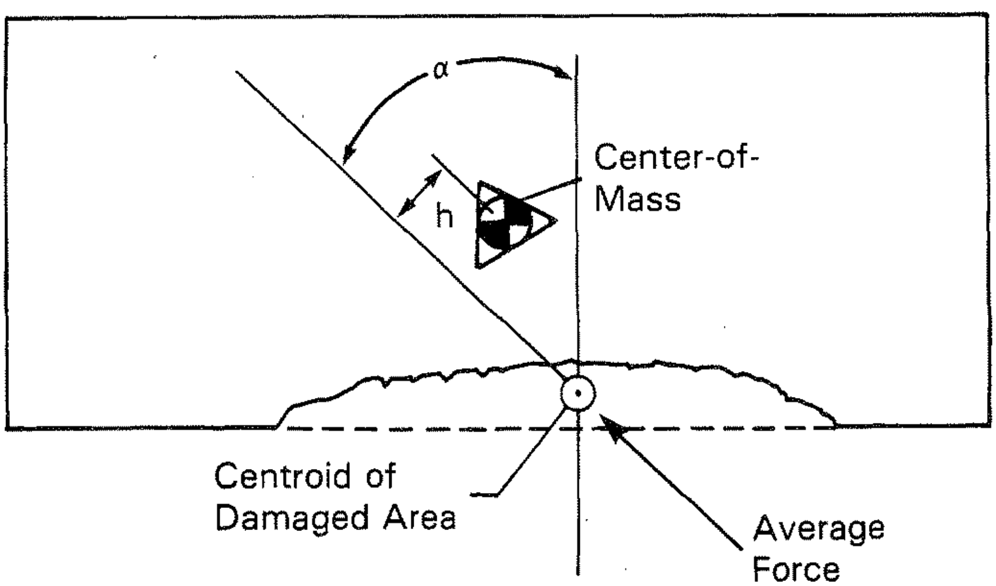
Estimation of Vehicle Mass, m

In addition to the energy of deformation, E, and the non-central impact factor, γ, the delta-V as obtained in Eqn.(1) is influenced by the

Figure 2. Front- and Side-Damaged Vehicle Damage Parameters



(a) Front-Damaged Vehicle



(b) Side Damaged Vehicle

investigator's estimate of vehicle mass. Although the mass could be placed in a vehicle-class category as is done with the radius of gyration, the practice is to estimate the mass using tables for curb weight and adding to this the weight of the occupants and any known cargo weights.

With regard to this practice, it is noted that the vehicle, its occupants and other cargo combine to form a system. The occupants and cargo may not be rigidly connected to the vehicle structure, and they consequently may not contribute directly to the total system momentum as a true single lumped mass. Even restrained occupants are connected to the vehicle by a linkage (restraint) with elastic and inelastic properties. The effect of this coupling is ignored in the assumption that they contribute directly to the system lumped mass. It is assumed that unrestrained occupants and cargo very quickly impact the interior vehicle surface during a collision event, and thereafter behave as an integral part of the system lumped mass. The error introduced by these assumptions is not considered here, although it is believed to be quite small for cargo and occupants whose mass constitutes less than 10 percent of the system lumped mass. Of course, if one is studying the forces and accelerations sustained by the occupants or the cargo, this simplified lumped mass approach is clearly invalid.

Calculation of Sensitivity

As discussed briefly in the Introduction, sensitivity herein refers to the circumstance in which imperfect field measurement leads to error in delta-V. It is assumed further that these measurements are normally distributed about a mean. The effect of imperfect measurements can lead to an error in any one delta-V calculation; however, the effect of a large number of measurements for any delta-V calculation is to produce a normal distribution about a mean value. This distribution could be described by the mean itself and the standard deviation or variance of the distribution. We do not have the opportunity of repeating the measurement process independently a number of times for each desired delta-V; consequently the mean value and the confidence limits of this mean value are estimated from a field experiment including independent pairs of measurement. One can then observe how these confidence limits in measurement of crush depth, length, and location, direction of force and estimation of vehicle mass each contribute to the confidence limits.

Consider delta-V to be a multi-dimensional function of the variables C_1, $C_2 \ldots C_6$, L, γ, α, and m*. The functional form of

$$\Delta V = F(C_1, C_2 \ldots\ldots C_6, L, \gamma, \alpha, m)$$

will itself determine how these errors in the measurements create an error in delta-V.

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* We include the parameter, γ, and the mass, m, in the category of field measurements because they are estimated on the basis of field observation.

If a function, F, is dependent upon a group of variables, x_1, x_2, x_3.....x_n, then

$$F = F(x_1, x_2 \ldots\ldots x_n)$$

and the total differential of F is represented by

$$dF = \frac{\partial F}{\partial x_1} dx_1 + \frac{\partial F}{\partial x_2} dx_2 + \cdots\cdots\cdots \frac{\partial F}{\partial x_n} dx_n$$

Assuming the differential quantities to be incremental values of the variables themselves, these differential or incremental values can be interpreted as field measurement "errors." The total differential becomes an expression that demonstrates how each individual variable, x_n, can contribute to the total error in F. Effectively, the partial derivatives become weighting functions which, when applied to the respective errors, sum to the total error.

The total error is not as much of interest here as its standard deviation and variance. It can be shown [4] that, if the individual measurement errors are uncorrelated with one another , the variance of the function, F, can be expressed by

$$\sigma_F^{\,2} = \sigma_{x_1}^{2}\left(\frac{\partial F}{\partial x_1}\right)^2 + \sigma_{x_2}^{2}\left(\frac{\partial F}{\partial x_2}\right)^2 + \cdots\cdots \sigma_{x_n}^{2}\left(\frac{\partial F}{\partial x_n}\right)^2$$

and that the 95 percent confidence limits are

$$2\sigma_F = \sqrt{\left(2\sigma_{x_1}\frac{\partial F}{\partial x_1}\right)^2 + \left(2\sigma_{x_2}\frac{\partial F}{\partial x_2}\right)^2 + \cdots\cdots\cdots \left(2\sigma_{x_n}\frac{\partial F}{\partial x_n}\right)^2}$$

Thus, the 95 percent confidence limits for F can, in effect, be found from the RMS sum of the 95 percent confidence limits of the individual errors weighted by the respective partial derivatives.

In the case of delta-V, expressed by Eqn.(1), then the precision or 95 percent confidence limit of a calculation of delta-V is

$$2\sigma_{\Delta V_1} = \sqrt{\left(2\sigma_{E_1}\frac{\partial \Delta V_1}{\partial E_1}\right)^2 + \left(2\sigma_{E_2}\frac{\partial \Delta V_1}{\partial E_2}\right)^2 + \left(2\sigma_{m_1}\frac{\partial \Delta V_1}{\partial m_1}\right)^2 + \cdots + \left(2\sigma_{m_2}\frac{\partial \Delta V_1}{\partial m_2}\right)^2 + \left(2\sigma_{\gamma_1}\frac{\partial \Delta V_1}{\partial \gamma_1}\right)^2 + \left(2\sigma_{\gamma_2}\frac{\partial \Delta V_1}{\partial \gamma_2}\right)^2} \qquad (8)$$

The various derivatives in Eqn. (8) are readily determined by appropriate differentiation of Eqn. (1); however, what is required is the evaluation of Eqn. (8) in terms of the field measurements which were discussed above.

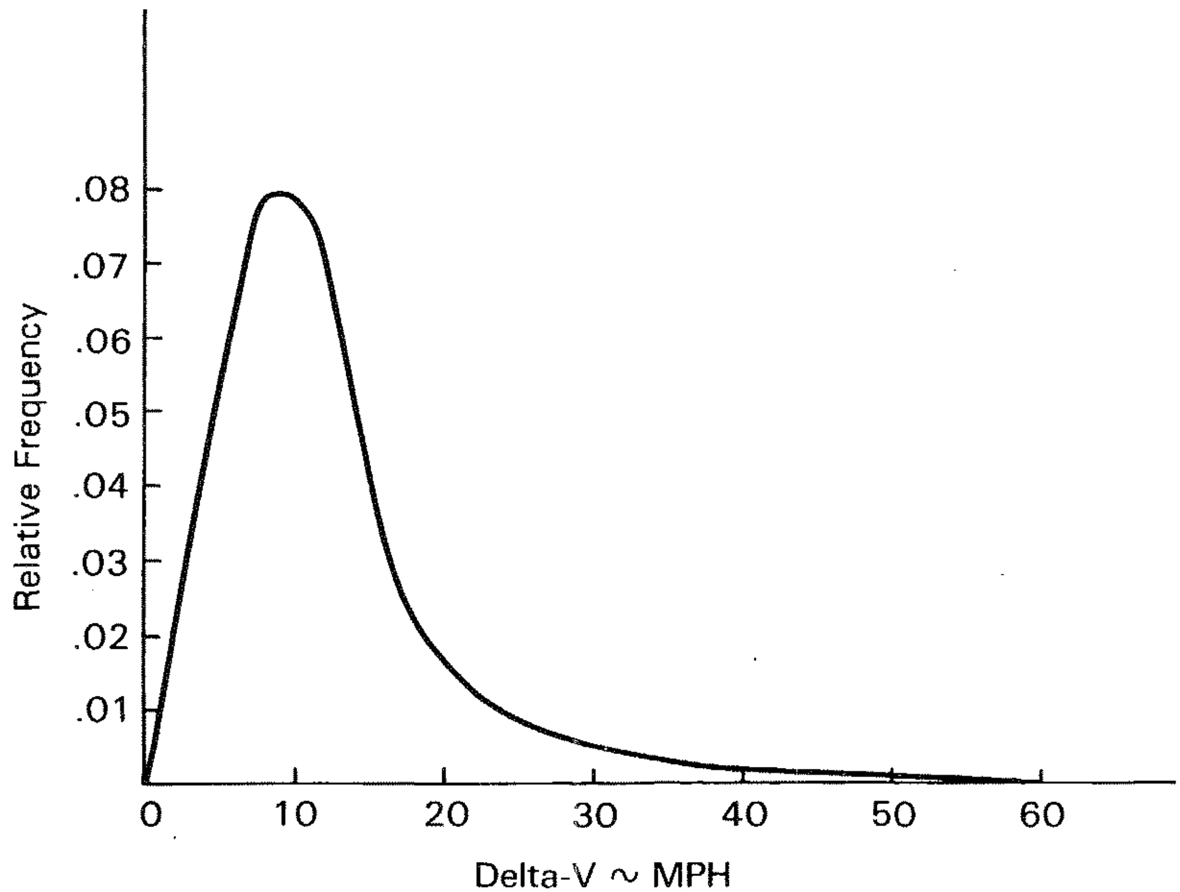
The calculation of the confidence limits for a single delta V estimate is based on the procedure of first evaluating the confidence limits for the energy, E, the non-central impact factor, γ, and the field measurement of C_1, C_2, C_3- - -C_6, L, and α.

Then the sensitivity or confidence limits for delta-V is obtained subsequently by evaluating Eqn. (8). The formulae used in this procedure are presented in Appendix A. The determination of the confidence limits on the field measurements was made from the results of comparative field measurements conducted independently [2] on 34 damaged vehicles, the details of which are presented in Appendix B.

Precision of the Distribution Function of Delta-V

A method for determining the sensitivity, described in terms of a 95 percent confidence limit, of a particular estimate for delta-V has been discussed. It is of further interest to consider how this affects a frequency distribution of delta-V calculations. In particular, what are the confidence limits on a distribution function of delta-V determined by the CRASH algorithm and field measurements. This will be called the "precision of the distribution function for delta-V." The distribution function itself, intended to represent the accident population rather than a single crash event, is determined from data collected in the National Crash Severity Study [5]. It is described in Fig. (3). Although the shape is unremarkable, certain quantitative features are important. Any one interval of delta-V necessarily contains a variety of crash modes or conditions that includes both single and multi-vehicle impacts, as well as impacts involving front, side and rear damage. Indeed, such as in Ref. [5], distribution functions for different crash modes can be illustrated. The precision of this function will be estimated at two intervals of delta-V, giving due consideration to the various crash configurations. One interval is over the range 10-15 mph (16-24 kph), chosen

Figure 3. Frequency Distribution for Delta-V (All Crash Modes)



because it includes the delta-V range at which non-minor injury begins to occur. The second delta-V interval is over the range 25-30 mph (40-48 kph), chosen because it includes a region of crash severity that results more frequently in serious or life threatening injury.

Within each interval of delta-V, the number of vehicles contributing to the function was determined for a variety of impact types. A total of nine impact types and the frequency of observations obtained from the National Crash Severity Study file are identified in TABLE 1. If each impact type is denoted by a subscript, i, for identification, then

N = total number of vehicles in a given delta-V range

n_i=total number of vehicles in a specific impact-type in a given delta-V range. ($i = 1, 2, 3 \ldots\ldots\ldots\ldots 9$)

$$N=n_1+n_2+n_3+\ldots\ldots\ldots\ldots n_i+\ldots\ldots\ldots n_9$$

The precision (using 2 σ confidence limits) for a particular range in delta-V is then obtained by a weighted average of the confidence limits for each impact type. The precision of delta-V for each impact type was determined by choosing a "median" impact in each cell. If the delta-V range was 10-15 mph,

TABLE 1

NUMBER OF DELTA-V OBSERVATIONS CONTRIBUTING TO DISTRIBUTION FUNCTION AT HIGH (25-30 MPH) AND LOW (10-15 MPH) DELTA-V

IMPACT TYPE	HIGH DELTA-V 25-30 MPH (40-48 KPH)	LOW DELTA-V 10-15 MPH (16-24 KPH)
TWO-VEHICLE ACCIDENTS:		
Front-Front (n_1)	199	1094
Front-Side (n_2)	76	1688
Side-Front (n_3)	99	1659
Back-Front (n_4)	15	282
Front-Back (n_5)	7	762
SINGLE VEHICLE ACCIDENTS:		
Front-Fixed Object (n_6)	126	1187
Side-Fixed Object (n_7)	18	124
Other-Fixed Object (n_8)	1	6
Other Single Vehicle (n_9)	29	142
TOTALS (N)	570	7044

the median delta-V was taken as 12-13 mph, and if the range was 25-30 the median delta-V was 27-28 mph. For vehicles in head-on or rear-end accidents the median direction-of-force was observed to be 12 o'clock or 6 o'clock, respectively. For vehicles in side-damage accidents, the striking or front-damaged vehicle had a median direction of force of 11 o'clock or 1 o'clock, and the side-damaged vehicle had a median direction of force of 10 o'clock or 2 o'clock depending on the side of the vehicle sustaining damage. The above intervals for defining a "median" crash typcially identified more than one vehicle in each interval. When this occurred, a random selection among the vehicles so identified was performed.

In this manner for each of the two delta-V classes, a total of 9 impacts were identified, each impact being representative of a number of impacts in a given crash configuration. The number of impacts in each configuration is specified in Table 1. Using the technique described above by Eqn. (8), the confidence limits for the delta-V in each impact-type were determined. The particular NCSS case, identified by case number, the impact type and delta-V interval it represents, and the resulting confidence limits are given in TABLE 2. The weighted average, which is considered the precision of the distribution in this delta-V interval, is also presented in Table 2. The weighted average is simply calculated by

$$(2\sigma_{\Delta V})_{AVE} = \frac{1}{N}\sum_{i=1}^{9} n_i \, 2\sigma_{\Delta V_i}$$

TABLE 2
RESULTS OF SENSITIVITY COMPUTATIONS FOR SELECTED IMPACT TYPES

IMPACT TYPE	HIGH DELTA-V 25 - 30 MPH NCSS Case Number	HIGH DELTA-V 25 - 30 MPH Sensitivity* 95 Percent Confidence Limits	LOW DELTA V 10 - 15 MPH NCSS Case Number	LOW DELTA V 10 - 15 MPH Sensitivity* 95 Percent Confidence Limits
TWO-VEHICLE ACCIDENTS:				
Front - Front (n_1)	5804055	.095	3701027	.141
Front - Side (n_2)	5701001	.144	3809003	.191
Side - Front (n_3)	3703017	.204	6704021	.230
Back - Front (n_4)	4808096	.092	1808039	.163
Front - Back (n_5)	6902043	113	1703028	133
SINGLE VEHICLE ACCIDENTS:				
Front - Fixed Object (n_6)	6809059	.168	2804013	.163
Side - Fixed Object (n_7)	7701011	.090	3712005	.147
Other - Fixed Object (n_8)	6801056	.247	3804041	.161
Other Single Vehicle (n_9)	1806057	.092	6803049	.254
MEAN		.137		.178

*Expressed as fraction of the delta-V

In seven of the nine impact types defined, the sensitivity was less at high delta-V than at low delta-V. In one impact type there was no significant change, and in the remaining category, the sensitivity increased. There were only seven impacts in this latter impact configuration (of a total of 7,614 impacts), thus it is not representative of many crashes. It is not surprising to observe that, in general, the sensitivity is reduced at high delta-V. This is explained by the effect of crush and the effect of direction-of-force on sensitivity. First, with respect to crush, the relative error due to field measurement is reduced at high delta-V because the actual or absolute error is treated as a constant (see Appendix B) over the entire range of crush. Consequently, the relative error is reduced at the higher values of crush or deformation. Second, the contribution of field error in direction-of-force measurement is smaller at higher delta-V because at increased levels of deformation, the assumed error in the direction-of-force produces a smaller error in the non-central impact parameter, γ. This is true because at increased values of crush, the centroid of the damaged region is closer to the vehicle center-of-mass, and as a result the moment-arm (h) of the direction-of-force is smaller. It is clear from the definition of the non-central impact parameter γ in Eqn. (6), that errors in the moment arm will likely result in smaller errors to γ when the moment arm is reduced.

Relative contributions to sensitivity in delta-V from the various field measurements are exhibited in Table 3. The largest contribution to the confidence limits for a particular delta-V is generally attributable to sensitivity in field measurement (or estimation) of α, which defines the

TABLE 3
CONTRIBUTION TO SENSITIVITY FROM VARIATION IN FIELD MEASUREMENT OF AVERAGE IMPACT FORCE, DEFORMATION AND MASS

	Sensitivity* (95 Percent Confidence Limits)	Percent Contribution To Sensitivity		
		Δα	Δ (CRUSH)	Δ (MASS)
HIGH DELTA-V Range (25-30 MPH) TWO-VEHICLE ACCIDENTS:				
Front-Front	.095	98	1	1
Front-Side	.144	86	10	4
Side-Front	.204	98	1	1
Back-Front	.092	97	2	1
Front-Back	.113	88	6	6
SINGLE VEHICLE ACCIDENTS:				
Front-Fixed Object	.168	46	53	1
Side-Fixed Object	.090	9	75	16
Other-Fixed Object	.247	94	4	2
Other-Single Vehicle	.092	45	52	3
MEAN**	.137	79	19	2
LOW-DELTA-V RANGE (10-15 MPH) TWO-VEHICLE ACCIDENTS:				
Front-Front	.141	97	2	1
Front-Side	.191	85	13	2
Side-Front	.230	96	3	1
Back-Front	.163	98	1	1
Front-Back	.133	41	54	5
SINGLE-VEHICLE ACCIDENTS				
Front-Fixed Object	.163	14	85	1
Side-Fixed Object	.147	11	88	1
Other-Fixed Object	.161	79	20	1
Other-Single Vehicle	.254	72	28	1
MEAN**	.178	70	28	2

* Expressed as a fraction of the delta-V
** Weighted by the populaton distribution in Table 1

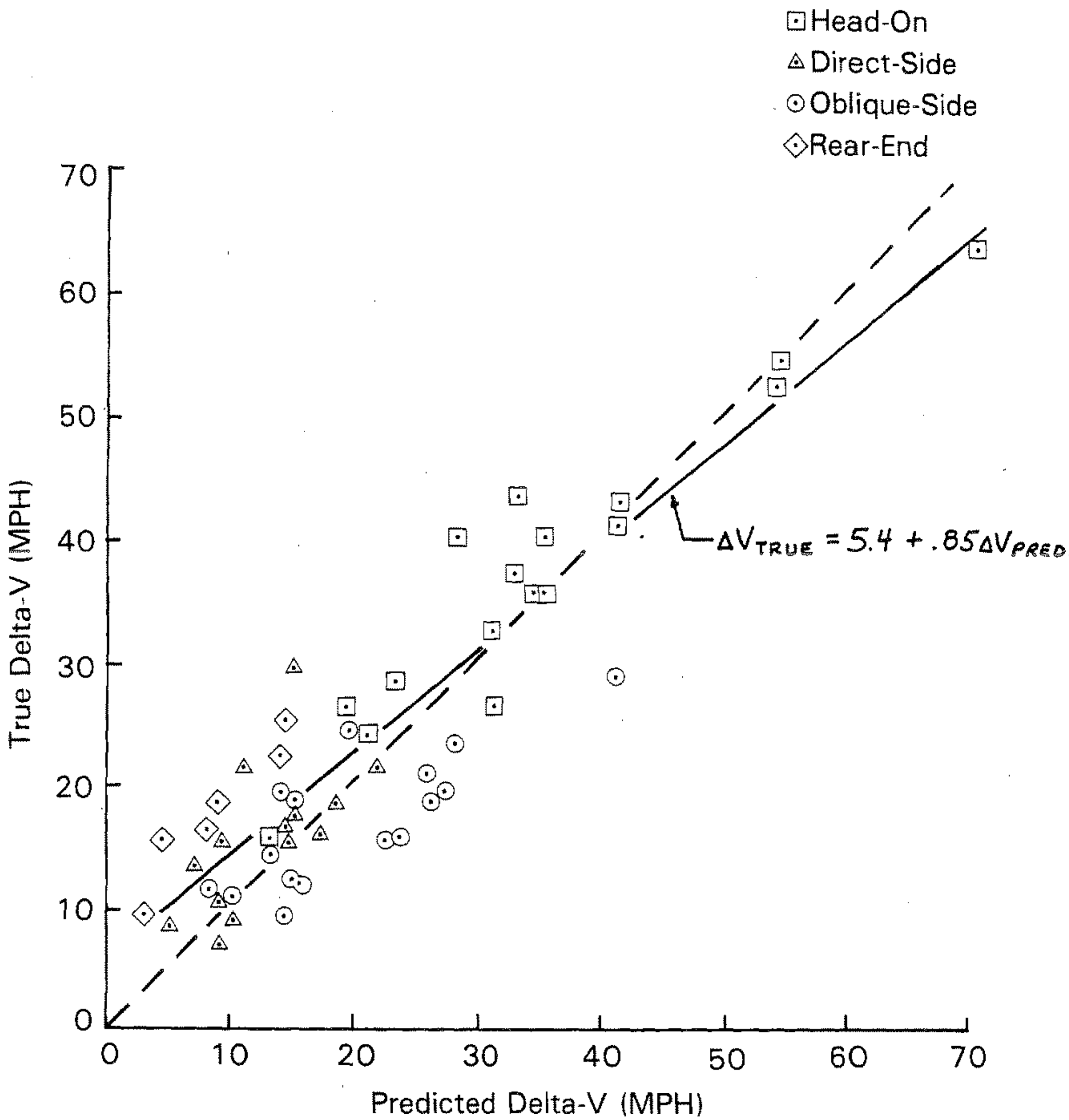
line-of-action of the average impact force. Based on the sensitivity confidence limits computed for high delta-V and for low delta-V, the contribution for error in delta-V from errors in the direction of the average impact force is 3 to 4 times that from errors in crush measurements. The contribution from variation in estimates of mass is very low and in only one instance of the 18 cases studied did it exceed 6 percent.

ACCURACY

Although it is reasonable to assume the field measurements are normally distributed about some mean as done above in the discussion of sensitivity and precision, it is clear that this mean is not necessarily the true value. There are numerous potential errors that can cause the resulting mean delta-V to be in error or different from the true value. These include conceptual (or even algebraic) errors in the CRASH algorithm. Errors of this type may be "discovered" and then corrected, but for practical purposes they must be recognized as potential yet undiscovered error that can produce a biased or erroneous mean value. In addition, certain coefficients or parameters in the CRASH algorithm are not based on the investigators field measurement, but are based on estimated class or categorical values. These estimated values are intended to be the best possible estimate within the limited resources devoted to their determination. As discussed earlier these would include the estimates of vehicle deformation characteristics expressed by the coefficients A and B in Eqn. (2), and the radius of gyration value used in the estimation of the non-central impact parameter γ. These coefficients may be erroneous for the vehicles involved. Considering the possibility of such errors, an expression of accuracy is needed to assess the reliability of the mean itself. This is accomplished herein by examining results of a number of staged collisions where conditions are controlled and sufficient instrumentation is available to make an independent computation of the delta-V that is considered the "true" delta-V. Such a calculated result will be subject to field or investigator error; however, we can minimize this by relying on the controlled nature of the staged crash to achieve virtually perfect field observation. This "true" or actual delta-V can be compared with the calculated delta-V obtained by the CRASH algorithm. The difference between the actual delta-V and the CRASH-computed delta-V is considered to be an expression of accuracy or error in the mean value.

Several sources of staged collision data were examined. The number useful for the purpose described herein are surprisingly limited due to the frequent absence of recorded data on deformation and/or delta-V. Full barrier crash data are considered insufficiently representative of real-world crashes to

Figure 4. Comparison of True Delta-V and Crash 2 Results for 53 Staged Collisions



warrant their use for this purpose. Furthermore, such barrier crashes are used extensively with selective vehicle-to-vehicle crashes to determine the vehicle stiffness coefficients, A and B in Eqn. (2). These crashes must be omitted as a basis for the determining accuracy for they are clearly not independent observations. It must be remembered also that the "true" delta-V is itself subject to an unknown uncertainty, for it must be obtained by data reduction from several sources. The chief sources used were accelerometer outputs from multiple locations in the vehicle, high speed photography and the measured vehicle impact speed.

With these restrictions, a total of 53 staged collisions were identified from which a "true" delta-V could be obtained, as well as a computed or estimated delta-V from the CRASH algorithm using measurements obtained under laboratory conditions. In addition to these results, 29 collisions staged using European cars are examined. The results of the tests used are listed with their reference source in Appendix C (U.S. data) and Appendix D (United Kingdom data).

The comparison of these true delta-V measurements with estimated or computed delta-V measurement using the U.S. data are summarized in Figure 4. Perfect agreement would result in all of the data points lying on a straight line through the origin with a 45-degree slope. The results indicate overall agreement between the predicted and true delta-V.

However, two features are striking upon observing the data presented in Figure 4. First, the results from these crashes suggest that CRASH tends to underestimate delta-V in the range of 0-30 mph where most highway crashes occur. The linear regression line for these data is (expressed in mph)

$$(\text{Delta-V})_{\text{True}} = 5.4 + .85\ (\text{Delta-V})_{\text{Predicted}}$$

This line is above the line of perfect agreement within the range of delta-V normally encountered in highway crashes.

The second feature is the variability in the data itself. This variability can be in part a consequence of the instrumentation error associated with the staged collision. Undoubtedly this is a contributing factor; however, it is more likely that a far larger part of this variability is associated with the inability of the CRASH algorithm to predict precisely the true delta-V in a specific impact. The forces produced during an impact and the resulting impulse produced are complicated transient phenomena. They involve elastic and plastic deformation, buckling and ultimate failure of strength-bearing members. The entire process is further complicated by strain-rate and dynamic buckling effects. In addition the forces are complicated by vehicle-to-vehicle interaction. This interaction produces frictional forces between two sliding vehicle surfaces that are modeled in the CRASH algorithm by the simple assumption that tangential frictional force is proportional to the force normal to the surface. Considering these phenomena, it is not surprising to observe that the simple algorithm utilized in CRASH is sometimes significantly in error.

Much the same observation is apparent upon observing in Fig. 5 the results of the British data (Ref. [7]). These data are limited to head-on collisions and collisions with offset and angled barriers. The scatter in these data is somewhat less than that exhibited in Fig. 4; however, this is likely a consequence of these data being limited to frontal impacts, and consequently being a more homogeneous set.

The data of Fig. 4 are denoted in the figure according to the type of impact or collision. It appears that the side collision modes tend to result in more variability or scatter than do other collision modes. The data associated with oblique side collisions appears to be the only circumstance in which CRASH often predicts high rather than low. (Oblique side collision refers in these data to that orientation in which the striking vehicle axis is oriented 60 degrees out of alignment with the struck vehicle axis, in contrast to direct side impact where the orientation is 90 degrees out of alignment.) In addition, the rear-end collisions, though few in number, appear to consistently predict a low delta-V in comparison to the "true" value.

In recognition of the apparent variations in error for different kinds of impacts, these data were examined in separate groups formed by grouping them according to area of damage and according to impact type. Considering only head-on impacts, Fig. 6, the error as expressed by the regression line is approximately 25 percent low at 20 mph and approximately 5 percent low at 40 mph. Above 40 mph the error is less than 5 percent; however, there are few data (5 tests) for comparison in this range. A similar observation is made by

Figure 5. Comparison of True Delta-V and Crash 2, Results for 21 British Staged Head-On, Offset, and Angled/Barrier Collisions

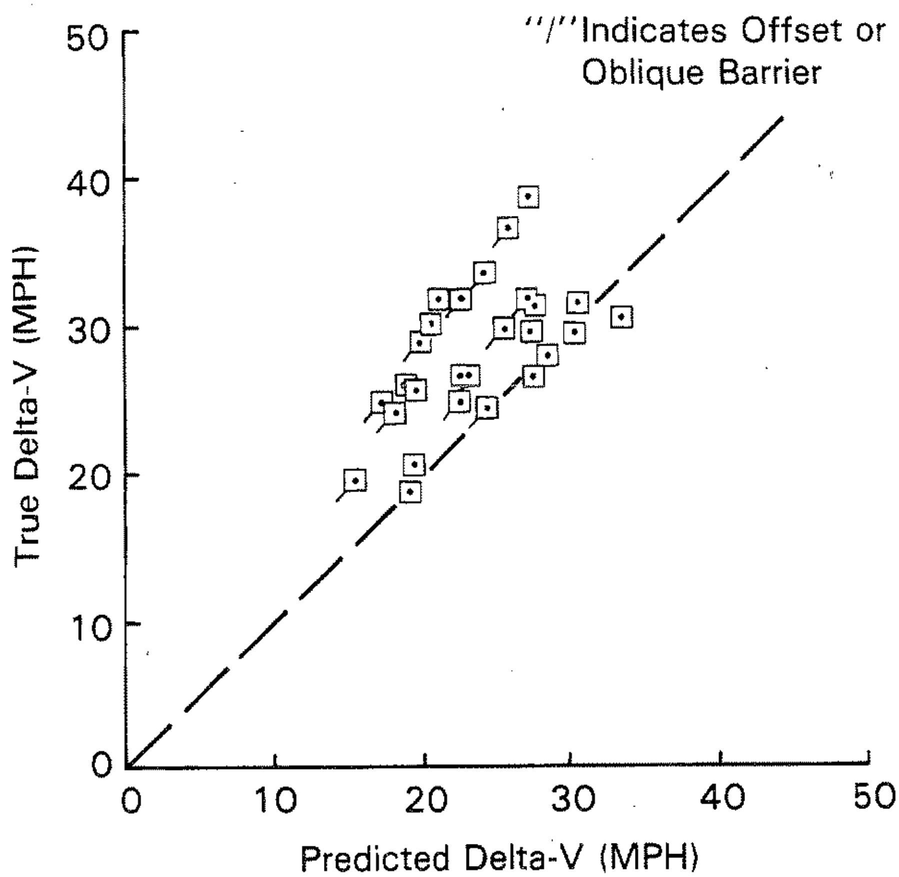
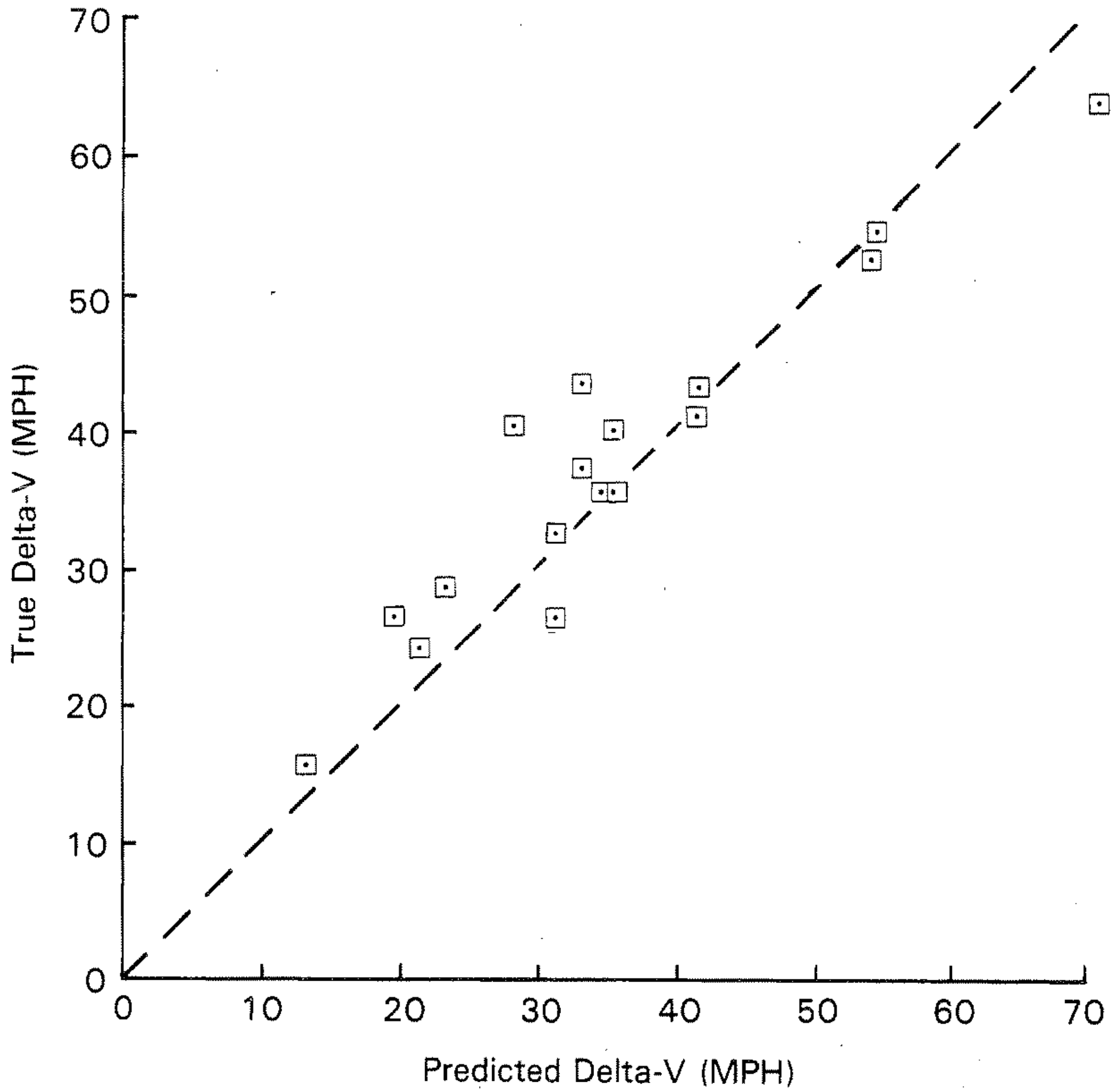


Figure 6. Comparison of True Delta-V and Crash 2 Results for Head-On Collisions



considering all front damage cases in Fig. 7. In this comparison, the error as expressed by the difference between the regression line and the line of 1-to-1 slope is reduced somewhat; however, the variability in the data is greater. The increased variability is a consequence of the inclusion of the front-damaged vehicles from side impact tests.

Consider next the cases involving side impacts (Fig. 8) and the smaller set involving only side damage (Fig. 9). Below approximately 15 mph, the data suggests that CRASH predicts low, and above 15 mph it tends to predict high for side impacts, and not surprisingly this trend is sustained for side damage cases. For delta-V above 16 mph, this trend is a consequence of the oblique side impact crashes. There are too few examples to confirm the trend exhibited which suggests that in the 20-30 mph range the oblique side impact cases are in error (high) by about 25 percent; however, the impression is clear that such impacts do tend to predict a high delta-V. Considering only direct side impacts, the side damage cases are more closely located near the line of 1-to-1 slope, albeit predicting a little low. There is one exception to this otherwise consistent trend for direct- side impacts. One case involving front damage exhibits such large error that it tends to distort the results of such a small sample size.

The data involving rear-end impacts are presented in Fig. 10. There are only three collisions, so it is easy to discriminate in this single figure the rear-end damage and the rear-end impact data which includes the front damaged

Figure 7. Comparison of True Delta-V and Crash 2 Results for Front-Damaged Vehicles

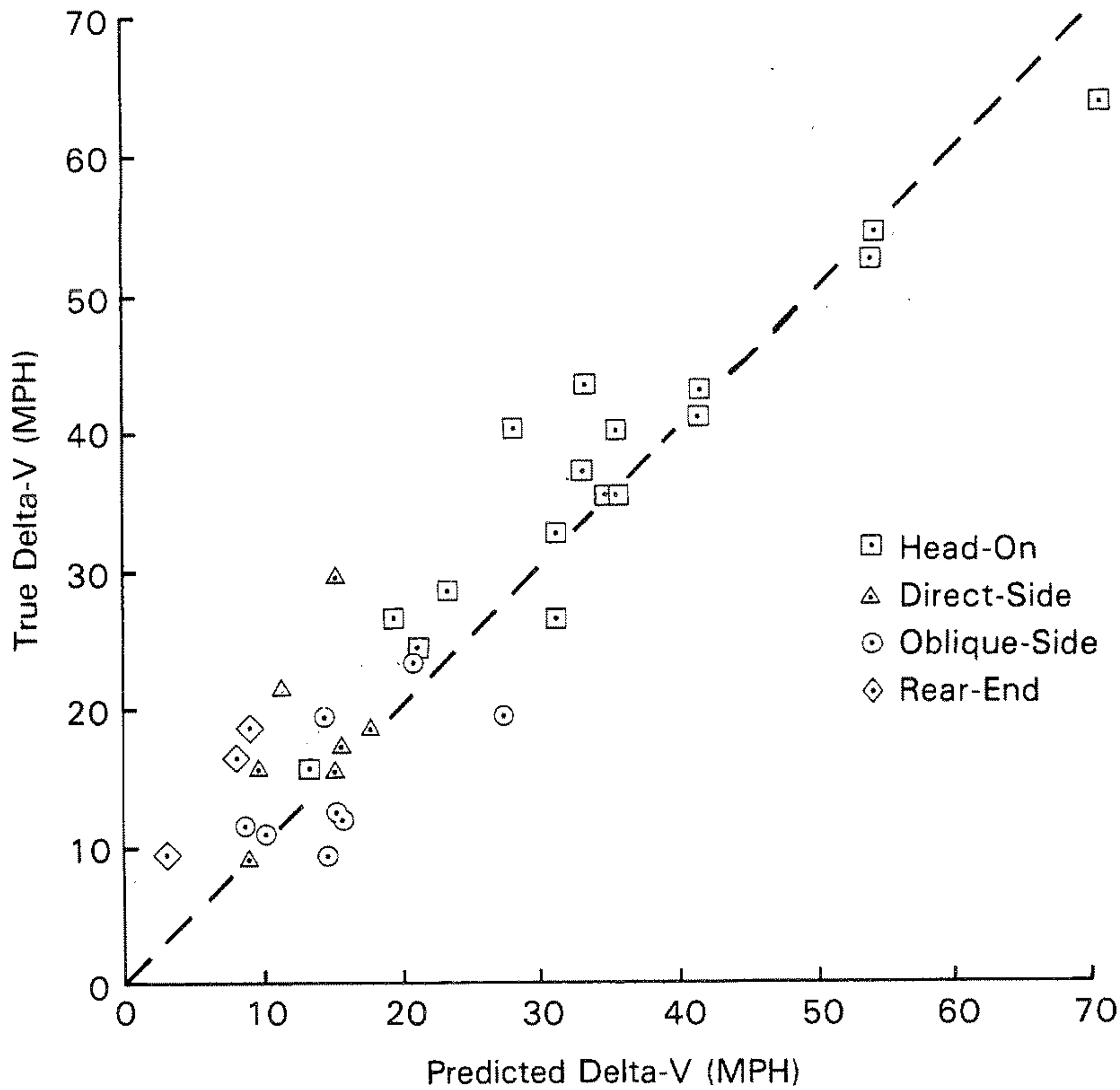


Figure 8. Comparison of True Delta-V and Crash 2 Results for Side Impact Crashes

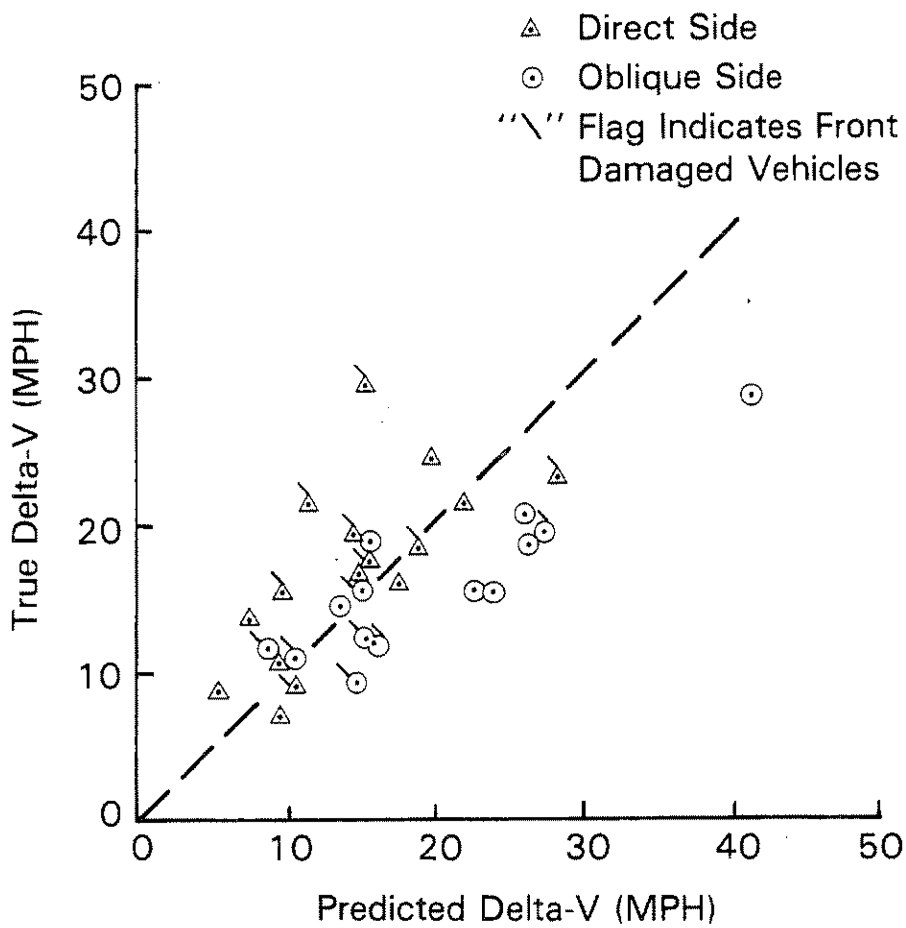


Figure 9. Comparison of True Delta-V and Crash 2 Results for Side-Damaged Vehicles

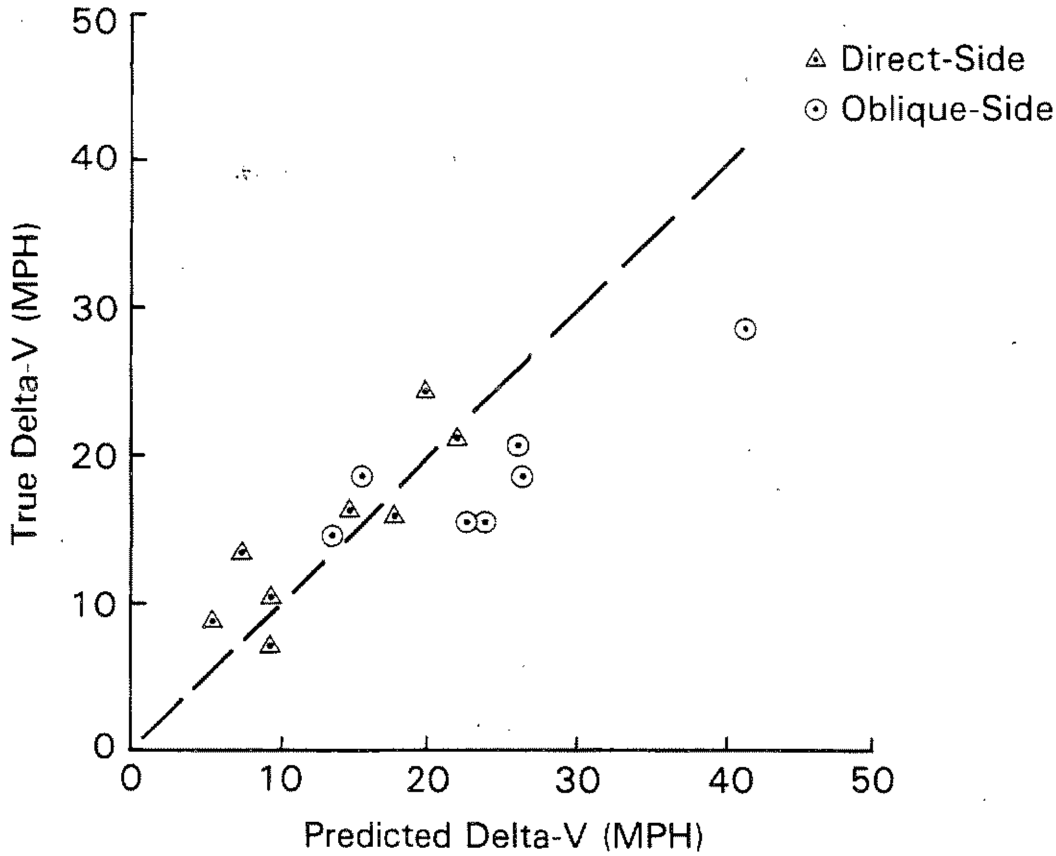
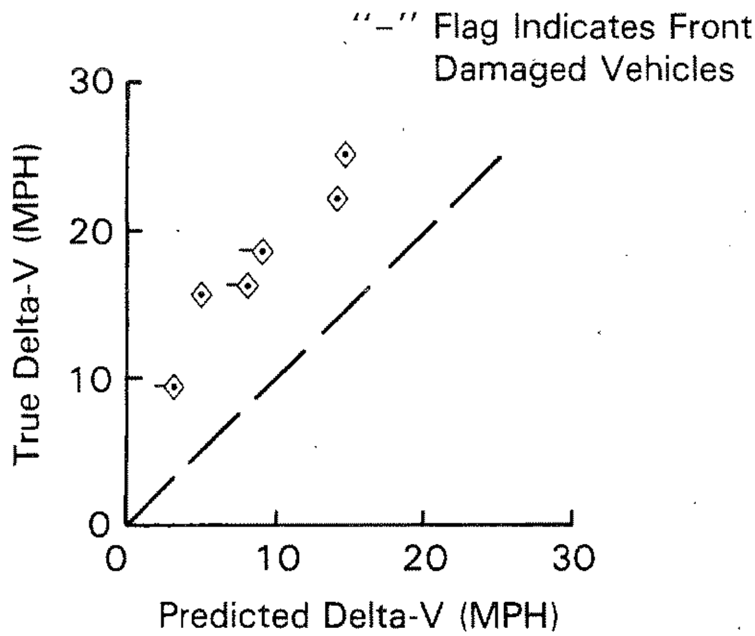


Figure 10. Comparison of True Delta-V and Crash 2 Results for Rear Impacts



vehicles in rear-end impacts. It is clear from Fig. 10 that the delta-V for both vehicles in rear-end impacts is predicted low by approximatey 8 mph over the range 10-to-25 mph.

In summary, the accuracy of delta-V predictions using the CRASH 2 algorithm depends upon the type of collision studied. Head-on impacts appear to be accurate (less than 5 percent error) at high delta-V, but appear to predict low by up to approximately 10-25 percent in the lower range of 15-25 mph delta-V. Direct-side impacts tend to predict accurately in the range 10-20 mph and oblique side impacts tend to predict high over the range 15-30 mph. At the high end of this range, oblique side impacts may predict approximately 30 percent high, although this observation is based on sparse data. Rear-end impacts appear to be predicted low by a consistent amount of approximately 8 mph over the range of 10-25 mph.

Effect of Revisions in the Crush Coefficients A, B

The data on which the coefficients A and B were based when the CRASH 2 computer program was implemented in field studies in 1977 were recognized to be sparse in amount. In 1979 a program was initiated in cooperation with the NHTSA Safety Research Laboratory aimed at compiling new and larger sources of vehicle crush data and, on the basis of these new data, estimating new values for the A and B coefficients. The results will be reported in reference [13], and for convenience they are tabulated in Appendix E. New coefficients for front and rear areas have been incorporated into a revised computer program identified as CRASH 3. The only change between CRASH 2 and CRASH 3 that affects the results of a damage-only prediction of delta-V is the revision in the A, B coefficients for front and rear damage. Consequently, the staged collision data were computed again using CRASH 3 to observe any influence of the revisions in these crush coefficients. The results are presented for head-on impacts in Fig. 11, side impacts in Fig. 12 and rear-end impacts in Fig. 13. It is clear, when comparing these data with their counterparts based on CRASH 2 (exhibited in Figs. 6, 8 and 10 respectively), that the revision of coefficients A and B had negligible effect on the accuracy as expressed by these staged collisions except for the rear-end impacts. There was a distinct improvement in the accuracy for estimating delta-V in rear-end impacts.

Sensitivity of Delta-V to Coefficients A, B in Force-Deflection Equation

The discussion of sensitivity included the influence of random measurement error in the field. The calculation of absorbed energy, and as a consequence delta-V, depends upon these field measurements, but it also depends upon the coefficients A, B in Equation 2. As noted earlier, it would be desirable to know these coefficients for each make and model vehicle on the road; however, it would require an extraordinary number of tests to establish and maintain coefficients for so many vehicles. Consequently, vehicles are grouped into size categories [1], and coefficients are determined from available data among vehicles in those categories. Such categorization admits the possibility of error in the coefficients, and it is of interest to know how such error can

Figure 11. Comparison of True Delta-V and Crash 3 Results for Head-On Impacts

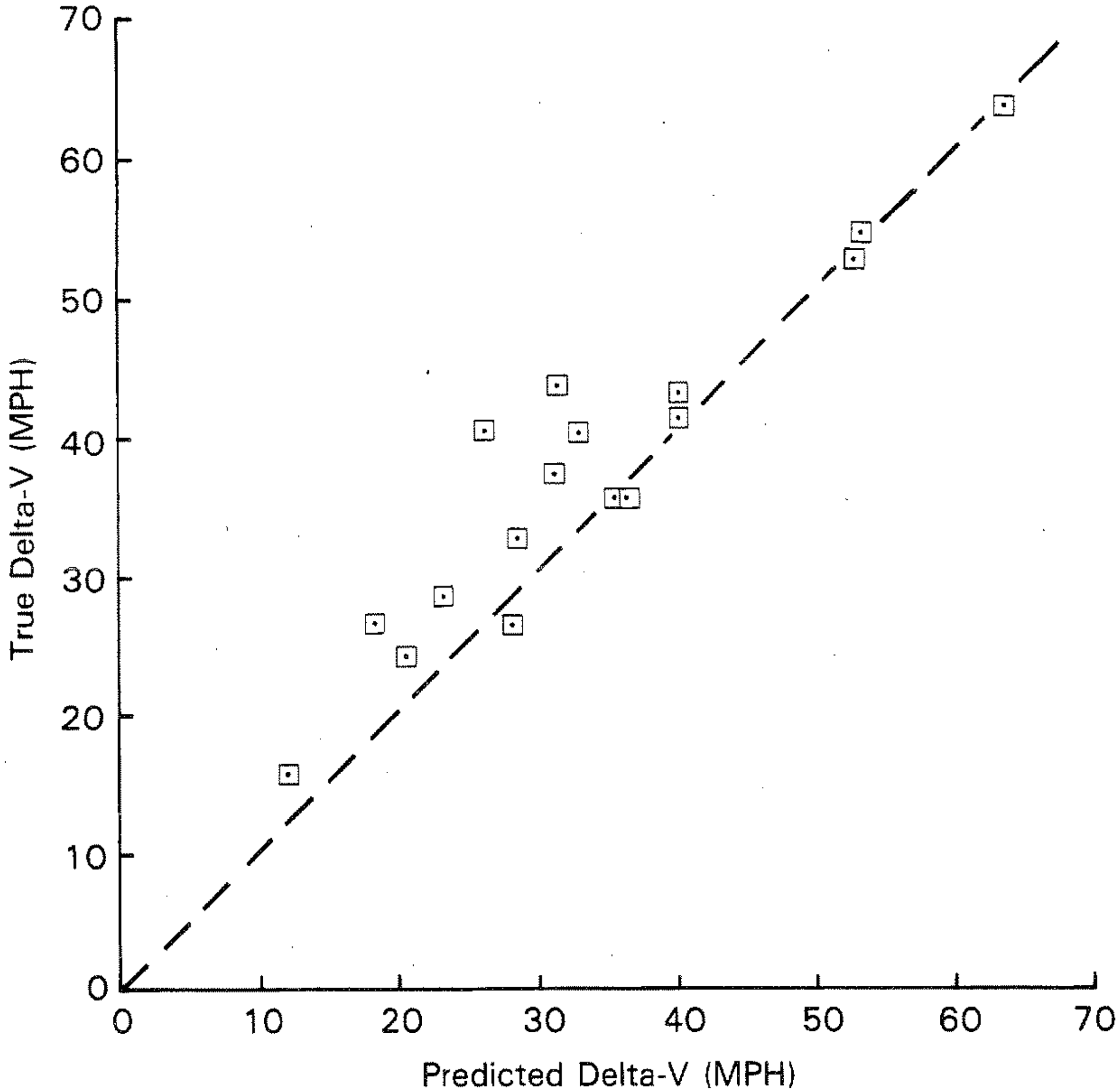


Figure 12. Comparison of True Delta-V and Crash 3 Results for Side Impacts

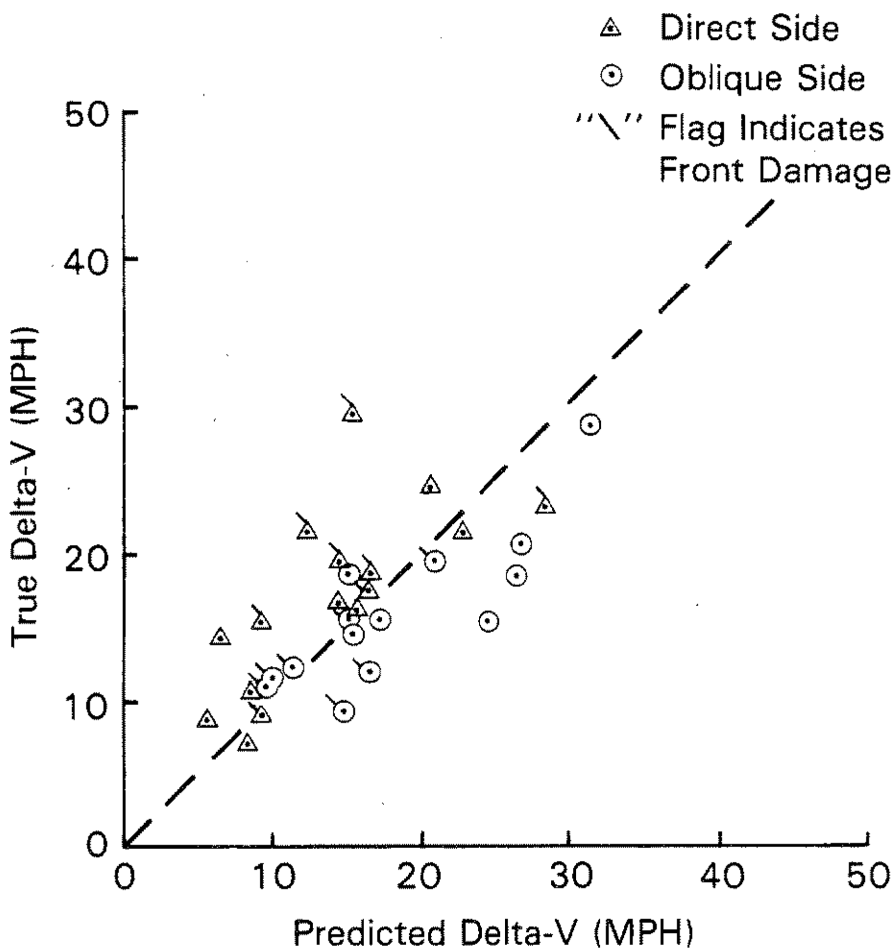
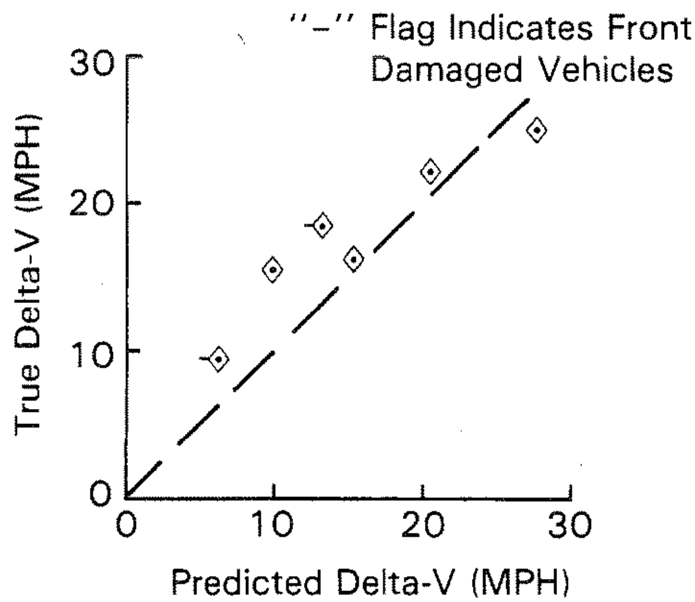


Figure 13. Comparison of True Delta-V and Crash 3 Results for Rear End Impacts



effect the delta-V calculation. This can be determined by the total differential of delta-V. In this instance one considers all measurement quantities to be constant and allows the coefficients A, B to vary.

From Equations (1), (4) and (5), we observe the functional relations, in which E, A and B are the independent variables

$$\Delta V_1 = F\left[E_1(A_1, B_1) \right]$$

where the subscript indicates the vehicle whose A, B coefficients are allowed to vary. Then,

$$d(\Delta V_1) = \frac{\partial \Delta V_1}{\partial E_1} dE_1$$

$$dE_1 = \frac{\partial E_1}{\partial A_1} dA_1 + \frac{\partial E_1}{\partial B_1} dB_1$$

The required differentiation can be readily performed. If the result is expressed such that delta-V, A and B are fractional differentials, we obtain

$$\frac{d(\Delta V_1)}{\Delta V_1} = \frac{(1 + \tan^2\alpha_1) L_1}{60(E_1 + E_2)} \left[\left(A_1 F_1(C) + \frac{30 A_1^2}{B_1} \right) \frac{dA_1}{A_1} + \cdots \right.$$

$$\left. \cdots \left(B_1 H_1(C) - \frac{15 A_1^2}{B_1} \right) \frac{dB_1}{B_1} \right]$$

where

$$F(C) = 3\left(C_{(1)} + 2C_{(2)} + 2C_{(3)} + 2C_{(4)} + 2C_{(5)} + C_{(6)} \right)$$

$$H(C) = \left(C_{(1)}^2 + 2C_{(2)}^2 + 2C_{(3)}^2 + 2C_{(4)}^2 + 2C_{(5)}^2 + \cdots \right.$$

$$\cdots + C_{(6)}^2 + C_{(1)}C_{(2)} + C_{(2)}C_{(3)} + C_{(3)}C_{(4)} + \cdots$$

$$\left. \cdots + C_{(4)}C_{(5)} + C_{(5)}C_{(6)} \right)$$

In the above expressions, the subscript 1 refers to the vehicle under observation and the subscripts in parenthesis (1), (2)---(6), refer to the six deformation measurements described in Figure (1). The result depends upon the deformation itself so no simple statement will suffice to summarize the results for all crashes. The expression was evaluated for some representative crashes and the results are presented in TABLE 4.

These results indicate that single vehicle crashes are more sensitive to the coefficients A and B than are two-vehicle crashes. This is not surprising since the two-vehicle accident includes two energy terms, only one of which is varying as a consequence of changes in A and B. (If the coefficients for both vehicles are in error, the error is compounded.) It can also be observed that the percent change in delta-V for a unit percent change in A and B is less than the unit change in A and B. This is a consequence of the square root relation between delta-V and energy, which reduces somewhat the sensitivity of delta-V to errors in energy.

DISCUSSION

The use of the CRASH program for computing delta-V to accident involved vehicles has become commonplace in Federal government sponsored accident research programs. The success of delta-V in modeling functions which predict injury as a function of the crash environment* has been well discussed in

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*Other factors contributing significantly to these models include occupant age, restraint use, directions-of-force, ejection and seat position.

TABLE 4

PERCENT CHANGE IN DELTA-V
FOR A 10 PERCENT CHANGE IN
THE COEFFICIENTS A AND B

VEHICLE DAMAGE AND TYPE ACCIDENT	PERCENT CHANGE IN DELTA-V
Front damage; Head-on Impact	2.6
Front damage; Side Impact	4.1
Side damage; Side Impact	0.9
Front damage; Rear-end Impact	1.8
Back damage; Rear-end Impact	3.2
Front damage; Fixed Object Impact	6.7
Side damage; Fixed Object Impact	5.0

recent literature [14]. Nevertheless, one must be aware and cautious of the limitations associated with delta-V calculations. Some important limitations have been exhibited in this study, including the sensitivity to field measurement and the accuracy.

Differences in field measurement will inevitably occur. That they occur in measuring the damage on accident involved vehicles is not surprising. Based on a limited set of independent observations, the 95 percent confidence limits on deformation measurements were estimated in this study to be approximatey ± three inches (Appendix B). It is likely that a more exhaustive study would demonstrate some dependence on the depth of deformation. There was insufficient data here to establish such a condition. Variations in the measurement of direction of force led to an estimate of ±20 degrees for the confidence limits on this important parameter (Appendix B). The result of such confidence limits then led to the observation that confidence limits on delta-V in specific impact types ranged from approximately 9 to 25 percent of the delta-V computation. The mean confidence limits, averaged over 9 impact types weighted by their frequency, were then observed to be approximately ± 14 percent in the range of 25-30 mph (40-48 kpm) and ± 17.8 percent in the range of 10-15 mph (16-24 kph). These results emphasize well the limitations of field measurements when obtained in large data sampling programs* and place in perspective the role of field data as a research tool. Individual observations

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* Undoubtedly, more accurate field measurements can be obtained if increased resources are devoted, such as in the case of selected catatrosphic or high interest accidents.

are each subject to random observational errors and the confidence limits of calculations for delta-V based on these observations may be as high as twenty-five percent. The strength of field data lies in its obvious real-world or operational experience. In this context, field data is best used in a statistical study that aggregates a wide body of experience, and in the identification of the range and frequency of occurrences in the operating environment.

Though observational error cannot be avoided, its magnitude and source can be controlled. For this purpose, continuing programs such as the National Accident Sampling System (NASS) should institute formal programs of independent measurement in order to monitor field errors objectively as well as to support analysis efforts which require estimates of the confidence limits.

In addition to the field measurement errors and the inaccuracy inherent in the algorithm, the sensitivity of delta-V calculations to the coefficients A,B in the force-deflection relation was studied. These coefficients are obtained for size-class categories because of the extraordinary effort required to determine such data for every make and model vehicle. It was observed that small errors in the coefficients of a given magnitude, say 10 percent, resulted in errors in delta-V of 2 to 5 percent. Although such error might be considered negligible, it is important to maintain a program of continuously reviewing these coefficients. New vehicles in particular may have different structural features and materials that result in important changes. Furthermore, though vehicle deformation data is sparse, only by continuously collecting and reviewing these data can assurance be gained that the coefficients employed are reasonable approximations. The importance of this review can be seen in the revisions that occurred when CRASH 3 was implemented. The CRASH 2 coefficients for rear-end damage were based on very sparse data and resulted in relatively large errors (see Fig 11). The CRASH 3 coefficients have evolved after reviewing additional moving barrier impacts to vehicle rear-ends and are a substantial improvement in the accuracy of the three rear-end staged collisions. By focusing limited resources on new models, coefficients for the various classes can be updated, or occassionally new vehicles may be placed in a size category not otherwise anticipated by traditional measures of weight and wheelbase on which the categories are roughly based.

Regarding the study of the accuracy of the CRASH damage-only algorithm, as described in the Introduction, two limitations appear noteworthy. At low delta-V, particularly below approximately 21 mph (32 kph), CRASH consistently underestimates the delta-V except for oblique side impacts. In oblique side collisions CRASH appears to overestimate the delta-V.

Underestimation of delta-V at low speeds suggests that the effect of restitution, which is neglected in the CRASH algorithm, may be the source of this error. The effect of restitution is to restore kinetic energy to the impacting vehicles through the release of stored elastic energy by rebounding after the vehicles have reached their greatest deformation. Such stored elastic energy is present in every impact, but its influence would be greatest in the range of low delta-V and relatively low crush where the change in kinetic energy experienced by the vehicle is small. This behavior of restitution has been observed by past research [15], in which, for example, the coefficient of restitution, r, was found to follow the relation in a selected series of frontal impacts,

$$r = .574e^{-.1634 Vo}$$

where ΔVo is the velocity change achieved at maximum dynamic crush. That elastic behavior or restitution is the source of an error is further supported by the results at high delta-V in which the error becomes very small. The conclusion that the error disappears at high delta-V is supported by the data in Figure (4); however, it must be acknowledged that the amount of evidence in high delta-V crashes is limited. Nevertheless, it would be expected that the importance of stored elastic energy in the vehicle deformation would be relatively less important at higher delta-V, and the entire trend of error in predicted delta-V (with the exception of oblique side impacts) suggests that the accuracy of CRASH could be improved by including restitution effects in the algorithm.

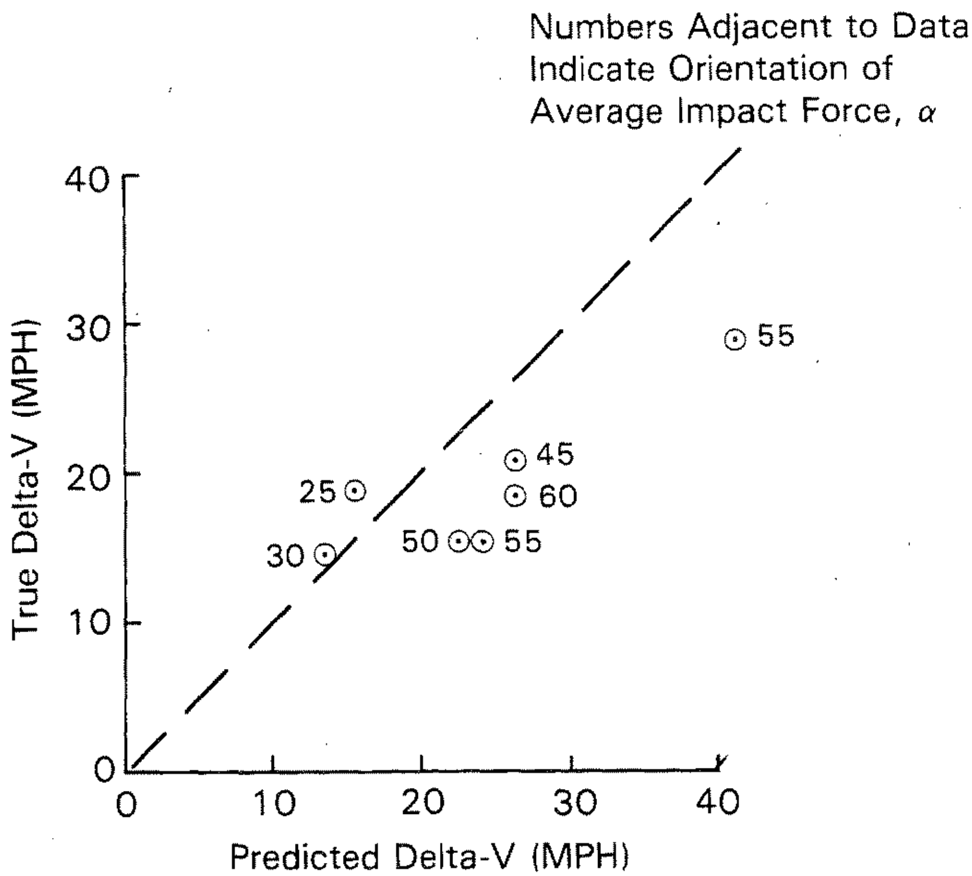
It is also recognized that a potential source of error for calculation of delta-V in the range of 0-20 mph (32kph), may be the accuracy of the assumed force-deflection relationship, Eqn. (2). The coefficients, A and B, in this equation are based mostly on crash-test data into rigid barriers at 30 and 35 mph (48 and 56 kph). There are very few low speed data from barrier or other crashes contributing to the present estimates of A and B. Recent data gathered in the study of front and rear-end damage-resisting characteristics of vehicles by the insurance industry is now available. A future revision of these coefficients will include such data and will extend the range in delta-V over which the coefficients of Eqn (2) have been evaluated.

The behavior in oblique side impacts is quite different in that delta-V appears to be overestimated over the entire range for which data is available. It is characteristic of some oblique side impacts that the direction of resultant force is highly inclined to the side surface normal. The effect on the energy of deformation for such an orientation of force is described by Eqn. (5), in which the term $(1+ \tan^2\alpha)$ appears. As α increases from 1 to 45 degrees, this term doubles in magnitude and becomes even more pronounced for angles in excess of 45 degrees.

The results for side-damaged vehicles in seven oblique-side impacts are presented in Figure (14) along with a notation of the direction of resultant force as determined by the direction of delta-V. The orientation of the angle α is 45 degrees or larger in every case in which delta-V is predicted high. This emphasizes that the overestimation of delta-V in these impacts appears to be associated with estimates of force directions in excess of approximately 45 degrees from the side-surface normal.

The inclination of the force in side impacts is a result of friction and of the deformation in the side which may encourage snagging of the striking vehicle structures in severe impacts. The term, $1+\tan^2\alpha$, in Eqn. (5) is clearly based on a simple model that may be inappropriate at higher angles of force, and an improved model might preclude extraordinarily large estimates of energy of deformation at oblique angles in excess of approximately 45 degrees.

Figure 14. Comparison of True Delta-V and Crash 2 Delta-V for Oblique Side Impacts, Side Damaged Vehicles



Finally, it must be acknowledged that the range of collision types on which the comparison of accuracy is based is not exhaustive. Though head-on, rear-end and side-impacts are included, no cases are available that well define the limitations on types of impact for which the CRASH algorithm may apply. It is recognized, for example, that side-swipe impacts are not applicable to the model; however, the condition of highly oblique impacts that result in significant deformation and significant relative motion between the impacting vehicles are not available in the library of staged collisions. In other words just what maximum oblique angle of impacts causes CRASH to be unacceptably large in error has not been determined. Certainly this is one phenomenon that deserves attention in future staged collision programs.

Work addressing these problem areas is being conducted by the staff of the National Center for Statistics and Analysis in the National Highway Traffic Safety Administration. This includes additional staged collisions and improvements in the force-deflection relation [Eqn. (2)], as well as research into improvements in the algorithm itself as it treats oblique side impacts and the phenomenon of restitution.

SUMMARY

The accuracy and sensitivity of the CRASH computer program in computing delta-V by damage-only data have been examined. The 95 percent confidence limits on field measurements were estimated for a set of independent measurements, and these data were used to estimate the sensitivity of a delta-V calculation. The 95 percent confidence limits on selected individual delta-V calculations resulting in measurement error ranged from nine to 25 percent. The average 95 percent confidence limits of 9 crash modes, weighted by the frequency in the towaway accident population, were observed to be approximately ± 13.8 percent in the range 10-15 mph (16-24 kph), and ± 17.8 percent in the range 25-30 mph (40-48 kph).

The sensitivity of delta-V calculation to the variation in the coefficients of the force-deflection relationship was examined. It was observed that for selected impact types, a 10 percent error in the coefficients of this relationship resulted in errors of approximately 2 to 5 percent in delta-V.

The accuracy of the CRASH algorithm was examined by comparing the results of its application to the measured outcome of 53 staged collisions. In this comparison it was observed with one exception that CRASH tends to underestimate delta-V at low values of delta-V, and that it estimates accurately at high delta-V, above approximately 25-30 mph (40-48 kph). This behavior suggests that improvement in accuracy could be achieved by including the effect of restitution to the model and by obtaining low-speed data, particularly in the range of 0-10 mph (0-16 kph), for improved estimation of the coefficients of the force-deflection relationship.

The exception to this behavior appears to be oblique side collisions in which delta-V is often estimated high. The reason for this behavior is likely a consequence of the treatment of the resultant impact force, in which the algorithm over-estimates the magnitude of the energy of deformation when this force is inclined more than approximately 30-40 degrees to the surface normal. A careful study of oblique side impacts under controlled changes in orientation and force direction would contribute data necessary to resolve this problem.

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APPENDIX A

FORMULAE FOR CONFIDENCE LIMITS AND DERIVATIVES FOR E, m and γ

As described by Eqn. (1) of the text, the velocity change experienced by vehicle no. 1 in a two-vehicle impact is

$$\Delta V_1 = \sqrt{\frac{2\gamma_1 (E_1 + E_2)}{m_1 \left(1 + \frac{\gamma_1 m_1}{\gamma_2 m_2}\right)}}$$

The terms for energy, E, and the non-central impact factors, γ can be related to the field measurements C_1, C_2, C_3........C_6, L, D and γ.

Sensitivity of Energy to Field Measurement

For the energy, it was noted in Eqns. (4) and (5) how energy was related to these measurements. Thus, combining Eqns. (4) and (5) yields

$$E = \frac{1}{30}(1+\tan^2\alpha) L \Big[3A(C_1 + 2C_2 + 2C_3 + 2C_4 + \cdots + 2C_5 + C_6) + B(C_1^2 + 2C_2^2 + 2C_3^2 + \cdots + 2C_4^2 + 2C_5^6 + C_6^2) + C_1C_2 + C_2C_3 + \cdots + C_3C_4 + C_4C_5 + C_5C_6) + 30G \Big] \quad (A1)$$

which is of the form,

$$E = E(C_1, C_2, \ldots\ldots C_6, L, \alpha)$$

Thus

$$dE = \frac{\partial E}{\partial C_1} dC_1 + \cdots\cdots \frac{\partial E}{\partial C_6} dC_6 + \frac{\partial E}{\partial L} dL + \frac{\partial E}{\partial \alpha} d\alpha$$

and

$$2\sigma_E = \sqrt{\left(2\sigma_{C_1}\frac{\partial E}{\partial C_1}\right)^2 + \cdots\cdots \left(2\sigma_{C_6}\frac{\partial E}{\partial C_6}\right)^2 + \cdots \cdots \left(2\sigma_L \frac{\partial E}{\partial L}\right)^2 + \left(2\sigma_\alpha \frac{\partial E}{\partial \alpha}\right)^2}$$

Differentiation of Equation (A1) yields the following derivatives*

$$\frac{\partial E}{\partial C_1} = \frac{(1+\tan^2\alpha)L}{30}\left[3A + B(2C_1 + C_2)\right] \quad (A2)$$

$$\frac{\partial E}{\partial C_2} = \frac{(1+\tan^2\alpha)L}{30}\left[6A + B(4C_2 + C_1 + C_3)\right] \quad (A3)$$

$$\frac{\partial E}{\partial C_3} = \frac{(1+\tan^2\alpha)L}{30}\left[6A + B(4C_3 + C_2 + C_4)\right] \quad (A4)$$

$$\frac{\partial E}{\partial C_4} = \frac{(1+\tan^2\alpha)L}{30}\left[6A + B(4C_4 + C_3 + C_5)\right] \quad (A5)$$

$$\frac{\partial E}{\partial C_5} = \frac{(1+\tan^2\alpha)L}{30}\left[6A + B(4C_5 + C_4 + C_6)\right] \quad (A6)$$

$$\frac{\partial E}{\partial C_6} = \frac{(1+\tan^2\alpha)L}{30}\left[3A + B(2C_6 + C_5)\right] \quad (A7)$$

$$\frac{\partial E}{\partial L} = \frac{E}{L} \quad (A8)$$

$$\frac{\partial E}{\partial \alpha} = 2E\tan\alpha \quad (A9)$$

---

*These derivatives may be thought of as weighting factors for the individual errors in field measurement or as sensitivity coefficients.

Equations (A2)-(A9) are used in conjunction with Equation (A1) to determine the confidence limits for the energy terms E_1 and E_2, for vehicles 1 and 2 respectively. The partial derivative or sensitivity coefficient for E_1 and E_2 is obtained by direct differentiation of Equation (1). Thus, we observe

$$\frac{\partial \Delta V_1}{\partial E_1} = \frac{\partial \Delta V_1}{\partial E_2} = \frac{\Delta V_1}{2(E_1 + E_2)} \qquad \text{(A10)}$$

<u>Sensitivity of Non-Central Impact Factor to Field Measurement</u>

The non-central impact factor γ was defined by Equation (6).

$$\gamma = \frac{k^2}{k^2 + h^2}$$

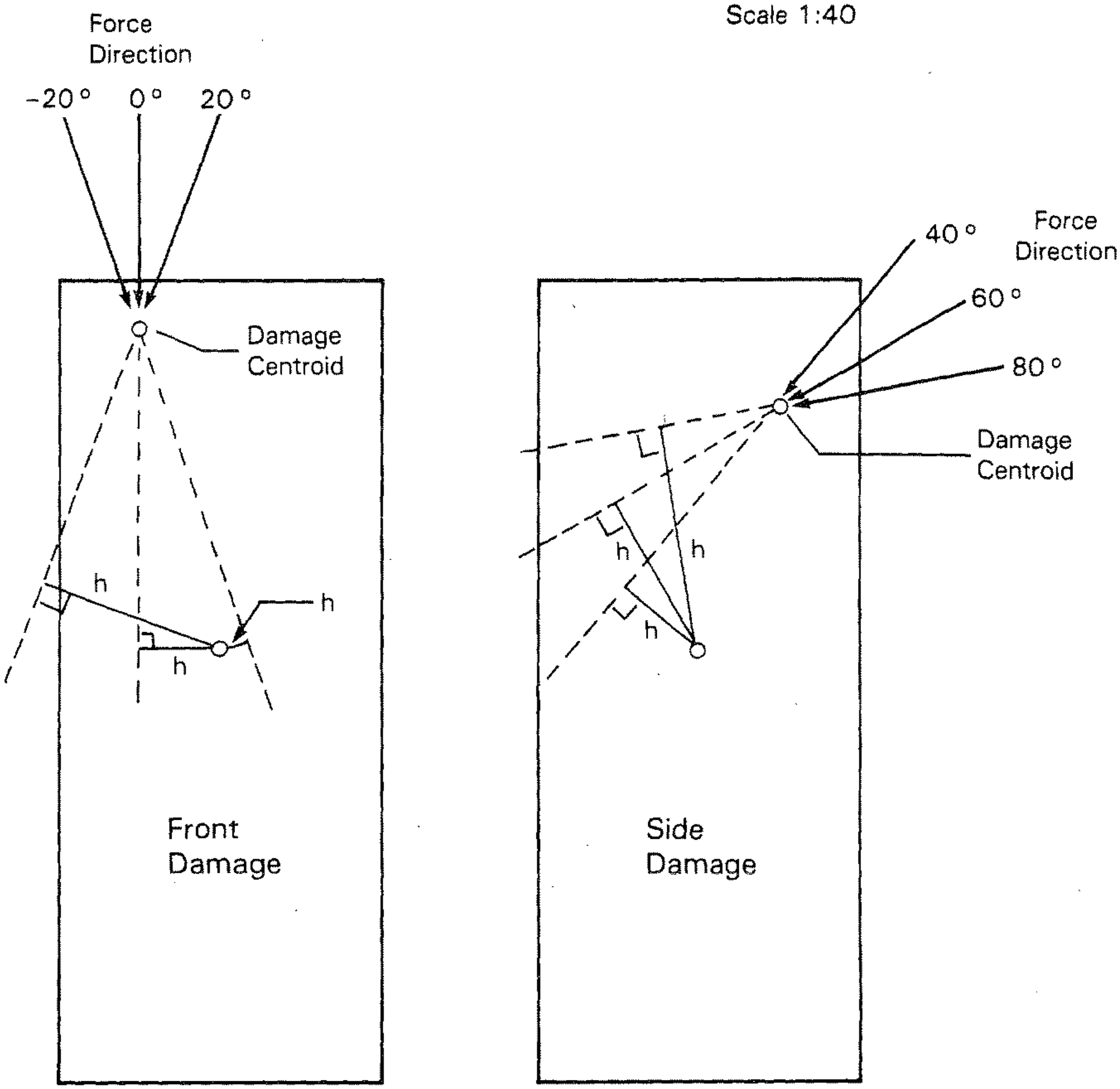
Where k is the radius of gyration and h is the moment arm of the line-of-action of the average force acting through the damage centroid about the vehicle center-of-mass. The radius of gyration is not estimated in the field, but is determined by the choice of vehicle class or size. Thus the radius of gyration is fixed for all full-size vehicles, intermediate sizes and so forth down to the mini-car size. As a parameter "stored" in the CRASH algorithm it is not treated as a contributor to field measurement sensitivity or precision, but is considered to be a potential source of bias or error. Accordingly, its effect is lumped with that of the stiffness coefficients, A and B, and is considered in the discussion of accuracy.

The moment arm, h, is sensitive to field measurement error. It depends on the line-of-action of the force which is determined in part by the angle, α. It also depends upon the location of the centroid of the damage area because the average force is assumed to act through this point. The centroid itself depends upon the location, shape, and size (D, C, and L measurements) of the damage profile. Because no unique analytical relation has been derived relating γ and these field measurements, it was necessary to estimate the confidence limits on γ by choosing a particular damage profile and direction of force, and then simply observing how much the factor γ varied with the confidence limits of the field measurements. It was observed that h is most sensitive to the direction of force, and an idea of this sensitivity can be observed in Figure A1, in which two selected points of application of force or centroids are depicted along with three lines-of-action of force through each point. For each line-of-action (or direction of force), the non-central impact factor is indicated. Over a ± 20 degree range in α , one can observe a $\Delta\gamma$ of approximately 0.2 in this particular side damage example and a $\Delta\gamma$ of approximately 0.28 in this particular front damage example. In this manner the confidence limits on γ can be determined for any particular damage pattern.

To evaluate Equation (8), it is also necessary to evaluate the derivatives, $\frac{\partial \Delta V_1}{\partial \gamma_1}$ and $\frac{\partial \Delta V_1}{\partial \gamma_2}$. This may be done by direct differentiation of Equation (1), yielding in non-dimensional format

$$\frac{\gamma_1}{\Delta V_1} \frac{\partial \Delta V_1}{\partial \gamma_1} = \frac{1}{2\left(1 + \frac{\gamma_1 m_1}{\gamma_2 m_2}\right)} \tag{A11}$$

$$\frac{\gamma_2}{\Delta V_1} \frac{\partial \Delta V_1}{\partial \gamma_2} = \frac{\frac{\gamma_1 m_1}{\gamma_2 m_2}}{2\left(1 + \frac{\gamma_1 m_1}{\gamma_2 m_2}\right)}$$



a. Computation of Δγ for PDOF = 0°; Front Damage

b. Computation of Δγ When PDOF = 60°, Side Damage

Force Angle	α	h	γ	Δγ
20°	20°	-47.5	.624	
0°	0°	-20.0	.903	.28
-20°	20°	6.5	.989	
40°	50°	-23.0	.876	
60°	30°	42.5	.674	.20
80°	20°	55.0	.553	

c. Results of Computations

Figure A1. Procedure Used to Estimate Δγ [Note: $\gamma = h^2/(h^2 + k^2)$; $k^2 = 3{,}741\ in^2$]

Sensitivity of Mass to Field Measurement

The necessary derivatives with respect to vehicle mass can be obtained by differentiation of Equation (1), yielding in non-dimensional format.

$$\frac{m_1}{\Delta V_1}\frac{\partial \Delta V_1}{\partial m_1} = -\frac{1 + 2\frac{\gamma_1 m_1}{\gamma_2 m_2}}{2\left(1 + \frac{\gamma_1 m_1}{\gamma_2 m_2}\right)} \tag{A12}$$

$$\frac{m_2}{\Delta V_1}\frac{\partial \Delta V_1}{\partial m_2} = \frac{\frac{\gamma_1 m_1}{\gamma_2 m_2}}{2\left(1 + \frac{\gamma_1 m_1}{\gamma_2 m_2}\right)} \tag{A13}$$

The confidence limits on the estimate of mass were obtained as explained in Appendix B.

APPENDIX B

ESTIMATION OF CONFIDENCE LIMITS ON FIELD MEASUREMENTS

The field measurements of deformation, $C_1, C_2 \ldots . C_6$, the damage length, L, and its location, D, are each measurements made upon a damaged or deformed vehicle. Although measurement guidelines can and were prepared for field investigators, no damaged vehicle is going to yield precisely the same set of measurements by different investigators. This circumstance occurs because no convenient fixed reference line exists on the vehicle and because the damage pattern itself is highly irregular in both horizontal planes as well as in vertical planes. This irregular pattern actually would defeat even an elaborate optical bench measuring system unless it was documented in three space dimensions, a level of detail and complexity that far exceeds the needs or even the accuracy of the CRASH algorithm. Consequently, we must accept the condition that results in uncertainty in the measurements, and document this uncertainty.

The estimation of the line-of action of the average force is also confounded with uncertainty. In this estimate, one must observe the damage pattern on each involved vehicle, consider the dynamic interaction of the vehicles and effectively estimate an average direction of force that actually is an integration over both space (area of damage) and time (duration of impact) of the collision forces.

To obtain estimates of the precision of such measurements, a study was conducted early in the field application of the CRASH program for the National Crash Severity Study [2]. Essentially, a procedure was established to obtain two independent sets of measurements of these field quantities for a large number of accident-involved vehicles. One set of measurements was obtained by a highly skilled team of two investigators conducting on-scene investigations. This team completed the damage, direction-of-force and vehicle mass estimates having the benefit of a cooperative two-person effort and extensive on-scene investigation experience. They possessed the greatest possible understanding of the impact dynamics and these measurements were consequently interpreted to be the "true" values.

Subsequently, one person inspected the scene, and measured the involved vehicles in a wrecking yard or repair garage some 2-5 days later. This one-man team was a less skilled and experienced investigator, but one who had been trained in making the desired measurements. The environment in which he worked, including vehicles not located at the accident scene or even at a common site, a scene inspection whose available evidence was degraded by time, and working alone, simulated a typical investigation conducted for studies like the National Crash Severity Study and the National Accident Sampling System. This set of measurements was interpreted to be the "field" measurements. The comparison between the "true" and the "field" measurements formed the basis for estimating the confidence limits on C_1, C_2, C_3.....C_6, L and σ.

A total of 34 vehicles were observed in the experiment, and the results of the comparison described above are presented in Table B-1. (The detailed measurement sets are given in Ref. [2].) The average error in crush depth (C) from six sets of C-measurements was determined to be 3.0 inches. This value was then used for the 95 percent confidence limits on all C-measurements.

TABLE B-1

Results of Comparison of Pairs of Measurements to 34 Damaged Vehicles

(all measurements in inches)

	Average Measurement	Error In The Mean	Standard Deviation	95 Percent Confidence Limits
C_1	5.6	.3	1.5	3.0
C_2	6.1	.5	1.5	3.0
C_3	8.1	.2	1.7	3.4
C_4	8.6	.3	1.6	3.2
C_5	8.5	.3	1.6	3.2
C_6	6.9	.2	1.2	2.4
D	18.0	-.1	1.8	3.6
L	48.0	-.5	3.0	6.0

In addition to measuring the damage profile, the investigators obtained independent estimates of vehicle mass (including occupants and significant cargo) and direction-of-force. The results of the comparison of mass estimates are given in Table B-2 below.

TABLE B-2

Results of Comparison of Mass Estimates to 34 Accident-Involved Vehicles

Average Error	Standard Deviation	95 Percent Confidence Limits
24 lbs.	65 lbs.	130 lbs.

The estimation of direction-of-force was accomplished by placing each force direction estimate in a class interval as prescribed by the SAE J224.b. Recommended Practice for the Collision Deformation Classification. This places each force-direction estimate in a 30-degree sector described by the hours of the clock with 12 o'clock being straight ahead, or a force direction from the direction 000 on a 360-degree compass. The 12 o'clock sector then includes all force estimates between 345° and 015°, or 15 degrees in either direction, clockwise or counterclockwise, from the direction 000 or straight ahead. The results of these 34 estimates showed 3 occurrences of error or differences in placing the direction-of-force in the proper clock sector. Each difference was one clock sector. This suggests a confidence level of

31/34 or 91 percent in describing the direction-of-force within a one clock sector. Because the sector is 30 degrees in angular measure, one may conclude that in these 34 trials one is 91 percent confident of estimating direction-of-force within 15 degrees.

This statement somewhat underestimates the actual confidence limits because the sector mid-points are fixed at 000 (12 o'clock sector), 030 (1 o'clock sector), 060 (2 o'clock sector) and so forth. The actual confidence limits on direction-of-force and its measurement can be improved by relaxing the requirement of the clock-face sectors which are fixed, and allowing the investigator to make estimates in 10 degree increments rather than the 30-degree increments. When an investigator makes an observation in the field that the direction-of-force is "slightly" in a clockwise direction from 000 or straight-ahead, this estimate can be quantified better for purposes of the CRASH program by choosing 010 or 020 rather than having to choose between the greater extremes of 000 (12 o'clock) and 030 (1 o'clock). A review of the experience in carrying out the study Ref. [2], and a review of the more common experience of training investigators prompted a change in the field procedures for estimating force direction. These investigators were instructed to estimate to the nearest 10-degrees for purposes of obtaining a refined force direction for the CRASH algorithm computation. Subsequently, the proper clock direction was chosen for purposes of the CDC coding.

A controlled field experiment does not exist for purposes of estimating the confidence limits on the use of 10-degree increments for force measurement. As described above, the results for the 12 increments fixed by the clock-force indicated that the confidence limits for ±15 degrees was approximately 91 percent. It was assumed in this exercise that for 10-degree increments, the 95 percent confidence limits were ±20 degrees, which is likely a somewhat conservative assumption for the reasons described above

APPENDIX C
STAGED COLLISION RESULTS
UNITED STATES DATA

DELTA-V MEASURED MPH (KPH)	PREDICTED CRASH 2 MPH (KPH)	PREDICTED CRASH 3 MPH (KPH)	IMPACT CONFIGURATION	DAMAGE AREA	VEHICLE** SIZE	SOURCE*
21.4 (34.2)	22.0 (35.2)	22.9 (36.6)	Direct Side	S	M-FWD	8329-1 [9]
17.2 (27.5)	15.5 (24.8)	16.2 (25.9)	Direct Side	F	I	8329-1 [9]
14.5 (23.2)	13.3 (21.3)	15.2 (24.3)	Oblique Side	S	M-FWD	8330-2 [9]
11.6 (18.6)	8.7 (13.9)	10.0 (16.0)	Oblique Side	F	I	8330-2 [9]
24.5 (39.2)	19.9 (31.8)	20.5 (32.8)	Oblique Side	S	M-FWD	8329-3 [9]
19.2 (30.7)	14.2 (22.7)	14.6 (23.4)	Oblique Side	F	I	8329-3 [9]
18.9 (30.2)	15.4 (24.6)	15.0 (24.0)	Oblique Side	S	M-FWD	8330-4 [9]
11.0 (17.6)	10.3 (16.5)	9.8 (15.7)	Oblique Side	F	I	8330-4 [9]
52.5 (84.0)	54.1 (86.6)	53.0 (84.8)	Head-On	F	C	D [11]
54.6 (87.4)	54.7 (87.5)	53.4 (85.4)	Head-On	F	C	D [11]
43.0 (68.8)	41.7 (66.7)	40.2 (64.3)	Offset Head-On	F	C	O [11]
41.0 (65.6)	41.6 (66.6)	40.1 (64.2)	Offset Head-On	F	C	O [11]
32.6 (52.2)	31.2 (49.9)	28.9 (46.2)	Head-On	F	S	34-492 [12]
40.0 (64.0)	35.6 (57.0)	33.0 (52.8)	Head-On	F	S-FWD	34-492 [12]
37.1 (59.4)	33.1 (53.0)	31.3 (50.1)	Head-On	F	S	38-498 [12]
43.3 (69.3)	33.3 (53.3)	31.5 (50.4)	Head-On	F	S	38-498 [12]
35.4 (56.6)	34.9 (55.8)	35.5 (56.8)	Head-On	F	M	39-499 [12]
35.4 (56.6)	35.4 (56.6)	36.1 (57.8)	Head-On	F	M	39-499 [12]
63.8 (102.1)	70.9 (113.4)	63.9 (102.2)	Head-On	F	M	C14 [6]
26.3 (42.1)	31.3 (50.1)	28.2 (45.1)	Head-On	F	I	C14 [6]
9.0 (14.4)	10.4 (16.6)	9.2 (14.7)	Direct Side	F	I	C84 [6]
7.0 (11.2)	9.3 (20.8)	8.3 (13.3)	Direct Side	S	I	C84 [6]
18.3 (29.3)	18.7 (29.9)	16.4 (26.2)	Direct Side	F	I	C85 [6]
16.0 (25.6)	17.5 (28.0)	15.2 (24.3)	Direct Side	S	I	C85 [6]
23.1 (37.0)	28.1 (45.0)	28.2 (45.1)	Oblique Side	F	I	C54 [6]
18.7 (29.9)	26.2 (47.8)	26.3 (42.1)	Oblique Side	S	I	C54 [6]

*Number in brackets is reference listed on p. 53-54; other number is series number within the reference.
**I - intermediate, S - sub-compact, M - mini compact, C - compact, FWD - front wheel drive

APPENDIX C (continued)
STAGED COLLISION RESULTS
UNITED STATES DATA

DELTA-V MEASURED MPH (KPH)	PREDICTED CRASH 2 MPH (KPH)	PREDICTED CRASH 3 MPH (KPH)	IMPACT CONFIGURATION	DAMAGE AREA	VEHICLE** SIZE	SOURCE*
15.5 (24.8)	15.0 (24.0)	14.5 (23.2)	Direct Side	F	I	T2 [8]
16.4 (26.2)	14.9 (23.8)	14.5 (23.2)	Direct Side	S	I	T2 [8]
28.4 (45.4)	23.2 (37.1)	23.2 (37.1)	Pole	F	I	T1 [8]
12.2 (19.5)	15.1 (24.2)	11.4 (18.2)	Oblique Side	F	I	R1 [10]
15.6 (25.0)	22.7 (36.3)	17.0 (27.2)	Oblique Side	S	S	R1 [10]
19.6 (31.4)	27.4 (43.8)	20.9 (33.4)	Oblique Side	F	I	R2 [10]
28.9 (46.2)	41.1 (65.8)	31.4 (50.2)	Oblique Side	S	S	R2 [10]
9.2 (14.7)	14.6 (23.4)	14.9 (23.8)	Oblique Side	F	I	R6 [10]
15.4 (24.6)	23.9 (38.2)	24.4 (39.0)	Oblique Side	S	M-FWD	R6 [10]
12.0 (19.2)	15.7 (25.1)	16.3 (26.1)	Oblique Side	F	I	R7 [10]
20.9 (33.4)	26.0 (41.6)	26.8 (42.9)	Oblique Side	S	M-FWD	R7 [10]
15.3 (24.5)	9.7 (15.5)	9.1 (14.6)	Direct Side	F	I	R8 [10]
10.7 (17.1)	9.2 (14.7)	8.7 (13.9)	Direct Side	S	I	R8 [10]
21.4 (34.2)	11.3 (18.1)	12.1 (19.4)	Direct Side	F	M-FWD	R9 [10]
8.9 (14.2)	5.2 (8.3)	5.6 (9.0)	Direct Side	S	I	R9 [10]
29.6 (47.4)	15.1 (24.2)	15.1 (24.2)	Direct Side	F	M-FWD	R10 [10]
13.4 (21.4)	7.4 (11.9)	7.4 (11.9)	Direct Side	S	I	R10 [10]
24.0 (38.4)	21.1 (33.8)	20.7 (33.1)	Offset Frontal	F	S	R11 [10]
15.7 (25.1)	13.2 (21.1)	12.1 (19.4)	Offset Frontal	F	I	R11 [10]
40.1 (64.2)	28.2 (45.1)	26.2 (41.9)	Offset Frontal	F	S	R12 [10]
26.4 (42.2)	19.6 (31.4)	18.2 (29.1)	Offset Frontal	F	I	R12 [10]
9.5 (15.2)	3.1 (5.0)	6.2 (9.9)	Rear-End	F	I	R3 [10]
15.8 (25.3)	4.9 (7.8)	9.8 (15.7)	Rear-End	B	S	R3 [10]
18.7 (29.9)	9.1 (14.6)	13.1 (21.0)	Rear-End	F	I	R4 [10]
22.2 (35.5)	14.1 (22.6)	20.4 (32.6)	Rear-End	B	S	R4 [10]
16.3 (26.1)	8.1 (13.0)	15.2 (24.3)	Rear-End	F	I	R5 [10]
25.1 (40.2)	14.8 (23.7)	27.7 (44.3)	Rear-End	B	M-FWD	R5 [10]

*Number in brackets is reference listed on p. 54; other number is series number within the reference.
**I - intermediate, S - sub-compact, M - mini compact, C - compact, FWD - front wheel drive

APPENDIX D
STAGED COLLISION RESULTS
UNITED KINGDOM DATA

DELTA-V MEASURED MPH (KPH)	PREDICTED CRASH 2 MPH (KPH)	IMPACT CONFIGURATION	DAMAGE AREA	VEHICLE** SIZE	SOURCE*
28.1 (45.3)	28.3 (45.5)	Offset Head-On	F	S-FWD	N1 [7]
31.8 (51.1)	30.4 (48.9)	Offset Head-On	F	M	N2 [7]
30.2 (48.6)	20.5 (33.0)	Offset Head-On	F	S	N7 [7]
31.9 (51.3)	21.0 (33.8)	Offset Head-On	F	M-RE	N8 [7]
27.4 (44.1)	28.1 (45.2)	Offset Head-On	F	S	N9 [7]
26.8 (43.2)	27.8 (44.7)	Offset Head-On	F	S	N10 [7]
18.6 (29.9)	19.0 (30.6)	Offset Head-On	F	M-RE	N11 [7]
20.7 (33.3)	19.3 (31.1)	Offset Head-On	F	M-FWD	N12 [7]
30.6 (49.2)	33.3 (53.6)	Offset Head-On	F	S	P1 [7]
29.5 (47.4)	30.1 (49.2)	Offset Head-On	F	S	P2 [7]
31.4 (50.6)	27.9 (44.9)	Offset Head-On	F	M	P5 [7]
29.8 (47.9)	27.3 (43.9)	Offset Head-On	F	M-FWD	P6 [7]
25.7 (41.4)	22.5 (36.2)	Offset Head-On	F	M-RE	P7 [7]
26.3 (42.4)	22.9 (36.8)	Offset Head-On	F	M-FWD	P8 [7]
38.8 (62.4)	27.1 (43.6)	Offset Head-On	F	S	P18 [7]
25.8 (41.5)	19.6 (31.5)	Offset Head-On	F	C	P19 [7]
26.0 (41.8)	18.9 (30.4)	Offset Barrier	F	M-FWD	N5 [7]
19.9 (32.0)	17.1 (27.5)	Offset Barrier	F	M-RE	N6 [7]
24.4 (39.2)	24.4 (39.3)	Offset Barrier	F	M-FWD	P9 [7]
26.4 (42.5)	23.0 (37.0)	Offset Barrier	F	M-FWD	P10 [7]
24.0 (38.7)	18.1 (29.1)	Offset Barrier	F	S	P11 [7]
31.9 (51.4)	22.7 (36.5)	Offset Barrier	F	S	P12 [7]
33.3 (53.6)	24.2 (38.9)	Offset Barrier	F	S	P13 [7]
25.0 (40.3)	22.3 (35.9)	60° Angle Barrier	F	M-FWD	N3 [7]
19.3 (31.1)	15.1 (24.3)	60° Angle Barrier	F	M-RE	N4 [7]
28.8 (46.4)	19.8 (31.8)	60° Angle Barrier	F	M-RE	P14 [7]
31.8 (51.3)	27.3 (43.9)	60° Angle Barrier	F	S-FWD	P15 [7]
29.9 (48.1)	25.7 (41.4)	60° Angle Barrier	F	S	P16 [7]
36.5 (58.7)	25.9 (41.7)	60° Angle Barrier	F	S	P17 [7]

* Number in brackets is reference listed on p. 53; other number is series number within the reference.

**I - intermediate, S - sub-compact, M - mini-compact, C - compact, FWD - front wheel drive, RE - rear engine

APPENDIX E

COEFFICIENTS A, B, AND G IN CRASH 2 AND CRASH 3

SIZE CLASS	1		2		3		4		5	6
Wheelbase (in)	80.9 - 94.8		94.8-101.6		101.6-110.4		110.4-117.5		117.6-123.2	123.2-150
CRASH Model	2	3	2	3	2	3	2	3	2	3
FRONT										
A(lbs/in)	85	302	95	259	155	317	234	356	308	325
B(lbs/in^2)	64	47	71	43	70	56	50	34	37	37
G(lbs)	57	967	63	778	172	901	547	1,874	1,281	1,429
SIDE										
A(lbs/in)	77	77	140	140	173	173	143	143	177	177
B(lbs/in^2)	37	37	67	67	57	57	50	50	47	47
G(lbs)	81	81	148	148	263	263	203	203	331	331
REAR										
A(lbs/in)	66	366	66	391	78	410	86	357	93	297
B(lbs/in^2)	13	38	13	41	16	44	17	13	19	70
G(lbs)	165	1,755	165	1,874	195	1,931	214	4,986	233	628