The Engineering Society
For Advancing Mobility
Land Sea Air and Space
400 COMMONWEALTH DRIVE WARRENDALE, PA 15096

SAE Technical Paper Series

870045

An Overview of the Way EDCRASH Computes Delta-V

Terry D. Day and Randall L. Hargens
Engineering Dynamics Corp.

Reprinted from P-193-
Accident Reconstruction: Automobiles, Tractor-Semitrailers, Motorcycles, and Pedestrians

International Congress and Exposition
Detroit, Michigan
February 23-27, 1987

The papers included in this volume are abstracted and indexed in the SAE Global Mobility Database

SAE GLOBAL MOBILITY DATABASE

ISSN 0148-7191

Printed in U.S.A.

870045

An Overview of the Way EDCRASH Computes Delta-V

Terry D. Day and Randall L. Hargens
Engineering Dynamics Corp.

ABSTRACT

The two procedures, DAMAGE and OBLIQUE IMPACT, which are used by EDCRASH for computing delta-V, are described in detail. Enhancements in EDCRASH Version 4 which improve the DAMAGE method of computing delta-V are also described. The advantages and disadvantages of each method are explored, and the numerical and graphical output and use of warning messages are reviewed. In general, it was found the two methods are complimentary: The DAMAGE procedure is best-suited for the conditions in which the OBLIQUE IMPACT procedure is least-suited, and vice-versa.

DELTA-V IS DEFINED as the change in the velocity of a vehicle's occupant compartment during the collision phase of a motor vehicle crash (i.e., from the moment of initial contact between vehicles until the moment of their separation). The delta-V is frequently used as an indicator of severity of impact because it approximates the speed of the "second collision" - the collision between the occupant and vehicle interior - that causes occupant injury [1,2,3]*.

The EDCRASH computer program can estimate the delta-V as well as the impact speed for one or two vehicles involved in a crash. Accident site and vehicle inspections performed after the crash provide the input data for the analysis.

The purpose of this paper is to describe the two methods which are used by EDCRASH to compute the delta-V.

GENERAL PROCEDURES

The EDCRASH program is modular: Certain sections are devoted to certain calculation procedures. The calculation procedures are relatively simple and straight-forward and, although very lengthy, most can be accomplished with a hand-held calculator. An overview of these procedures is provided by the flow chart below (see figure 1).

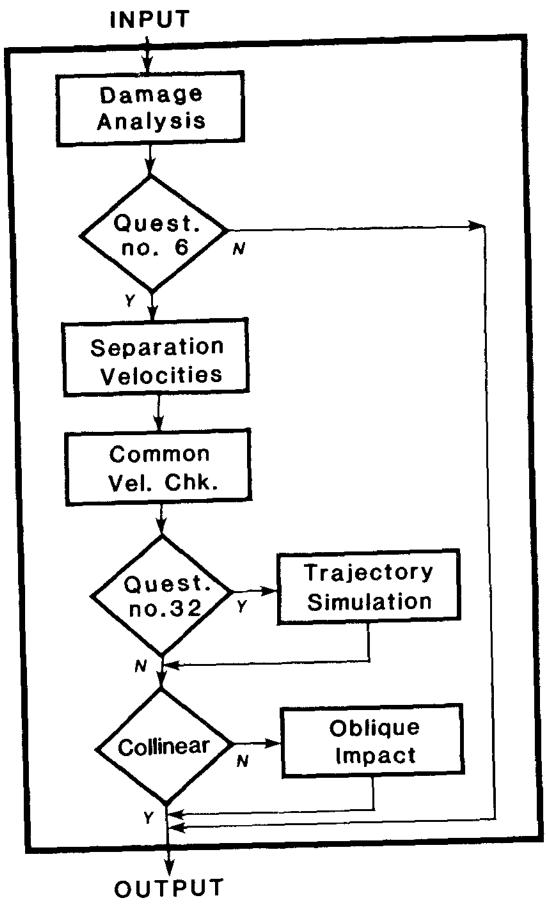


Figure 1 - EDCRASH Processing Phase Flow Chart

*Numbers in brackets designate references at the end of the paper.

As shown in the flow chart, there are five major calculation procedures which occur during the EDCRASH processing phase. These procedures (in order) are:

- DAMAGE
- SEPARATION VELOCITIES
- COMMON VELOCITY CHECK
- TRAJECTORY SIMULATION
- OBLIQUE IMPACT

The DAMAGE section computes the delta-V directly from vehicle crush measurements taken during the vehicle inspection. The SEPARATION VELOCITIES section computes the linear and angular separation velocities (speed and direction of the vehicles at separation) and angle of the path at separation from measurements taken at the accident site. COMMON VELOCITY CHECK compares the separation velocities calculated for each vehicle to insure the velocities are compatible with the "common velocity assumption," which requires the damaged portions of each vehicle to reach approximately the same earth-fixed velocity (i.e., sideswipe collisions cannot be analyzed). TRAJECTORY SIMULATION performs a simulation of the impact-to-rest phase of the accident, using the calculated separation velocities, to confirm the results. Finally, OBLIQUE IMPACT computes the delta-V from the accident site measurements for oblique collisions. For a complete discussion of each of these calculation procedures, the reader is referred to the literature [4].

COMPUTATION OF DELTA-V

A quick review of the calculation procedures reveals the delta-V is computed using two independent methods: from vehicle damage measurements (for all collisions) and from accident scene data (only for oblique collisions, i.e., angled type collisions - see figure 2).

The vehicle damage data are always analyzed. This analysis, called the DAMAGE analysis, uses measurements of vehicle damage to estimate the damage-based delta-V for each vehicle, even if no scene data are available.

If scene data (positions at impact and rest and optional intermediate path positions) are supplied, the delta-V can also be calculated according to the laws of conservation of linear momentum. This trajectory-based approach, called OBLIQUE IMPACT, works well for oblique collisions. However, if the directions of the pre-impact velocity vectors are within +/- 10 degrees of parallel (i.e., collinear, or head-on; see figure 3), the momentum calculations become very sensitive to small errors in the scene data. Therefore, the damage-based delta-V is automatically used in this case.

The DAMAGE and OBLIQUE IMPACT computation procedures are described in detail below.

DAMAGE ANALYSIS PROCEDURE

Figure 4 shows two vehicles colliding. During the collision a linear impulse (a function

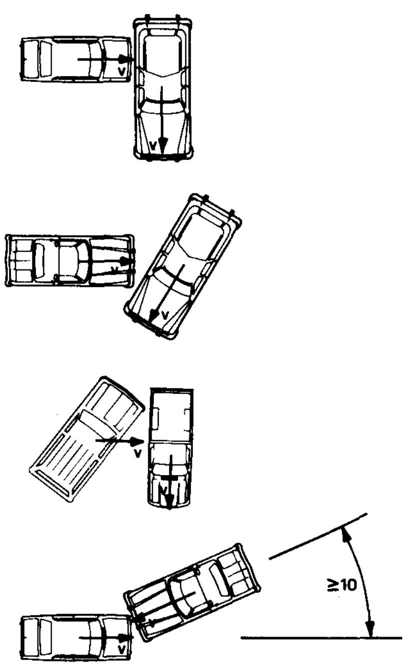


Figure 2 - Typical Oblique Collisions

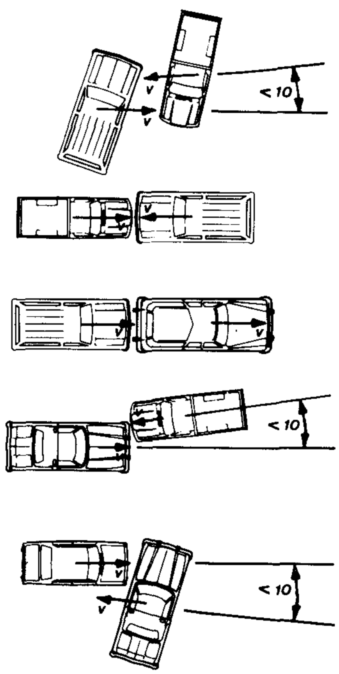
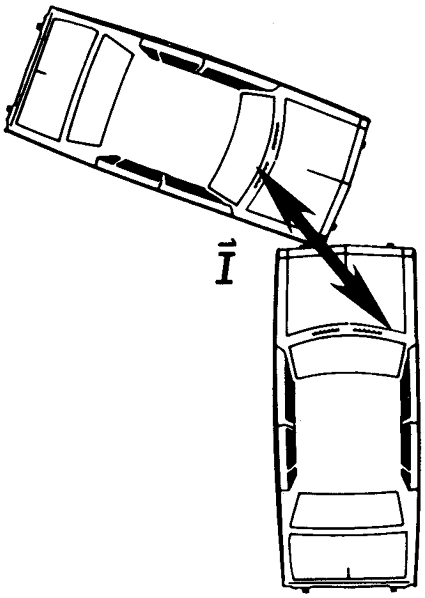


Figure 3 - Typical Collinear Collisions



$$\vec{I} = \int \vec{F} \; dT$$

Figure 4 - Linear Impulse During Collision

of the impact force and time) is produced between the vehicles. According to Newton's third law, the force between the vehicles is shared equally. Therefore, the impulse is also shared equally.

From basic physics, it is known the delta-V of the vehicle (or any colliding object) is equal to the linear impulse divided by its mass. Since the mass of the vehicle is known or easily found in tables, the goal of DAMAGE is really to determine the linear impulse. The basis of the DAMAGE calculation procedure is Newtonian physics and the conservation of linear momentum, not the conservation of energy as reported by some authors [5]*.

Calculation of the Linear Impulse

Since the mid-seventies, information on the structural stiffness of vehicles has been gained from barrier crash testing. This information allows the calculation of the magnitude of the linear impulse between the vehicles during the crash by assuming the exterior of the vehicle has a linear resistance to crush.

* Although the conservation of energy can be derived from Newton's laws of motion, the conservation of energy is not the basis of the calculations in the DAMAGE procedure.

From Newton's 2nd Law (the change in an object's motion is proportional to the forces exerted against it, $\Sigma F = Ma$) applied to vehicle #1, the external force to cause a crush displacement in the exterior having a crush stiffness, K_1, from its original shape to its as-crushed condition, $X_1 - X$, is

$$-K_1(X_1-X) = M_1 d^2X_1/dt^2$$

and for vehicle #2 , Newton's second law states

$$-K_2(X-X_2) = M_2 d^2X_2/dt^2$$

Letting $\delta = X_1-X_2$, these equations can be written in the form

$$d^2\delta/dt^2+(K_1K_2/(K_1+K_2))((M_1+M_2)/M_1M_2)\delta = 0$$

The above equation is the differential equation of motion which describes the two vehicles during a plastic collision (no restitution, i.e., the vehicles reach a common velocity at the end of the impulse). To apply the solution of this differential equation to the case of vehicle collisions, observe that the initial conditions are known: The rate of crush deflection at the beginning of contact between the vehicles is simply equal to the closing velocity between the vehicles,

$$d\delta/dt_{t=0} = V_{1o} - V_{2o}$$

where V_{1o} and V_{2o} are the initial vehicle velocities.

If the exteriors of vehicle 1 and 2 have linear crush stiffnesses K_1 and K_2 and total crush deflections δ_1 and δ_2, respectively, then $K_1\delta_1^2/2$ and $K_2\delta_2^2/2$ are the energies absorbed by vehicles 1 and 2 at the moment of common velocity, V_{com}.

Defining these energies as E_1 and E_2, the linear impulse is

$$I = \sqrt{2(E_1 + E_2)(M_1M_2/(M_1 + M_2))}$$

Since the linear impulse is shared between the vehicles,

$$I = M_1\text{delta-}V_1 = M_2\text{delta-}V_2$$

and the delta-Vs for each vehicle are (see the following page)

$$\text{delta-}V_1 = V_{1o} - V_{com}$$
$$= \sqrt{2(E_1 + E_2)(M_1 M_2/(M_1 + M_2))} \; / M_1$$

and

$$\text{delta-}V_2 = V_{com} - V_{2o}$$
$$= \sqrt{2(E_1 + E_2)(M_1 M_2/(M_1 + M_2))} \; / M_2$$

By definition, the linear impulse acts on the vehicle at an angle equal to the Principal Direction of Force, PDOF. The linear impulse and the delta-V occur in the same direction. Therefore, the delta-V also occurs in the direction of principal force. This important fact is illustrated in figure 5.

The PDOF is an important parameter because it is the direction of the force that exposes the vehicle occupants to injury. For example, if the PDOF is from the front, the front-seat occupants move forward (relative to the vehicle) during the crash and hit the steering wheel or dashboard. If the PDOF is from the right, the occupants move to the right during the crash. A general rule: The occupants always tend to move in the direction opposing the PDOF.

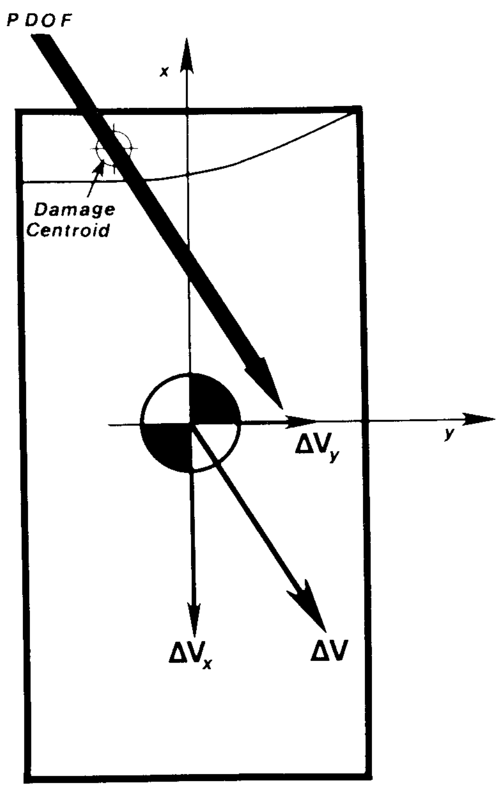


Figure 5 - Delta-V Relationship to PDOF

Thus, the delta-V is a vector: It has both a magnitude and a direction, described by its longitudinal component (delta-V_x) and lateral (delta-V_y) component (see figure 5). Delta-V_x is simply the change in the forward velocity and delta-V_y is the change in the lateral velocity. According to the convention defined by SAE Vehicle Dynamics Terminology [6], a vehicle which loses forward speed (i.e., due to a head-on collision) has a negative delta-V_x while a vehicle which gains forward speed (i.e., due to a rear-end collision) has a positive delta-V_x. Similarly, if a vehicle is struck on the left side, it gains lateral speed and has a positive delta-V_y; if a vehicle is struck on the right side, its resulting delta-V_y is negative (think of it as gaining speed in the negative direction).

The longitudinal and lateral components of the delta-V are related to the PDOF by

$$\text{delta-}V_{long} = \text{delta-V}\,[\text{COS(PDOF-180)}]$$

and

$$\text{delta-}V_{lat} = \text{delta-V}\,[\text{SIN(PDOF-180)}]$$

This derivation is based on Newton's laws of motion and the conservation of linear momentum. Although the crush deflections are expressed by their stored energies, the above development is not based on, or related to, the conservation of energy. In fact, since EDCRASH performs consistency checks for momentum and energy, a review of EDCRASH warning messages will frequently show that, mathematically, energy is not conserved because of inappropriate crush stiffnesses.

Determination of Damage Energy

To apply the mathematical model we have just developed, it is necessary to convert the measurements taken during the vehicle inspection into a damage energy value. The damage profile, the PDOF and the crush stiffness coefficients are the data required by EDCRASH to estimate the damage energy for use in the mathematical model.

Specifying the Damage Profile - The width and depth of crush generate what is referred to as the damage profile. The default damage profile is assigned according to the collision deformation classification (CDC), a seven-character alpha-numeric code [7] which describes the general damage characteristics of the vehicle. The default damage profile can (and should) be replaced with the measured damage profile by specifying (a) the width of the damaged area, (b) the depth of the damaged area, and (c) the location of the center of the damaged area, called the damage offset (see figure 6 for a typical end damage profile and figure 7 for a side damage profile). Simple profiles, such as uniform, frontal crush, may require only two depth of crush entries. Other, more complicated damage

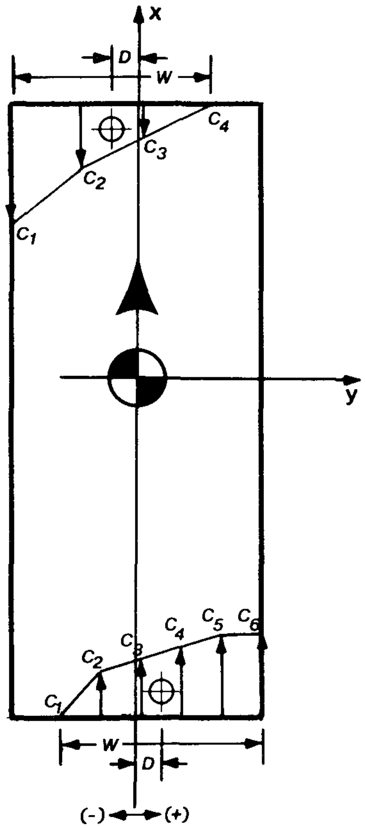


Figure 6 - Typical End Damage Profiles

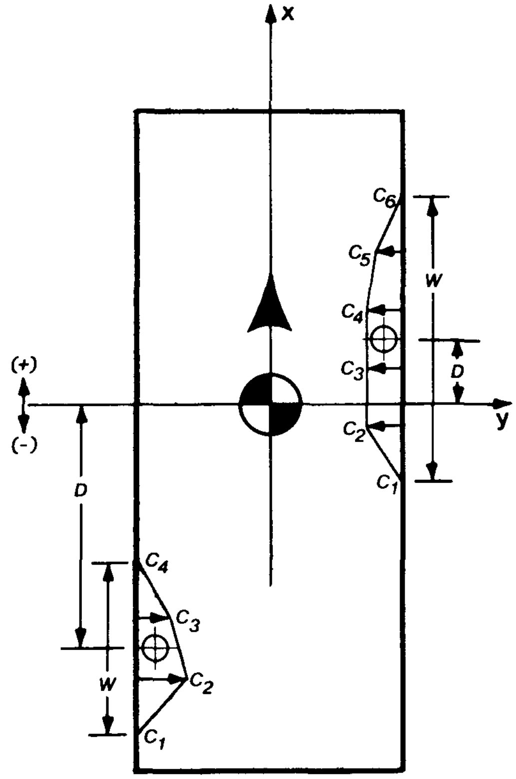


Figure 7 - Typical Side Damage Profiles

profiles may use four or six depth of crush entries. Use of more than six entries has not been shown to provide any significant improvement in the results.

Specifying the PDOF - The principal direction of force (PDOF) during impact is the direction of the force that causes crush and sheet metal displacement on the damaged vehicle. It is assigned by the CDC as hour angles on the face of a clock (i.e., 12-o'clock is a "head-on" impact, 06-o'clock is a "rear-end" impact and 03- and 09-o'clock refer to perpendicular impact to the right and left sides, respectively. Angles in between are noted accordingly. For cases where the PDOF is known more accurately than specified by the clock direction (which, by virtue of the one hour increments, is rounded to the nearest 30 degrees), the PDOF may be entered in degrees (see figure 8).

The PDOF must be estimated from vehicle damage characteristics, such as the direction of crush and lateral shifting of the structure. When scene data are available, the OBLIQUE IMPACT procedure computes the angle of the impulse for comparison with the estimated PDOF.

By default, the impulse, or principal force, is assumed to act through the damage centroid (see figure 5), which is not the same as the center of damage specified by the damage offset. This helps to account for crush which is not evenly distributed along the width of the dent. The location of the damage centroid is computed from the damage measurements (width, depths of crush and damage offset).

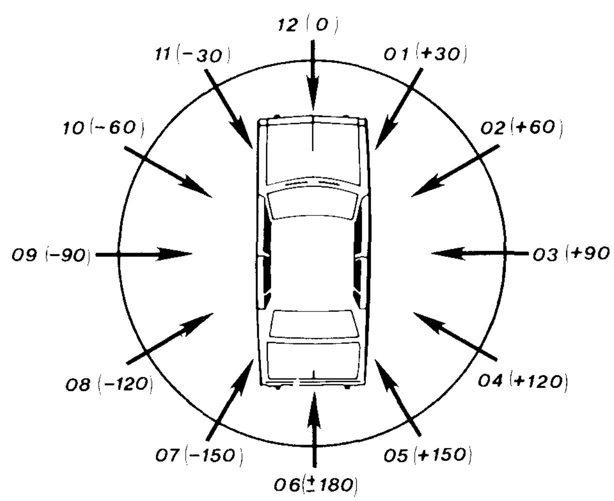


Figure 8 - Relationship Between Hour Angles and PDOF

Specifying the Stiffness Coefficients - The process of estimating the damage energy is based on the assumption that the exterior surface of the vehicle resists inward crush (displacement) like a linear spring. The exterior of the vehicle can be thought of as being surrounded by such springs, as described in figure 9. Note the free ("uncrushed") length of these springs actually extends out beyond the exterior of the vehicle. This allows the model to account for an impact force which is not great enough to damage the vehicle. Constant, A, which has a different value for the front, rear and sides (see Table 1), is used to account for this effect. A (units, pounds of force per inch of vehicle width, or simply lb/in) is the preload force per inch of damage width required to deflect the spring an amount equal to the free length, A/B (constant B is described below). Alternatively, A may be thought of as the force per inch of contact width required to initiate damage.

Each spring has a linear spring constant, B, which also has a different value for the front, rear, and sides (see Table 1). B has the units of pounds per inch of crush depth per inch of damage width, or simply lb/in^2.

To simplify data entry, a stiffness category is specified for each vehicle. The stiffness category automatically assigns the default A and B stiffness coefficients according to the general structural characteristics of the vehicle.

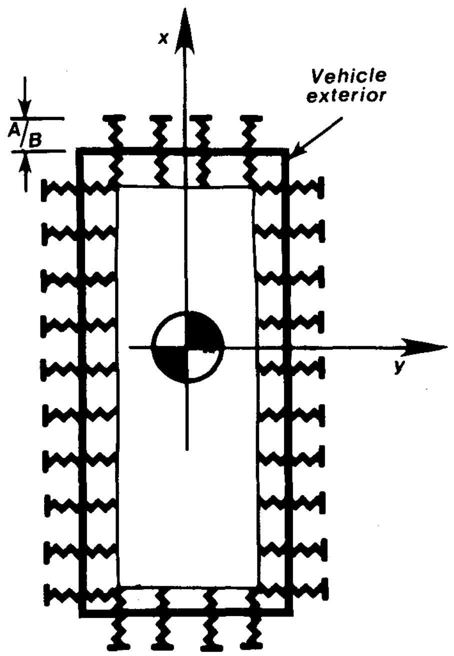


Figure 9 - Conceptual Vehicle Exterior

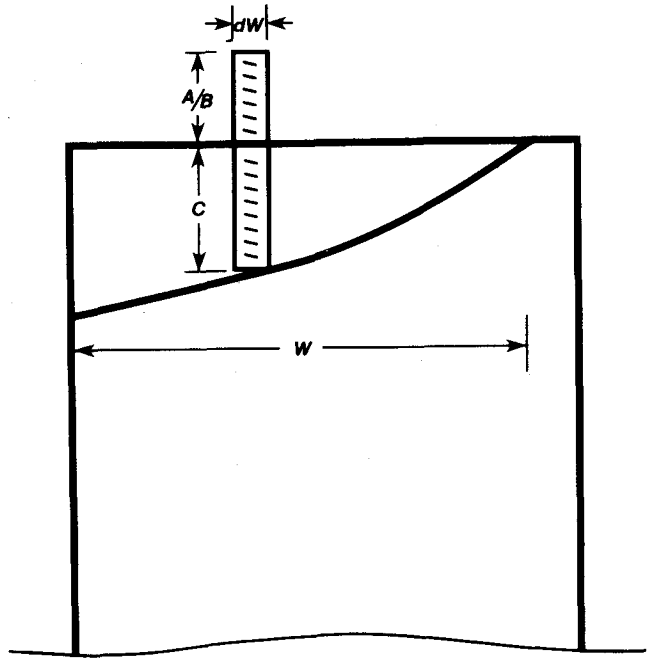


Figure 10 - Computing the Damage Energy

Computing the Energy Absorbed by Damage

A typical damage profile is shown in figure 10. The damage profile has a total width, W. Each increment of the damage width, dW, has a measured crush depth, C, and a spring deflection, $\delta = C + A/B$. In order to determine the amount of damage energy associated with the total damage profile, the spring deflections are integrated over the total damage width. For any linear spring, the energy stored in the spring due to deflection, δ, is $E = (1/2)K\delta^2 d\delta$. When this formula is applied to our vehicle model,

$$E = \int (B/2)((A/B) + C))^2 dW$$
$$= \int ((A^2/2B) + AC + (C^2B/2))dW$$
$$= \int (A^2/2B)dW + ACdW + (B(C/2)C)dW$$

A crush zone exists between each set of crush depth measurements (see figure 11). Since there may be two, four or six crush depths entered, there may be one, three or five crush zones. Integration along the width of damage between each set of crush depths, $C_n - C_{n+1}$, results in the energy absorbed in each crush zone,

$$E = (A^2/2B)W + ACW + (B(C/2)C)W$$
$$= (A^2/2B)W + (A + B\bar{x})\text{Area}$$

TABLE 1. VEHICLE CRUSH STIFFNESS CATEGORIES AND COEFFICIENTS [10]

STIFFNESS* CATEGORY →		1	2	3	4	5(6)	7	8	9	10	11
VEHICLE** MODELS		Pinto (FRONT) Accord Honda CVCC Prelude Corolla Chevette Fiesta Bobcat Datsun 210 Datsun 310 Arrow Champ Colt Porche 924 Mazda GLC Fiat 124 Spider Fiat X/19 Datsun 280ZX Opel MG Miget Tri. Spitfire VW Rabbit VW Scirocco	Pinto (REAR) Chev. Monza Celica ST Celica GT Corona Spirit Pacer Gremlin VW Dasher Vega Skyhawk Omni Sunbird Starfire Mustang (74-) Horizon Fiat 128 Sedan Capri 280 ZX 2+2 Challenger BMW 320i Audi Fox Mazda Cosmo Mazda RX-7 Renault LeCar Saab 900 Saab 99 Subaru	Celica Supra Mustang (-73) AMC Concord Malibu (78-) Monarch Zephyr Fairmont Granada Firebird Cressida Datsun 810 Monte Carlo(78- Grand Prix (78- Cutlass (78-) LeMans (78-) Regal Aspen Peugot 604L BMW 528i Volvo (all) Audi 5000	Chevelle (-76) Monte Carlo(-77) Grand Prix (-77) Cutlass (-77) LeMans (-77) Phoenix Chev V-8 (-77) LaSabre (77-) Volare Monaco (77-) Magnum Century LeBaron Riveria (77-) Marquis (77-) LTD (77-) Cordoba Nova Eldorado (79-) Delta 88 (77-) Diplomat T-Bird (77-) Seville Ventura Cougar	LeSabre (-76) Chev V-8 (-76) Monaco (-76) Riveria (-76) Marquis (-76) LTD (-76) Eldorado (-78) Delta 88 (-76) T-Bird (-76) Olds 98 St. Regis Newport Brghm. DeVille Electra Fleetwood Continental Checker Cab	VANS*** Econo. E150 Dodge B-200 Chev G-20 Ford P-500 GMC G-35 GMC G-1500 VW Vanagon OTHER*** Datsun P/U Honcho 4X4 P/U Wagoneer Scout II Chev. Blazer	PICKUPS*** Courier El Camino Ford F150 Chev LUV Ford F250 Dodge D-100 Ranchero F10 Ford F100 1/2Ton GMC 1500 Toyota SR5 lg. bd.	FRONT DRIVE**** Citation Phoenix Skylark Omega Reliant Aries Escort Lynx	MOVABLE BARRIER	IMMOVABLE BARRIER
(F) FRONT	A	302 lb/in	259	317	356	325	383	480	373	-	-
	B	47 lb/in^2	43	56	34	37	126	50	38	-	-
	G	967 lb	778	901	1874	1429	580	2315	1849	-	-
(B) REAR	A	366	391	410	357	297	300	346	*	-	-
	B	38	41	44	13	70	55	25	*	-	-
	G	1755	1874	1931	4986	628	818	2373	*	-	-
(R,L) SIDE	A	77	140	173	143	177	*	*	*	-	-
	B	37	67	57	50	47	*	*	*	-	-
	G	81	148	263	203	331	*	*	*	-	-

*For test modes or vehicle models not listed, use a structurally similar category or choose a category by wheelbase dimension (Table 3). (NASS teams should consult their zone center if in doubt as to proper stiffness category.)

**Includes all model years unless otherwise specified.

***Front and rear crash modes only; for side damage, pick a category (1 - 6) by wheelbase

****Front crash mode only; for side and rear, pick a category (1 - 6) by wheelbase

TABLE 2. VEHICLE CLASS CATEGORIES AND DEFAULT DIMENSIONS [10]

Class Categories →

PARAMETER	1	2	3	4	5	6	7 VANS		MOVABLE 10 BARRIER	IMMOVABLE 11 BARRIER
WHEELBASE (IN)	80.9-94.8	94.8-101.6	101.6-110.4	110.4-117.5	117.5-123.2	123.2-150	109"-130"	No Data for Cat. 8 (P/U) and 9 (FWD). Select 1 - 6 by Wheelbase.	120.	-
TRACK (IN)	51.1	54.6	58.9	61.8	63.7	63.7	67.6"		60.0	-
LENGTH (IN)	159.8	174.9	196.2	212.8	223.7	229.4	183.6"		180.0	-
WIDTH (IN)	60.8	67.2	72.6	77.0	79.8	79.8	79."		78.0	-
a (IN)	45.1	46.3	51.3	54.7	58.1	60.1	48.5		54.0	50.
b (IN)	48.1	50.1	55.5	59.2	63.0	65.1	68.5		66.0	50.
X_F (IN)	76.0	83.3	89.8	98.8	101.8	104.2	75.6		84.0	50.
X_R (IN)	-83.8	-91.6	-106.4	-114.0	-121.9	-125.2	-107."		-96.0	-50.
Y_S (IN)	30.4	33.6	36.3	38.5	39.9	39.9	39.5"		50.0	50.
RSQ (IN^2)	2006.	2951.	3324.	3741.	4040.	4229.	3713.		4024.	10^6
M (LB-SEC^2/IN)	5.70	7.90	9.18	10.99	12.59	13.74	11.2		10.35	10^6
CURB WT (LBS)	2469.	2753.	3247.	3947.	4565.	5009.	4300.		4000.	-

DEFINITIONS:
- a = distance from c.g. to front axle
- b = distance from c.g. to rear axle
- X_F = distance from c.g. to front of vehicle
- X_R = distance from c.g. to rear of vehicle (measured in the negative direction)
- Y_S = distance from c.g. to side of vehicle
- RSQ = radius of gyration, squared
- M = vehicle mass (includes 2 passenger loading)

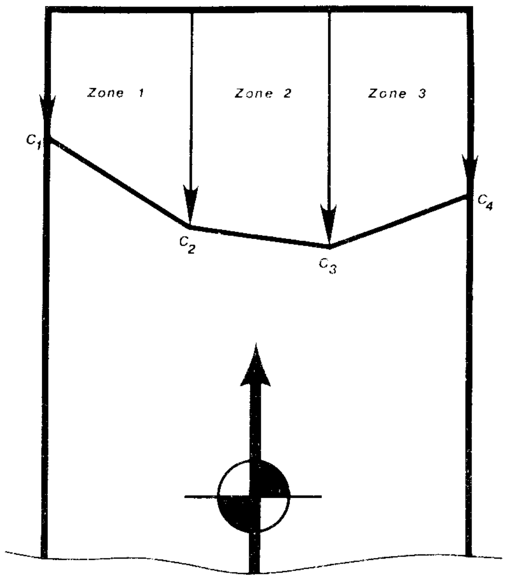


Figure 11 - Crush Zones

The total damage energy is simply the sum of the damage energies within each individual crush zone. Similarly, the magnitude of the total maximum crush force is simply the sum of the force in each individual crush zone.

Modifications

Two modifications in the above development are necessary to allow its use for motor vehicle collisions: non-perpendicular crush and non-central impact.

Non-perpendicular Crush - During the vehicle inspection, the depth of crush is always measured perpendicular to the undeformed surface. When the collision force (PDOF) acts at a non-perpendicular angle, ϕ (see figure 12), the distance through which the force acts is greater than the measured crush by a factor equal to $1/\cos\phi$. Therefore, a factor is required for collision forces which are applied at an angle which is non-perpendicular to the surface of the vehicle.

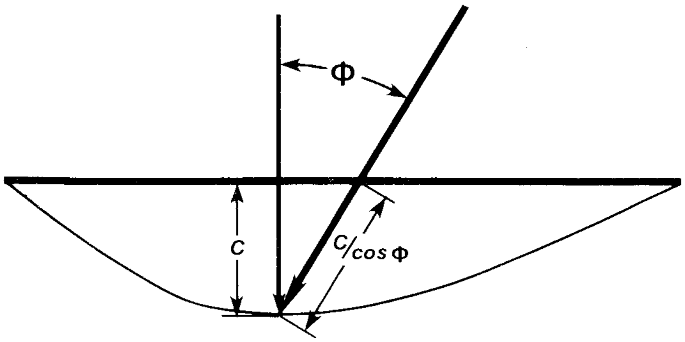


Figure 12 - Non-perpendicular Crush

Since the terms involving crush depths are squared (remember, the crush energy is proportional to the square of the crush depths), the factor must take on the form $1/\cos^2\phi = 1 + \tan^2\phi$. Therefore, the computed energies are multiplied by a factor of $1 + \tan^2\phi$.

This "angled crush" factor has an important influence on the damage-based energy estimate. For example, when $\phi = 20$ degrees, the factor is $1 + \tan^2(20) = 1.36$, thus increasing the estimated damage energy by 36 percent. When $\phi = 45$ degrees, the factor becomes $1 + \tan^2(45) = 2.0$, effectively doubling the estimated damage energy. This factor is not allowed to exceed 2.0, so any increase of the angle beyond 45 degrees will not increase the damage energy estimate.

Non-central Impact - The model developed in the preceding section was based on the assumption of a central impact, i.e., the force of impact (impulse) occurs along a straight line through the center of mass of each vehicle (figure 13). Most vehicular collisions are non-central. During a non-central collision, the force of impact does not act through the center of mass. Non-central collisions always produce rotational kinetic energy in the vehicle. This rotational kinetic energy must be accounted for, since damage energy spent in creating vehicle rotation is not available for creating a delta-V. Therefore, delta-V will be lower for non-central collisions than for an equivalent amount of damage during a central collision.

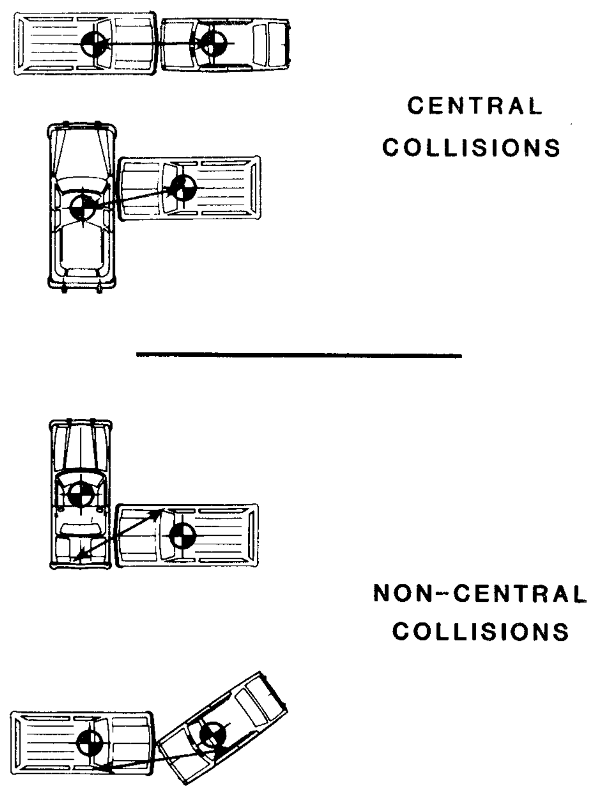


Figure 13 - Central vs Non-central Collisions

To account for the rotational kinetic energy in non-central collisions, the distance from the line of action of the impulse to the vehicle CG must be determined. This is accomplished from geometry since the line of action goes through the damage centroid at an angle equal to the PDOF. For a frontal collision (see figure 14) with a damage centroid located at $(\bar{x},\bar{y})$ and an impulse angle equal to the PDOF, the distance from the line of action of the impulse to the center of mass is

$$h = (X - \bar{x})[SIN(PDOF)] - \bar{y}[COS(PDOF)]$$

For a side collision, the value of h is computed in a similar manner.

A vehicle's radius of gyration, k_{gy}, is defined as the radius of a circular hoop having the same mass and rotational, or yaw, moment of inertia as the vehicle. For a non-central collision where the impulse acts a distance, h, from the center of mass, the effective mass of the vehicle is reduced by the factor γ, where

$$\gamma = k_{gy}^2/(k_{gy}^2 + h^2)$$

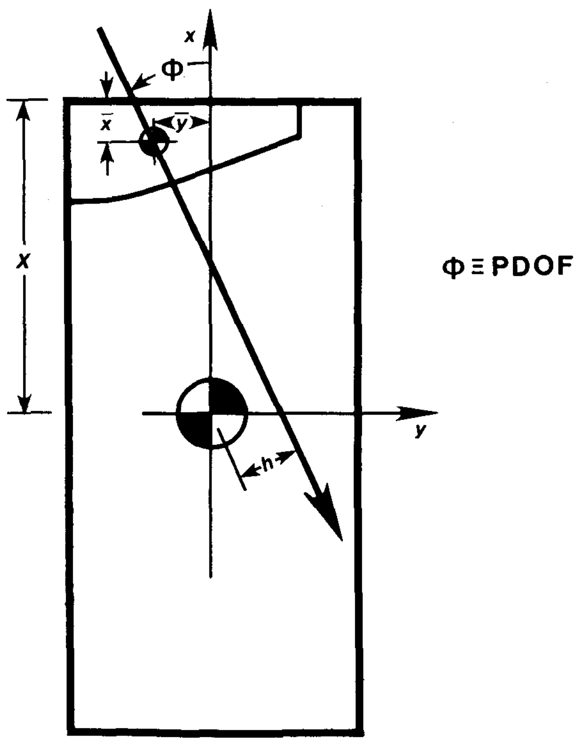


Figure 14 - Offset Impulse Due to a Non-central Collision

In the equation for delta-V developed previously, the mass is multiplied by the mass reduction factor, γ. Note that when h = 0 the mass reduction factor equals 1.0 and the impulse equation reduces to that of a central collision (γM = 1.0*M = M). There is no rotational kinetic energy to account for in central collisions.

Refinements to the Simplified Model

The damage procedure described above is used in CRASH3 and EDCRASH Versions 2 and 3. The procedure is very useful for its intended purpose (i.e., the development of a large statistical database of accident statistics which includes delta-V). In such a database, estimation errors tend to cancel out. However, four refinements are necessary to make the DAMAGE analysis useful for individual cases. These important refinements are: (a) allow user-entered vehicle dimensional data, (b) allow user-entered A and B crush stiffness coefficients, (c) allow user-entered variation in crush stiffness coefficients along the damage width, and (d) relocate the point through which the impulse acts. These refinements, incorporated in EDCRASH Version 4, are described below.

User-entered Vehicle Data - The default vehicle properties are assigned by vehicle class category (see Table 2). These data represent an average vehicle within a specified wheelbase range. Individual vehicles sometimes have properties which differ significantly from the default data. The centroid of the damage profile may be incorrectly located because of faulty vehicle dimensions, resulting in the calculation of an incorrect offset dimension, h. The radius of gyration may also be incorrect. Each of these inaccuracies can cause an error in the delta-V. This effect is usually quite small unless the subject vehicle is larger than can be specified by the available class categories. The separation velocities and trajectory simulation can also be adversely affected due to errors in the wheelbase, trackwidth and radius of gyration. To remedy this problem, the default data can be replaced with the actual vehicle dimensions, inertias, and tire data.

User-entered A and B Crush Stiffness Coefficients - The default A and B stiffness coefficients automatically assigned by the crush stiffness category (see Table 1) may not apply for all collisions. A classic case is "bumper override", a condition where the bumper and frame of the striking vehicle strike above the bumper and/or frame of the target vehicle. Only soft sheet metal on the target vehicle is crushed, and its damage energy is over-estimated (this occurred in several of the RICSAC cases, causing gross errors in the damage energy predictions and associated EDCRASH warning messages [8,9,10,11]). To remedy this problem, the default coefficients can be replaced with the actual stiffness coefficients derived from test data.

The default stiffness coefficients were developed during the late seventies. Since then, automobiles have undergone significant structural changes (front-wheel drive and unibody chassis construction). The manufacturers have conducted barrier crash tests for many of the new vehicles, but the data have yet to be analyzed and converted into A and B stiffness coefficients.

Variation in Crush Stiffness Coefficients Along the Damage Width - The default calculations assume the zone between each set of crush measurements has an identical stiffness and assign an identical set of A and B coefficients to each zone. In reality, the vehicle's exterior is not "homogeneous". There are hard spots at the wheels and soft spots at the body panels between frame support structures. This variation can be accounted for by specifying the appropriate A and B stiffness coefficients within each crush zone.

Relocation of the Impulse - The default calculations assume the impulse acts through the damage centroid. This assumption is valid for relatively symmetrical damage profiles on relatively homogeneous surfaces. However, there are cases where the impulse acts far away from the damage centroid. An example is the case where one end of the damage profile includes soft sheet metal while the other end involves a wheel (see figure 15). The damage centroid will be located in the region associated with the greatest crush (to the soft sheet metal), while the impulse actually acts at the wheel, which has less crush because of its higher stiffness.

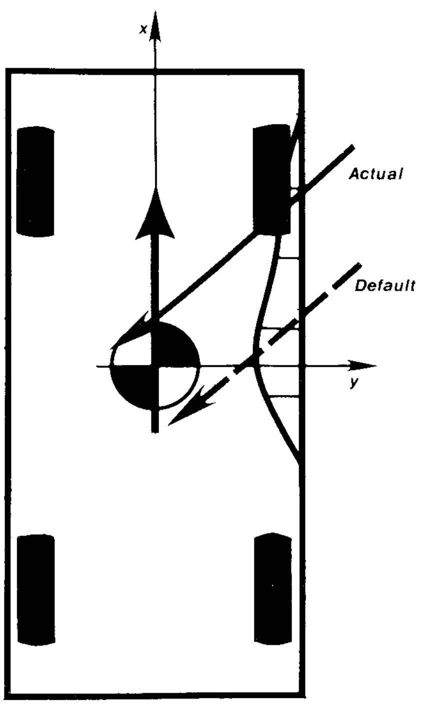


Figure 15 - Relocation of the Impulse

EDCRASH accounts for this by (a) allowing for the entry of the actual stiffnesses for each crush zone (the zone including the wheel will have a much higher stiffness) and (b) computing the location through which the force acts by summing moments and forces in each of the individual crush zones.

Relocating the point of force application eliminates a warning message which occurs because the mislocated force acts on the wrong side of the vehicle CG (the warning message indicates the vehicle should rotate in the opposite direction between impact and rest). Also eliminated is the potential miscalculation of the offset distance, h (see figure 15).

Discussion of DAMAGE

The advantages and disadvantages of the DAMAGE procedure for computing delta-V are as follows:

Advantages

1. It yields acceptable results when good vehicle data, damage profile measurements and crush stiffness coefficients are available.

2. It is easy to use because the input is generally available and easy to measure.

3. It is a practical means of independently determining the delta-V of a vehicle when good accident site data are unavailable.

Disadvantages

1. There is a lack of good crash test data and A and B coefficients for many vehicle types.

2. It does not account for vertical variation in crush depth (the typical "bumper over-ride" problem).

3. It requires the vehicle damage centroids to reach a common velocity at the moment of separation (sideswipes cannot be analyzed).

4. It assumes a linear relationship exists between stiffness and crush. As a result, it may underestimate the delta-V for minor crashes, partially because restitution is ignored [12], and because of a lack of low speed crash tests. It overestimates the delta-V for major crashes (delta-V greater than 50 mph) in which structural disintegration occurs because the crush stiffness becomes non-linear with crush depth (the B crush stiffness coefficient obviously is reduced when the vehicle structure disintegrates).

5. It assumes the impulsive force is the only force acting on the vehicle. Tire forces are neglected. This is usually not significant except in the case of a minor impact involving a heavy vehicle on a road with high friction.

6. The angle of the impulse, or PDOF, cannot be computed without accident scene data.

OBLIQUE IMPACT ANALYSIS PROCEDURE

The conservation of linear momentum simply states the momentum of the system (both vehicles) at the beginning of the impact is equal to the system momentum at the end of the impact. The concept is shown graphically in figure 16.

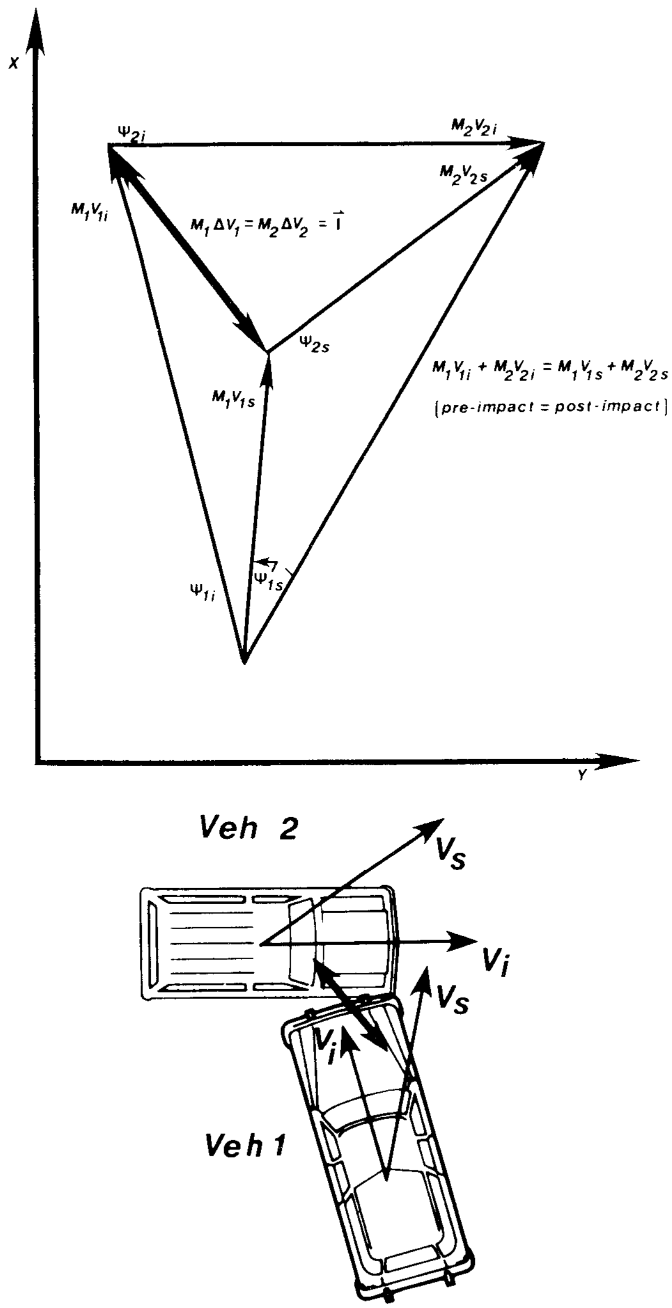


Figure 16 - Conservation of Linear Momentum for Oblique Collisions

There are two equations of linear motion (X-direction and Y-direction) for the system linear momentum just prior to impact.

In the X-direction:

$$XOBL = M_1V_1COS(\beta_1 + \psi_1) + M_2V_2COS(\beta_2 + \psi_2)$$

In the Y-direction:

$$YOBL = M_1V_1SIN(\beta_1 + \psi_1) + M_2V_2SIN(\beta_2 + \psi_2)$$

There are also two equations of linear motion (X-direction and Y-direction) for the system linear momentum at the instant of separation (the end of impact).

In the X-direction:

$$AOBL = M_1(Usep_1COS(\psi_1) - Vsep_1SIN(\psi_1))$$
$$+ M_2(Usep_2COS(\psi_2) - Vsep_2SIN(\psi_2))$$

In the Y-direction:

$$BOBL = M_1(Usep_1SIN(\psi_1) + Vsep_1COS(\psi_1))$$
$$+ M_2(Usep_2SIN(\psi_2) + Vsep_2SIN(\psi_2))$$

In the above equations,

$M_{1,2}$ = vehicle masses

$Usep_{1,2}$ = forward (vehicle-fixed) component of separation velocities

$Vsep_{1,2}$ = lateral (vehicle-fixed) component of separation velocities

$\psi_{1,2}$ = heading vectors at impact

$\beta_{1,2}$ = sideslip vectors at impact

The above variables are available as a result of inspecting the accident site (the vehicle mass is obtained by measurement or from tables).

By the conservation of linear momentum, the pre-impact system momentum is equal to the post impact system momentum in the X- and Y-directions

$$XOBL = AOBL$$

and

$$YOBL = BOBL$$

The velocity of each vehicle can now be easily solved using simultaneous solutions:

$$V_1 = (BOBL(COS(\beta_2 + \psi_2)) \\ -AOBL(SIN(\beta_2 + \psi_2)))/M_1 SIN((\beta_1+\psi_1)-(\beta_2+\psi_2))$$

and

$$V_2 = (AOBL(SIN(\beta_1 + \psi_1)) \\ -BOBL(COS(\beta_1 + \psi_1)))/M_2 SIN((\beta_1+\psi_1)-(\beta_2+\psi_2))$$

To display the effects of pre-impact sideslip, these velocities are reported in their forward and lateral components,

$$Vfwd_1 = V_1 COS(\beta_1), \quad Vlat_1 = V_1 SIN(\beta_1)$$

and

$$Vfwd_2 = V_2 COS(\beta_2), \quad Vlat_2 = V_2 SIN(\beta_2)$$

The delta-V computed by the momentum analysis is simply the difference between the pre-impact and post-impact velocities:

$$\text{delta-}V_x = Vfwd - Usep$$

and

$$\text{delta-}V_y = Vlat - Vsep$$

When $(\beta_1 + \psi_1) - (\beta_2 + \psi_2)$ equals 0 or 180 degrees, the result is undefined because the sine of 0 (and 180) degrees equals zero. This occurs when the pre-impact velocity vectors are parallel, usually the case for head-on and rear-end collisions. As a consequence of this fact, one of the equations vanishes and we are left with one equation and two unknowns; one of the impact velocities must be known in order to compute the other. This is the algebraic singularity in the linear momentum solution. When these vectors are nearly parallel, the results are extremely sensitive to the input data. For this reason, EDCRASH will not use the linear momentum solution for delta-V if the pre-impact velocity vectors are within +/-10 degrees of collinear; the damage-based solution is used instead.

Discussion of OBLIQUE IMPACT

The advantages and disadvantages of the linear momentum procedure are as follows:

Advantages

1. It is based purely on physics; there are no empirical coefficients (no crash test data are required).

2. The direction of the impulse can be computed for comparison with the estimated PDOF.

3. It is not sensitive to an irregular damage profile, such as bumper over-ride.

Disadvantages

1. It is not useful for determining pre-impact velocities for collinear collisions and becomes extremely sensitive for nearly-collinear collisions.

2. It requires a detailed accident site inspection (impact and rest positions and a description of the path between impact and rest, as well as tire-ground friction coefficient).

3. Like the DAMAGE procedure, it assumes the impulsive force is the only force acting on the vehicle. Tire forces are neglected. This is usually not significant except in the case of a minor impact involving a heavy vehicle on a road having a high friction coefficient.

4. It assumes the impact is instantaneous. Thus impact and separation heading angles are identical. While this has no direct effect on delta-V, it can produce a separation sideslip angle in the calculations for separation velocity when none may actually exist [4].

OUTPUT

The results of analysis are displayed in three forms: numerical, graphical and warning messages. Each form of output serves a different purpose, which is described below.

Numerical Output

The results of a typical EDCRASH analysis are shown in figure 17. The impact speeds are displayed in their forward and lateral components. When there is a non-zero lateral velocity (indicating pre-impact sideslip), the total speed of the vehicle is

$$V = \sqrt{V_{fwd}^2 + V_{lat}^2}$$

The method of calculating delta-V used for determining the impact speed is also displayed (linear momentum for the above case - see arrow).

The damage-based delta-V is then displayed. The total delta-V and the longitudinal (forward) and lateral components are shown, along with the PDOF entered by the user (remember, the components of the delta-V are related to the PDOF).

The momentum-based delta-V results (total, longitudinal and lateral) are displayed next. The angle of the impulse (ANG) is computed by the momentum analysis and displayed for comparison to the user-entered PDOF (above).

S U M M A R Y   O F   E D C R A S H   R E S U L T S

Lic. User: Engineering Dynamics   S/N: CRA64000   Date: 12-04-1986

RICSAC Case No. 6, Chevelle vs Rabbit

WARNING MESSAGES: NO WARNING MESSAGES

IMPACT SPEED (TRAJECTORY AND CONSERVATION OF LINEAR MOMENTUM)

	FORWARD	LATERAL
VEH #1	24.0 mph	0.0 mph
VEH #2	25.3 mph	0.0 mph

SPEED CHANGE (DAMAGE)

	TOTAL	LONG.	LAT.	PDOF
VEH #1	15.2 mph	-14.3 mph	5.2 mph	-20.0 deg
VEH #2	24.9 mph	-19.1 mph	-16.0 mph	40.0 deg

SPEED CHANGE (LINEAR MOMENTUM)

	TOTAL	LONG.	LAT.	ANG.
VEH #1	14.3 mph	-13.3 mph	5.2 mph	-21.1 deg
VEH #2	23.5 mph	-18.3 mph	-14.7 mph	38.9 deg

ENERGY DISSIPATED BY DAMAGE: VEH #1   55424.8 ft-lb   VEH #2   63215.9 ft-lb

Figure 17 - Typical Form of Numerical Output (Abbreviated Listing).

The Summary of Results concludes by displaying the total damage-based crush energy for each vehicle.

This form of output is useful for reviewing the main calculation results - Impact Speeds and Speed Changes (Delta-V). It is also useful for quickly checking for the consistency between damage-based and momentum-based results, factors which can trigger warning messages. A lengthy form of output, which displays the input data and separation conditions, is also available. This "Complete Listing" can be used for final documentation of the analysis.

Graphical Output

The graphical results for displaying delta-V can have two forms: Damage Profiles and Impact Configuration.

Damage Profiles (see figure 18) displays the vehicle with its user-entered damage profile, along with the damage data and the calculated delta-V.

The Damage Profiles display is useful for viewing the shape of the damage profiles and the location and direction of the PDOF. The magnitude of the principal force at maximum penetration is also displayed for each vehicle, allowing for an easy method of checking for consistency with Newton's third law (if the computed impact force for one vehicle is more than twice the force computed for the other vehicle, a warning message will be issued).

Impact Configuration (see figure 19) displays the vehicles at impact, including the damage outline, the PDOFs and the impulse centers (the point where the PDOF acts on the vehicle). The total delta-V and its component vectors are displayed. If scene data were entered, the impact and separation velocity vectors can also be displayed.

Since the vehicles share the same impulse, the Impact Configuration display is very useful for properly orienting the vehicles at impact. This can be done by locating the vehicles so the impulse centers overlap.

It is difficult, even for skilled investigators, to spot a missing minus sign or other errant values in the input data. Yet these errors can produce major errors in the results. Using graphics, however, it is easy to spot a vehicle heading in the wrong direction or a damage profile located on the wrong side of the vehicle. The Damage Profiles and Impact Configuration graphical outputs make these errors obvious, thus helping to insure integrity of the input data and consistency of the results.

The use of color graphics greatly enhances the visual images, especially for the illustration of complex images containing several vectors. By displaying each of the vehicles and vectors in different colors, each vehicle and its associated vectors can be easily distinguished.

Graphic output also proves to be especially useful for presentations, where the results of a

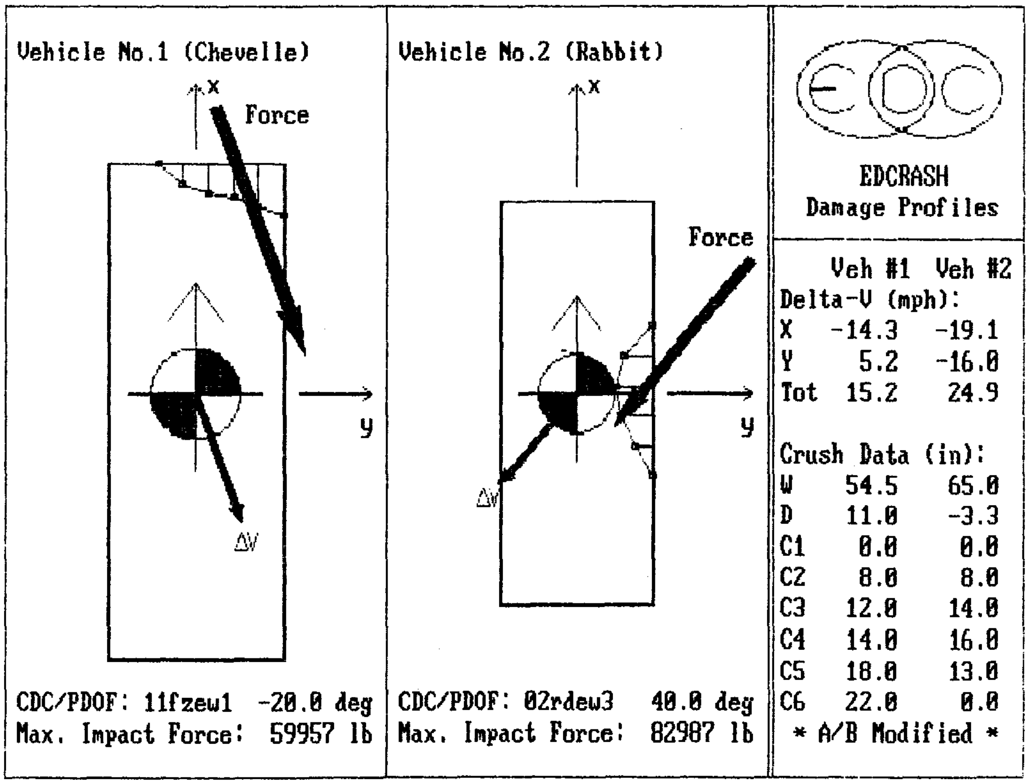


Figure 18 - Vehicle Damage Profiles

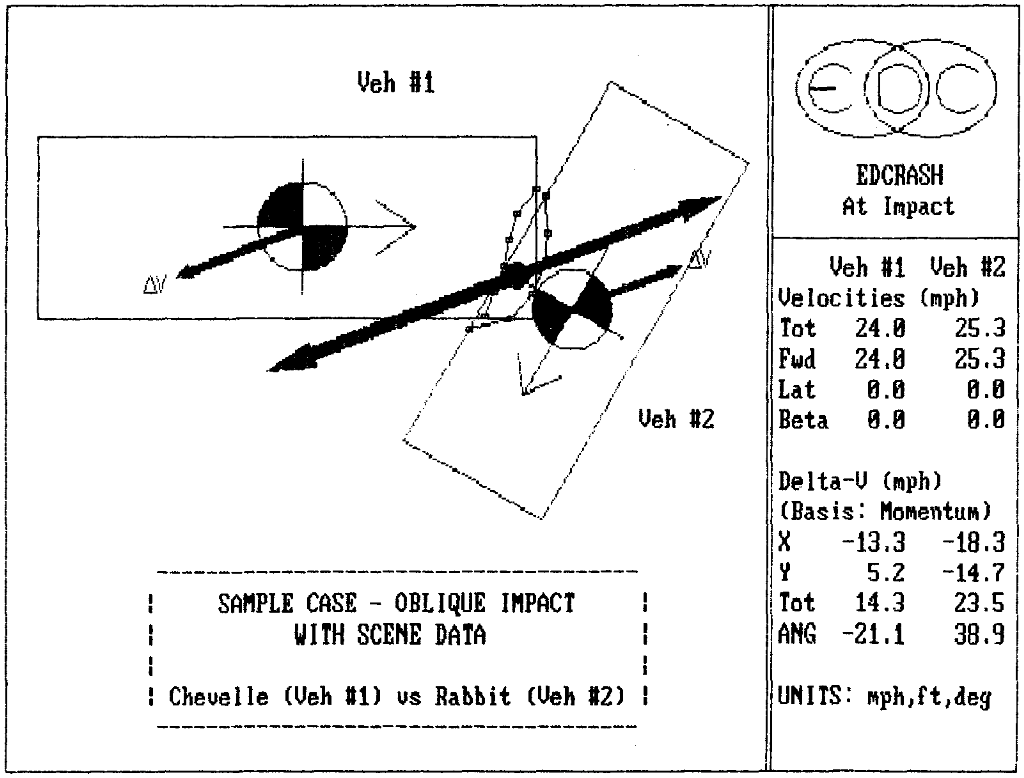


Figure 19 - Vehicle Impact Configuration

technical analysis must be presented to persons not familiar with vehicle dynamics and crash investigations.

Warning Messages

Fifteen potential warning messages help to insure that errors are identified and measures to correct the errors are suggested. Six messages may occur which affect the delta-V:

1. Common Velocity Error
2. Newton's Third Law Violation
3. Momentum/Damage-based Delta-V Comparison
4. Impulse Angle/PDOF Comparison
5. Conservation of Energy
6. Separation Angular Velocity/PDOF Comparison

All the messages except Newton's Third Law Violation require scene data. The delta-V and impulse angle/PDOF comparisons require oblique impacts. A complete description of these messages is available in the literature [10].

The investigative data (the results of accident site and vehicle inspections) for most crashes produce EDCRASH warning messages during the first run. Even staged collisions generate them [9]. Frequently, the cause is poor data. Examples of potentially poor data include the use of limited photographs to estimate the damage profile (vehicle data), failure to identify the proper impact and rest positions and headings (scene data), and errant impact-to-rest path data, such as a missing point on curve. These messages can help to lead the investigator to the source of the suspicious data.

Another cause for warning messages is attempting to analyze a crash beyond the scope of the CRASH analysis (i.e., sideswipes).

The presence of warning messages does not necessarily indicate the results are faulty. Rather, the warning messages indicate a law of motion or an assumption inherent to the calculations has been violated according to the input data. The extent to which the violation adversely affects the accuracy of the results must be considered on an individual basis. For example, consider the case of bumper over-ride in an oblique collision. Warning message nos. 2, 3, and 5 (above) will probably be issued by EDCRASH. However, the basis of results for delta-V and impact speed will be the conservation of linear momentum, not the inapplicable damage data which triggered the messages.

DISCUSSION

During the development of crash test data, most crash tests were head-on barrier tests. Therefore, the DAMAGE analysis is best suited to collinear (head-on) impacts. Because of the sensitivity of the momentum analysis to collinear collisions, the OBLIQUE IMPACT analysis is best suited to oblique impacts. Therefore, the DAMAGE and OBLIQUE IMPACT analyses nicely complement each other.

Crash test data for deriving A and B stiffness coefficients are badly needed. However, the integrity of the data is essential. The prior RICSAC studies [11] which were of such great benefit for validation of impact speeds were less useful for the validation of delta-V because much of the actual test data violates the conservation of energy and momentum [5].

Recent research has suggested the DAMAGE procedure might provide improved results if a coefficient of restitution were included [12]. It is recommended this possibility be pursued by conducting staged collision experiments with an emphasis on accurately recording the delta-Vs.

The linear momentum solution for delta-V has been used successfully for many years. It can be used as a final value problem, where the separation velocities are known and the impact velocities are computed (such as in EDCRASH) or it can be used as an initial value problem, where the impact velocities are known and the associated separation velocities are computed. As a final value problem, the momentum solution is a closed-loop "reconstruction" of the delta-V based on accident scene data. As an initial value problem, the momentum solution is an open-loop "simulation," where the initial conditions are adjusted until the desired separation conditions are achieved.

<u>Procedures for a Critical Review of Output</u> - The foregoing development and discussion should lead to the conclusion that one can critically review the results of an EDCRASH (or any "CRASH") analysis to determine its validity. Indeed this is the case. The following procedure describes how.

Step 1. - Review the warning messages (if any) at the beginning of the output. (Most of the compatibility checks which produce the warning messages described in this paper are available only from EDCRASH.)

As was mentioned previously, the presence of warning messages does not necessarily indicate the results are faulty. Determine the cause of each message and its effect on the results. When reviewing cases involving collinear collisions, remember the damage-based delta-V is used. Therefore, pay particular attention to violations of Newton's third law and conservation of energy, since no other compatibility checks are possible.

Step 2. - Review the EDCRASH graphics. Display the impact and rest positions (Site Drawing), the damage data (Damage Profiles), and the Impact Configurations to insure all the data were correctly entered.

Step 3. - Review a Complete Listing of the output. Start by inspecting the echoed input data (Scene Data, Damage Data, Tire/road Data, and Vehicle Class and Stiffness Categories).

Default vehicle data, automatically assigned by EDCRASH according to the general vehicle type, will have asterisks adjacent to it. If the default data (vehicle dimensions, inertias, and tire data and crush stiffness coefficients) have been changed, determine the basis for the change.

Next, review the results for impact speed and delta-V. Do they make sense? This question must always be asked, even though there are extensive warning messages. If the results are suspicious, isolate the input variable(s) causing the discrepancy and rerun with appropriate data.

In virtually all cases, any differences in results will lie in the investigator's quantitative assessment of such factors as tire/ground friction, damage measurement interpretation and estimates of scene data. In a classroom setting, the typical range among impact speed estimates of 20 investigators analyzing the same data from a well-documented police accident report may be up to 10 mph in a 60 mph collision without triggering warning messages [13].

CONCLUSIONS

1. The DAMAGE and OBLIQUE IMPACT procedures for determining delta-V each have their advantages and disadvantages.

2. The primary advantage of the DAMAGE procedure is that it can be accomplished from vehicle inspections alone; it does not require scene data. The primary advantage of the OBLIQUE IMPACT procedure is its basis in pure physics.

3. The primary disadvantage of the DAMAGE procedure analysis is the lack of available A and B stiffness coefficients from crash data. The primary disadvantage of the OBLIQUE IMPACT procedure is its singularity, and resulting inapplicability, for collinear impacts.

4. The two procedures are complimentary: The DAMAGE procedure is best-suited for the conditions in which the OBLIQUE IMPACT analysis is least-suited, and vice-versa.

5. EDCRASH Version 4 removes many of the prior limitations in the CRASH3-type DAMAGE analysis which had made it less useful for investigating individual accidents.

6. Graphical results are an extremely valuable addition to the delta-V analysis because they help to insure the integrity of the input data and provide a visual image of the results.

7. The use of extensive warning messages is an essential and valuable tool for helping to insure valid results by alerting the investigator of gross violations of the laws of physics which may be the result of an inadvertent error in data entry or an error due to inherently poor data.

REFERENCES

1. Mackay, G.M., "Injury and Collision Severity," SAE Paper No. 680779, October, 1968.

2. Advances in Belt Restraint Systems: Design, Performance and Usage, Society of Automotive Engineers, Publication P-141, February, 1984.

3. Day, T.D., Nagle, D.G., Beals, R.K., "Case Studies Involving the Use and Non-use of Seatbelts," SAE Paper No. 861091, November, 1986.

4. Day, T.D., EDCRASH Training Manual, Engineering Dynamics Corporation, Lake Oswego, OR 1986.

5. Woolley, R.L., Warner, C.Y., Tagg, M.D., "Inaccuracies in the CRASH3 Program," SAE Paper No. 850255, February, 1985.

6. Vehicle Dynamics Terminology, Society of Automotive Engineers Technical Report SAE - J670e, July, 1976.

7. Collision Deformation Classification, Society of Automotive Engineers Technical Report SAE - J224 MAR80, March, 1980.

8. Oppenheim, T., "CRASH2 Maintenance Volume 2 - Listing of Test Runs," NTIS PB81-246175, May, 1981.

9. Day, T.D., Hargens, R.L., "Differences Between EDCRASH and CRASH3," SAE Paper No. 850253, February, 1985.

10. Vehicle Analysis Package - EDCRASH Program Manual, Version 4.0, Engineering Dynamics Corporation, Lake Oswego, OR, 1986.

11. Jones, I., Baum, A., "Research Input for Computer Simulation of Automobile Collisions - Volume IV: Staged Collision Reconstructions," DOT HS- 805 040, December, 1978.

12. McHenry, R.R., McHenry, B.G., "A Revised Damage Analysis Procedure for the CRASH Computer Program," SAE Paper No. 861894, October, 1986.

13. MAPTAR (Microcomputer Application Programs for Traffic Accident Reconstruction) Course, The Traffic Institute, Northwestern University, Evanston, IL, March to September, 1986.

20 page booklet. Printed in U.S.A.