THE ALGORITHMS OF CRASH

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INTRODUCTION

The acronym CRASH stands for the Computer Reconstruction of Automobile Speeds on the Highway. The CRASH computer program is an accident reconstruction program. With CRASH you input the vehicle properties, the impact and rest positions, and the vehicle damage measurements. The program produces approximations of the vehicle speeds at impact the impact speed change or Delta-V (ΔV).

The **Impact Speed Change (ΔV)** is defined as the impulsive change in vehicle speed (i.e., produced by an impact) that occurs along the direction of action of the principal collision force[1].

The magnitude and direction of the impact speed-change of a vehicle, that occurs during a collision, serve as primary descriptors of impact severity, since they reflect the effect of the ratio of the masses of the two colliding bodies as well as that of the closing speed. The impact speed-change is expressed in miles per hour and the clock direction from which the principal force was applied is generally stated.

For example, a 20 MPH, 06 o'clock impact speed-change would correspond to a principal force acting from the 06 o'clock direction (i.e., a longitudinal rear-ender) with a sufficient impulse (i.e., time-integral of applied force) to produce a 20 MPH impact speed-change of the subject vehicle.

In a central, collinear collision, the impact speed-change of vehicle #1, ΔV_1, and the closing velocity, $(V_{10} - V_{20})$, are related as follows:

$$\Delta V_1 = \frac{(V_{10} - V_{20})}{\left(1 + W_1/W_2\right)}(1 + \epsilon) \text{ MPH}$$

Where V_{10}-V_{20} = closing velocity, MPH

W_1 = weight of vehicle #1, lbs.,

W_2 = weight of vehicle #2, lbs., and

ε = coefficient of restitution.

The terms barrier-equivalent speed and impact speed-change are sometimes used interchangeably. However, this is appropriate only for that portion of the impact speed-change that precedes restitution.

A further discussion of impact speed-change is presented in **Figure 1** from **Reference 2**.

ΔV = velocity change during impact

Why is ΔV so important as a measure of collision severity? It is important because it is related to the impact forces of the collision and to the deceleration* the vehicle experiences. Other factors being equal, the greater the velocity change during a collision, the greater the potential for occupant injury. By comparing ΔV to vehicle damage and occupant injuries, we learn about the crashworthiness of vehicles and the effectiveness of protective devices for occupants.

The ΔV of a collision is analogous to the dose of a poison. The greater the dose, the more likely is death or disability. But we can innoculate animals and people to enable them to survive higher doses of poison. Similarly, we can design vehicles to enable them to withstand greater ΔVs. By knowing the ΔV for our sampled collisions, we can find out how well different vehicles withstand crashes and protect occupants.

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IV
CRASH MEASUREMENTS

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Figure 1 The significance of Impact Speed Change

Brief History of CRASH

In 1952, a pioneer program in highway safety research, the Automobile Crash Injury Research program (ACIR), was created with the objective of determining injury causation among occupants of cars involved in accidents, in order that the injuries might be prevented or mitigated through improved vehicle design. By the mid sixties, 31 states had participated in the program and provided over 50000 cases for study. The main criterion for classifying severity in the ACIR program was through the use of comparison pictures of damaged vehicles.

Also during the 60's the digital computer was coming of age. Mainframe computers, which filled entire floors of buildings and cost hundreds of thousands to millions of dollars had evolved into time-sharing, batch processing machines. These were used in conjunction with 9 track tapes, card punch machines and terminals to provide to scientists, engineers and others number crunching capabilities unlike any utility ever before imagined. The digital computer quickly became an integral part of scientific research and development.

In September 1966, President Lyndon Johnson signed the National Traffic and Motor Vehicle Safety Act and the National Highway Safety Act. These established the authority to develop both the Federal Motor Vehicle Safety Standards (FMVSS) and the National Traffic Safety Agency (currently known as the NHTSA). As part of signing the legislation President Johnson stated that "auto accidents are the biggest cause of death and injury among Americans under 35". In 1965, 50,000 people were killed on the nation’s highways in auto accidents.

The SMAC computer program was initially created as a feasibility study by researchers at Cornell Aeronautical Lab (currently known as Calspan). The researchers at Cornell were interested in demonstrating the feasibility of a mathematical model of automobile collisions which could achieve improved uniformity and accuracy in the interpretation of evidence in automobile accidents. SMAC applications would give more accurate indications of collision severity. This would help to establish priorities, provide monitoring and assist in establishing the regulatory role of the government.

At the time of the creation of SMAC, limitations in the detail and the accuracy of the ACIR study had spawned a number of different exploratory approaches to the ACIR objectives. The SMAC program was evaluated as a possible tool for the investigative teams. SMAC is an "open-form" accident reconstruction program. A requirement of "open-form" programs like SMAC is that the user must initially estimate the impact speeds. The program also generally requires iterations to achieve an acceptable match of the accident evidence. One of the difficulties which arose in setting up SMAC simulations by the investigative teams was that the initial estimate of the speeds were not always obvious. Also, the user had to provide vehicle properties and specifications, many of which were not readily available. Those requirements, combined with the relatively high cost per run for a SMAC simulation run, required that a pre-processor be created which could provide the initial estimate.

The CRASH computer program was initially created to assist SMAC users in determining first estimates of the impact speeds. The original CRASH program utilized both piecewise-linear trajectory solution procedures and a damage analysis procedure to provide an initial estimate. The CRASH program was subsequently adopted by NHTSA as an integral part of the National Accident Sampling Study (NASS) investigations. The rationale for the use of the CRASH program was that for statistical studies, the average error in severity determinations is more important than any individual errors. The CRASH program, with it's question and answer mode, vehicle categorization, single step solutions procedure, and most importantly low cost, redirected the NHTSA interest from SMAC towards the CRASH computer program.

CRASH Program Assumptions and Recommended Inputs

From the CRASH3 User's Guide and technical manual, NHTSA, US Dept of Transportation:

"The CRASH3 program is a simplified mathematical analysis of automobile accident events. As is the case with any such analytical procedure, certain simplifying assumptions have been made to reduce the complexity and the operating cost of the program. Any accident event that violates the CRASH3 program's simplifying assumptions either degrades the accuracy of the solution, or, in the extreme, completely invalidates it. Thus, while CRASH3 users do not need to know the minute details of the analysis procedure, it behooves them to know the major simplifying assumptions so that accidents that violate them may be either avoided or handled with special techniques."

- **Ballistic Post-Impact Trajectory**

  CRASH3 assumes that the vehicles spin out to rest with constant rolling resistances, no active steering, and over a single friction surface, although a secondary friction surface may be specified in the trajectory simulation option.

- **Point of Common Velocity During Impact**

  CRASH3 assumes that at some time instant during the impact, the contact point on both vehicles reaches a common velocity. There are certain situations, notably sideswipes, when this is not the case and a CRASH3 analysis will not be successful.

- **Flat, Single Friction Surface Traversal**

  CRASH3 is a two-dimensional analysis. The program assumes both vehicles traverse the same friction surface.

- **Quantization of Vehicle Properties**

  CRASH3 maintains tables of vehicle properties that divide the vehicle population into discrete categories.

- **Uniform Crush Stiffness**

  CRASH3 assumes uniform individual crush stiffnesses for the side, front and back of a vehicle. The crush stiffnesses have been empirically derived from data generated in crash tests. Obviously the uniformity notion does not account for the fact that a vehicle side is fairly stiff near the axles but less so near the doors. Again, this is a compromise of complexity, convenience and cost.

The original CRASH program utilized both piecewise-linear trajectory solution procedures and a damage analysis procedure.

- **CRASH Trajectory Algorithms**
- **CRASH Damage Analysis Algorithms**

CRASH Trajectory Algorithms

On the basis of Newton's 2nd and 3rd laws, the total momentum of an isolated system of masses remains constant. This principal, which is referred to as the *Conservation of Momentum*, serves as the theoretical basis for reconstruction of impact speeds in vehicle-to-vehicle collisions.

For the moment we will assume that the system is isolated and will ignore the external forces produced by the tires and other possible sources, such as gouging and scraping of vehicle components on the ground, during the collision. The magnitudes of these external forces are normally small when compared with the magnitude of the forces of the collision. However, they can not be totally ignored.

A trajectory analysis is used to determine each vehicle's velocity and direction subsequent to the collision, thereby providing a definition of the ***system*** momentum at separation. This can then be used to define the ***system*** momentum at the instant of collision and thereby provide a procedure to determine the vehicle's impact speeds. This procedure for estimating impact velocities also directly provides estimates of the impact speed-changes (ΔV) in the form of the vector differences between impact and separation velocities for each vehicle.

Our presentation of trajectory analysis will begin with the simplest form of vehicle motion, linear motion without yawing:

Linear Motions Without Yawing

For the simplest case of straight-line travel without yawing rotation and with constant drag forces, the corresponding change in velocity can be approximated with analytical relationships for constant deceleration:

$$V = V_0 - at \quad (1)$$

From integration of (1),

$$S = V_o t - 1/2\, at^2 \quad (2)$$

$$t = \frac{(V_o - V)}{a} \quad (3)$$

Substitution of (3) into (2) yields

$$S = \frac{(V_o^2 - V^2)}{2a} \quad (4)$$

Solution of (4) for V yields

$$V^2 = V_o^2 - 2aS \quad (5)$$

where

V	=	Velocity
V_0	=	Initial velocity
a	=	Acceleration
t	=	Time

$S \quad = \quad$ Distance

In applications of equation (5), a distinction must be made between the prevailing average friction coefficient, μ, and the deceleration, a. If the full 100% friction coefficient is utilized, i.e., wheels locked or pure lateral travel, a =μg ft/sec^2.

For longitudinal motions with one or more wheels not fully locked and/or sideslip angles less than 90 degrees, , the friction utilization will be less than 100 percent and, thereby, a < μg ft/sec^2 .

In the case of a vehicle coming completely to rest without further obstacle contacts, $V_f = 0$, and equation (5) becomes:

$$V_o^2 = 2aS \qquad (6)$$

The decrease of speed with travel distance, for the case of constant deceleration, is depicted in **Figure 2**.

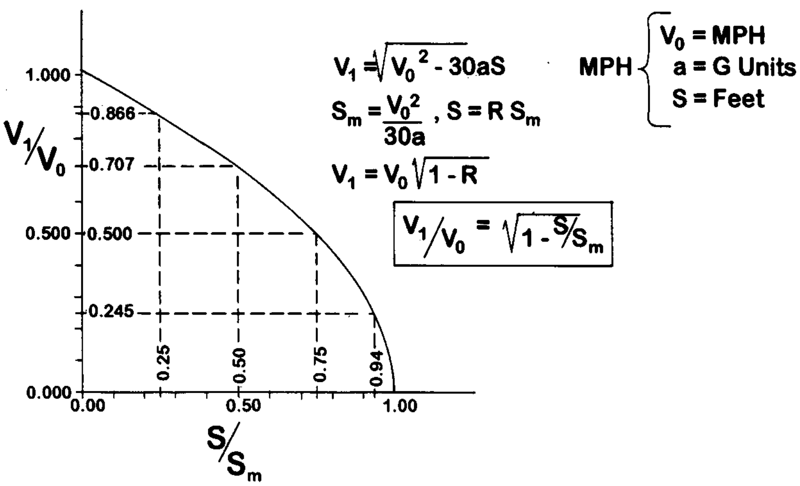
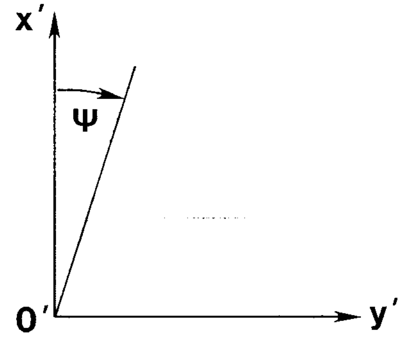


Figure 2 Speed Decrease with travel at Constant Deceleration

Spinouts on Flat, Uniform Surfaces

A space-fixed coordinate system is necessary to define measured spinout trajectories for analysis (e.g., **Figure 3**). The relationship of the X' and Y' axes in **Figure 3** reflects the aeronautical convention for three-dimensional coordinates, in which the Z' axis points downward. In the selected coordinate system, the Y' axis is directed to the right of the X' axis and the angle Ψ is measured in the clockwise direction with respect to the X' axis.



SPACE-FIXED COORDINATE SYSTEM

Figure 3 Space Fixed Coordinate system

While the position and orientation of the space-fixed reference coordinate system for a given case are arbitrary, it is generally desirable to relate them to permanent reference points at the accident scene (e.g., curb lines, utility poles, etc.).

The position data used in trajectory calculations refers to the location of the vehicle center of gravity, something which is not readily measurable at the accident scene. The reconstructionist must interpret tiremark evidence and/or measurements to wheel locations and from these data ascertain the center of gravity location.

In simple spinout motions, the actual distances traveled to rest can be approximated, with reasonable accuracy, by straight lines between the separation and rest positions. The separation velocities can be estimated on the basis of the total work done by each vehicle against tire-terrain friction forces between separation and rest. The rate of energy dissipation by tire forces is dependent on the heading direction of the vehicle in relation to its direction of motion and on the extent of rotational resistance at the individual tires. For example, in a broadside slide, all tires produce important resistance forces. In forward or backward motion, only those tires with applied brakes, damage effects, large steered angles or driveline braking produce significant drag forces. At a given sideslip angle, or over a limited range of a changing sideslip angle, the motion resistance can be approximated in the manner depicted in **Figure 4**. For the case of rotation about a vertical axis (i.e., yawing rotation) a vehicle alternates between the two conditions of motion.

Several different conditions of the vehicle tires may exist which can produce different extents of rotation during a spinout and therefore produce differing amounts of energy dissipation. Either the wheels may be freely rotating or there may be some resistance to rotation due to either vehicle damage or connection to a driveline (which produces the drag on the vehicle that is called ‘driveline braking’).

With freely rotating wheels, the linear and angular velocities of a vehicle are decelerated alternately as the heading direction changes with respect to the direction of motion. When the vehicle slides laterally, the side forces at the front and rear tires tend to have the same direction despite the existence of a yawing velocity (**Figure 5(a)**). Therefore, during this phase of motion, the angular velocity tends to remain constant while the linear velocity is decelerated. When the longitudinal axis is aligned with the direction of the linear velocity, the side forces at the front and rear tires act in opposite directions and the angular velocity is decelerated while the linear velocity tends to remain constant **(Figure 5(b))**. The general nature of the alternating decelerations is depicted in **Figure 6.**

The other situation which can occur is if one or more of the wheels has rotational resistance. In that situation the linear velocity is decelerated, generally at different rates, during both phases of the spinout motion. The amount and location of the wheel drag on a vehicle directly affects its behavior. A vehicle with all wheels locked tends to decelerate at a faster rate than one with less than all wheels locked. Also, the location of the locked wheel with respect to the velocity direction and heading (i.e., lateral vs. longitudinal) of a vehicle in a spinout affects the characteristics of its angular deceleration time history.

Differences which are related to wheel rotation drag become most apparent when either the amount of yaw rotation is greater than 60 degrees and/or the vehicle spends a significant amount of time in a near longitudinal side-slip. A random sampling of angular velocity time histories for four different cases with either none, one, two, three, or four wheels with drag is illustrated in **Figure 7** from **Reference 3**.

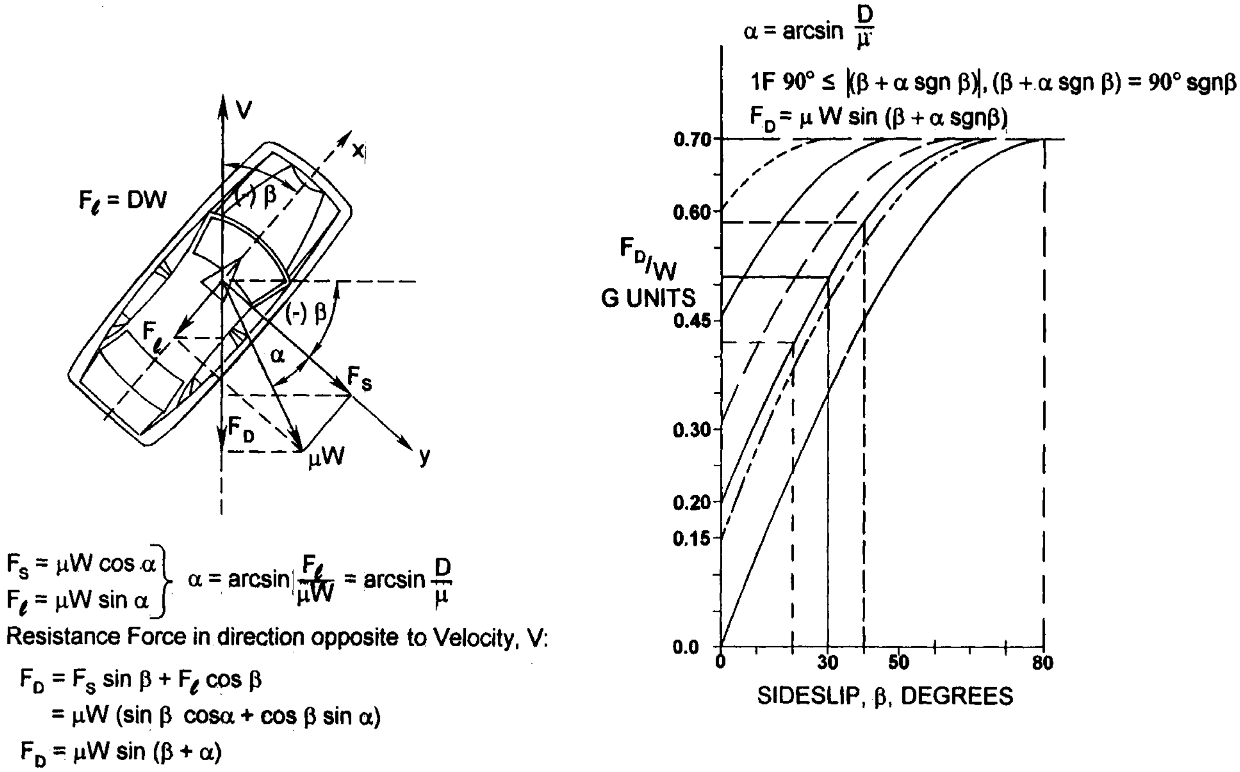


Figure 4 Approximation of Motion Resistance in Sideslip

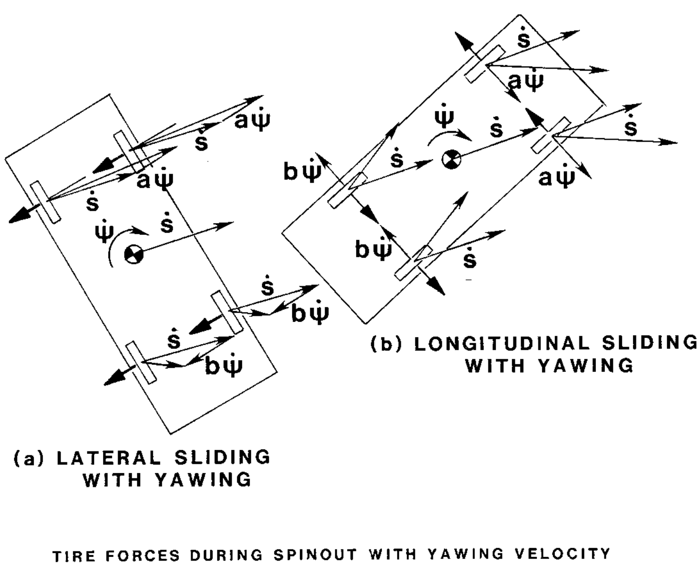


Figure 5 Tire Forces During Spinout

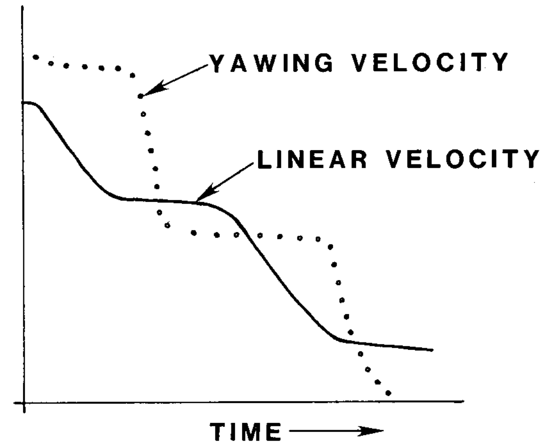


Figure 6 Linear and Angular (Yawing) Velocity vs. Time (no braking)

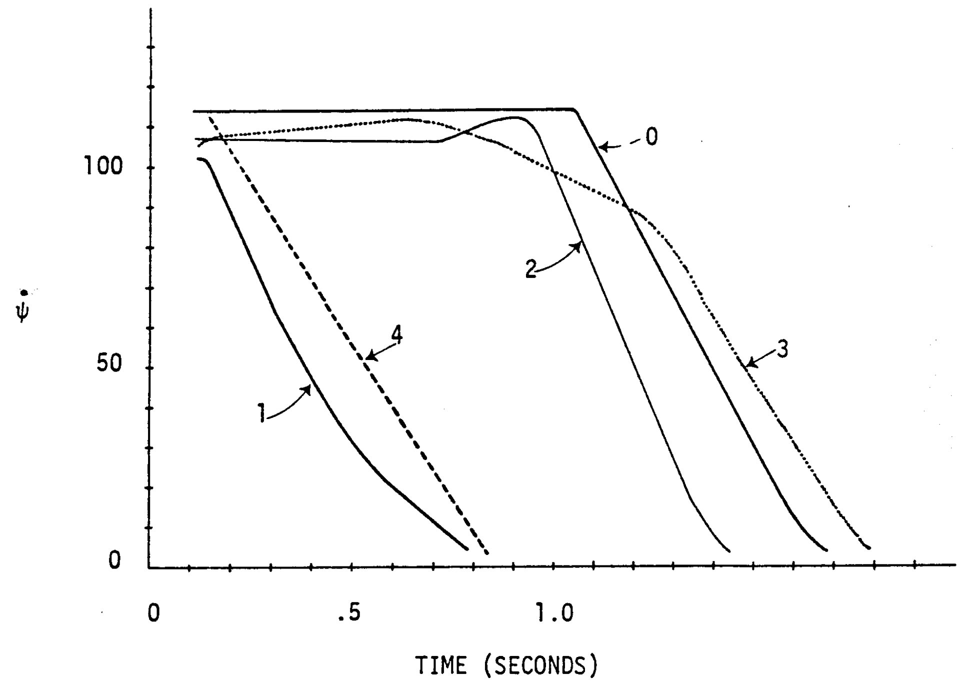


Figure 7 Random sampling illustrating angular velocity deceleration variations due drag

(For conditions with 0,1,2,3 and 4 wheels with drag (from Reference 3))

SPIN2: Combined Rotation and Translation Subsequent to Collision

In the following an analytical procedure is presented for approximating the linear and angular velocities of a vehicle at the start of its motions subsequent to a collision, which was first defined by Marquard in **Reference 4**, and which served as a starting point for corresponding aspects of the CRASH computer program **(Reference 5).** The cited procedure takes into account the fact that the linear and angular (i.e., yaw rotation) displacements of a four-wheeled vehicle subsequent to a collision occur under conditions of intermittent deceleration when the wheels are free to rotate. By approximating the linear and angular deceleration rates of a vehicle with either (1) all wheels freely rotating or (2) all wheels locked during the different phases of a spinout motion, Marquard developed approximate relationships for the relationship between the total linear and angular displacements during the travel from separation to rest. He then estimated the corresponding linear and angular velocities of the vehicle at separation from its collision partner, for two cited cases of rotational resistance at the wheels. The procedure has been generalized in the following to include intermediate conditions of rotational resistance at the wheels.

A technique for generating initial estimates of the collision separation conditions:

INPUTS

X'_{CR}, Y'_{CR}, ψ_R = Rest position and orientation (feet and degrees)

X'_{CS}, Y'_{CS}, ψ_S = Position and orientation at separation (feet and degrees)

a + b = Wheelbase, inches

k^2 = Radius of gyration squared for complete vehicle in yaw, in^2

μ = Nominal tire-ground friction coefficient

θ = Decimal portion of full deceleration $0 \le \theta \le 1.000$

g = Acceleration of gravity = 386.4 inches/sec^2

1.0 $$S = 12\sqrt{\left(X'_{CR} - X'_{CS}\right)^2 + \left(Y'_{CR} - Y'_{CS}\right)^2} \quad \text{inches}$$

2.0 $$\Delta\psi = \frac{\left(\psi_R - \psi_S\right)}{57.3} \quad \text{radians}$$

3.0 $$\gamma_s = \arctan\left(\frac{Y'_{CR} - Y'_{CS}}{X'_{CR} - X'_{CS}}\right)$$

4.0 *If* $0.02 < |\Delta\psi|$ and $\theta < 1.000$ **GO TO 10.0**

5.0 $$PR = \frac{|\Delta\psi|(a+b)}{2\,S} \quad (\text{path ratio}).$$

6.0 $$\phi_\psi = \begin{cases} 0.78\,(PR) - 0.16\,(PR)^2, \text{ for PR} < 1.50 \\ 0.80, \text{ for } 1.50 \le \text{PR} \end{cases}$$

7.0 $$\phi_v = \begin{cases} 1.00 - 0.10\ (\text{PR})\ - 0.28\,(\text{PR})^2, \text{ for PR} < 1.50 \\ 0.20, \text{ for } 1.50 \le \text{PR} \end{cases}$$

8.0 $$\dot{\psi}_S = 57.3\left\{\sqrt{\left(\frac{\phi_\psi (a+b)\mu g}{k^2}\right)\left(|\Delta\psi|\right)}\right\} \ \text{sgn}\ (\Delta\psi) \quad \text{deg/sec}$$

9.0 $\dot{S} = \sqrt{2\phi_V \theta \mu g S}$ inches/sec

GO TO 12.0

10.0 $\dot{\psi}_S = 57.3 \left\{ \sqrt{\dfrac{\mu g (\Delta\psi)^2}{\left[\dfrac{k^2(1-\theta)}{a+b}\right] \left[|\Delta\psi|\right] + \dfrac{S}{1.70}}} \right\} \operatorname{sign}\{\Delta\psi\}$ deg/sec

11.0 $\dot{S} = 1.70 \left[\dfrac{57.3\,\mu g\,(\Delta\psi)}{\dot{\psi}_S} - \dfrac{k^2(1-\theta)\left|\dot{\psi}_S\right|}{57.3(a+b)} \right]$ inches/sec

12.0 $u_S = \dot{S}\cos(\gamma_S - \psi_S)$ inches/sec

13.0 $v_S = \dot{S}\sin(\gamma_S - \psi_S)$ inches/sec

14.0 Return with starting values: u_S, v_S inches/sec
$\dot{\psi}_S$ degrees/sec

Note that the above calculations can be simplified by means of the following steps:

Let

$$Q = \sqrt{\frac{\mu g}{\dfrac{k^2(1-\theta)|\Delta\psi|}{(a+b)} + \dfrac{S}{1.7}}} \qquad (7)$$

Then

$$\dot{\psi}_s = \Delta\psi * Q * 57.3 \text{ deg/sec} \qquad (8)$$

$$\dot{S} = S * Q \text{ inches/sec} \qquad (9)$$

Several possible shortcomings in the cited technique for the generalized case have been investigated (see **Reference 3).** This technique should be considered a first approximation technique for the estimation of separation conditions which will produce better approximations than conventional constant deceleration techniques (i.e., V^2=2as).

Options Implemented in CRASH3 to improve SPIN2 results

The following option were implemented in CRASH during various phases of the development. The main objective in the implementation of the options was to improve the correlation with full-scale tests.

- Point on Curve
- End of Rotation
- Trajectory Simulation Option

SPIN2 Updates

The SPIN2 procedure of the original CRASH program uses as a starting point the relationships developed by Marquard [**6**]. The Marquard procedure takes into account the fact that the linear and angular (i.e., yaw rotation) displacements of a four-wheeled vehicle subsequent to a collision each occur under conditions of intermittent deceleration when the wheels are free to rotate. By approximating the linear and angular deceleration rates of a vehicle with either (1) all wheels freely rotating or (2) all wheels locked during different phases of spinout motion, Marquard developed approximate relationships between the total linear and angular displacements during the travel from separation to rest and the corresponding linear and angular velocities of a vehicle at separation from its collision partner, for the two cited cases of rotational resistance.

In the CRASH program [**11**], the SPIN2 routine was developed to extend the relatively simple Marquard relationships to include the cases of partial braking and/or damage-locked individual wheels. Evaluations of the resulting, modified relationships by means of trial applications to spinout trajectories generated with SMAC [3] revealed several shortcomings of the initial SPIN2 relationships. First, a residual linear velocity frequently exists at the end of the rotational (i.e., yawing) motion. Next, the general shapes of plots of linear and angular velocity vs. time changed substantially as functions of the ratio of linear and angular velocity at separation from the collision. Finally, the transitions between the different deceleration rates of linear and angular motions were found to occur gradually rather than abruptly. Slope changes in the plots of linear and angular velocity vs. time were found to generally occur in the form of rounded "corners" in the curves.

To improve the accuracy of approximations of separation velocities, provisions for the introduction of a residual linear velocity at the end of the rotational motion and the development of empirical coefficients, in the form of polynomial functions of the ratio of linear to angular velocity at separation, were incorporated in the SPIN2 analytical relationships of the CRASH program. Since the separation velocity ratio is initially unknown, a solution procedure was developed whereby several trial values of the ratio, based on an approximate equation, were used to test multiple solutions.

The cited analytical developments, reported in [**12**], involved only limited efforts which were aimed primarily at demonstrating the feasibility of the CRASH concept. Polynomial functions to generate empirical coefficients were developed, on the basis of 18 single-vehicle SMAC runs with relatively high linear and angular velocities for starting (i.e., separation) conditions. In the more common, real-life accident case, a relatively small rotation (i.e., yawing) velocity may exist at separation. In such a case the initial direction of the velocity vector with respect to the longitudinal axis of the vehicle will obviously affect the sequence and the duration of the linear and angular deceleration rates of the vehicle.

In consideration of known shortcomings of the SPIN2 aspect of the CRASH program, a subcontract to refine SPIN2 was undertaken in 1979 [3]. A representative sample of actual accident cases was selected from the NCSS [**7**] files for use in the study. A total of 50 cases were selected and then reconstructed with the SMAC computer program. For each of the SMAC reconstructions, separation information was used to formulate a basis for a refinement of the SPIN2 empirical coefficients.

A careful examination of the time-history plots of linear and angular velocities for all of the cases in the sample revealed a significant number of cases in which the SMAC-predicted behaviour deviated from the analytical assumptions upon which the SPIN2 routine is based. Attempts were undertaken within the research project to discriminate characteristics of separation conditions. Unfortunately, only partial success was achieved in the attempts to accommodate deviations by means of the use of logic and discriminators. As a result, a realistic appraisal of residual scatter in the empirical fits led to the conclusion in [3]:

"To achieve a general improvement in the reliability and accuracy of approximations of the angular and linear velocities at separation, a step-by-step time history form of trajectory solution should be implemented."

Subseqent work which has been performed on investigation and refinement of the SPIN empirical coefficients [Error! Bookmark not defined., **8**, **9**] and the corresponding modifications to CRASH is subject to the effects of 'scatter'. Any proposed refinements of the SPIN empirical coefficients and any reconstruction techniques which are based on the refinements of the SPIN empirical approach will ultimately fail in some applications to individual case reconstructions due to the possibililty that the particular case being investigated may be characteristic of a "scatter" point. The research cited in this paper strongly supports the conclusion from 1981 that implementation of a trajectory solution procedure should utilize an iterative time-history simulation.

Trajectory Simulation Option: USMAC Update [10]

The original form of the CRASH [**11**, **12**, **13**, **14**] computer program, which culminated in the CRASH3 version, was not intended to be a detailed, highly accurate reconstruction program. Rather, it was developed to serve as a simple preprocessor for the SMAC program. While the results of CRASH3 applications can be useful in providing approximate measures of accident severity for use in statistical studies, where the average error is most important, it has been demonstrated in validation tests to produce results which when compared to those of full-scale crash tests can include individual errors as great as 45%[**14**]. The possible error levels of the CRASH3 computer program are also generally applicable to the EDCRASH [**15**, **16**, **17**] computer program, since the CRASH3 program and the widely distributed EDCRASH clone are essentially identical. No significant analytical refinements have been made to the trajectory solution or trajectory simulation procedures of EDCRASH. The EDCRASH program, while claiming to be "within -6 to +7 percent of the combined impact speeds at a 95 percent level of confidence"[**16**] is subject to errors in individual speeds as great as 43.5% (Table 2, case 12, vehicle No. 1 [**16**]). Any "improvement" of the EDCRASH results over CRASH3 is mainly due to the "optimization" of the inputs to EDCRASH (to produce better correlation with known results) and modification of the error reporting techniques [**16**].

The CRASH3 program also includes an exploratory *trajectory simulation* option solution procedure based on the SMAC trajectory model. The optional *trajectory simulation* procedure (USMAC) includes routines from the trajectory portion of the SMAC program to permit time-history simulations in CRASH of the spinouts of the individual vehicles from separation to rest.

The USMAC *trajectory simulation* model is a three degree of freedom (X, Y, PSI) mathematical representation of planar motion. The tire side force calculations are based upon a nondimensional side force function whereby the small-angle properties of the tires "saturate" at larger angles. The "friction circle" concept is used to approximate the interactions between side and circumferential (braking or tractive) tire forces. The "friction circle" concept is based on the assumption that the maximum value of the resultant tire friction force is independent of its direction relative to the wheel plane.

The purpose of the USMAC routine in CRASH3 was to serve as a check of the SPIN2 approximations of separation speeds. An optional iterative procedure was also included in the CRASH3 *trajectory simulation option* to automatically adjust the SPIN2 separation velocities in an attempt to reduce errors in the predicted vs. actual final rest positions. The initial form of the trajectory iteration routine was implemented merely to demonstrate feasibility and was not thoroughly tested and evaluated. The costs of a CRASH run increased ten-fold by the use of the exploratory iterative trajectory solution procedure (USMAC) (e.g., [**18**] , circa. 1976, p1.,"The computer costs … of the CRASH program …range from approximately $1.00 to $10.00 per case. The upper end of the indicated cost range corresponds to a run in which the option for testing and refining the trajectory analysis portion of the calculation has been exercised"). There was no further NHTSA sponsored development of the original exploratory implementation of the USMAC routine.

By the mid 1990's, with the prevalence of extremely powerful and inexpensive Pentium PC's, and therefore the availability of virtually unlimited computer resources, consideration was given to internal research by McHenry Consultants, Inc. to further develop the *trajectory simulation* routine of the CRASH3 program. The objective in our refinements of the CRASH3 accident reconstruction procedures has been to simplify the input requirements of the program while providing a significantly improved correlation of the reconstruction results with known test results. A secondary consideration in the form of the refinement has been to limit the total computational time for convergence on a solution to a reasonable amount of time.

Effective refinements of the *trajectory simulation* procedure can substantially increase the usefulness of the simple "closed-form" CRASH3 accident reconstruction procedure by producing a general refinement of the *trajectory solution* procedure. The CRASH3 *trajectory solution* procedure requires a minimum amount of input information about the accident scene and vehicles. An effective improvement of the *trajectory solution* procedure can be expected to substantially improve the correlation or "validation" of the CRASH3 model when comparing the reconstruction results with full-scale test results. A 1989 study [**16**] concluded that the original form of the CRASH3/EDCRASH *trajectory simulation* option can actually degrade the *trajectory solution* results of the CRASH3 program.

A secondary task required in order to further refine and enhance the *trajectory solution* procedure of the CRASH3 program was a reactivation and refinement of the angular momentum solution procedure. The original CRASH program included conservation of linear momentum in the trajectory based solution to determine the impact speeds based on the separation velocities. A contract performed on CRASH2 to implement an angular momentum solution achieved mixed results [**19**]. A major hurdle for any procedure which includes an angular momentum solution is the need to approximate movement of the vehicles during the collision. In the CRASH2 formulation the impact and separation positions and headings were assumed to be identical. The research in [**19**] revealed that the accuracy of an angular momentum solution procedure for accident reconstruction which includes the assumption of no movement between impact and separation will produce unacceptable error levels (>>20%) in many cases.

Other analytical accident reconstruction techniques which include provision for an angular momentum solution procedure and/or which are based on conventional momentum analyses, include the somewhat subjective input requirement that either a vehicle-to-vehicle contact "point" [**20**], or a "point of maximum engagement" [**21**] or an "impact center" [**22**] be specified. The additional input is required to compensate for the cited solution procedure's lack of an independent determination of separation positions and orientations.

The requirement that the user specify either an arbitrary impact contact "point" or an arbitrary "point of maximum engagement" detracts from the objectivity of the reconstruction techniques.

Figure 5 demonstrates representative changes in positions and orientations during the contact phase of collisions.

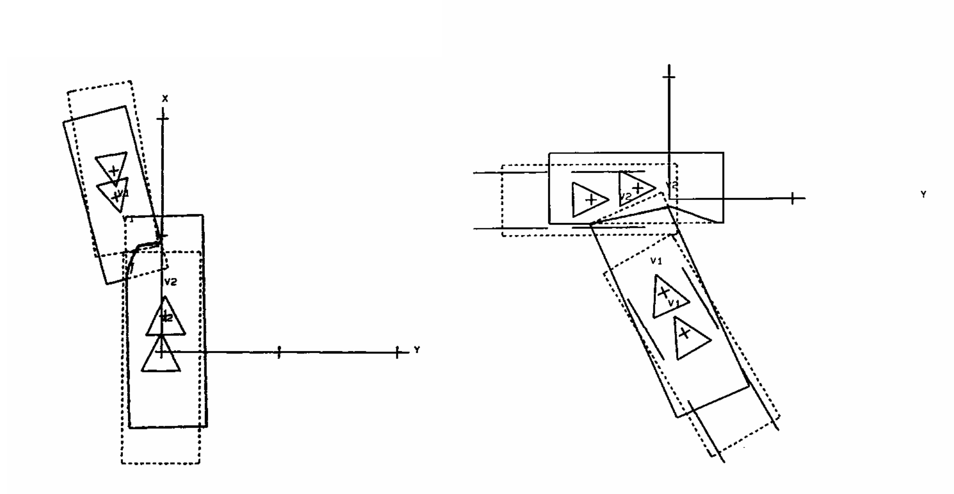


Figure 8 Impact and Separation Positions and Orientations for RICSAC Test#12 and Test#1

The subjective choice of a "point" can produce a large variation in the predicted results. During "validation," when the results are known, the user has some guidance in choice of the subjective "point." In real-world applications, where the answer is not known, the determination and arbitrary specification of a "point" can and will produce a wide range of predicted results. The normal input requirements of accident reconstruction programs of damage dimensions and approximate impact configurations should provide more than adequate information for any accident reconstruction program to independently achieve the function of any contact "point" or "point of maximum engagement" without user intervention. The movement of the vehicles between impact and separation can be initially approximated, for example, by moving the vehicles in their initial directions of motion to positions where the damage regions match. The procedure to determine a separation position should be automated to prevent subjective variations between users in the positions of match and therefore the results.

Other assumptions of the cited techniques [**20,21,22**] which may detract from the validity of their impact models for objective application to accident reconstruction are:

- During the impact no consideration is given for ***tire-to-ground "external" forces***
- The ***impact duration*** and time for exchange of momentum is assumed to be infinitesimally small.

TIRE-TO-GROUND "EXTERNAL" FORCES: The effects of tire-ground forces must be considered in a motor vehicle collision reconstruction. During the early development of the SMAC program [**23**, **24**] tests were performed to determine the effects of external tire forces on the collision solution procedure. It was concluded that "The conventional assumptions that the effects of vehicle deformations and of tire forces can be neglected in analytical reconstructions of collisions can lead to significant errors. This is particularly true for intersection-type collisions at low to moderate vehicle speeds, in which prolonged or multiple contacts and significant movements of the involved vehicles occur" and that "therefore it is essential in a general procedure for reconstruction calculations that both the collision and tire forces be considered simultaneously."

IMPACT DURATION: The duration of a motor vehicle collision cannot be assumed to be infinitesimally small. Normally the exchange of momentum requires 50 to 125 milliseconds. Significant changes in positions and orientations can occur during the collision which can produce changes in the collision moments acting on the collision partners. Any accident reconstruction solution procedure which contains the assumption of an instantaneous exchange of momentum should be carefully evaluated.

ORIGINAL CRASH3/EDCRASH RESULTS

Datasets were prepared of the 12 RICSAC tests and run with the CRASH3/EDCRASH programs and the results are depicted in **Figure 9** and **Figure 10.** These figures represent the starting point for the ***refined CRASH3*** research project and they demonstrate the general inability of the CRASH3/EDCRASH programs to consistently reconstruct.

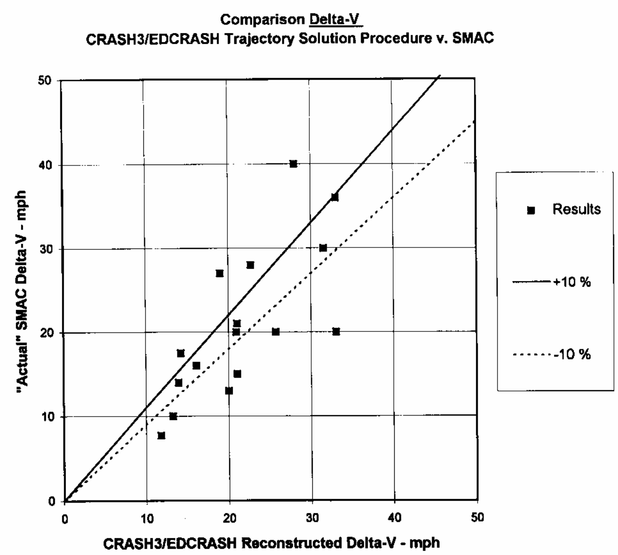


Figure 9 Initial comparison of reconstructed ΔV of CRASH3/EDCRASH Trajectory Solution vs. SMAC

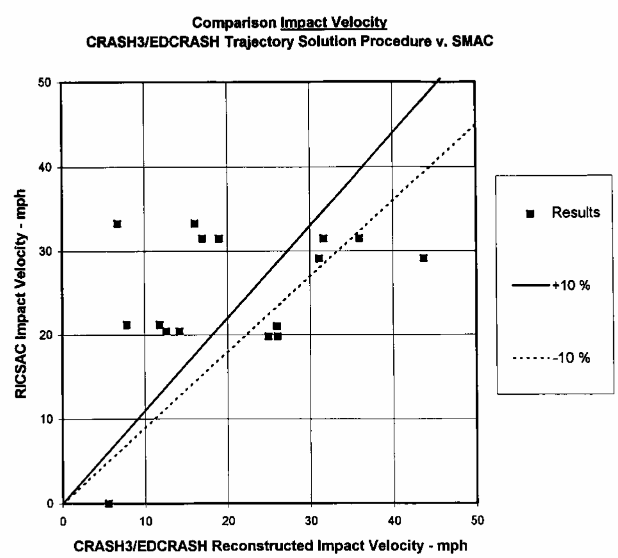


Figure 10 Initial comparison of reconstructed Impact Velocity of CRASH3/EDCRASH Trajectory Solution vs. RICSAC Test

RESULTS OF RESEARCH ON USMAC [10]

A comparison of the ***refined CRASH3*** trajectory solution procedure with the RICSAC tests is presented in graphical form for ΔV in **Figure 11** and Impact Velocity in **Figure 12.** The results demonstrate that the "closed-form" ***refined CRASH*** program can reconstruct within less than ±10% of the impact speeds and impact speed-changes.

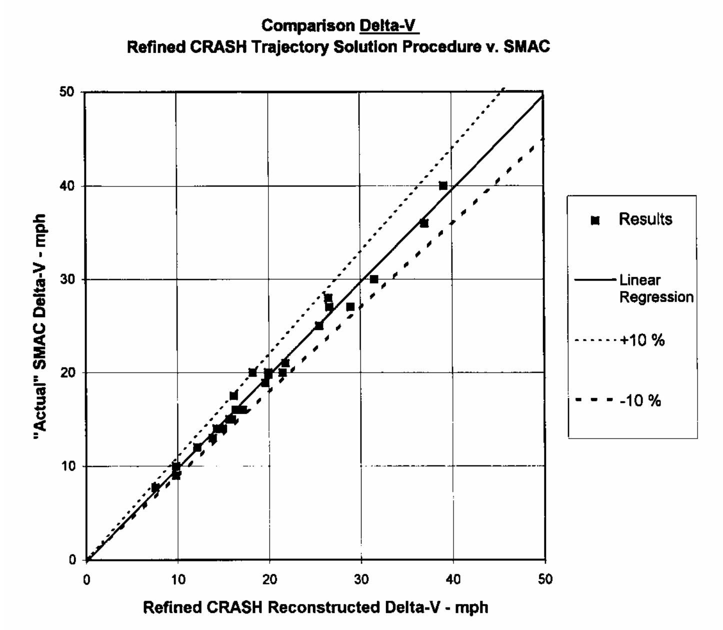


Figure 11 Comparison of reconstructed ΔV of *refined CRASH3* Trajectory Solution vs. SMAC

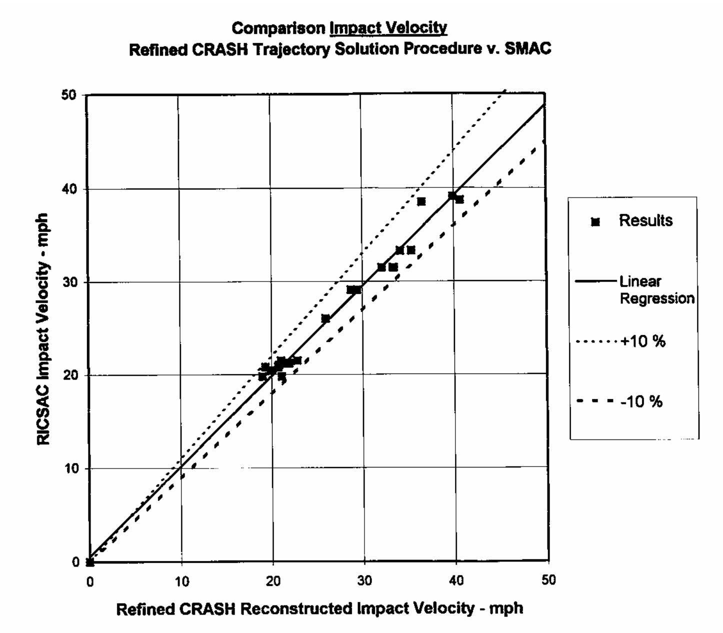


Figure 12 Comparison of reconstructed Impact Velocity of *refined CRASH3* Trajectory Solution vs. RICSAC Test Data

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CRASH Damage Analysis Algorithms

Damage analysis procedures (e.g., SMAC and CRASH computer programs) were originally focused on interpolation/extrapolation of the early available crash test results, most of which were in the ΔV range of 25 to 45 MPH.

Combined assumptions of (a) linearity of ΔV_c (i.e., the ΔV preceding restitution) as a function of residual crush and (b) a ΔV_c intercept near 5 MPH, at which no residual damage occurs, have served as the basis for extrapolations outside the range of available test data.

The cited assumptions, combined with either (a) neglect of restitution (CRASH, EDCRASH) or (b) a crude approximation of restitution (SMAC, EDSMAC) have limited the reliability of damage-based ΔV results obtained with current techniques, near the lower end of the range for airbag deployments. As a result, it is necessary to supplement such damage-based reconstructions with separate analyses based on conservation of linear and/or angular momentum and on work-energy principles, until such time that validated refinements of the existing damage analysis procedures are developed and made available.

Another aspect of damage analysis that has been the focus of recent attention is that of offset frontal collisions. While the CRASH type of damage analysis permits the direct entry of induced damage along with contact damage, the original form of the SMAC type of damage analysis does not include induced damage.

In the following, a brief review of the history and of the analytical basis of damage analysis is presented. It is followed by a presentation and discussion of preliminary results of recent extensions to damage analysis procedures.

History and Analytical Basis

The early Automotive Crash Injury Research (ACIR) study (**Reference 25**), which was initiated in 1952 and aimed at (1) identification of injury causes and (2) measurement of the effectiveness of countermeasures, relied on relatively gross evaluations of vehicle damage as a basis for the classification of exposure severity. Photographs of the damaged vehicles were compared with reference photographs to segregate individual cases into four accident categories (front, side, rear and rollover) and five categories of severity (minor, moderate, moderately severe, severe and extremely severe). Travel speeds were based on police estimates.

In 1969, a "Tri-Level Accident Research Study" was initiated in which a Vehicle Deformation Index (VDI) similar to that defined in SAE J 224a was adopted as a more refined damage descriptor (**Reference 26**).

During the late '60's and early '70's, a number of technical papers in the field of highway safety indicated that reasonably accurate estimates of the speed-changes that occur in wide-contact collisions could be obtained through the use of simple linear relationships between the impact speed-change and the extent of residual crush (e.g., **References 26, 27**, **28**, **29**, **30**). While such relationships obviously constitute a gross simplification of complex automobile structures, they were found to be capable of yielding impact speed-change results with approximately a plus or minus 10 percent accuracy when applied to a limited number of staged collisions (e.g**., Reference 31**). In a more comprehensive evaluation **(Reference 32) ,** it was found that the 95 percent confidence limits on individual calculations of delta-V ranged from 9 to 25 percent.

In **Reference 31**, empirical linear fits to the crush properties of six different size categories of late '60's and early '70's vintage vehicles are presented and discussed. It should be noted that, in many of the cited empirical fits, a very limited number of staged collision data points were found to be readily available. Further staged collision data were collected and summarized in **References 33** and **34** for the purpose of supporting refinements of the fits presented in **Reference 31**.

The use of linear relationships may be viewed as a simple empirical process for interpolation and extrapolation of the results of staged collisions. The application process must include provisions to account for the impact configuration, the "effective" mass and stiffness of the struck object, the contact area and irregular damage profiles. Clearly, the cited factors must be considered in any interpretation of collision damage. Such an interpretation procedure can be extended to accommodate nonlinear crush properties when sufficient crash-test results are available to permit the fitting of more exact empirical relationships. For example, it appears that bilinear fits might yield more accurate application results when a large ΔV range is included in the fitted data.

The general form of the existing linearized fits is depicted in **Figure 13**. With this assumed form of crush resistance, the energy absorbed by vehicle crush may be obtained by double integration of equation 1 **(**Error! Reference source not found.**).**

$$F = A + BC \text{ Lb/in/in} \tag{1}$$

where A = Unit width Force Level for 'no residual damage', lb/in.

B = Linear Force-Deflection Rate, lb/in^2.

C = Residual Crush, Inches.

F = Crush Resistance per Unit Width, lb/in.

the double integration of the equation is:

$$E = \int_0^L \int_0^C (A + Bc)\, dc\, d\ell \text{ inch lbs.} \tag{2}$$

where E = Energy Absorbed, inch lbs.

C = Residual crush, inches.

L = Length of contact damage area, inches.

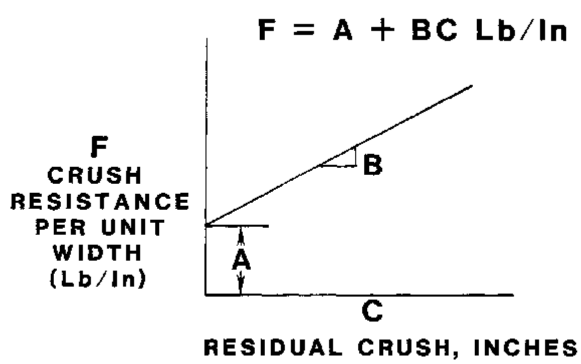


Figure 13 **Assumed Linear Form of Crush Resistance**

For application of Equation (2) to a damaged vehicle, the damage dimension format of **Figure 14** may be used. In **Figure 14**, a uniform vertical damage profile is depicted. It should be noted, however, that the existing empirical fits (**Reference 34**) are based on the maximum extent damage profile.

Integration of equation (2) yields

$$E = \int_0^L \left(AC + B\frac{C^2}{2} + G \right) d\ell \text{ inch lbs.} \tag{3}$$

where G = constant of integration.

If the linear slope, B, is assumed to exist in the non-damage range of the applied force, the constant of integration, G, is equal to the work done in reaching the maximum force value for no-damage, the variable A. Thus, for a full frontal impact into a rigid barrier, an elastic deflection equal to A/B and involving an energy absorption of $A^2/2B$ per unit width will exist at C=0. Therefore, $G=A^2/2B$.

Integration of Equation (3) yields

$$E = A\int_0^L C d\ell + B\int_0^L \frac{C^2}{2} d\ell + \frac{A^2}{2B} L \text{ inch lbs.} \tag{4}$$

Since $\int_O^L C d\ell$ is equal to the plan view contact damage area, in^2 (see **Figure 14)** and $\int_O^L \frac{C^2}{2} d\ell$ is equal to the first moment of the plan view contact damage area about the line defining the original (undeformed) surface, in^3 (see **Figure 14),** equation (4) may be expressed as

$$E = A\alpha + B\beta + GL \text{ inch lb.} \tag{5}$$

where

α = Plan view contact damage area, in^2.

β = First moment of the plan view contact damage area about the line defining the original undeformed surface, in^3.

G = Constant of integration $\approx A^2/2B$.

L = Length of contact damage area, inches.

$$\left.\begin{array}{l} A = \text{lb/inch} \\ B = \text{lb/inch}^2 \\ G = \text{lb} \end{array}\right\} \text{Fitted empirical coefficients for crush resistance.}$$

For the case of symmetrical, full-frontal impacts, Equation (4) becomes

$$E = \left\{ AC + \left(\frac{B}{2} \right) C^2 + \frac{A^2}{2\,B} \right\} L \tag{6}$$

If the absorbed energy is equated to the corresponding dissipated kinetic energy of the subject vehicle,

$$\frac{1}{2} M \left(\Delta V \right)^2 = E \tag{7}$$

$$\left(\Delta V \right)^2 = \left(\frac{2AL}{M} \right) C + \left(\frac{BL}{M} \right) C^2 + \frac{A^2 L}{MB} \tag{8}$$

where ΔV = Impact speed-change preceding restitution

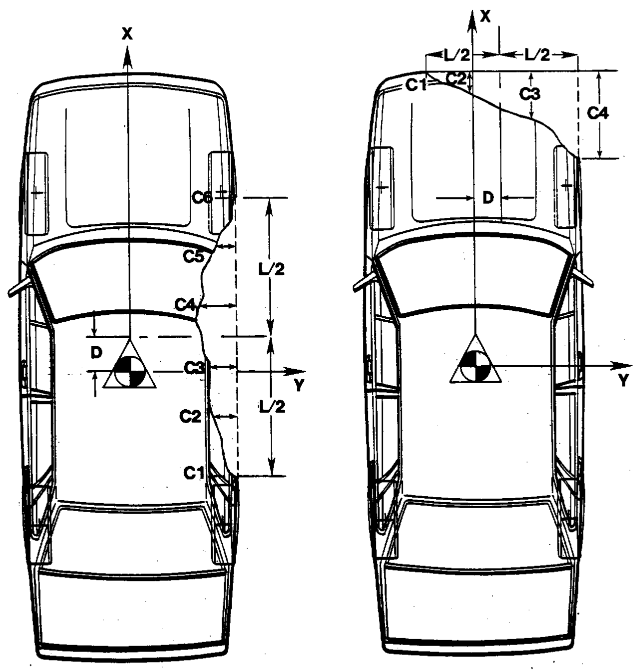


Figure 14 Damage Dimensions

Equation (8) may be restated

$$\Delta \mathrm{V} = \sqrt{\frac{\mathrm{BL}}{\mathrm{M}}} \left(\mathrm{C} + \frac{\mathrm{A}}{\mathrm{B}} \right) \quad \text{in/sec} \tag{9}$$

Therefore, in this special case (i.e., symmetrical, full-frontal) the impact speed-change ΔV is a linear function of the residual crush (C) and has an intercept at

$$\Delta V = A \sqrt{\frac{L}{BM}}. \ \text{in/sec}$$

The relationship is depicted in **Figure 15**.

Campbell (29) has used the symbols b_0 and b_1 for the intercept and slope of plots similar to **Figure 15**, and he has presented some representative values. It is of interest to relate his variables to A, B and G.

$$b_0 = A\sqrt{\frac{L}{BM_s}} \qquad \text{in/sec} \qquad (10)$$

$$b_1 = \sqrt{\frac{BL}{M_s}} \qquad \text{in/sec/in} \qquad (11)$$

where

M_s= Standard test mass, lb sec^2/in.

Solution of (10) and (11) for A and B yields

$$A = \frac{b_0 b_1 M_s}{L} \qquad \text{lb/in} \qquad (12)$$

$$B = \frac{b_1{}^2 M_s}{L} \qquad \text{lb/in}^2 \qquad (13)$$

$$G = \frac{A^2}{2B} = \frac{b_0{}^2 M_s}{2L} \qquad \text{lb} \qquad (14)$$

$$\Delta V = \sqrt{\frac{BL}{M}}\left(C + \frac{A}{B}\right) \qquad \text{In/sec}$$

Application of equations (12), (13) and (14) to the frontal barrier test data presented by Campbell (**Reference 29**) yields the results presented in **Table 1**.

	Std. Wgt. (Lbs)	Width (In)	b_0 MPH	b_1 MPH/In	A Lb/Inch	B Lb/In^2	G Lb.
71-72 Std. Full Size	4500	79.2	6.85	0.88	274.6	35.27	1068.6
73-74 Std. Full Size	4500	79.2	7.5	0.90	307.5	36.89	1281.1
73-74 Intermediate	4000	76.8	7.5	0.90	281.8	33.82	1174.3
71-74 Compact	3400	71.4	3.0	1.35	154.6	69.57	171.78
71-74 Subcompact	2500	62.2	3.0	1.35	130.5	58.72	144.94

Table 1 Frontal Barrier Test Data (Based on Reference 9**)**

It should be noted that the crush coefficients for CRASH, (A, B & G) and those for Campbell (b_0, b_1), represent *virtual* crush resistance properties. The simplifying assumption of these techniques is to use the *residual* crush to compute the energy absorbed up to the point of a common velocity to determine the equivalent barrier impact speed. The crush is the residual crush that will exist *after* the vehicle undergoes dynamic crush and restitutes to its residual deformation. It does not give any indication of the actual stiffness of the structure of the vehicle.

Consider two vehicles with the same residual crush for a given impact speed into a barrier (for example, at 30 MPH). One vehicle is structurally very stiff and deforms dynamically only up to approximately the residual amount (i.e., very little or no restitution). On the other hand, the other vehicle is structurally very soft. It initially deforms to a value twice that of the residual value after which it's structural properties produce a restoration of the front structure to produce a residual crush equal to that of the very stiff vehicle. By the simplifying assumptions of a CRASH-type of damage analysis, both vehicle's have the same *virtual* stiffness (Same A & B and/or b_0 & b_1), whereas in reality the structures of the two vehicles are very different. Do not make the mistake of referring to the stiffness of a particular vehicle on the basis of its CRASH-type crush coefficients. A careful examination of the actual tests on which the CRASH-type crush coefficients are based should be performed to determine the actual crush properties.

The damage-analysis technique of the CRASH computer program produces an approximation of the approach-period portion of the impact speed-change, rather than the total impact speed-change. The clearly defined selection of analytical approach (**Reference 35**) was based on a lack of definitive information, in 1975, on the actual magnitude and variation of the coefficient of restitution as a function of both deflection extent and position on the vehicle periphery. The resulting underestimate of the total impact speed-change in low speed collisions, where restitution effects are greatest, was fully recognized and acknowledged in **Reference 35.**

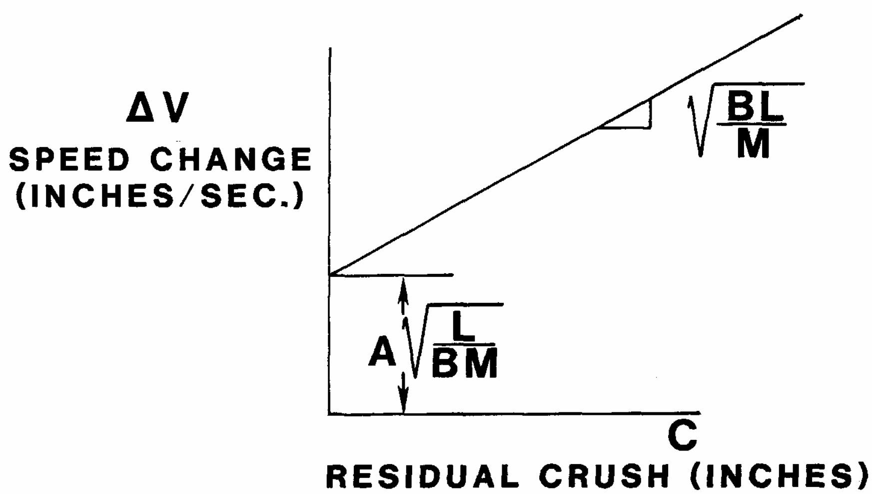


Figure 15 Speed-Change vs. Residual Crush in Full-Frontal Symmetrical Impacts

In 1987, a proposed revision to the Damage Analysis Procedure for the CRASH computer Program was presented in **Reference 36**. In the paper it was noted that Smith and Noga (**Reference 32**) properly conclude that the damage algorithm of the CRASH computer program tends to underestimate low ΔV values as a result of the neglect of restitution effects. The original formulation of the CRASH3 program (**Reference 35**) addressed only the speed change (ΔV) up to the point of common velocity. The omission of restitution effects in CRASH was based on several important considerations: First, the original formulation of CRASH had limited objectives in terms of accuracy. It was developed primarily as a pre-processor for use with the SMAC accident reconstruction program (**Reference 37**). Second, at the time of the CRASH formulation (1975), restitution effects of vehicle structures were not found to be sufficiently well defined to support the added complexity of inclusion of a provision to model restitution. The simplifying assumption which included the neglect of restitution was clearly pointed out in the original Crash documentation (**References 38,35**).

The widespread use of the damage analysis portion of CRASH3, as a primary technique rather than a simple pre-processor, justified a re-examination of the analytical formulation of CRASH. The proposed revised algorithm for Crash, "CRASH4", included the original Crash stiffness Coefficients, A & B, as well as four new internal coefficients, K_1, K_2, RHO and GAMMA. As previously discussed CRASH3 assumes a *virtual* Crush Stiffness based on a relationship between the residual Crush and absorbed energy for a given crash test speed. The new internal coefficients in CRASH4 were included to provide a means of accommodating variations in the restitution properties of vehicle structures.

When we examine a damaged vehicle, the damage that we observe is called the residual or permanent damage. This permanent damage is the result of a dynamic collision event. During the collision the vehicle normally deforms a certain amount greater than the observed final residual damage. The amount that a vehicle initially deforms is called the peak or maximum dynamic crush. This period of the collision is also referred to as the period of deformation, which refers to the time from initial impact to the point of maximum deformation. It is during this time that the maximum collision forces and resulting impulses act on the vehicles. Subsequent to the peak dynamic deformation, the vehicles begin the restitution phase. The restitution phase is the time from the maximum deformation condition to the instant at which the bodies separate. During this period additional forces and therefore additional impulse acts on the vehicles as some of the structure restores or springs back. The rate, both in terms of force level and duration, at which the vehicle structure restores from the peak dynamic damage to the final residual damage determines the amount of additional impulse the vehicle undergoes during the restitution phase. The restitution phase acts to increase the accident severity by prolonging the acceleration exposure while also reducing the amount of residual damage. This accounts for an inherent error in the simplifying assumptions of a damage analysis procedure which ignores the restitution phase of a collision.

The amount of restitution and the rate at which a vehicle restitutes can produce a range of variation of collision severity between different vehicles for a given residual crush on a vehicle. The magnitudes of the increases in the total speed change (using CRASH4 and including a range of hypothetical restitution properties) over the impact speed-change for the approach period only (using CRASH3 with its assumption of no restitution) may be seen from **Reference 36** to range from 3.9% to 15.5% at 30 inches of static crush and from 8.9% to 58.2% at 10 inches of static crush.

To date there has been only a limited number of crash tests performed which include an investigation of the restitution properties of vehicle structures. Therefore there is too limited an amount of data available to include directly the effects of restitution in the CRASH type of analysis. However, any reconstruction which utilizes a CRASH3 based damage analysis procedure should consider the possibility that significant restitution effects may have been ignored.

Impulse-Energy Relationship

The relationship between the impact speed-changes and the maximum absorbed energy is made more understandable by consideration of the fact that the impact speed-change is determined by the impulse of the collision force while the absorbed energy is determined by the work done by the collision force.

$$dE = F(\delta)d\delta$$

$$\frac{dE}{dt} = \frac{dE}{d\delta}\frac{d\delta}{dt} = F(\delta)\frac{d\delta}{dt}.$$

$$\text{Absorbed Energy}, E = \int_o^t F(\delta)\frac{d\delta}{dt}dt \quad \text{inch - lb.} \tag{31}$$

$$\text{Impulse}, I = \int_o^t F(\delta)dt = M_i \Delta V_1 \quad \text{inch - lb.} \tag{32}$$

At the end of the approach period, the relative velocity, dδ/dt, is near zero while the collision force, F(δ), is at its maximum value. Thus, the change in absorbed energy, equation (31), is very small while the total impulse, equation (32) increases rapidly.

Side Impacts:

In most side impact cases the maximum extent of damage involves override of the sill structure. Also, most of the available side impact test results have not included direct contacts on the wheels. The need for a "zoned" approach to empirical fits for side structures is clearly indicated, but it is presently precluded by data limitations. The effects of side impacts at wheel locations and of sill structure contacts are compensated, to some extent, by the fact that the energy absorbed by the two involved vehicles is summed in the approximation of speed-changes. Contacts with the more resistant portions of the struck vehicle produce a greater deformation and, thereby, a greater energy absorption by the striking vehicle.

In the case of side impacts, determination of the energy absorption by vehicle crush is somewhat more complicated than the case of end impacts. First, the "effective" mass at the point where a common velocity is reached must be determined from the impact configuration and the inertial properties of the two colliding bodies. The present version of the **CRASH** computer program includes the assumption that the common velocity is reached at the centroid of the damaged area **(Reference 39).** Next, energy absorption produced by a tangential component of the collision force must be subtracted from the total, since the fitted empirical crush characteristics apply only to the intervehicle force component perpendicular to the involved side or end**.**

For cases in which the principal force is not perpendicular to the involved side or end, the analytical relationship defining the maximum relative displacement makes use of the crush resistance and deflection along the line-of-action of the resultant force. In other words, the effective peripheral crush resistance that is used in the derivation of equations is in the direction of the resultant force. Therefore, the calculation of absorbed energy must reflect this fact.

If the specified direction of the principal force is assumed to be approximately correct, a corresponding tangential force component must have existed during the deflection. In **Figure 16**, the components of a resultant intervehicle force are depicted.

It may be seen that

$$F_R = F_N / \cos\alpha \quad \text{and}$$
$$C_R = C_N / \cos\alpha \tag{33}$$

The work done in the direction of the resultant force may be determined from

$$\int_0^{C_R} F_R \, dc_R = \left(1 + \tan^2 \alpha\right)\int_0^{C_N} F_N \, dc_N \tag{34}$$

Application of (34) to the calculation of absorbed energy yields a correction factor $(1 + \tan^2\alpha)$ for the effective crush stiffness in oblique collisions. Note that the maximum value of α is limited to plus or minus 45 degrees in the **CRASH3** computer program. Further refinement and discussion of the energy correction factor can be found on page 32.

The moment arms of the resultant force on the two vehicles determine the effective masses acting at those vehicle points that achieve a common velocity during the collision (assumed to be the centroids of the damaged areas). Thus, the accuracy of ΔV results corresponding to given damage patterns is directly affected by the moment arm approximations.

In **Figure 17** the moment arms of the resultant collision force are depicted. It is essential, or course, in applications of the described technique that the specified directions of the principal force on the two interacting bodies combined with the heading directions of the vehicles are consistent with oppositely directed forces (i.e., ±180°). Additional internal checks have been added to the CRASH3 program to insure such compatibility of inputs.

The following relationships defining the approach-period speed changes of the two vehicles are derived in **Reference 40**.

$$\Delta V_1 = \sqrt{\frac{2\gamma_1 (E_1 + E_2)}{M_1 (1 + \gamma_1 M_1 / \gamma_2 M_2)}} \quad \text{in/sec} \qquad (35)$$

$$\Delta V_2 = \sqrt{\frac{2\gamma_2 (E_1 + E_2)}{M_2 (1 + \gamma_2 M_2 / \gamma_1 M_1)}} \quad \text{in/sec} \qquad (36)$$

where

$$\gamma_1 = \frac{k_1^2}{k_1^2 + h_1^2}$$

$$\gamma_2 = \frac{k_2^2}{k_2^2 + h_2^2}$$

k_1^2, k_2^2 = radii of gyration squared of vehicles 1 and 2, respectively, in yaw, in^2

h_1, h_2 = moment arms of resultant collision force on vehicles 1 and 2, respectively, in).

(see **Figure 17**)

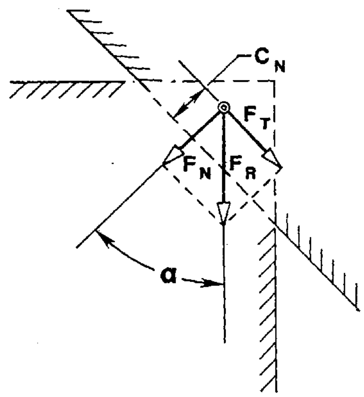


Figure 16 Force Components in Oblique Collision

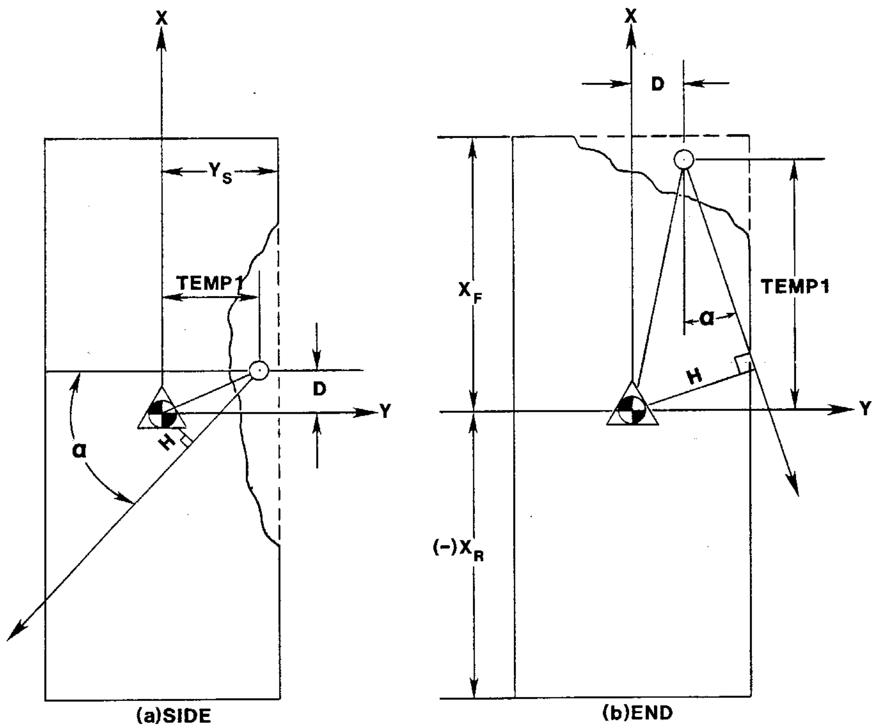


Figure 17 Moment Arms of Resultant Collision Force

NHTSA Research

Since 1990, TRC of Ohio, Inc. under the sponsorship of NHTSA has undertaken the task of performing a large number of crash tests of late model vehicles in support of and as justification for a refinement of the CRASH3 damage analysis procedure for the reconstruction of automobile collisions. The crash tests performed as a part of the research utilized the repeated test technique (**References 41, 42).**

Papers authored by Prasad (**References 43**, **44**, **42**, **45**, **46)** as a part of the NHTSA investigation discuss a CRASH3 "reformulation," "new algorithm" and "new model" based on the results of the significant number of crash tests of late model vehicles.

The reports address three separate topics related to the CRASH algorithm:

(1) Forced intercepts.

(2) Custom-fitted coefficients.

(3) Abandonment of A, B and G.

The first two items have already been proposed or adopted by researchers and/or entrepreneurs in the field (e.g., **References 47**, **48**, **49**, **50**, **51)** and, therefore, they are not new concepts. The first two items clearly should be adopted in a needed update of the existing CRASH3 coefficients (see discussion). The last item is an arbitrary, conceptual revision which cannot improve accuracy (see **Reference 45,** p.17, 2nd paragraph).

In the following paragraphs, the individual topics are addressed in greater detail:

Forced Intercepts

If a straight line is fitted through a clustered group of data points for delta-V versus the uniform or average value of residual crush (for known contact widths) that are all in the range of 30 to 35 MPH, the delta-V intercept at zero residual crush will clearly not be reliable (e.g., see "natural" intercept in **Figure 18**). Therefore, in the case where actual data from low speed collisions are not available, a forced intercept will be preferable to an unreliable one based on the slope of a linear fit through closely spaced, relatively high-speed points. This conclusion has been reached in a number of related publications **(e.g., References 47, 49)** and, therefore, it is not a new concept. Among the three topics addressed in the subject report, this one should clearly receive early attention in a needed update of the existing CRASH3 coefficients. However, such an update must not be based on single data points combined with the forced intercepts.

While the concept of a forced intercept may be accepted as a necessity with existing data limitations, the related use of real data points must include all available test results. Note that some individuals have based linear fits on single data points, combined with forced intercept.

A judicious engineering approach to the empirical fitting process will clearly require the use of more than one actual data point for a given collision direction on a given vehicle. The scatter that occurs in crash test data makes the use of a single test result, combined with a forced intercept, a highly unreliable basis for a linear fit.

For example, in a litigated matter, an EDCRASH (**Reference 48**) customer relied on an unrealistically low crush resistance for '70's vintage Plymouth, when available NHTSA crash test data for the specific vehicle and other closely related models clearly indicated that the EDCRASH fit was based on a forced intercept combined with a single NHTSA data point that was sufficiently different from the other data to be doubtful (see **Figure 19).**

Thus, all applicable data must be utilized in the case of a forced intercept in order to minimize errors in slope, (i.e., b_1) related to the scatter of the test data. Such straight line fits can simply utilize a linear regression technique that includes a forced intercept. In this manner, b_1, for full contact, fixed rigid barrier collisions can be directly obtained (e.g., see solid line in **Figure 18**). Note that crush corrections for variations in test weights are required when multiple data points are used to obtain a linear fit of delta-V versus residual crush.

The proposed abandonment of A, B and G in favor of b_0 and b_1, is a separate topic which has no direct bearing on the use of a forced intercept. In fact, A, B, and G are retained in **Reference 47** while forced intercepts are used. The fact that b_0 and b_1 have been defined in terms of A, B and G and vice versa, since 1975 (e.g., **Reference 31**) makes that general topic a superficial and arbitrary one.

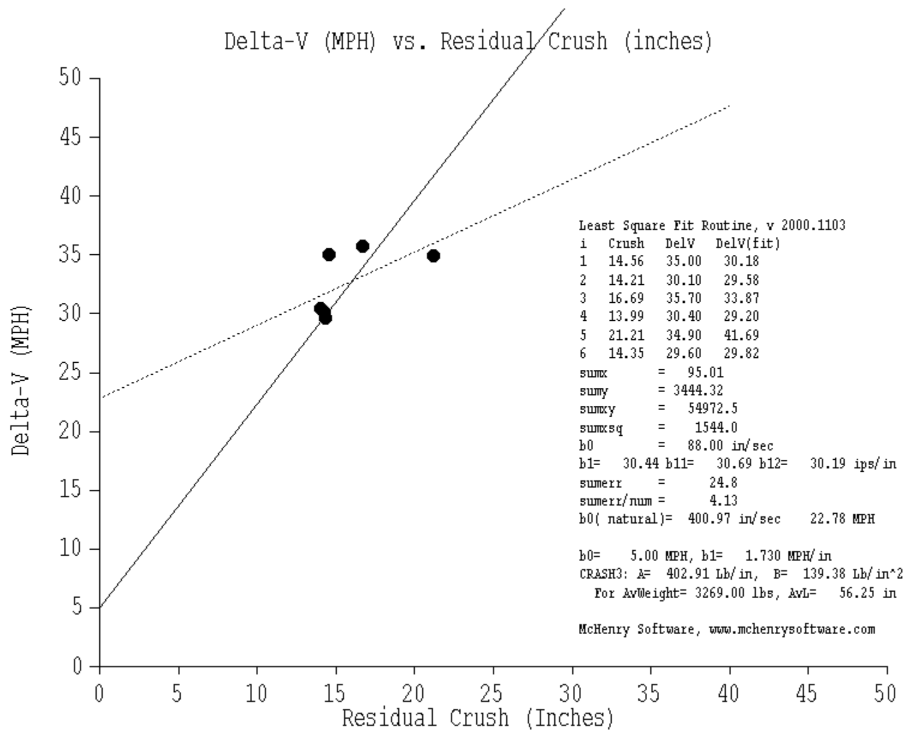
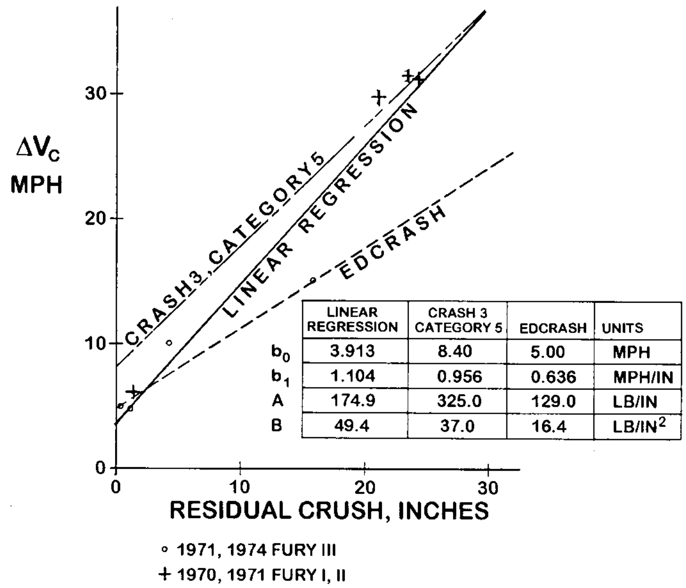


Figure 18 Comparison if "natural" and forced intercept fit for Delta-V vs Crush

Custom-Fitted Coefficients

It is obvious that custom-fitted crush coefficients can generally yield more accurate damage interpretations than those coefficients based on fits by vehicle categories (particularly for the crash conditions on which they are based) (**Reference 45,** p.20, paragraphs 3&4, p. 23, paragraph 4, p. 24, paragraph 1). **References 49**, **50**, and **51** make that point in relation to the reconstruction of "specific accidents" (i.e., litigated matters). Unfortunately, the concept may not be applicable to NASS because of limitations in available crash test data and practical considerations regarding the storage of individual crush properties for the entire U.S. vehicle population.

In **Reference 52 and 53**, an analytical approach is defined which potentially could achieve significant accuracy improvements while retaining the categorization of vehicle, by segregating stiffness and restitution properties. Thus, the approach of **Reference 52 and 53** may be more applicable to the needs of NASS than the custom-fitting of individual crush properties.



	LINEAR REGRESSION	CRASH 3 CATEGORY 5	EDCRASH	UNITS
b_0	3.913	8.40	5.00	MPH
b_1	1.104	0.956	0.636	MPH/IN
A	174.9	325.0	129.0	LB/IN
B	49.4	37.0	16.4	LB/IN^2

Figure 19 Comparison of CRASH3 Category and Linear Regression fit for a Plymouth Fury

Abandonment of A, B and G

In the original CRASH approach, absorbed energy was selected as the basis for fitting empirical crush coefficients, in recognition of the fact that the test weights of given makes and models of vehicle are generally not identical in available test data (e.g., empty vehicle vs. four test dummies). Also, the technique was designed to not be limited to uniform crush, central collisions against fixed barriers (e.g., **Reference 31**). Thus, while the crush properties are assumed to be the same in different tests of a make and model of vehicle, the extent of crush must be related to the actual energy absorption rather than to speed-change alone (e.g., effective mass in oblique collisions, irregular damage profiles, actual test weights).

A cited review of the 'reformulation' of CRASH3 by Prasad indicates that it consists mainly of the addition of new crash test data points and a rework of the formula to use different symbols. All the simplifying assumptions of CRASH3 are retained and no additional refinements are introduced.

Comparison of Crush Property Definitions

A comparison of the Crush coefficient symbols related to the 'reformulation' by Prasad, the original CRASH3 coefficient symbols and the Campbell symbols are as follows:

Campbell : b_o = MPH or IN/SEC

b_1 = MPH/IN or IN/SEC/IN

McHenry (CRASH3): A = LB/IN

B = LB/IN^2

Prasad: $d_0 = \sqrt{Newton}$

$d_1 = \frac{1}{cm}\sqrt{Newton}$

Conversions between:

A = $d_0 * d_1 * 0.57101$ LB/IN

B = $d_1^2 * 1.45036$ LB/IN^2

$$b_0 = A\sqrt{\frac{L}{BM_s}}$$ inches/sec

$$A = \frac{b_0 b_1 M_s}{L}$$ lbs/inch

$$b_1 = \sqrt{\frac{BL}{M_s}}$$ in/sec/in

$$B = \frac{b_1{}^2 M_s}{L}$$ lb/in^2

$$G = \frac{A^2}{2B} = \frac{b_0{}^2 M_s}{2L}$$ lb

where

M_s= Standard test mass, lb. sec^2/inch.

The reformulation proposed and used by Prasad was basically to change the units of the Crush Coefficients:

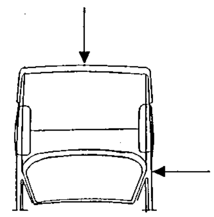
Campbell :	Speed change for full width
McHenry:(Crash3):	Force per unit width
Prasad:	Energy Dissipated per unit width.

Updates to Energy Correction Factor and Coefficient of Restitution

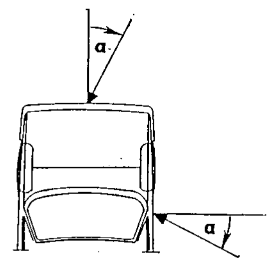
Continuing efforts to refine existing procedures for damage analysis have included developments related to the topics of (1) an energy correction factor to approximate the effects of tangential friction forces in oblique collisions, and (2) restitution effects. In the following, a brief summary is presented along with measures of the magnitudes of the cited effects.

Energy Correction Factor

Crush properties of vehicles are measured and fitted for crush directions that are perpendicular to the involved end or side of a vehicle. However, in an oblique collision, a component of the tangential friction force acts to increase the effective crush resistance in the direction of crushing and thereby, the absorbed energy (**Figure 20**). Therefore, an Energy Correction Factor (ECF) is needed for applications of crush coefficients to oblique collisions.



(a) Crush Properties are measured in directions that are perpendicular to the involved side or end.



(b) In applications, the directions of crushing are generally not perpendicular to the involved side or end.

Figure 20 Application of Fitted Crush Properties

In the early development of CRASH (**Reference 40**) the need was recognized and a simplistic ECF was defined in the form of $(1 + \tan^2 \alpha)$, where α is the angle of crushing relative to a perpendicular to the involved end or side of the vehicle.

As application experience increased and evaluations were made of results at large angles, α, the ECF was limited to the angular range of ±45 degrees, so that the maximum value of the ECF was limited to 2.000 (e.g., **Reference 39**).

On the basis of a recognition of the limitations on energy absorption that are imposed by realistic levels of tangential friction, a revised form of the ECF was proposed in 1986 (**Reference 52**). Applications of the ECF by the author since that time have generally been restricted to the angular range of ± 45 degrees so that only a limited evaluation of the effects of the revised ECF was possible.

The topic has recently been revisited. A detailed review of the earlier analytical assumptions and the corresponding derivation of relationships has led to the proposed form of the modified ECF being further revised, on a purely analytical basis, to the following:

$$ECF = (1.0 + \mu_v \tan \alpha) \qquad (1)$$

It is proposed that the angular range of the ECF should be limited to ± 60 degrees, so that the maximum value of ECF is limited to approximately 1.95.

The analytical derivation of Equation (1) is contained in the literature.

Coefficient of Restitution

During a motor vehicle collision, the maximum dynamic deformation generally exceeds the residual deformation. Subsequent to the peak dynamic deformation, the collision partners begin a restitution phase as the deformed structures restore kinetic energy, or "spring" back. The restitution force level and duration determine the impulse that acts on the collision partners during the restitution phase.

When an accident vehicle is examined, the residual, or permanent, deformation is observed and/or measured. The original form of damage analysis in CRASH does not include provisions for the effects of restitution. The original SMAC collision routine includes a simplified restitution model which is cumbersome to apply, can be sensitive to time increment size, and tends to over-predict the residual damage. The resulting effects on the accuracy of damage-based reconstructed values of ΔV, for the case of direct, central barrier collisions, ranges from approximately 10 to 30% underestimates, depending on properties of the specific vehicle and the extent of residual crush. For the case of oblique, non-central collisions, a similar range of effects is anticipated on the basis of indirect measures of corresponding restitution values [**1, 2**][54].

At the present time, crush coefficients for vehicle collision analysis are predominantly based on impact speeds and damage measurements from rigid, fixed barrier crash tests. The residual damage is correlated with the impact speed by means of fitted linear relationships. In general, there is no consideration given to the effects of restitution in applications of the fitted crush coefficients. However, the ignored effects of restitution on the total impact speed-change, corresponding to a given amount of residual crush, are compounded by the fact that restitution acts to <u>reduce</u> the amount of residual deformation, for a given maximum dynamic crush, while also acting to <u>increase</u> the total impact speed change. Thus, substantially different vehicles can share nearly equal slopes and intercepts in CRASH-type plots of the approach period speed-change as a function of residual crush. This can occur even though the actual exposure severity for a given residual crush may be significantly different.

Available information on the restitution behavior of automobile structures (e.g., **References 55**, **56**, **57**, **58**) is limited. However, the general nature of the measured behavior has served as the basis for the development, in **Reference 52 and 53**, of corresponding analytical relationships.

The purpose of that development has been an attempt to refine the existing crush property descriptors by segregating the effects of stiffness and restitution. The overall objective is, of course, to achieve improved accuracy in damage-based reconstruction results.

In the CRASH implementation of restitution, the restored energy for each of the collision partners is separately calculated by means of integration across the damage interface. The resulting values are added and then combined with the total absorbed energy for application in the calculation of ΔV_1 and ΔV_2.

The effective overall coefficient of restitution in a given collision includes effects of the width and location on each vehicle of the contact area, the detailed damage profiles and the individual unit-width crush properties of the collision partners. This combination of effects is believed to constitute a realistic analytical representation of the actual physical system during the unloading process.

Progress toward a rigorous and complete validation study to support a general release of the developments is data-limited at the present time.

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