An Overview of Selected Computer Programs for Automotive Accident Reconstruction

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ABSTRACT

Seven computer programs that have been extensively used by the authors and others for reconstruction of automobile accidents are discussed. These programs are CRASH, EES, IMPAC, VTS, TBS, SMAC, and HVOSM. Some programs have become well established in the last 10 years whereas others are new. They provide simulations of collision and vehicle trajectory to varying levels of complexity, sophistication, and ease of use.

It is a common inclination to adopt a "broad-brush" attitude toward complex subjects, leaving the details to others. This inclination is widespread among computer-program users, especially in crash reconstruction applications. It must be emphasized, however, that computer-accident reconstruction programs do not reason or evaluate; they are simply computational robots that carefully follow detailed instructions. The instructions embedded in the program, together with the input data, combine to determine the result. Programs written for one purpose may not be expected to yield accurate estimates in other situations. Programs validated for one case or series of cases may not always yield valid results in other (even similar) cases, for a variety of reasons.

It is the authors' experience that people too often lend unwarranted authority to computer program results for myraid reasons, such as

1. Programs sanctioned or distributed by government;
2. Intricate, detailed, sophisticated models are incorporated;
3. Impressive visual output graphics are produced; and
4. Results have been validated by selected application.

Often black-box programs are accepted because a personal evaluation of the innards of the box is too difficult or time consuming. This appears to be particularly true of large programs that have gained a substantial following from the government and users.

No mathematical approximation can ever represent reality exactly. Programs cannot be substituted for experience or judgment; they can only assist the analyst by doing calculations. Model limitations, coding errors, and program bugs will always plague the computer program user; it is not possible to wait for that utopia when all of these drawbacks are resolved. The informed user must be willing to understand the program in its current, if imperfect, condition and must carefully prepare and edit its input. Further, he must be ready to admit the limitations that any computer program process has, and he must use it in combination with other methods to reach educated conclusions.

Although myraid individually styled computer routines undoubtedly exist to aid in the calculations related to automobile crash reconstruction, research sponsored by the U.S. Department of Transportation (DOT) has resulted in three major routines (SMAC, CRASH, and HVOSM) quite widely known in the scientific community. These were developed in a series of contract research projects under DOT auspices at Cornell Aeronautical Labs (CAL) (later Calspan Corporation) and are the result of considerable effort by R.R. McHenry. This pioneering work of 10 to 15 years ago resulted in substantial contributions to computer-assisted reconstruction, and because of the substantial government funding and effort involved, it also resulted in an attitude of awe and infallability that may have tended to discourage individual competitive efforts. Only recently have other computer program efforts appeared that are effective competitors for CRASH and SMAC in some applications. The authors are aware of no HVOSM competitors, other than some locally altered versions.

Most of the computer programs discussed here have evolved as use has suggested shortcomings and improvements. This evolution has often left a poorly marked trail of reasoning and documentation. In this paper an attempt is made to touch only the high points, and some insight gained from the authors' limited experience and study is shared. It is not all-inclusive, even by identification of programs, let alone descriptive or evaluative. It is hoped that this paper can assist in providing a referenced overview as an aid to further study and in inspiring participative interaction that will result in the long-range improvement of the seven programs mentioned previously, the development of better ones, and the overall utility of the computer in automobile crash reconstruction. A summary comparison of pertinent features and limitations of the seven programs is presented in Table 1.

CRASH--CALSPAN RECONSTRUCTION OF ACCIDENT SPEEDS ON THE HIGHWAY PROGRAM

CRASH in the form of CRASH3 (C1) and its predecessor, CRASH2 (C2) has probably been utilized more times than any other reconstruction program. The "damage only" option of this program has been the basis for establishment of accident severity (vehicle delta-V) in the National Crash Severity Study (NCSS) accident data base (C3) and is currently be-

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TABLE 1 Summary Comparison of Reconstruction Programs

	CRASH3	EES-ARM	IMPAC	VTS	TBS	SMAC	HVOSM
Developed by	CALSPAN	D-Benz	CSE	CSE	UMTRI	CALSPAN	CALSPAN
Dimensions	2	2	2	2	2	2	3
Initial/final value problem	F	F	I	I	I	I	I
Time steps/impulsive	I	I	I	T	T	T	T
Number vehicles	2	2	2	1	1+1	2	1
Trajectory model	Yes^a	No	No	Yes	Yes	Yes	Yes
Tire model	No	No	No	Yes	Yes	Yes	Yes
Collision model	Yes	Yes	Yes	No	No	Yes	Yes
Computer time required	Medium	Low	Low	High	High	High	Very high
Degree of input difficulty	Medium	Low	Low	Medium	Medium	High	Very high
Trajectory and tire model features							
Steering control	No	–	–	Yes	Yes	Yes	Yes
Braking control	No^a	–	–	Yes	Yes	Yes	Yes
Traction control	No	–	–	Yes	No	Yes	Yes
Tire force model	Table	–	–	CS	CS	CS	CS
Friction limit	Circle	–	–	Elipse	Circle	Circle	Elipse
Dynamic tire normal force	No	–	–	Yes	Yes	No	Yes
Articulated vehicle	No	No	No	No	Yes	No	No
Graphics output	No	No	No	Yes	No	Yes	Yes
Trajectory parameter plot	No	–	–	DTPLOT	No	DTPLOT	No
Collision model features							
Common velocity point	Yes	Yes	Yes	–	–	No	No
Preimpact rotation	No^a	No	Yes	–	–	Yes	Yes
Tire forces during collision	No	No	No	–	–	Yes	Yes
Multiple collisions	No	Yes^a	Yes^a	–	–	Yes	No
Sideswipe type collision	No	No	Yes^a	–	–	Yes^a	No
Crush stiffness parameters	2-linear	Tests	–	–	–	1-linear	1-linear
Stiffness varies with width	No^a	Yes	–	–	–	No	Yes^a
Crush profile usage	Input	Zones	–	–	–	Generate	Yes^a
Number of points in crush profile	Six max	–	–	–	–	100 max	Many
Occupant trajectory	No	No	Yes^a	–	No	PLOTTK	No
Crush energy output	Yes	Yes	Yes	–	–	No	No
Delta-V output	Yes	Yes	Yes	–	–	Yes	Yes

Note: CS = cornering stiffness model. DTPLOT and PLOTTK are supplemental programs used at CSE to present graphical output. PLOTTK also contains a point occupant trajectory feature; dash = not applicable.

[a] Indicates limited capability if Yes, or partial capability if No. For an elaboration of this point refer to the text describing the program.

ing used in the National Accident Sampling System (NASS) accident data collection program (C4), which is ongoing. About 45 percent of the accidents investigated in NCSS were assigned an accident severity measure by CRASH. The others were either not suitable for the CRASH algorithm or there were infulficient input data (C3).

The major advantage of using the CRASH algorithm for assessment of vehicle delta-V from damage is that it is completely independent of traditional reconstruction methods that use skid distances and momentum. The CRASH algorithm, which is based on the method proposed by Campbell (C5), requires comparative crash test data and crush measurements taken from the accident vehicles or estimated from photographs.

Measurements of impact and rest positions taken at the scene have been known to be greatly in error. In addition, it is often difficult if not impossible to adequately estimate drag factors (average vehicle deceleration from impact to rest). For example, drag factor estimation is subjective when the automobile traverses multiple surfaces with widely different friction coefficients; when it is not known if tires are braked or locked by damage; when the automobile spins to rest; or when no tire marks are left on the pavement because of wet conditions. With the increased use of antiskid brakes, traditional reconstruction methods will be even less applicable. Hence, the damage method of reconstruction, as in the CRASH3 program or by other means, is gaining in importance.

The central disadvantage of damage analysis is that it can only yield information about speed change (delta-V) or the relative approach speed of the two colliding vehicles. Road speed or speedometer speed cannot be obtained by the damage method alone. However, vehicle speed change has been found to be an important measure of injury exposure for unrestrained occupants, hence its use in the accident data and its importance in assessment of crashworthiness.

In addition to the damage method for reconstruction, CRASH3 contains a version of the more traditional reconstruction method referred to in the program documentation as Spinout Trajectories and Conservation of Linear Momentum. This method will be referred to hereinafter as Spin2+CLM. The trajectory part, Spin2, calculates postimpact velocities based on the distance between the point of impact and the point of rest, surface friction, average rolling resistance of the tires, direction of rotation, number of revolutions, and the curvature of the center-of-gravity (CG) path. The trajectory calculation is not a time-step procedure as in SMAC (C6). Instead, the programmers of CRASH have devised a complex multivariable interpolation algorithm using a matrix of coefficients based on 18 SMAC runs. This may or may not produce acceptable results. In its present form, the CRASH program does not display the result of the Spin2 procedure. An optional correction feature is present that performs five iterative runs of the TRAJ routine from SMAC to refine the Spin2 result. This is an unfinished option that usually does not converge and should not be invoked.

The momentum calculation uses the assumption that there is a common velocity at one point in the mutual crush zone (or common CG velocity in the case of colinear collision). The centroid of the crush volume of each car is selected as the common point. The collision force is directed along the line of action, which passes through the common point and has the direction specified by the user (Figure 1). Thus the user must determine the principal direction of force (PDOF) from an examination of the damaged vehicle. The user must also specify heading and slip angles of the two vehicles at impact. These three angles are combined by the program to define the

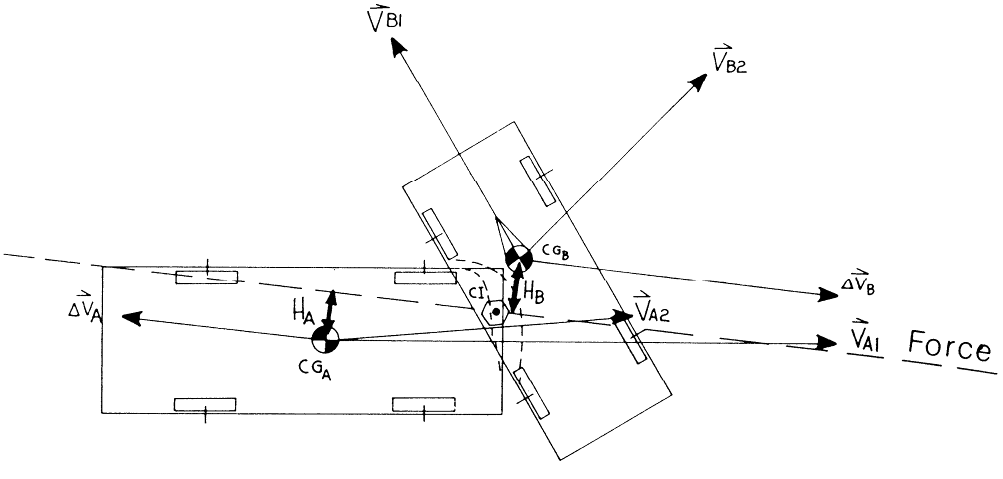

FIGURE 1 Delta-V, force line of action, and impulse moment arms.

force direction relative to the surface. The program then checks to see if the force on each car is oppositely directed, per Newton's third law. If the forces are not opposite within ±15 degrees, the computation terminates, if they are within this range they are then averaged to be made opposite.

The momentum formula is apparently coded in such a way that it has a singularity when the impact velocities are aligned (there is no singularity in the principle of conservation of momentum). In order to avoid this problem, CLM is abandoned if the impact velocities are aligned within ±10 degrees. In such cases the result of the damage option is used in combination with the Spin2 result to obtain preimpact speeds.

In practice, prespecification of the PDOF angles is difficult at best. Displacement of metal parts is an indication of PDOF, assuming that the analyst can find a suitable reference and properly take into account the complex buckling pattern of the vehicle structure. However, calculation is greatly simplified by requiring this input. Because by Newton's second law the direction of the impulse (time integral of the force) is parallel to the momentum change, the direction of the delta-V vector is specified by PDOF. This required input is one-half the desired answer, the other one-half being the magnitude of delta-V as shown in Figure 1.

The Spin2+CLM method produces good results when Spin2 is able to develop a good estimate of separation conditions and when the user accurately specifies vehicle heading at impact. Too often this is not the case. Furthermore, if the result of Spin2+CLM is not close to that of the damage method, the analyst is forced to choose one method over the other. Judging by the exclusive use of the damage method in the NCSS and NASS studies, the damage option of CRASH3 is preferred. The damage option has also been studied more extensively by the National Highway Traffic Safety Administration (NHTSA), which funded the development of CRASH, via comparison with crash tests to establish accuracy and sensitivity of the damage option for use as a statistical averaging tool (C7).

For the previously stated reasons, reference to the CRASH program reconstructions generally refers to the damage option results. The cornerstone of this success is the data base of staged crash tests on which crush energy correlation coefficients are based. Tables 8-1 and 8-2 of the CRASH3 users manual (C1) present nine categories of vehicles for which test data have been correlated. These coefficients, A, B, and G, are tabulated for frontal, side, and rear impacts for each of the nine categories. The test data on which A, B, and G depend are primarily for 1970s vintage cars.

It is important to note that the calculation algorithm used by the damage option of the CRASH program can be readily accomplished with a programmable calculator. There are three steps involved:

1. Integrate the damage profile over the crush width using appropriate crush energy coefficients, A, B, and G = $A^2/2B$. CRASH uses six equally spaced points over the crush width. Trapezoidal rule integration with unequally spaced points is easily programmed.
2. Correct the crush energy for oblique crush (PDOF at an angle to the front, side, or rear) and other nonbarrier effects. CRASH corrects for oblique crush by multiplying the integral by the factor $1+\tan^2\alpha$, where alpha is the angle between the crush direction and the surface normal. This correction factor has a physical basis when alpha is small, for example, less than 20 degrees, but becomes outlandish as alpha approaches 90 degrees. CRASH3 arbitrarily cuts off the correction factor at 45 degrees based on the recommendation by Monk and Guenther (C8) who also recommended as an alternative that the correction factor be eliminated. At 45 degrees the factor doubles the value of the integral. The analyst must also make allowances for crush damage that does not correspond to flat-face barrier crush damage from which the data are taken. Currently there are no general guidelines for dealing with such problems as underride and override, large induced crush, offset crashes, and crashes with either substantially more or substantially less crush than that of the crash tests (generally 30 or 35 mph fixed-barrier frontals, 30 mph moving barrier for rears, and 20 mph moving barrier into the door region for sides). These would appear to be fruitful research areas.
3. The final step in the procedure is the calculation of speed. For essentially colinear impacts with little or no rotation, the closing speed or the vehicle delta-Vs may be calculated knowing only the crush energy, as previously determined, and the vehicle weights. For noncolinear collisions, the vehicle delta-Vs may be found if the analyst is also able to estimate the PDOF relative to the road surface, the point of application of the force resultant on the cars, and the distance offset between the force and the CG of each vehicle (C1). CRASH

does this by interpreting vehicle heading, sideslip angle, crush profile, and PDOF relative to each vehicle. As noted previously, determination of these angles with precision is difficult. The analyst may only be able to give a wide range of possibilities that will produce a range of delta-V. When the accuracy and sensitivity of the damage option in crash was studied by the NHTSA (C7), it was reported that estimation of PDOF was the most critical measurement reported by field investigators, accounting for 18 percent error in vehicle delta-V.

Whether the damage analysis is completed by the CRASH program or by other means, it is appropriate to check the results for viability by computations based on Newton's laws either as an impulse model, such as IMPAC, or as a time-stepping model such as SMAC.

Program output for the CRASH3 program is given in the following paragraphs for the number 2 staged crash test reported by Smith and Noga (C9). All 16 of these NHTSA-sponsored tests have been reconstructed by the CRASH3 program using both the damage and Spin2+CLM options (C10). The performance chart obtained for just the damage option is shown in Figure 2, wherein Test 2 appears as cars B and b on the figure. The input for Test 2 with abbreviated output is shown in Figure 3.

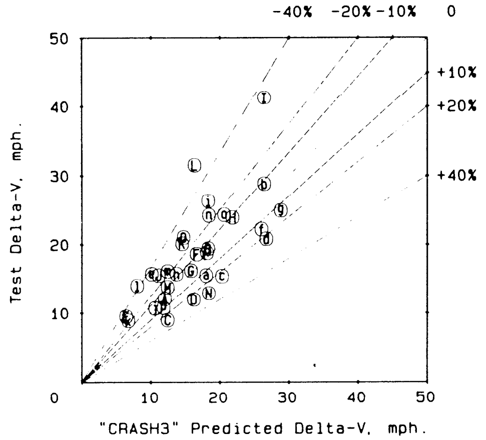

FIGURE 2 CRASH3 predicted delta-V using damage.

NHTSA is pursuing a modest development and updating program for CRASH3. Preliminary results from application of a microcomputer version called MICROCRASH were presented in October 1985 at the Volvo Delta-V workshop in Washington, D.C. Also exhibited at that time were the results of a planar graphics program driven by MICROCRASH. It is the authors' understanding that this graphics version was based on a substantial degree of interpolation of vehicle planar position, based on the three positions employed in the SPIN2 subroutine within CRASH. The accuracy of these graphics is only a rough approximation of what may have happened (oral communication of Nick Tsongas, NHTSA, October 1985).

NHTSA representatives also clarified an important issue in the same meeting. The CRASH program was never intended for litigation applications, nor does it have the accuracy needed for such application. On the other hand, it was NHTSA's intent that CRASH3 be applied primarily to provide information about crash severity that could be summarized statistically in the NCSS and NASS files, the hope being that the inaccuracies resulting from individual application of CRASH3 would balance each other and result in a reasonable estimate of statistical distributions of severity (statement by Carl Nash, NHTSA Office of Research, at Volvo Delta-V workshop, Washington, D.C., October 1985). Whether this balance is actually achieved has not been proven.

The source code Fortran listing for CRASH3 is available on tape from the National Center for Statistics and Analysis, NHTSA, U.S. Department of Transportation. Operational versions may be run via modem at 1200 baud using the computer facilities at the University of Michigan Transportation Institute, or at the Boeing Computer Services Company, Vienna, Virginia. The CRASH3 program has also been ported to personal computers (PCs) with runtime modules offered for sale for several popular PCs (C11).

A summary of crash test data is currently being compiled by the NHTSA and presently contains nearly 1,000 tests (C12). [Note that the authors' research indicates that source documentation is not available to address apparent physical inconsistencies observed in some of the tests reported.] For purposes of accident reconstruction (as contrasted with statistical data gathering), these test data provide a basis for the determination of stiffness coefficients for the accident vehicles along lines recommended by Strother et al. (C13). A summary of the equations needed to program the damage option on a calculator or a personal computer is provided in the appendix of "Crush Energy in Accident Reconstruction" (C13).

EES-ARM--EQUIVALENT ENERGY SPEED-ACCIDENT RECONSTRUCTION PROGRAM

The EES-ARM program has been widely used in Europe for speed reconstruction in automobile crashes. It is designed to evaluate the collision phase relationships, using physical principles and approximations customarily used in hand calculations (E1-E3). The method is based on the graphical Drive Balance procedure derived by Slibar (E4) in 1973 as an aid to hand-calculated reconstruction.

Like the crush damage calculations in CRASH, EES-ARM automates the methods normally usable for hand calculation of collision-phase speeds based on the principles of momentum and energy. Common to CRASH3, it requires that the user provide quality input regarding the angular relationships in the collision. This requirement is clearly stated in the documentation (E1) as contrasted with some confused claims made in the documentation for CRASH3 (C1,C10). The energy inputs are required in the form of an "energy equivalent speed" (EES) for each car, based on interpretation of crash test data and adjustments for test and vehicle mass variations. The user is fully responsible for the EES inputs and attendant crash-related analysis and stiffness evaluations. The calculation procedure also allows for solution without the EES inputs, using an alternate computation based on more complete specifications of inlet trajectory angles. The angular momentum theorem is used in the EES-ARM method only to provide a check on the calculations made independently from runout-skidmark-rest position evidence. The program itself does not calculate the runin or runout trajectory processes.

Zeidler has developed regression equations for EES values based on crash tests of three series of Mercedes Benz vehicles. The equations are two-parameter regressions based on Equivalent test deformation [(ETD), millimeters] and equivalent overlap degree [(EOD), percent overlap], with the result presented in kilometers per hour. An example, for the 201 series, is $\text{EES} = 0.491(\text{ETD})^{0.758}(\text{EOD})^{0.369}$,

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CRASH3:  Calspan Reconstruction of Accident Speeds on the Highway
 NHTSA version 3, Jan 1982

 Enter a question mark (?) for help
 (Complete, Abbrev., Rerun, Print, Document, SMAC, File, Get, End)
 Which option? (first letter is fine!)            a
  1. TITLE?   NHTSA Staged Crash Test # 2 by Smith & Noga (RICSAC-2).
  2. CLASS/WEIGHTS?   4 4710 1 3261
  3. CDC/PDOF # 1?    11fdew2 -32.5
  4. CDC/PDOF # 2?    02rdew4 35.1
  5. VEHICLE 1 AND VEHICLE 2 STIFFNESS CATEGORIES?   4 1
  6. REST & IMPACT? (Y OR N)    n
 38. DAMAGE DIMENSIONS? (Y OR N)  y
 42. END DAMAGE WIDTH #1   75.5
 43. END DAMAGE DEPTH #1   .5 2.4 3.7 6.9 12.0 16.5
 44. END DAMAGE MIDPOINT OFFSET #1    0
 45. SIDE DAMAGE WIDTH #2     118.5
 46. SIDE DAMAGE DEPTH #2   6.8 22.8 23.5 21.3 10.0 0.0
 47. SIDE DAMAGE MIDPOINT OFFSET #2     13.7

                        CRASH INPUT COMPLETED

            SUMMARY   OF   CRASH3   RESULTS
 NHTSA Staged Crash Test # 2 by Smith & Noga (RICSAC-2).
     Speed change (Damage)
           total          long.          lat.           ang.
 Veh#1   18.1 mph     -15.3 mph       9.7 mph      -32.5 deg.
 Veh#2   26.1 mph     -21.4 mph     -15.0 mph       35.1 deg.
 Energy dissipated by damage   Veh#1  47733.9 FT-LB  Veh#2 139914.7 FT-LB

 SUMMARY OF DAMAGE DATA                 (* indicates default value)
             Vehicle # 1                          Vehicle # 2
 Stiffness---category 4                  Stiffness---category 1
 Weight------   4710.0 lb.               Weight------   3261.0 lb.
 CDC---------11FDEW2                     CDC---------02RDEW4
 L-----------    75.5 in.                L-----------    118.5 in.
 C1----------      .5 in.                C1----------      6.8 in.
 C2----------     2.4 in.                C2----------     22.8 in.
 C3----------     3.7 in.                C3----------     23.5 in.
 C4----------     6.9 in.                C4----------     21.3 in.
 C5----------    12.0 in.                C5----------     10.0 in.
 C6----------    16.5 in.                C6----------       .0 in.
 D-----------      .0                    D-----------     13.7
 RHO---------    1.00       *            RHO---------     1.00        *
 ANG---------   -32.5 deg.               ANG---------     35.1 deg.
 D'----------    15.0 in.                D'----------      5.6 in.
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FIGURE 3 CRASH3 input for RICSAC-2.

as given by Zeidler (E1). Hence a full overlap crash of a 201 Mercedes that resulted in a 20-in uniform frontal crash would be predicted to result from a 55.2 km/hr (34.0) mph barrier crash. By comparison, the CRASH3 category 3 frontal crush parameters A = 317 lb/in, B = 56 lb/in^2, and G = 901 lb predict a total crush energy of 108,000 ft-lbs, or a barrier test speed of 31.4 mph for a 70.3-in wide 3,265-lb$_f$ Mercedes 200D, neglecting restitution (C5).

It is unclear how or whether restitution effects are included in the EES method. Characteristically, in a 30-mph barrier crash the delta V felt by the occupants is 32 to 34 mph, due to restitutions of the order of 0.1. This restitution is probably somewhat higher than that observed in car-to-car impacts, however, because flat barriers do not allow intermingling yield of the stiff load-carrying structures, and hence tend to involve stiffer springback.

The input and output data tables for a typical EES-ARM application are given in Table 2 as taken from Zeidler's recent SAE paper, which also contains a more complete presentation, including a program listing (E1).

Zeidler's EES methods are complemented by several compilations of crash tests readily available to European users (E5,E6). His program is reported to be available through DEKRA in Stuttgart (E7).

HVOSM--HIGHWAY VEHICLE OBJECT SIMULATION MODEL

The first chronology of the U.S. Government-sponsored reconstruction programs was the HVOSM developed under Federal Highway Administration Contract CPR-11-3988 between 1966 and 1971. This model is intended to describe the three-dimensional motion of an automobile in space, including interaction with roadway, shoulders, ramps, berms, and the like. It is supplied in two versions emphasizing either highway design or vehicle dynamics as given in Table 3, taken from the HVOSM User's Manual (H1).

The first HVOSM version (Roadside Design: HVOSM-RD) makes provisions for simplified modeling of collisions with fixed objects. The collision deformation force is modeled by a classic linear force-deflection characteristic as dF = KA(x) dx, where x represents deformation associated with a given area A(x) over an isotropic, weightless layer surrounding a point mass approximation for the sprung mass of the vehicle. This represents a generalization to three dimensions of the crush layer model used in the planar representation of SMAC. HVOSM-RD also provides for representation of two "hard-points" within the layer, modeled by localized $F_i = k_i x$ load paths. The use of this version in actual fixed object modeling is not documented in the HVOSM Users Manual, nor is the modeling of the impact partner elucidated (H1).

TABLE 2 Input Data for EES-ARM

	Vehicle 1	Vehicle 2	Unit
Vehicle Data			
Vehicle length	L1 = 4.42	L2 = 4.96	m
Wheelbase	R1 = 2.67	R2 = 2.87	m
Mass	M1 = 1325.0	M2 = 1895.0	kg
Running-Out Conditions			
Running-out velocity	V1′ = 41.60	V2′ = 28.40	km/h
Running-out angle	Ny1′ = 350.0	Ny2′ = 171.0	Degree
Angle of rotation[a]	Fi1′ = +82.0	Fi2′ = +78.0	Degree
Coefficient of friction rotation	MyR1 = 0.15	MyR2 = 0.10	–
Running-In Conditions			
Yaw angle	Psi1 = 0	Psi2 = 181.0	Degree
Angular velocity[a]	Om1 = 0	Om2 = 0	1/s
Angle of running-in velocity	Ny1 = 0[b]		Degree
Using EES Values			
Energy equivalent speed	EES1 = 48.0	EES2 = 42.0	km/h
Equivalent test deformation	ETD1 = 0.9	ETD2 = 1.0	m
Not Using EES Values			
Angle of running-in velocity		Ny2 = –.–	Degree
Check Calculation by Theorem of Angular Momentum			
Impact force lever arm	SHA1 = 1.1	SHA2 = 1.5	m
Angle of direction[a]	Rho1 = +35.0	Rho2 = 32.0	Degree

[a] (-) means clockwise rotation; (+) means counterclockwise rotation.

[b] Defined by coordinate system, in every case Ny1 = 0.

TABLE 3 Summary of HVOSM Capabilities

	HVOSM-RD Roadside Design Version	HVOSM-VD Vehicle Dynamics Version
Degrees of freedom		
Sprung mass	6	6
Unsprung mass	4	4
Steer	1	1
Wheel spin	–	4
External forces		
Tire forces	Friction circle	Friction ellipse
Impact forces	Yes	–
Aerodynamic forces	–	Yes
Rolling resistance	–	Yes
Road roughness	Yes	Yes
Terrain	Rigid-five tables	Rigid-five tables
Curbs		Yes
Suspension stops	Asymmetric-energy absorbing	Asymmetric-energy absorbing
Control inputs		
Steer table	Yes	Yes
Wheel torque table	Yes	–
Brake system pressure	–	Yes
Throttle setting and transmission ratio	–	Yes
Closed-loop driver	–	Yes

Note: Dash = not applicable.

The primary use of the vehicle dynamics version of HVOSM is for the evaluation of vehicle trajectories due to launch, vault, or handling maneuvers. HVOSM-VD includes a detailed model of the suspension, from the tire interface through the geometry to the body mass. As such, it requires that measured or assumed data be supplied for detailed inputs such as spring rates, damping rates, rear axle inertia, and even aerodynamic drag. It also contains built-in models for engine torque and drag, hydraulic brake pressure versus brake torque at a given wheel, and so forth. The HVOSM-VD version also allows for assumptions about driver control inputs. This version of HVOSM has been used successfully to predict vehicle dynamics in complex roadway design situations. The example cited most often arose from the design of ramps for a barrel-roll stunt used successfully by an automobile stunt troupe and used in a James Bond movie (H2,H3). Applications of HVOSM to real-world rollovers is limited by the inability of either standard HVOSM program to tolerate ground contact by any vehicle component other than the tires, although its ability to predict pretouchdown kinematics appears to be quite good. An improved version for touchdown and roll applications is reportedly under development at the Texas Transportation Institute (personal Communication from Donald Ivie, July 1985).

Because much of the HVOSM input data are not readily available in the open literature, and are often somewhat difficult and always tedious to measure, an auxiliary preprocessing program has been developed to predict these inputs from measurements of six 1971-1973 production automobiles including a 1971 Volkswagen Beetle and a 1973 Ford Galaxy 4-door (H1). Even with the preprocessor, the required input is voluminous and tedious. Formatting requirements are typical 1968-vintage, which makes the program accessible only to those with extraordinary patience. For those who persevere, however, HVOSM presents a timewise output of minutely detailed tables of predicted vehicle dynamic information. A postprocessor program formerly proprietary to Calspan corporation is now available to produce three-dimensional graphics (private Communication, McHenry Consultants, Cary, North Carolina).

HVOSM, in the Roadside Design version, has 11 degrees of freedom (6 for sprung mass, 4 for unsprung masses, and one steering input). It employs a friction circle tire interface model, and allows a basic road roughness to be specified over a rigid terrain specified by five input tables. It allows the specification of curb geometries and models suspension stops by asymmetric energy-absorbing relations. It allows tabular steering and wheel torque controls.

Gross distinctions between the HVOSM-RD version and HVOSM-VD are that while impact forces are missing, the VD version includes 4 more degrees of freedom (15 total) for tire spins, provisions for aerodynamic and rolling restrictive forces, and brake system modeling. It requires inputs for brake system pressure, throttle setting, transmission ratio, and closed-loop driver controls actions. A summary of advertised HVOSM capabilities is given in Table 3. Examples of the graphic output is shown in Figures 4 and 5.

A more complete but still somewhat sketchy documentation of the HVOSM models is contained in an FHWA report (H1). The program is available for use, either through DOT contract computer auspices, or it may be obtained on tape from the FHWA. A list of related references is supplied for those interested in further reading (H6-H16).

IMPAC--IMPACT MOMENTUM OF A PLANAR ANGLED COLLISION PROGRAM

The IMPAC program (I1) is intended to provide a straightforward and simple analysis of angled collisions, providing something that allows the user to at once avoid the tedious hand calculations of momentum and the complexity of SMAC (S1) while achieving a useful technical result. The conceptual model is similar to that used in the CLM part of CRASH3 (C1) in that one point within the crush zones of the two planar collision partners has the same velocity

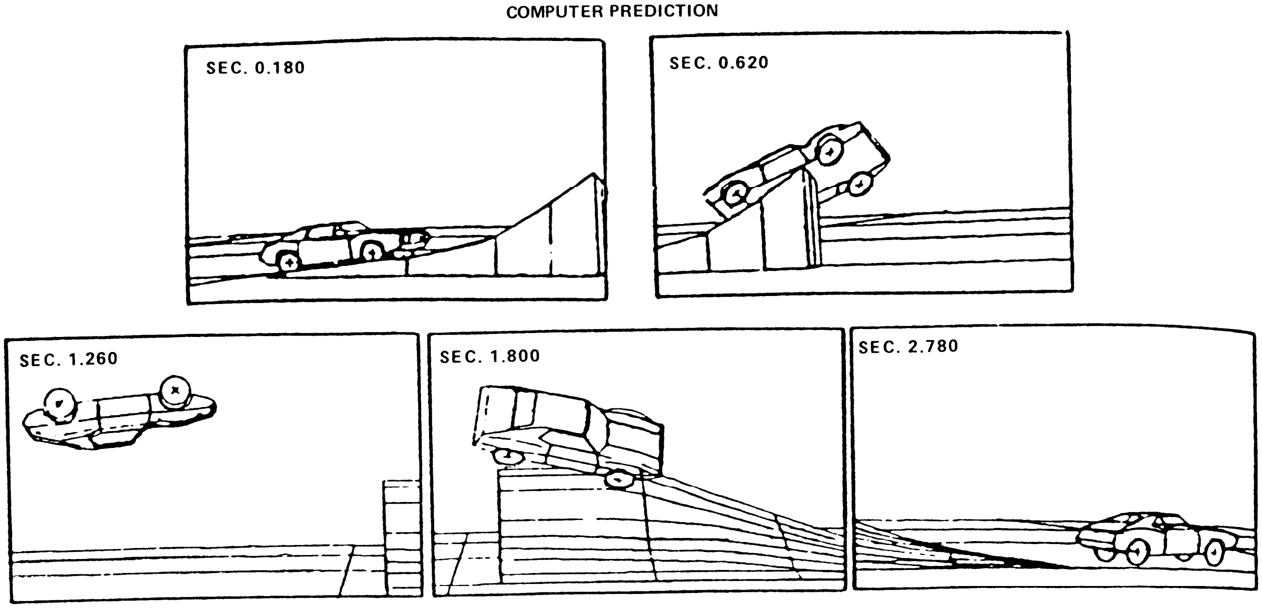
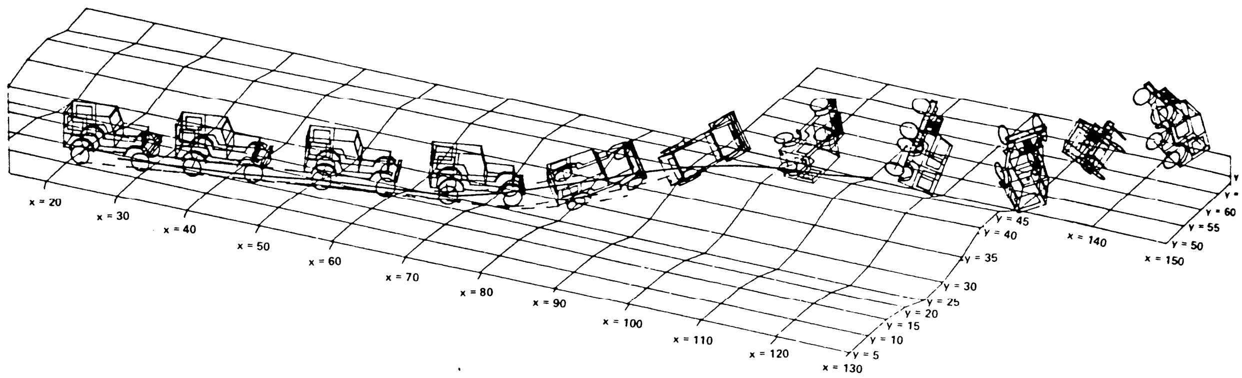


FIGURE 4 HVOSM graphics of car stunt.



TIMES DISPLAYED: 0.0 TO 2.50, 0.25 INC

FIGURE 5 HVOSM graphics of rollover.

at the end of the momentum exchange. The similarity ends there because IMPAC is posed as an initial value problem rather than as a final value problem (the user specifies pre-impact conditions and the program calculates post-impact conditions). The math model and coded equations are also quite different because the six simultaneous equations that are solved come from four vector equations (11). The governing equations for this planar model are (a) conservation of linear momentum, (b) conservation of angular momentum, and (c) the constraint condition of a common velocity at the center of impact.

Program IMPAC provides a simple, easily used collision model to reconstruct accidents that are beyond hand calculation. It has also been used in combination with vehicle trajectory simulation (VTS) for trajectory analysis, as a preprocessor for SMAC to reduce the number of runs required to obtain a reconstruction, and to study sensitivities in proposed crash test alignments, both car-to-car and car-to-barrier.

Because each collision is analyzed individually, cases involving multiple impacts can be examined. The output of one impact can be entered into a trajectory simulation, such as VTS, or directly back into IMPAC if the time interval is small as in a side slap. Use of the IMPAC program to reconstruct side-slap collisions has been compared to three crash tests with good results (11,12).

IMPAC also contains one feature that is as yet not validated because of the absence of test data, the sideswipe algorithm. Sideswipes, which imply no lockup in the crush zone, are modeled via replacement of the common velocity constraint condition with a sideswipe constraint. A slip interface plane is defined relative to one of the cars at the common contact point. Along this plane the cars may slide past one another but the velocity of each car normal to the plane must be identical and system momentum must be conserved. The user specifies the relative velocity of sliding, attempting to match the length of the contact damage for the prescribed collision time interval.

The simplicity of the IMPAC program is illustrated by the sample run that follows in which case number 2 of the NHTSA test data is analyzed (C9)

(Figure 6). Figure 7 shows the simplified geometry required by the program. Only dimensional information about the position of the centers of impulse relative to the CGs is needed. The exterior dimensions are not required.

The procedure for solution of the reconstruction problem with program IMPAC is as follows:

1. Collect all available scene data from the accident site.
2. Measure the crush deformation on the vehicle(s).
3. Estimate the total crush energy dissipated by the impact (by comparing with crash test data, comparing to the CRASH program data correlations via hand computations, or by running the damage-only option of CRASH).
4. Estimate the total runout energy dissipated from impact to rest (by hand calculations or trajectory simulation programs, etc.).
5. Estimate the runout angles, rotational directions, and an order of magnitude for the rotational rate postimpact.
6. Estimate the one point in each vehicle within the crush zone that most closely represents the point of lockup during the impact (or a representative contact point on the slip interface plane). This point is representative of the time-averaged center of impulse for the collision.
7. Estimate the vehicle weight and radius of gyration for each vehicle.
8. Make a first approximation for the preimpact speeds and heading of each vehicle.
9. Iterate by changing preimpact conditions until a solution is obtained. By solution it is meant that the predicted postimpact conditions and crush energy all correspond to their estimated values within a reasonable tolerance.
10. Perform additional computations with input perturbed from the solution run to obtain an understanding regarding the sensitivity of the result.

One minor feature of IMPAC is the output of postimpact velocity at two selected points within each vehicle. This information may be used as an aid in analyses of occupant kinematics if the points correspond to occupant contact areas such as the dash in a frontal impact or the opposite door in a side impact. In accidents with substantial postimpact rotation, the contact point may have a substantially greater or lesser velocity than the vehicle CG. The motion of the occupant contact point during the short collision interval should also be in agreement

```
Staged Crash Test #2.  NHTSA, Smith & Noga, "Examples of Staged Collisions..."
 Vehicle A:                 PROGRAM IMPAC                       Vehicle B:
74 Chevelle Malibu.         Case #2 or RICSAC #2         74 Ford Pinto - 2 door
    4710.0 lbm              Vehicle mass                      3261.0 lbm
      60.9 inches           Radius of gyration                  49.5 inches
      89.0 inches           Impulse center, fwd from veh CG     13.0 inches
        .0 inches           Impulse center, lat from veh CG     23.0 inches
     -30.0 degrees          Vehicle heading at impact           90.0 degrees
      31.3 mph              Forward speed at impact             31.3 mph
        .0 mph              Lateral speed at impact               .0 mph
        .0 deg/sec          Pre-impact rotational velocity        .0 deg/sec

      24.0 inches           Selected point-1, fwd from CG         .0 inches
     -18.0 inches           Selected point-1, lat from CG       24.0 inches
      24.0 inches           Selected point-2, fwd from CG       30.0 inches
      18.0 inches           Selected point-2, lat from CG       24.0 inches

        .0 deg              Angle of slip plane (relative to vehicle A)
        .0 % slip           Slip velocity, % of approach vel along slip plane.
       80. millisec         Time duration of impulse        version: R85L01W25.

Staged Crash Test #2.  NHTSA, Smith & Noga, "Examples of Staged Collisions..."
A: 74 Chevelle Malibu.      PRE-IMPACT CONDITIONS   B:  74 Ford Pinto - 2 door
                 -30.0 deg  Vehicle Heading                           90.0 deg
  31.3 mph @ -30.00 deg     CG Velocity                  31.3 mph @  90.00 deg
    0. deg/sec              Rotational Velocity                     0. deg/sec
 154254.         0.ft-lb    Linear & Rotational KE      106799.          0.ft-lb

------------------------    IMPACT CONDITIONS           --------------------
  19.6 mph @ 135.27 deg     Crash Severity Index  (^V)  28.2 mph @ -44.73 deg
          -4060. lbf-sec    Longitudinal Impulse              -2954. lbf-sec
           1067. lbf-sec    Lateral Impulse                   -2983. lbf-sec
     2.4 ft &  -1.0 ft      X & Y Impact Motion of CG        1.2 ft &   2.5 ft
                            Approximate Mutual Crush                   3.18 ft
                            Impulse Duration                      80 milli-sec
                            Approach Velocity   - CG's  54.2 mph @--60.00 deg
                            Separation Velocity- CG's   15.0 mph @-117.23 deg
                            Slip Velocity along plane     .0 mph @ -27.14 deg
 Approach Vel @ IC's:  45.5 mph tangential &  -29.4 mph normal to slip plane.
                            Crush Energy of Collision         161010. ft-lbf

------------------------    POST-IMPACT CONDITIONS      --------------------
                 -24.3 deg  Vehicle Heading @ runout                  93.6 deg
  13.3 mph @  -8.14 deg     Runout velocity             23.1 mph @  29.66 deg
  143. deg/sec              Runout rotational speed      90. deg/sec
   8.4 ft                   Runout Work / Weight        18.5 ft
  21.1 mph @  26.21 deg     Velocity @ impulse-center   21.1 mph @  26.21 deg
  17.0 mph @   -.09 deg     Velocity @ point-1          22.2 mph @  24.76 deg
  12.7 mph @  10.44 deg     Velocity @ point-2          19.7 mph @  27.79 deg
  28056.    11735.ft-lb     Linear & Rotational KE      58122.      2129.ft-lb
```

FIGURE 6 Sample run from IMPAC program.

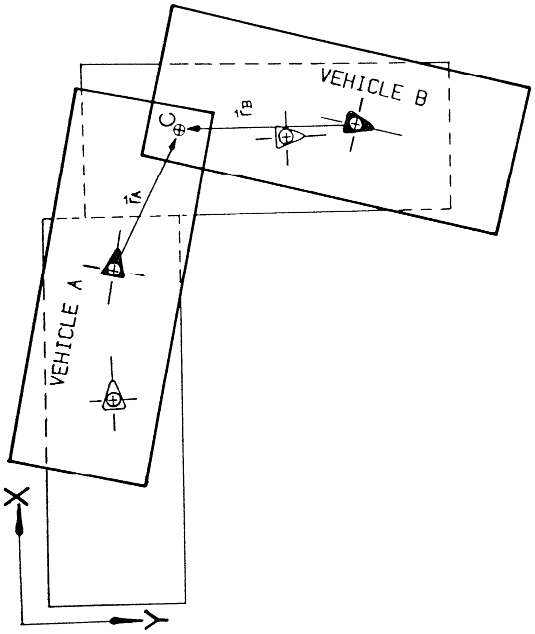


FIGURE 7 Center of impulse, point C.

with or evidence of car heading and alignment pre-impact.

Program IMPAC has been compared with 16 staged crash tests that were performed by the NHTSA for such purposes (C9). Figure 8 shows graphically the result of this comparison as tabulated in the introductory documents (I1,I2).

IMPAC may be accessed at CSE via telephone or modem at 1200 or 2400 baud from a variety of terminals or personal computers. The program operates on an HP-9000 series 500 computer under the UNIX operating system (HP-UX). Those who wish to experiment with the IMPAC or VTS programs may do so by contacting the authors to establish a dial-up connection.

SMAC--SIMULATION MODEL OF AUTOMOBILE COLLISION PROGRAM

The SMAC computer program was developed by McHenry for the U.S. Department of Transportation (DOT)

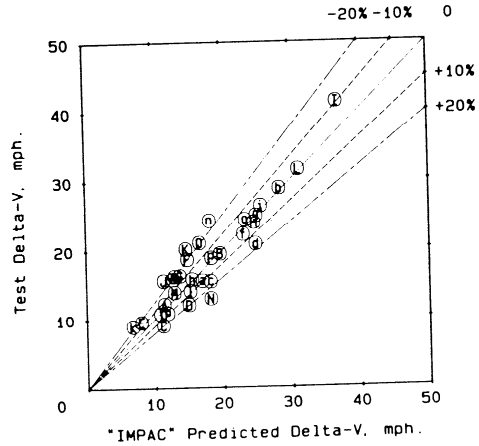


FIGURE 8 IMPAC predicted delta-V.

(S1-S6). SMAC represents each of (up to) two cars as a rectangular planar chassis with four contact points (wheels) on a planar ground surface. Each vehicle mass is surrounded by a crushable layer (body) characterized by a linear force-deflection relationship, whereby deflection is measured parallel to the longitudinal or lateral axis of the vehicle, depending on impact location. Intervehicular normal crush forces are generated by interacting crush zones subjected to local static force balance. Tangential crush forces are calculated from a frictional force model based on a circumferentially uniform friction coefficient. Residual crush depths and separation velocities are calculated from a rebound model that is based on a concept that uses energy rather than velocity as a separation criterion.

Pavement tire forces are calculated from a friction circle model that encompasses constant normal forces, tabulated wheel torques and pre-set cornering stiffnesses from each individual tire, and preset roadway friction, which may be represented differently on either side of a friction boundary along the planar roadway surface.

To conduct SMAC runs, vehicle geometry, mass, yaw inertia, and tire properties, together with time-dependent braking and steering, data are tabulated in program input for each vehicle; intervehicle friction and restitution are selected, and one or two roadway friction regions are described. Initial conditions of velocity and position in two rectangular and one angular coordinate are described for each automobile, and simulation control inputs are inserted to initiate and terminate the computer run (see Figures 9 and 10). The computer calculates individual tire forces and intervehicle crush forces for this initial-value problem at preassigned time steps by a Runge-Kutta integration scheme. The result is a time-based tabulation of position, velocity, and acceleration of the mass centers, planar outlines, and wheel contact locations of each vehicle in rectangular coordinates. Basic graphic subroutines exhibit tire tracks and residual crush profiles (see Figure 11).

DOT contract research has been devoted in efforts to upgrade the fidelity and efficiency of SMAC. James et al. (S7) introduced modifications designed to improve narrow-object crash simulations, to model a sloping terrain, and to include hard spots in the vehicle crush layer. Chi et al. (S8) revised the numerical integration scheme. Another DOT project has introduced optimization logic to semiautomate the process of matching input conditions and rest positions (S9).

The authors' experience with SMAC is common with that of Jones (S10,S11) with respect to spinout trajectory. The authors, too, have found it necessary to alter cornering stiffness values to effect appropriate trajectories in some cases involving shifting tire normal forces. This is cumbersome because it requires stopping and restarting the entire SMAC program. The problem was treated with a first-approximation simulation to the pitch and roll degrees of freedom. This simulation has since been abandoned with the advent of VTS as described in another section of this paper.

In earlier papers, the authors identified some programming errors and conceptual problems with SMAC that arose from early phases of industry-sponsored research with the program (S12-S15). Changes were proposed and implemented in the model features dealing with restitution, tire-force calculations, crush layer, and integration techniques. The revised model was identified by the name PRED (S14,S15). In addition, an input-preparation/editor program called SMACED (S14,S15), was developed to ease the task of preparing an input file for SMAC or PRED.

```
              Simulation Model of Automobile Collisions (SMAC)
              Example Problem
                                                                          CALCULATION CONSTANTS
                       INITIAL CONDITIONS
    VEHICLE NO. 1                          VEHICLE NO. 2
                                                                          DELPSI    =    3.000 DEGREES
XC10'     = 140.400 INCHES            XC20'     =  22.900 INCHES           DELRHO    =     .200 INCHES
YC10'     =  -4.000 INCHES            YC20'     = 120.000 INCHES           LAMBDA    =   12.000 LB/IN,PRESSURE ERROR
PSI10     =  82.500 DEGREES           PSI20     =   2.500 DEGREES          ZETAV     =    5.001 IN/SEC,MIN.FOR FRICT
PSI1D0    =    .000 DEG/SEC           PSI2D0    =    .000 DEG/SEC
U10       = 470.000 IN/SEC            U20       = 425.000 IN/SEC
V10       =    .000 IN/SEC            V20       =    .000 IN/SEC

                  DIMENSIONS AND INERTIAL PROPERTIES                       DEFORMABLE LAYER
A1        =  52.000 INCHES            A2        =  54.450 INCHES           KV1       =  50.000 LB/(IN**2)
B1        =  42.500 INCHES            B2        =  66.550 INCHES           KV2       = 124.500 LB/(IN**2)
TR1       =  52.500 INCHES            TR2       =  63.500 INCHES           MU,FRICT =    1.000
I1        =  12751. LB-SEC**2-IN      I2        =  46972. LB-SEC**2-IN     C0        =     .000 RESTITUTION
M1        =   5.311 LB-SEC**2/IN      M2        =  10.622 LB-SEC**2/IN     C1   =   .10000E+00   VERSUS
PSIR10    =    .000 DEGREES           PSIR20    =    .000 DEGREES          C2   =   .50000E+02 DEFLECTION
XF1       =  79.100 INCHES            XF2       =  93.850 INCHES
XR1       = -79.500 INCHES            XR2       =-122.150 INCHES
YS1       =  30.500 INCHES            YS2       =  39.900 INCHES

                                            TIRE PROPERTIES                 TIRE-TERRAIN COEF AND TERRAIN ZONES
                      CORNERING STIFFNESS                                  XB1' = 900.000 IN.     YB1' = 252.000 IN.
C(1)      =  -8580. LB/RAD            C(5)      =  -8580. LB/RAD           XB2' =-900.000 IN.     YB2' = 252.000 IN.
C(2)      =  -8580.  ''               C(6)      =  -8580.  ''              XMU1 =     .700
C(3)      =  -8580.  ''               C(7)      =  -8580.  ''              XMU2 =     .700
C(4)      =  -8580.  ''               C(8)      =  -8580.  ''              CMU  =   .00000E+00

                                                                            PROGRAM CONTROL DATA
     PSIB RANGE TESTS                     PSIBI FOR RHOBI TESTS
     COLLISION CRITERIA                   COLLISION CRITERIA               T0       =    .000 SEC.,BEGIN
PSILIM1  =  70.000 DEGREES            PSILIM5  =  10.000 DEGREES           TF       =    .500  ''  END
PSILIM2  = 110.000   ''               PSILIM6  = 170.000   ''              DTTRAJ   =    .050  ''  INTEG. INTVL,TRAJ
PSILIM3  = 250.000   ''               PSILIM7  = 190.000   ''              DTCOLL   =    .001  ''  INTEG.INTVL,COLL
PSILIM4  = 290.000   ''               PSILIM8  = 350.000   ''              DTCOLT   =    .010  ''  INTEG.INTVL,CPOS
                                                                           DTPRNT   =    .010  ''  PRINT INTERVAL
                                                                           UVMIN    =    .000 IN/SEC STOPPING TEST
                                                                           PSIDOT   =    .000DEG/SEC STOPPING TEST
                                                                           NO.OF VEHICLES = 2.
                                                                            FMOVIE =  0.(ZERO,FINAL DAMAGE TABLE TAPE
                                                                                        (NON-ZERO,DAMAGE HISTORY TAPE
                                                                                        (ALSO WRITTEN ON FORTRAN 2.
                                                                                          (TAPE IS ALWAYS FORTRAN 1)
```

FIGURE 9 SMAC sample input file—example problem.

The source code Fortran listing for SMAC is available on tape from the National Center for Statistics and Analysis, NHTSA, U.S. Department of Transportation. Operational versions may be run via modem at 1200 baud using the computer facilities at the University of Michigan Transportation Institute or at the Boeing Computer Services Company, Vienna, Virginia.

A combined collision and trajectory model that in many ways is similar to SMAC although independently designed and coded has recently been developed by the Japan Automobile Research Institute (S16). A released version of the "J2DACS" program (JARI 2 Dimensional Automobile Collision Simulator) is anticipated in mid-1986.

TBS--TRACTOR BRAKING AND STEERING SIMULATION

The TBS simulation was developed at the Highway Safety Research institute (HSRI) under the sponsorship of the Motor Vehicle Manufacturers Association

```
              Simulation Model of Automobile Collisions (SMAC)
              Example Problem

((PSIFI(I,K),I= 1, 2),K=1,   7) STEER TABLES ALL ZERO FOR VEHICLE NO. 1

((PSIFI(I,K),I= 3, 4),K=1,   7) STEER TABLES ALL ZERO FOR VEHICLE NO. 2

VEHICLE NO. 1                                                                       TRACTIVE OR BRAKING FORCE LB
           TRACTIVE OR BRAKING FORCE LB        TRACTIVE OR BRAKING FORCE LB     SEC     RF      LF      RR      LR
   SEC     RF      LF      RR      LR       SEC     RF      LF      RR      LR   .400 -322.90 -322.90 -394.60 -394.60
  .000 -322.90 -322.90 -394.60 -394.60     .200 -322.90 -322.90 -394.60 -394.60 .500 -322.90 -322.90 -394.60 -394.60
  .100 -322.90 -322.90 -394.60 -394.60     .300 -322.90 -322.90 -394.60 -394.60

VEHICLE NO. 2                                                                       TRACTIVE OR BRAKING FORCE LB
           TRACTIVE OR BRAKING FORCE LB        TRACTIVE OR BRAKING FORCE LB     SEC     RF      LF      RR      LR
   SEC     RF      LF      RR      LR       SEC     RF      LF      RR      LR   .400    .00     .00 -102.50 -102.50
  .000    .00     .00 -102.50 -102.50      .200    .00     .00 -102.50 -102.50   .500    .00     .00 -102.50 -102.50
  .100    .00     .00 -102.50 -102.50      .300    .00     .00 -102.50 -102.50
```

FIGURE 10 SMAC input file—continued.

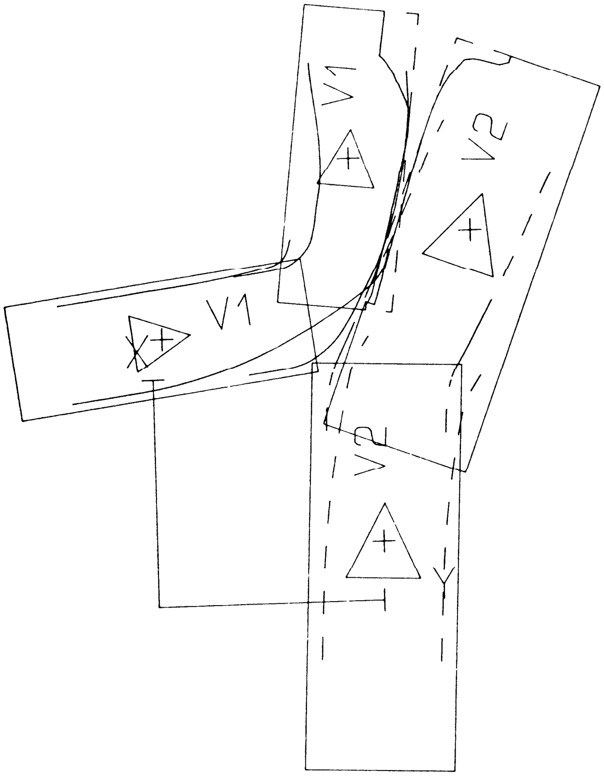


FIGURE 11 SMAC graphics—example problem.

(MVMA) in addition to earlier more comprehensive programs (T1-T3). During the course of development of the earlier programs, it became apparent that there was a need for less complex simulations that could be run interactively using minimal I/O. The BRAKES2 simulation was developed to simulate the straight-line response of commercial vehicles to a step brake input (T4). Following BRAKES2, the TBS simulation was developed. This simulation contains a simplified vehicle model for predicting the directional response of commercial vehicles to braking or steering inputs, or both. The simulation consists of two interactive computer programs--one for a straight truck (TBSTR) and the other for a tractor-trailer (TBSTT).

The mathematical model for TBS was constructed using the model developed by Leucht (T5) as a starting point. Additions and changes, particularly with respect to the tire model, were made to produce the present simulation.

The TBS simulation was formulated and programmed to describe the directional dynamics of a tractor-trailer. A similar model was then developed for a straight truck by simplifying the tractor-trailer model. The following discussion treats the tractor-trailer model only because the truck model is a simple derivative of the tractor-trailer model.

The vehicle model consists of two rigid bodies: one for the tractor and the other for the trailer. The model has four degrees of freedom, namely, the longitudinal velocity and the lateral velocity of the tractor, the yaw rate of the tractor, and the articulation angle of the trailer relative to the tractor. There are no roll or pitch degrees of freedom. Load transfers, both longitudinal and lateral are computed quasistatically.

In the simulation the hitch is assumed to transmit a yaw moment (but not a roll or pitch moment) through the hitch due to friction. The normal load on each wheel is equal to the sum of the static load on that wheel and the load transfer (both longitudinal and lateral) taking place at any instant of time. The load transfer at the trailer wheels is based on the trailer CG height, the hitch height, the forces on the trailer at the hitch and the road, the track width of the trailer, and the distance between the fifth wheel and the trailer axle.

The load transfer on the tractor wheels is not quite so straightforward. The apportionment of the lateral load transfer between the front and rear axles of the tractor depends on the properties of the suspension system, which are not included in the simple TBS simulation. The user must input the parameter that defines the fraction of the total lateral load transfer that takes place at the front axle of the tractor. The remaining fraction of the lateral load transfer takes place on the rear axle (or axles) of the tractor.

A simplified model for tandem axles is included. The properties of all the tires at both axles in the tandem pair are assumed equivalent and are specified for one tire. A quasistatic interaxle load transfer is specified by entering a load transfer coefficient for the tractor tandem axles and the trailer tandem axles.

The simulation incorporates the "friction circle" model for computing tire forces. An antilock model is included by supplying lateral and longitudinal antilock effectiveness coefficients. Dual tires are treated as two single tires, each sharing the vertical load on them equally and each yielding the same longitudinal and lateral forces.

Braking is handled in the model by specifying the time history of attempted brake force for the brakes on each side of each axle. This allows brake imbalance to be simulated. For a tandem axle pair, the two sets of brakes on one side of the tandem axles are assumed equivalent. Steering inputs are also entered as a table consisting of the time followed by the average steer angle for the front wheels.

The program is designed so that the user answers questions or enters data in response to questions or commands from the computer. In addition, data for the program may be optionally input from a file. A sample set of input parameters is shown in Figure 12. There are 83 output variables for the articulated vehicle and 52 for the straight truck. Each of these may be displayed as a function of time. A list of the available output variables is shown in Figure 13. The user specifies the number of output variables (six maximum), their identifying numbers, and the time step on which the output file is to be printed. After this output has been echoed, the user may demand an additional six output variables in the same manner and repeat until the desired output variables are obtained. There is no graphical output for the TBS simulation in its present configuration.

UMTRI has two additional tractor-trailer simulations for use in reconstructions that require use of more complex simulations: PHASE4 (T6) and YAW/ROLL (T7). PHASE4 was developed in 1980 for the MVMA as a consolidation of previous models. It is a nonlinear, time domain simulation of a tractor with an optional semitrailer and up to two additional full trailers. PHASE4 is applicable in directional response studies in which the influence of braking parameters such as brake pads, hysteresis, proportioning, antilock logic, stopping distance, brake timing, effect of split friction surfaces, and other braking performance parameters are to be considered. When used to study cornering performance behavior, the program provides a more realistic simulation of understeer and oversteer properties of articulated ve-

```
0,0,0             41 White tractor, Fruehauf trailer.  Page 23, 41 of manual.
1,1,1,1           42 Tandem/dual key: tractor tandem,dual; trailer tandem,dual
14970.            01 GVW1    Wt of tractor, (lbs).
11160.            02 GVW2    Wt of trailer, (lbs).
241636.           03 IZZ     Tractor yaw inertia, (in-lb-sec**2).
736983.           04 ITZZ    Trailer yaw inertia, (in-lb-sec**2).
54.4              05 AA      Dist. between tractor tandem axles, (in).
49.3              06 AAT     Dist. between trailer tandem axles, (in).
63.9              07 A1      Dist. from tractor CG to front axle, (in).
78.1              08 A2      Dist. from tractor CG to rear axle, (in).
261.2             09 A3      Dist. from trailer CG to 5th wheel, (in).
104.8             10 A4      Dist. from trailer CG to trailer rear axle, (in).
0.                11 BB      Tractor rear axle to 5th wheel, (in) (aft is neg).
40.               12 TRA1    One-half the tractor front track width, (in).
36.               13 TRA2    One-half the tractor rear track width, (in).
36.               14 TRA3    One-half the trailer track width, (in).
48.               15 Z0      Height of 5th wheel above ground, (in).
39.9              16 Z1      Height of tractor CG above ground, (in).
55.5              17 Z2      Height of trailer CG above ground, (in).
.05               18 MU5     5th wheel friction coefficient.
19.               19 RAD5    Equivalent radius of 5th wheel, (in).
.16               20 GAM1    Tractor front axle lateral load X-fer coef.
-.375             21 GAM3    Tractor tandem axle load X-fer coef.
-.375             22 GAM4    Trailer tandem axle load X-fer coef.
26.8              23 VEL     Initial forward velocity, (mph).
6.                24 TIMF    Max simulation time for run, (sec).
30.               25 IQUIT   Max articulation angle allowed, (deg).
467.              29 CALF(1) Cornering stiffness of front tires, (lb/deg).
208.              30 CALF(3) Cornering stiffness of tractor rears (lb/deg).
200.              31 CALF(7) Cornering stiffness of trailer rears (lb/deg).
n                    Do all tires have the same friction curve?
.942              32 MUP(1) Peak friction coef, tractor front.
.939              33 MUP(3) Peak friction coef, tractor rear.
.960              34 MUP(7) Peak friction coef, trailer rear.
.895              35 MUS(1) Sliding friction coef, tractor front.
.895              36 MUS(3) Sliding friction coef, tractor rear.
.895              37 MUS(7) Sliding friction coef, trailer rear.
.11               38 SP(1)  Slip corresponding to peak friction - tractor front.
.11               39 SP(3)  Slip corresponding to peak friction - tractor rear.
.11               40 SP(7)  Slip corresponding to peak friction - trailer rear.
0.0               41 PW     Payload weight, (lbs).
7                    number of lines in brake force table. (15 max)
0.000, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,     time,F(1),F(2),F(3),F(4),F(7),F(8)
2.190, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
2.215,77.4,77.4, 0.0, 0.0, 0.0, 0.0,
2.315,387.,387.,420.,420., 0.0, 0.0,
2.385,604.,604.,713.,713.,598.,598.,
2.410,682.,682.,713.,713.,812.,812.,
2.443,682.,682.,713.,713.,1094.,1094.,
2                    Number of lines in steering table.  (25 max)
0.,0.,                                   time, average steer angle.
1.,4.62,
```

FIGURE 12 TBS sample input file.

hicles, tandem-axle effects, jackknife prediction, and suspension effects.

The Constant Velocity Yaw/Roll program simulates the turning and rolling behavior of motor vehicles in constant speed maneuvers. Turning may be controlled either by defined steering versus time or by a driver model following a prescribed trajectory. In the absence of a brake model, YAW/ROLL features an expansion of axle and articulation arrangements for prediction of stability and turning behavior of articulated vehicles. A truck with up to three trailers may be examined with multiple-axle configurations and different types of hitching mechanisms between units.

The source code Fortran listing for TBS (and also PHASE4 and YAW/ROLL) is available on tape from the UMTRI (C12). Operational versions of TBSTT and TBSTR may be run via modem at 1200 baud using the computer facility at UMTRI.

VTS--VEHICLE TRAJECTORY SIMULATION PROGRAM

The VTS program (V1) simulates the trajectory of one vehicle on a horizontal surface. Its application to accident reconstruction is to study the preimpact and postimpact motion of a vehicle (automobile or two-axle truck, no trailers). The information obtained may then be used as parametric data for separate collision programs, using the modular approach to accident reconstruction.

Preimpact motion is studied to define vehicle capabilities in time, such as steering and braking vehicle responses based on assumed driver inputs. VTS is also useful in studying the vehicle response to sudden changes in surface friction (patches) when undergoing a maneuver such as cornering or braking.

The fictitious example VTS run of Figures 14 and 15 illustrates this capability whereby an unladen pickup encounters a patch of black ice when rounding a corner at 55 mph on an unbanked turn. The cause of the sudden rotation and loss of control is seen to be the change from a low friction to a high friction surface coupled with partial braking. Partial braking for this unladen pickup leads to rear brake lockup on the ice patch and exaggerates the small but highly significant rotation that takes place as the pickup slides across the patch. As the front tires leave the ice patch they have a slip angle because of the rotation and develop a large cornering

Variable #	Variable Name
*** POSITION VARIABLES ***	
1	XO-COORD
2	YO-COORD
3	PSI
4	GAMMA
*** VELOCITY VARIABLES ***	
5	U-VEL
6	V-VEL
7	PSIDOT
8	GAMMADOT
***	
9	TURN RAD
10	SIDESLIP
*** TIRE SLIP ANGLES ***	
11	ALFA 1+2
12	ALFA 3+4
13	ALFA 5+6
14	ALFA 7+8
15	ALFA9+10
*** ACCELERATION VARIABLES ***	
16	U-DOT
17	V-DOT
18	PSI-DDOT
19	GAM-DDOT
20	LONG ACC
21	LAT. ACC

Variable #	Variable Name
*** TIRE-ROAD INTERFACE FORCES *** *** BRAKE FORCES: FX(I), SIDE FORCES FY(I) ***	
22-31	FX(1-10)
32-41	FY(1-10)
*** LOAD TRANSFERS, LONG. DFX(I), LAT. DFY(I) ***	
42-51	DFX(1-10)
52-61	DFY(1-10)
*** INSTANTANEOUS LOAD FORCES ***	
62-71	FZ(1-10)
*** PROGRAMMED BRAKE FORCES ***	
72-81	FSX(1-10)
*** HITCH FORCES ***	
82	XH
83	YH

FIGURE 13 TBS output variables.

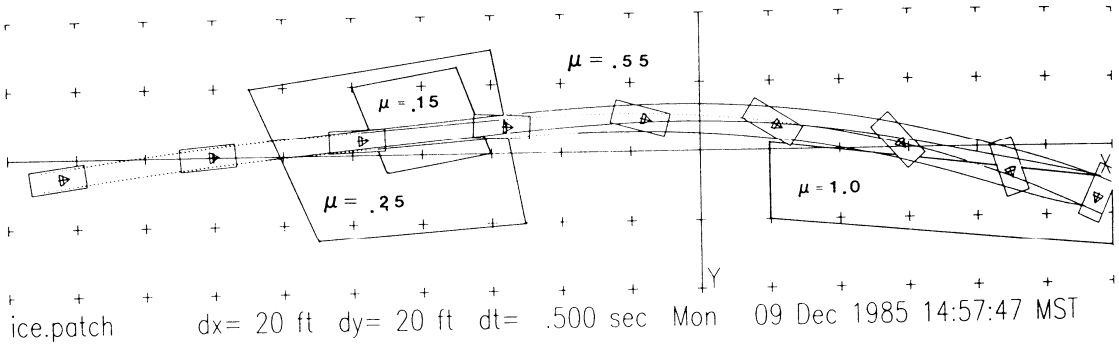


FIGURE 14 VTS graphic for ice patch run.

force. The result is similar in effect to that of a large and rapid steering input. VTS also reveals that the timing of this event is less than normal reaction times. This combination of factors illustrates one way in which a vehicle may leave the inside of a curve sideways or rearward. When rerun with full locked wheel braking (not shown here) VTS predicts that the vehcle will slide off the outside of the curve.

VTS's use in simulation of postimpact motions helps to define postimpact velocities and rotation rates or to determine the average deceleration of a damaged rotating automobile. These parameters are needed for subsequent collision calculations. Given an estimate of the point of impact and point of rest, VTS is used in an iterative manner to estimate launch conditions that produce plausible trajectories to rest. This application, though obviously tedious if the surface frictional conditions are not well established, is facilitated by graphical display of the output as it develops and by the ease in making changes to the input for the next iteration.

The VTS model is two-dimensional (planar) except that normal tire loads are adjusted for quasistatic weight shift associated with acceleration. Steering and traction (or braking) may be applied to any or all of the four wheels. All forces acting on the vehicle come from the tire-surface interaction.

The simulation surface is a horizontal flat plane with a uniform friction coefficient except for quadrilateral patches of user-specified size that may be assigned a different friction.

Tire longitudinal forces are set by a table of requested traction (braking) coefficients versus time, which may be viewed as requested friction coefficients (longitudinal force = traction coefficient * static equilibrium tire normal load).

Tire lateral force is defined by cornering stiffness and slip angle. The cornering stiffness model assumes that cornering stiffness for a given tire can be described as a parabolic function of tire load given the unloaded, peak, and overload values of cornering stiffness (V1). The limiting frictional condition is either the friction circle, as used in

```
! file - ice.patch  Unladen Pickup on a Curve.
RUN  Ice patches at 0.25 & .15 on road of 0.55 friction.
CASE Black Ice Study
USER RLW - CSE
!        xmin, xmax, ymin, ymax, friction
SURFACE -200., 120., -40., 40., .55
!        x1,    y1,   x2,    y2,    x3,    y3,    x4,   y4, friction
PATCH  -130., -20., -60., -30., -50.,  20., -110., 25., 0.25
PATCH  -100., -20., -70., -25., -60.,   0., -90.,   5., 0.15
PATCH    20.,  20.,  20.,  -2., 120.,  10., 120.,  30., 1.00
!          wb,  ftw,  rtw, CG%, weight, yaw_rg, CG_height
VEHICLE  117.8, 64.5, 65.5, 40.,  4400.,  61.3,     24.
!    loc, tire#, stiffness, offset_x, offset_y, offset_steer
WHEEL rf,   1,     1.0,         0.0,      0.0,      0.0,
WHEEL lf,   1,     1.0,         0.0,      0.0,      0.0,
WHEEL rr,   2,     1.0,         0.0,      0.0,      0.0,
WHEEL lr,   2,     1.0,         0.0,      0.0,      0.0,
!  tire#, model, cs_none, cs_nom, cs_over, nom_load, overload, frx, fry
TIRE   1,circle,   48.8,   164.2,  181.5,    1320.,     1720.,  1.0, 1.0
TIRE   2,circle,   48.8,   135.6,  181.5,     880.,     1720.,  1.0, 1.0
!         start_time, end_time, minimum_step, output_step, max_error
SIMULATION    0.0,       5.0,        .001,          .1,        .01
!   tick_x, tick_y, plot_interval, foh, roh, width
PLOT   20.,   20.,        .5,       32.5, 43.8,  81.,
!          xo,    yo, heading,  uo,  vo, yaw_speed, system
INITIAL -184.,  5.5,  -8.0,    88.,  0.,   4.8,VEHICLE
STEERING @steer.curve
TRACTION @brake.on.off
END

! file - steer.curve
! Constant radius turn of 1040 feet.
!-----------------------------------
! Time   Steer-angles (degrees cw)
!(sec)    (lf)   (rf)   (lr)   (rr)
!-----  -------------------------
0.0, 0.934, 0.934, 0.0, 0.0
1.8, 0.934, 0.934, 0.0, 0.0
2.5,-10.00,-10.00, 0.0, 0.0

! file - brake.on.off
! Brake slowing on ice patch (rear lock).
! Unladen pickup with brake apply, then release.
!Traction coefficients are dimensionless.
!Traction coefficients may be viewed as requested friction coefficients.
!Traction force - traction coefficient * static equilibrium tire load.
!---------------------------------------------------------------------
! Time  Traction coefficients (braking coefficients are negative)
!sec., lf,   rf,   lr,   rr
0.0,  0.0,  0.0,  0.0,  0.0
0.5,  0.0,  0.0,  0.0,  0.0
0.8, -.21, -.21, -.44, -.44
1.8, -.21, -.21, -.44, -.44
2.1,  0.0,  0.0,  0.0,  0.0
3.0,  0.0,  0.0,  0.0,  0.0
3.3, -.70, -.70, -.93, -.93
```

FIGURE 15 VTS input for ice patch run.

the SMAC program (V2), or the friction ellipse as used in the HVOSM program (H1), which provides for a different friction for side force.

Wheel position may have a damage offset from that defined by wheelbase and tread width. Each wheel may also be oriented to simulate damage and may be associated with one of several tire models.

Tire forces are calculated in the coordinate system of each individual tire, then transformed to the vehicle coordinate system where they are summed at the vehicle CG. The resultant force and torque are transformed to the surface coordinate system where the vehicle accelerations are defined by means of Newton's second law of motion. The resulting system of three second-order ordinary differential equations are solved as a system of six first order differential equations using a variable step, variable order Adams predictor corrector method.

VTS may be accessed at Collision Safety Engineering (CSE) via modem at 1200 or 2400 baud from a variety of terminals or personal computers. Graphics is supported only on HP terminals at present. The program operates on an HP-9000 series 500 computer under the Unix (HP-UX) operating system. Those who wish to experiment with the VTS or the IMPAC programs may do so by contacting the authors to establish a dial-up connection.

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