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SMAC-87

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ABSTRACT

A brief description and history of the SMAC computer program, including its relationship to CRASH, is presented. The rationale for a continued interest in the SMAC approach to reconstruction is discussed. Modifications and refinements that have contributed to the current capabilities of SMAC-87 are briefly described, representative results of applications are presented and planned future developments are defined.

THE RECONSTRUCTION OF HIGHWAY ACCIDENTS, which serves a number of purposes (e.g., law enforcement, statistical research, and litigation), has been accomplished to some extent since the early 1970's by the use of computer programs. Prior to that time, the analytical techniques (i.e. "hand" calculations) that were traditionally applied were predominantly "closed-form" calculations based on piecewise linear solutions of the equations of motion. The accuracy of such calculations varied widely with the level of sophistication of the specific selected relationships and with the subjective interpretations of evidence included in the reconstruction.

In 1970, NHTSA sponsored a research project to develop a computer program that would achieve improved uniformity, as well as improvements in accuracy and detail, in the interpretation of physical evidence in highway accidents. The resulting prototype computer program was the Simulation Model of Automobile Collisions (SMAC, Ref.1).

SMAC is a time-domain mathematical model in which the vehicles are represented by differential equations derived from Newtonian mechanics combined with empirical relationships for some components (e.g., crush properties, tires) that are solved for successive time increments by digital integration.

Each vehicle is limited to the three degrees of freedom associated with plane motion (i.e., 2 translation, 1 rotation). The tire forces are modeled by a non-dimensional side force function and the "friction circle" concept is included for the interaction between side and circumferential tire forces. The collision force simulation is achieved by means of the modeling of each vehicle as a rigid mass surrounded by an isotropic, homogeneous periphery that exhibits elastic plastic behavior.

The SMAC computer model is an "open-form" of reconstruction procedure wherein the user specifies the dimensional, inertial, crush and tire properties of the vehicles, the initial speeds, angles and driver-control inputs. The program, through step-wise integration of the equations of motion, produces detailed time-histories of the vehicle trajectories including the collision responses. The user compares the SMAC-predicted trajectories and collision deformations with the physi-

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cal evidence to determine the degree of correlation. Iterative runs can then be performed, varying initial speeds, heading angles and control inputs until an acceptable match of the physical evidence is achieved.

This "open-form" of solution can sometimes be frustrating and time-consuming depending on the degrees of complication of the accident and sophistication of the user. The initial "educated guess" of initial speeds, heading angles and driver-control inputs may differ greatly from those that will achieve an acceptable correlation with the physical evidence. The iterative adjustments of initial conditions by the user may not always achieve improved correlation. Therefore, many iterations may be required, particularly if the initial estimates are far from the actual impact conditions of the subject accident. It was for this reason that a "starting routine" for SMAC was created (i.e., CRASH, Ref. 2), which would give the SMAC user "ballpark" initial conditions based on a "closed-form" of reconstruction that uses damage dimensions and the relative positions and orientations at the points of impact and rest.

The specific objective of NHTSA in the development and use of the SMAC and subsequently the CRASH computer programs was achievement of improved <u>uniformity</u> of interpretations of physical evidence in investigations of highway accidents. As the CRASH program evolved, its combination of simplicity, economy, and general level of accuracy were seen as being more appropriate, as compared with the more sophisticated, expensive and sometimes time-consuming detail of SMAC, for NHTSA investigation programs that generate accident statistics. CRASH was subsequently incorporated into the NCSS and NASS investigation programs and further NHTSA funding and support for the development of reconstruction aids has been limited to the CRASH "closed-form" approach.

The support, funding and application of the CRASH program by NHTSA has resulted in its general acceptance by many as a "standard" accident reconstruction tool. This acceptance has also, unfortunately, resulted in the CRASH program being inappropriately applied to the reconstruction of specific accidents in litigation cases, with accuracy claims being bolstered by claims of NHTSA "endorsement."

CRASH was not intended to be a detailed, highly accurate reconstruction program. While the results of CRASH applications can be useful in providing approximate measures of accident severity, claims regarding its accuracy or the accuracy of other CRASH-type programs in specific applications should be carefully scrutinized.

Specific reasons for a continuing interest in the SMAC type of approach to accident reconstruction, particularly for applications where maximum accuracy is needed, are outlined in the following paragraphs:

1. Inherent accuracy limitations in the CRASH type of analysis produced by:

   (a) Neglect of dimensional changes and relative motions during collision contact, which precludes an effective use of angular momentum calculations.
   (b) Lack of assurance of the conservation of angular momentum, with the consequent absence of an effective use of calculations of the energy balance.
   (c) Reliance on user-specified directions of principal forces on the two vehicles, which are also assumed to be constant.
   (d) The use of constant moment arms for the principal forces on the two vehicles, which can produce significant errors in some impact configurations.
   (e) The neglect of restitution effects which produces underestimates of delta V, particularly in low closing-speed collisions(e.g., see Ref.3).
   (f) The use of "categorized" dimensional, inertial and crush properties, unless they are replaced by more accurate individual values.
   (g) The iterative adjustment of angular velocities at separation, within the trajectory option, which does not verify compatibility with the impact configuration or with conservation of angular momentum.
   (h) Other than the trajectory option, the lack of effective checks of the feasibility of the user specified positions and orientations at rest and other trajectory details.

2. The increasing availability of computers that are compatible with the SMAC type of time-history simulation program.

SMAC is a FORTRAN program which requires approximately 540K of main memory to compile and run. Therefore, it is compatible with Personal Computers and Minicomputers that are readily available today. (Note that one SMAC-based PC program, which is currently being sold, is actually a conversion of SMAC from the FORTRAN language to BASIC and, therefore, it must be viewed as being a different program).

3. The assured conservation of both linear and angular momentum in SMAC reconstructions.

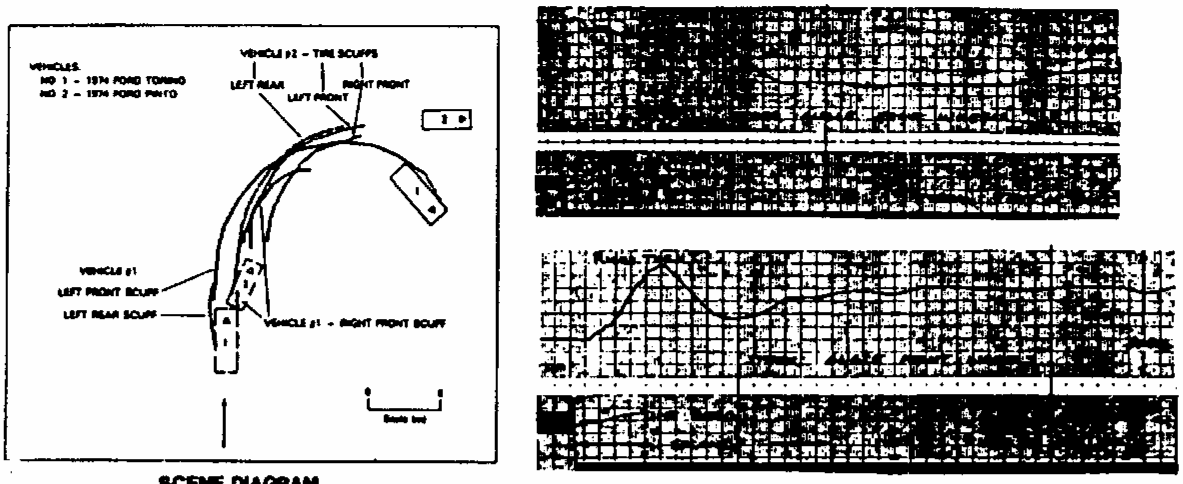
4. The integral testing, within a SMAC application, of the compatibility of results with positions and orientations at rest and with tire mark evidence, if reported.

MODIFICATIONS AND REFINEMENTS-In research reports related to the early development of the SMAC computer program recommendations were made for a number of modifications and refinements aimed at further enhancement of the generality of the technique (e.g., Ref. 4). In recent years, research efforts at McHenry Consultants have included the implementation of several of the proposed extensions and refinements which constitute part of the current extended capabilities of the SMAC 87 computer program. The modifications are as follows:

(1) Steer Degree-of-Freedom
(2) Impulsive Constraints
(3) Articulated Vehicle(s)
(4) TIRMU
(5) REREAD
(6) Polygon Friction zones
(7) TRAJ Correction

STEER DEGREE-OF-FREEDOM- The effects on vehicle behavior of responses of the undamaged steering system to external forces can be significant during spinout motions. For example, in an angled rear-ender (e.g.,Fig.1) in which the driver of the struck vehicle releases the steering wheel, the undamaged steering system responds to aligning torques at the front wheels. While the original form of tabular inputs of steered angle as a function of time can be used in such an application, the creation of an appropriate table requires a number of iterative adjustments to insure that the amplitude and timing of the steering system response is properly related to the vehicle side-slip behavior.

In SMAC-87, a simple approximation of a steering system degree of freedom, similar to that in the HVOSM program (Ref. 5), has been incorporated. A "pneumatic trail" dimension is used to simulate the aligning torques of the front tires. A friction torque is applied to the steering wheel to approximate the effects of driver restraint of the steering system and/or actual friction in the system. In Fig.2, the simulated steer degree of freedom is demonstrated in an application to the struck vehicle of RICSAC test No.4 (Ref. 6).



SCENE DIAGRAM

FRONT WHEEL STEER RESPONSE

Figure 1. Full scale test results for RICSAC Test No.4 (Ref.6) demonstrating effects of steering system responses.

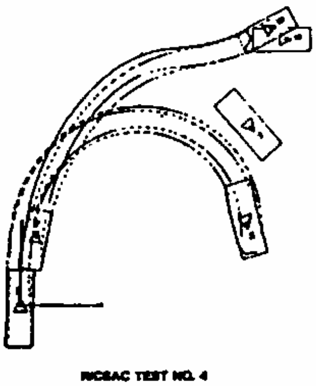


Figure 2. Illustration of Preliminary SMAC 87 results with steer degree-of-freedom option for RICSAC Test No.4.

IMPULSIVE CONSTRAINTS-The use of (1) a homogeneous representation of crush resistance and (2) simple Coulomb friction to approximate the tangential force acting between two colliding vehicles can produce unrealistic collision responses in some impact configurations. For example, in a narrow overlap, offset frontal collision where the front wheels momentarily interlock and resist lateral separation, the SMAC-predicted directions of yaw rotations can be reversed from actual by the cited simplifications (e.g., see Figure 3). Also, a pocketing sideswipe collision cannot be adequately reconstructed without some form of additional constraints.

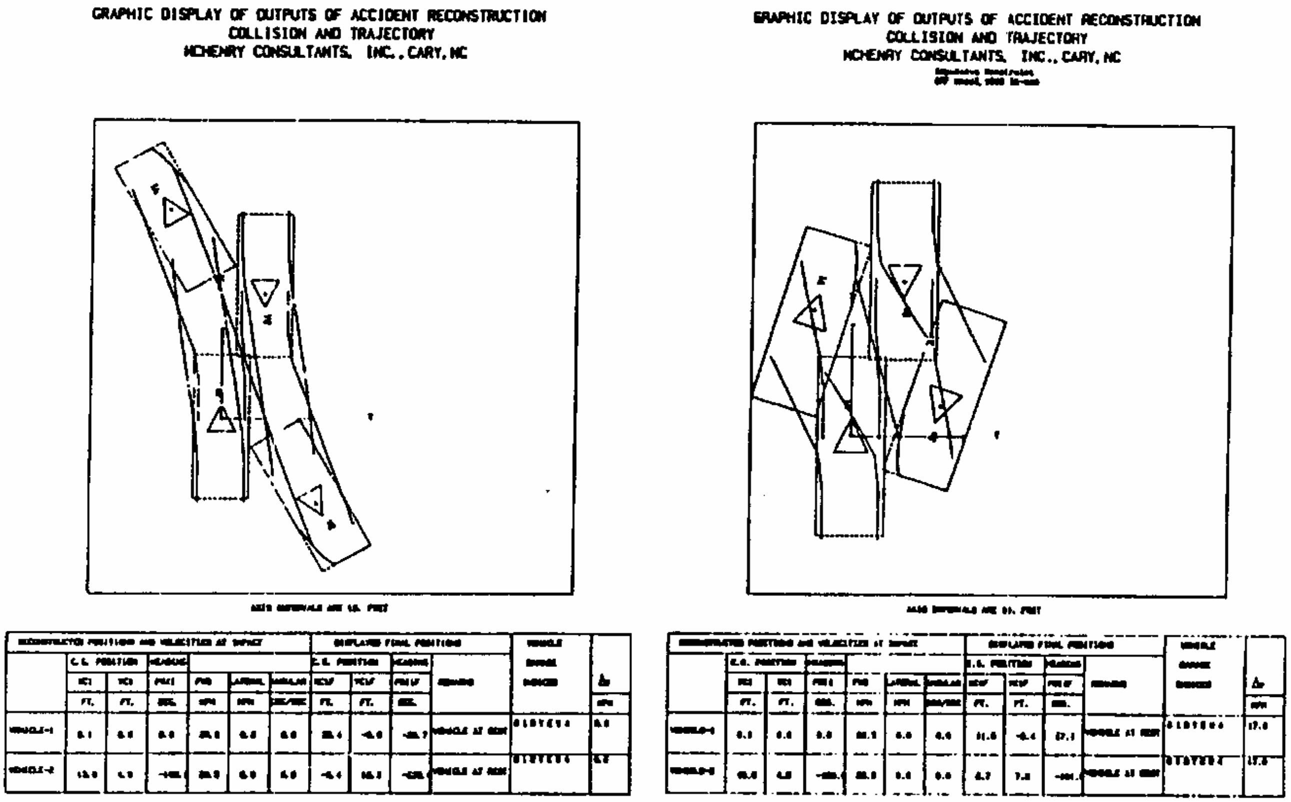
The early Calspan "SNAG option" overcame some of the indicated difficulties be means of the application of a momentary constraint on the relative motion of corresponding points on the two vehicles. The "SNAG option" constraint, which resisted relative motion of the points during a specified time interval, was limited to a user-specified maximum impulse. The constraint was applied in the form of equal and opposite linear impulses acting on the two vehicles to resist relative motion. Linear and angular momentum continued to be conserved during the time of the constraint application.

In SMAC-87, the Calspan "SNAG option" has been made more general in the form of an impulsive linear and/or moment constraint that resists relative motion by responding to relative displacements and/or relative velocities. The selected analytical approach consists of a straightforward application of the principles of impulse and momentum. It permits the application of relative motion constraints while limiting the maximum linear and/or angular impulse values to those that can be derived from collision experiments. Since the impulsive constraints act only to resist relative motion and, further, since they apply equal and opposite linear and angular impulses to the interacting bodies, they do not affect the linear or angular momentum of the two-body system.

It is proposed that the impulsive constraint form of program extension should be ultimately developed as an automatic call based on the impact configuration. In this manner, the uniformity of reconstruction results will not be affected by the program extension. The maximum impulse values must be defined as a part of further validation runs of the extended simulation program.

In applications of SMAC-87 in which impulsive constraints have been applied, the form and magnitude of the constraints should be clearly defined in any presentation of results.

ARTICULATED VEHICLE(S)-The reconstruction of highway accidents sometimes involves analysis of the collision responses of articulated vehicles (e.g., tractor-trailers, automobiles with trailers). In order to adapt the SMAC program for such applications, the equations of motion for each of the simulated vehicles were modified to include an optional additional degree of freedom along with corresponding tire forces. The additional degree of freedom consists of a user-specified mass, moment of inertia and tire definition at user-specified distances from a pivot point on the "main" SMAC vehicle. The revised definitions of the equations of motion are depicted in Figures 4 & 5. Note that the revised equations of motion reduce to the original SMAC equations of motion when the articulated vehicle option is not used (i.e., when $M_T = L_1 = L_2 = I_T = \theta = 0.0$).



Original SMAC

SMAC87

Figure 3. SMAC results for a narrow offset frontal with and without an Impulsive Constraint.

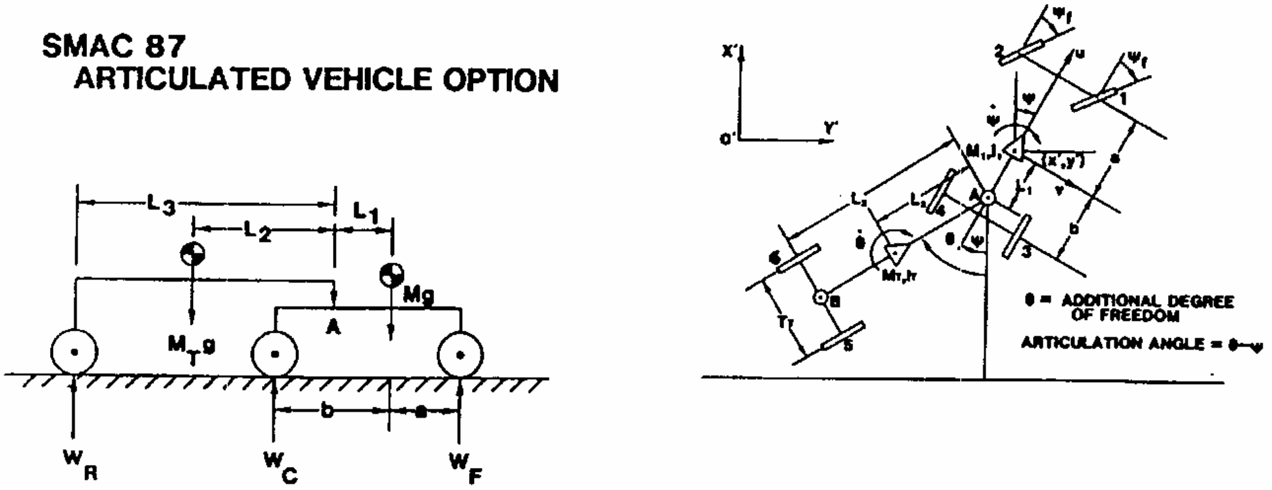


Figure 4. Schematic of SMAC 87 Articulated Option Specifications.

$$[D]\cdot\left\|\begin{array}{c}\dot{u}\\ \dot{v}\\ \ddot{\psi}\\ \ddot{\theta}\end{array}\right\| = [E]$$

$$D = \left\|\begin{array}{c|c|c|c} M+M_T & 0 & 0 & M_TL_2\sin(\theta-\psi) \\ \hline 0 & M+M_T & -M_TL_1 & -M_TL_2\cos(\theta-\psi) \\ \hline 0 & -M_TL_1 & I+M_TL_1^2 & M_TL_1L_2\cos(\theta-\psi) \\ \hline M_TL_2\sin(\theta-\psi) & -M_TL_2\cos(\theta-\psi) & M_TL_1L_2\cos(\theta-\psi) & I_T+M_TL_2^2 \end{array}\right\|$$

$$\|E\| = \left\|\begin{array}{l} (M+M_T)\,v\dot{\psi} - M_TL_1\dot{\psi}^2 - (M_TL_2\cos(\theta-\psi))\dot{\theta}^2 + (F_{x5}+F_{x6})\cos(\theta-\psi) \\ \quad - (F_{y6}+F_{y5})\sin(\theta-\psi) + \sum_1^4 F_{xi} + F_{cx} + F_{SNAGX} \\ \hline -(M+M_T)\,u\dot{\psi} - M_TL_2\sin(\theta-\psi))\dot{\theta}^2 + (F_{x5}+F_{x6})\sin(\theta-\psi) \\ \quad + (F_{y5}+F_{y6})\cos(\theta-\psi) + \sum_1^4 F_{yi} + F_{cy} + F_{SNAGY} \\ \hline (M_TL_1)\,u\dot{\psi} + (M_TL_1L_2\sin(\theta-\psi))\dot{\theta}^2 - (F_{x5}+F_{x6})L_1\sin(\theta-\psi) \\ \quad - (F_{y5}+F_{y6})L_1\cos(\theta-\psi) + (F_{x2}-F_{x1}+F_{x4}-F_{x3})\frac{T}{2} \\ \quad + (F_{y1}+F_{y2})a - (F_{y3}+F_{y4})b + N_c + N_{SNAG} \\ \hline M_TL_2\dot{\psi}(u\cos(\theta-\psi) + v\sin(\theta-\psi)) - (M_TL_1L_2\sin(\theta-\psi))\,\dot{\psi}^2 \\ \quad + (F_{x6}-F_{x5})\frac{T_T}{2} - (F_{y6}+F_{y5})L_3 \end{array}\right\|$$

Figure 5. Revised SMAC 87 equations of motion to include additional trailer degree of freedom.

New Inputs

L_1 =Longitudinal distance from tractor CG to 5th wheel pivot, inches.

L_2 =Longitudinal distance from 5th wheel pivot to trailer CG, inches.

L_3 =Longitudinal distance from 5th wheel pivot to trailer axle, inches.

T_T =Track width of trailer axle, inches.

M_T =Mass of trailer, lb-sec^2/in.

I_T =Moment of inertia of trailer about trailer CG, lb-sec^2-in.

C_5, C_6 =Cornering stiffnesses of trailer tires, lb/radian.

New Variable

θ =Trailer Angle, Degrees.

$\theta-\psi$ =Articulation angle, degrees.

The analytical approach used in SMAC 87 to model the 5th wheel coupling differs from that of the UMTRI PHASE4 3-Dimensional Truck and Tractor-Trailer Dynamic Response Simulation Computer Program (Ref.7). In the PHASE4 program, the coupling of the tractor and trailer is modeled as a critically damped spring, which constrains relative motion between the tractor and the trailer at the 5th wheel location. The probable justification for the spring coupling approach by the authors of the PHASE4 simulation model was to simplify the programming and analytical formulation requirements and to simplify the inclusion of additional capabilities for simulating doubles and triples combinations in the program. The use of springs allows doubles and triples to be simulated simply through the use of multi-dimensional arrays and looping on user-option choice. The properties of the critically damped spring for the PHASE4 simulation are internally calculated in the program as follows:

PIN = (VW(i) or VW (j), whichever is greater)

$$\text{CFW} = .5\sqrt{\text{PIN}*(\text{VM(i) or VM(j), whichever is greater)}}$$

Where:

PIN = Spring Stiffness, LBS/IN
VW = Vehicle Weight, LBS
i,j = vehicle to be coupled (i.e., 1,2 or 2,3...)
CFW = viscous damping coefficient, LB SEC/IN
VM = vehicle mass, LB SEC^2/IN

The relative positions and velocities of the coupling locations of the two bodies are then monitored and a corresponding PIN force is calculated by:

$$\text{FPIN} = S_{REL} * \text{PIN} + V_{REL} * \text{CFW}$$

Where:

FPIN = PIN FORCE
S_{REL} = Relative Distance between couplings, IN
PIN = Spring Stiffness, LBS/IN
V_{REL} = Relative velocity of PIN location, IN/SEC
CFW = damping coefficient, LB SEC/IN

For initial checkout purposes, in the absence of appropriate full scale test data, response predictions of the articulated vehicle option of the SMAC 87 were compared with results obtained from PHASE4. Further, as an additional comparison check of the SMAC 87 impulsive constraint option, two SMAC vehicles were coupled together by the same critically damped spring as PHASE4 (note that for the impulsive constraint test an additional modification was required to SMAC 87 to permit the proper weight distribution of the two coupled vehicles). The SMAC 87 articulated vehicle option, PHASE4 and SMAC 87 impulsive constraint option were then used to simulate an identical flat-surface lane-change maneuver for empty (Fig. 6) and loaded (Fig.7) tractor trailers. The displayed comparisons of results show a good correlation between the simulation programs. Note that the results obtained with the SMAC 87 articulated vehicle and impulsive constraint options were identical. However, the impulsive constraint option required twice as much computer time due to requirements for small time increments to model the critically damped spring coupling. Figure 8 displays a sample application in which the articulated vehicle option of SMAC 87 is exercised for both vehicles.

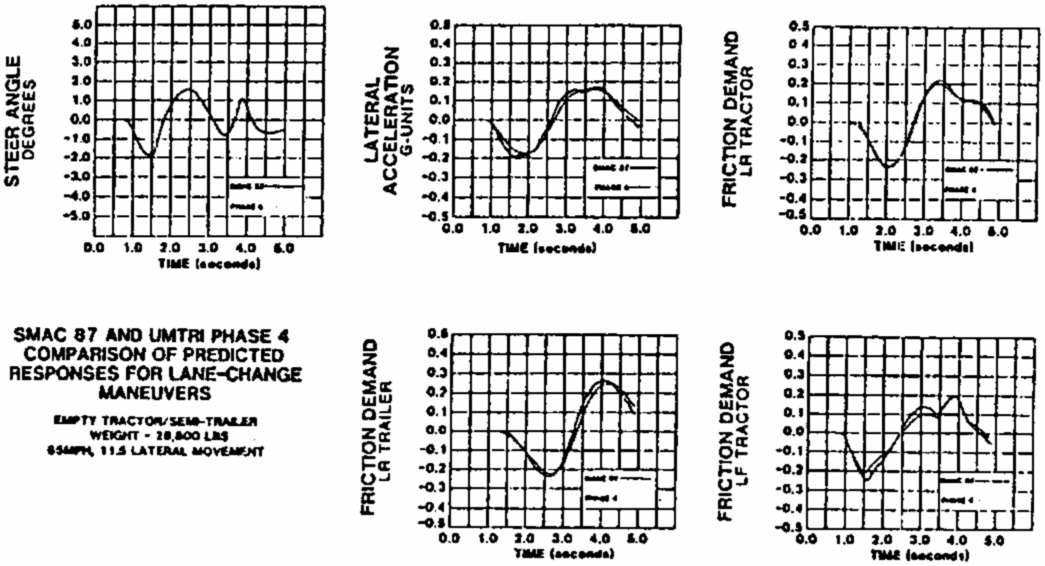


Figure 6. Comparison of predicted responses for a lane-change maneuver of an empty tractor trailer for SMAC 87 and PHASE4 programs.

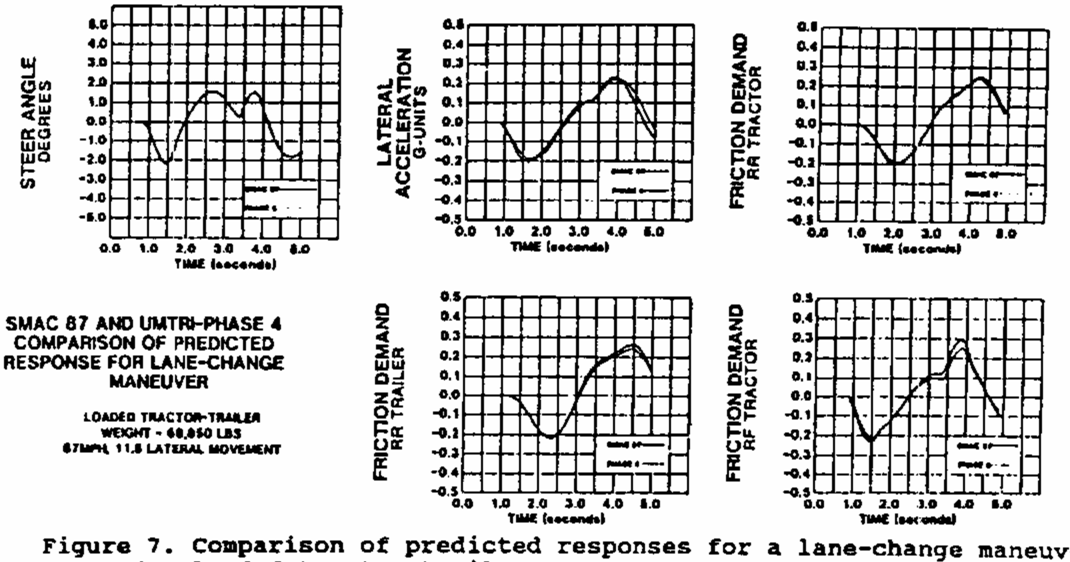


Figure 7. Comparison of predicted responses for a lane-change maneuver of a loaded tractor-trailer for SMAC 87 and PHASE4 programs.

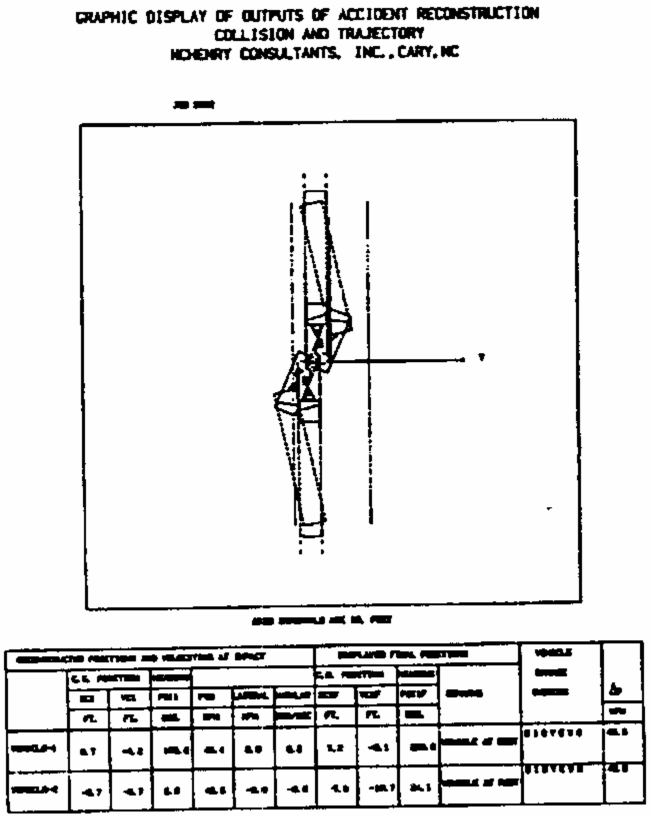


Figure 8. Sample SMAC 87 application with articulated vehicle option exercised for both vehicles.

TIRMU-In many instances, individual tires, because of low inflation pressure or air-out may exhibit side force properties which differ from those of the other tires corresponding to the user input for coefficient of friction (e.g., rim contact with ground). Also, use of the SMAC 87 articulated vehicle option for the case of a car-truck collision requires saturation friction levels for the truck tires that generally are less than those for for the automobile tires (i.e., different tread compounds). Therefore, TIRMU provides the option to specify a friction multiplier for each individual wheel of each vehicle. It permits variation of the saturation force level due to different tread compounds and/or individual tire/wheel condition (Default=1.0).

REREAD-In many collisions, tires become deflated during the crash phase and/or the subsequent spinout. When reconstructing such a collision with SMAC, changes need to be introduced in the tire side-force characteristics during the course of the time-history. Since the original form of SMAC did not include a provision for altering the cornering stiffness of individual tires during the simulation, the user had to restart the run at the time of the change (e.g., air out, rim gouge). The REREAD option was installed in SMAC 87 to permit the alteration of vehicle and/or tire properties at a selected time during the course of a simulation run. Subroutine Input is called and new cards are read while the time-integration is in progress.

POLYGON FRICTION ZONES-In addition to the existing linear boundary between terrain zones an option has been added to permit the additional definition of polygon terrain patches. In this manner, the simulated vehicle can enter and depart from terrain patches as well as zones that have different friction properties within a single run.

TRAJ CORRECTION-The original version of SMAC was found to contain a minor error in subroutine TRAJ related to calculation of the directions and magnitudes of the side and circumferential tire forces. The original form of the program uses the longitudinal component of velocity of the center of gravity of the vehicle instead of the longitudinal components of velocities at individual wheels. The effects of this error become significant only in cases involving large angular velocities combined with relatively small linear velocities. The corresponding coding has been corrected in SMAC 87.

AREAS OF FUTURE DEVELOPMENT AND REFINEMENT- Several other extensions and refinements which are in the process of being investigated for incorportaion into the SMAC 87 program are as follows:

(1) DYNAMIC WEIGHT TRANSFER
(2) COEFFICIENT OF RESTITUTION

DYNAMIC WEIGHT TRANSFER DURING IMPACT- It is well established that large pitch responses can be produced by frontal collisions. As a result of such pitching responses, the tire-terrain frictional resistance to yawing is reduced for a brief period after the collision. It is planned to explore the magnitude of the effect of the dynamic weight transfer produced by collisions on yawing responses. The proposed simulation approach will consist of simple equal and opposite alterations of the magnitudes of the tire-terrain friction forces at the two ends of the vehicle during a short interval subsequent to separation from the collision. In this manner, the simplicity of plane motion will be retained while an improvement over the previous assumption of constant wheel loadings and friction forces will be achieved.

COEFFICIENT OF RESTITUTION-In collisions, the term "restitution" refers to the generally incomplete recovery of the shape of a body deformed by the applied forces. The "coefficient of restitution" is defined, for central collisions, in terms of the ratio of the speed of separation divided by the speed of approach. For non-central, or eccentric collisions, the coefficient of restitution is not defined.

The simulation approach to restitution in the original SMAC program is based on control of the extent of recovery of the deformed radius vectors. Since the approach (a) involves a realistic and general mechanism, and (b) can be directly related, in application results for central collisions, to the definition of the "coefficient of restitution," it is believed to constitute an attractive approach for general applications. It is considered to be clearly preferable as a generalized reconstruction tool to any approach which requires user intervention. In other proposed reconstruction approaches, the user is given direct control of the separation velocities in general collision conconfigurations (e.g.,Ref.8). Note that even the most "expert" user of the arbitrary intervention type of simulation program would have difficulty justifying a selection for the separation velocity in a corner-to-corner, eccentric collision (i.e.,linear and angular vehicle responses in untested configurations).

The rationale for altering the original SMAC concept is based in Reference 8 on the opinion that it is complicated, cumbersome, uneconomical and inconsistent with the "implied accuracy." It is believed that the original concept of the simulation of restitution effects in general collision configurations should be retained. The manner of implementation can be further developed to reduce any unreasonable demands on the user and the sensitivity to time-increment size.

Developments which are currently in progress are program modifications which will distinguish between loading and unloading properties of the peripheral structure and thereby, will reduce sensitivity in the control of energy feedback.

In summary, a general discussion of the rationale for the use of the SMAC type of time-domain reconstruction program has been presented. Specific extensions and refinements that are implemented in SMAC 87 have been presented and future plans for additional refinements have been discussed.

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