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SMAC-97
Refinement of the Collision Algorithm

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ABSTRACT

The Simulation Model of Automobile Collisions (SMAC) computer program, developed in the early 1970's, includes a complex collision algorithm for monitoring, detecting and modeling the collision interactions of motor vehicles. A detailed review of some aspects of the logic, rationale and, in particular, limitations of the original SMAC collision algorithm is presented.

This paper presents refinements in the definition of the collision interface, the definition of collision type, the vehicle proximity and collision detection logic, and the form of supplementary impulsive constraints on relative motions.

The effects of the modifications of the SMAC algorithm on reconstruction results are presented in the form of direct comparisons of results obtained with the original and modified algorithms.

INTRODUCTION

The SMAC program was initially developed in the 1970's when all development of computer code was performed on time-share mainframe computer systems. The capabilities of computers at that time were limited by the maximum amount of available memory (e.g., limit on program size) and users were charged for computer use based on memory and CPU utilization. The costs associated with the development and execution of the SMAC program were relatively high (e.g., [**1**][1] ,circa 1971,p 48, "The range of costs,…,has been approximately $25.00 per application run" for the SMAC program).

These limitations during the original development of the SMAC program guided the selection of many of the simplifying assumptions of the mathematical model.

Since the early 80's and particularly by the mid 1990's, the prevalence of powerful mini-computers and more recently extremely powerful and inexpensive Pentium PC's, creates an availability of virtually unlimited and inexpensive computer resources. This has inspired a detailed re-evaluation and refinement of computer codes, particularly those developed in the 1970's. The general approach to the reported refinements of the SMAC computer program has been to reconsider the initial simplifying assumptions based both on the availability of additional full-scale test results and the virtually unlimited computer resources.

The reported research identifies and discusses artifacts and/or shortcomings of the original SMAC and the EDSMAC computer programs that have been encountered by the authors in relation to applications (SMAC) and evaluation of applications (EDSMAC) to actual accident cases.

It should be noted that any references to the original SMAC [**2**] computer program are also generally applicable to the EDSMAC [**3**] computer program. The original SMAC program and the widely distributed EDSMAC clone are essentially identical. No analytical refinements have been made by the distributors of EDSMAC which produce any significant changes in the results.

BACKGROUND

In the early 1970's, 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 **S**imulation **M**odel of **A**utomobile **C**ollisions (**SMAC)** [**1**,**2**,**4**,**5**]. At the completion of the NHTSA sponsored research at Calspan in 1974, a preliminary version of the SMAC program was delivered to the NHTSA and it has subsequently been distributed as the NHTSA SMAC computer program.

Subsequent follow-up contracts for research and development of the SMAC program sponsored by NHTSA went to other organizations [**6**,**7**,**8**]. Further research and development on the SMAC program was also continued independently at Calspan [**9**] and additional corporate-sponsored research to support criticism of the SMAC program [**10**,**11**] was also performed.

[1] Numbers in brackets [] indicate references at end of paper

There were no significant changes by NHTSA into the 1974 NHTSA SMAC at the completion of the NHTSA follow-up contracts.

In 1986, Day and Hargens created EDSMAC[**12**], a PC version of the 1974 NHTSA SMAC program **converted** to the BASIC programming language. Subsequent reports related to the EDSMAC program [**3**,**13**,**14**] reveal that except for very minor modifications, the EDSMAC program is essentially the same as the original 1974 NHTSA SMAC program. Related development efforts by the distributors of the EDSMAC program have been directed towards a mini-computer based high-end graphics environment [**14**,**15**,**16**,**17**,**18**].

In 1988, a number of suggestions for further refinement and extensions of the SMAC program were presented [**19**]. In 1989, some suggestions for avoiding misapplication of computer programs, including the EDSMAC program [**20**] were presented.

The widespread distribution of the EDSMAC program has dramatically increased its utilization for the reconstruction of individual accidents (e.g., accidents that are involved in litigation) . This creates a situation where in many instances, either through misuse, misapplication or due to shortcomings in the original NHTSA SMAC (and therefore EDSMAC), there have been applications of the program which include significant effects of artifacts of the original programming logic.

The current reported research defines some important refinements of the SMAC program, particularly with respect to the collision modeling algorithm. This paper also extends the suggestions in [**19**] and [**20**] to assist users in avoiding possible misapplication of the SMAC program. Note that any references to the "original" SMAC program refer to the 1974 NHTSA SMAC program and therefore to the EDSMAC program.

This paper constitutes a continuation of the research presented in [**19**] and more recently in [**21**]. Specific refinements to the original SMAC program collision modeling routines discussed herein are as follows:

1. Definition of the collision interface.
2. Collision type specification.
3. Supplementary impulsive constraints on relative motion.
4. Vehicle proximity and collision detection logic.

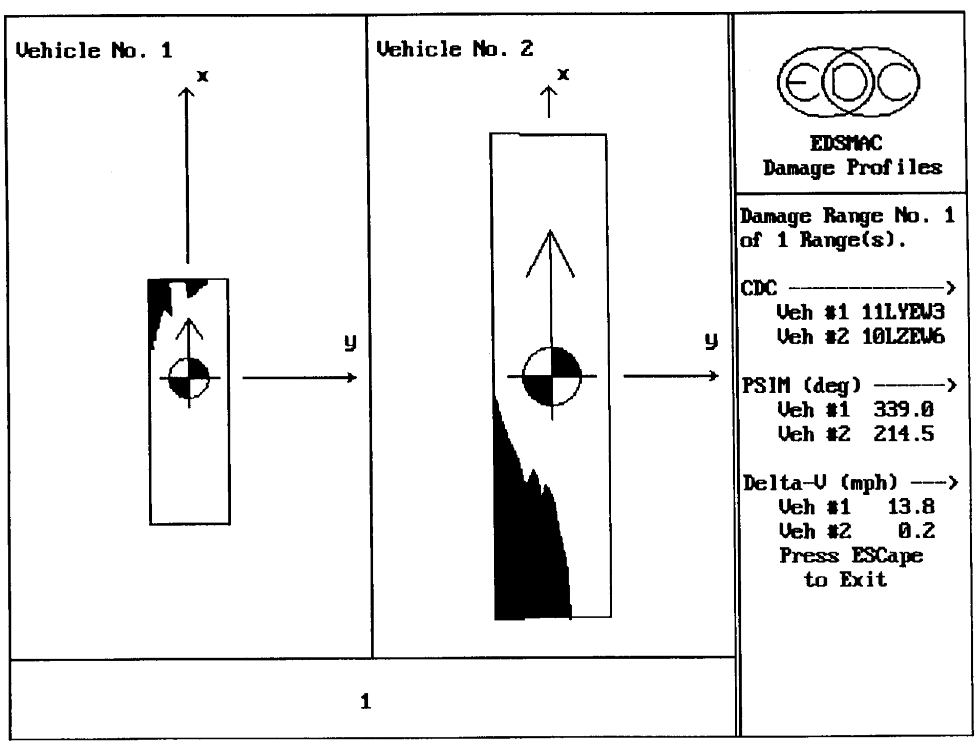

Figure 1 EDSMAC damage display for bus/auto impact simulation with 90 degree vector artifact demonstrated [22]

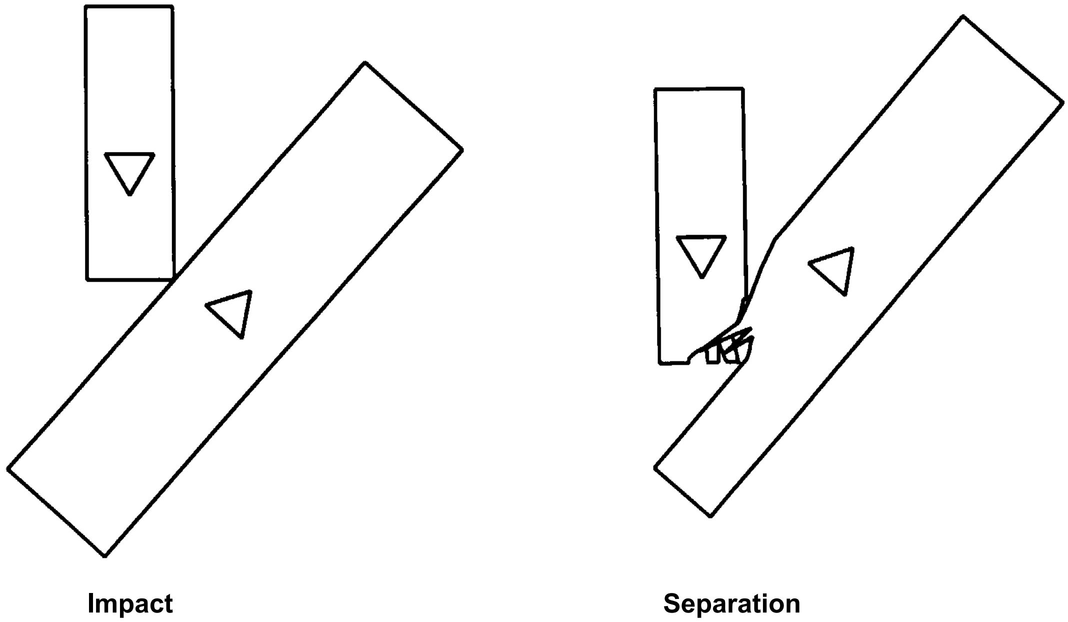

Figure 2 Original SMAC(EDSMAC) bus/auto impact simulation at 0.140 sec after initial impact with 90 degree vector artifact demonstrated.

DEFINITION OF THE COLLISION INTERFACE

Problems encountered in applications of the original version of the SMAC (and EDSMAC) programs in oblique impacts particularly when a long vehicle is struck on the side at a position away from the center of gravity (e.g., **Figure 1** and **Figure 2**) originate in limitations imposed by the selected original form of analytical definition of the vehicle peripheries.

In particular, radial vectors with origin at the center of gravity are used to define the peripheries of the two vehicles (e.g., **Figure 3**). During a collision, the lengths of the radial vectors in contacted regions are adjusted by an iterative procedure which seeks an equilibrium dynamic pressure on the collision partners. The dynamic pressures at individual peripheral points are assumed to be proportional to their displaced distances <u>from the undeformed periphery</u>.

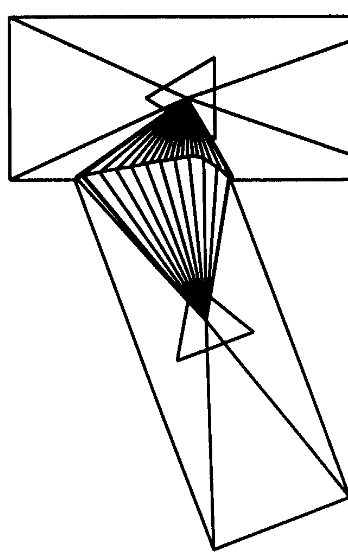

Figure 3 Mathematical representation of the SMAC periphery by radial vectors.

In the cited problem configuration, some of the radial vectors of the two interacting vehicles approach the condition of being perpendicular to each other and, as a consequence, the iterative adjustment procedure for the lengths of radial vectors cannot find a proper solution. The inter-vehicle pressure associated with these vector points cannot find an equilibrium. As a result, an unrealistic equilibrium interface is produced that includes a series of jagged notches (e.g., **Figure 1** and **Figure 2**). A close-up illustration of the phenomenon is included in **Figure 4** and a close up detail including display of the radial vectors is included in **Figure 5**. The error flag normally associated with the problem in the SMAC program is "PRESI (or PRESIJ) tends negative". In the original program the error flag sets the associated pressure to 0.0 and attempts to continue program execution. The setting of the zero pressure creates the jagged interface wherein only some of the vectors are "active". Other vectors have the error and, therefore, they are undeformed or partially deformed from the periphery. The original SMAC included a program stop if a sufficient number of PRESI/PRESJ type errors occurred in an individual simulation run.

The perpendicular vector problem is most obvious in the original SMAC with longer vehicles as a result of the large distance of the contact region from the origin. Individual vectors on the long vehicle are required to define a larger area of the vehicle periphery than that in a more typical impact configuration. This tends to amplify the near perpendicular vector problem where one radial vector on the long vehicle may affect several on the other vehicle.

An initial approach that was investigated for a generalized fix to the phenomenon was an increase in the number of vectors and, thereby, the detail included in the collision routine. In the original SMAC program the capabilities of the collision routine were limited due to computer memory storage considerations. The specific limitations were the maximum number of interacting vectors (100) and the maximum number of iterations the program could utilize to attempt to find equilibrium in inter-vehicle pressure (100). In consideration of the capabilities and capacities of modern day (1990's) computers, the capabilities have been increased to permit the use of 1 degree vectors and smaller values for the acceptable error in inter-vehicle pressure. Users of SMAC should never make use of an angle greater than 3 degrees between radial vectors. The use of 1 degree increments reduces the problems associated with near 90 degree vectors by decreasing the area of coverage of individual vectors for longer vehicles. It also provides a generalized increase in the detailed equilibrium interface of the collision routine for normal simulations. However, the described changes did not solve the problem with perpendicular vectors.

The indicated problem is resolved in the revised SMAC program by means of locating the origin of the radial vectors of the collision interface at a position on the vehicle other than the center of gravity. In this manner, the origin of the vectors defining the vehicle periphery can be moved longitudinally to be near the location of the collision contact (e.g., see **Figure 6** and **Figure 7**) and/or moved laterally away from the initial contact location (e.g., see **Figure 8** and **Figure 9**).

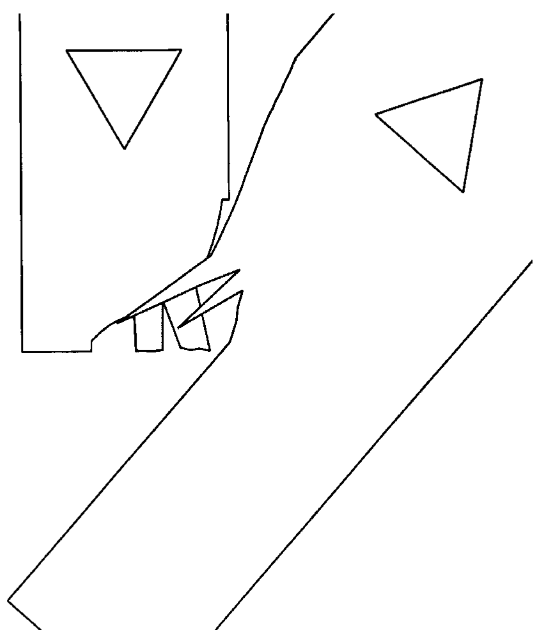

Figure 4 Close-up detail of NHTSA SMAC (EDSMAC) collision interface problem of perpendicular radial vectors (0.14 sec after initial impact)

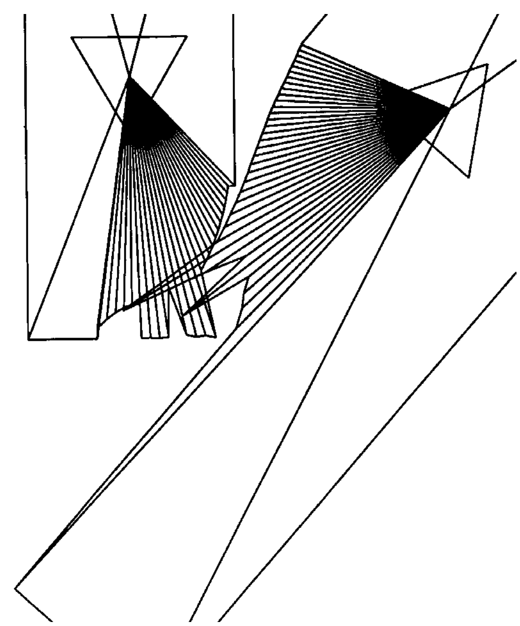

Figure 5 Close-up detail including radial vectors

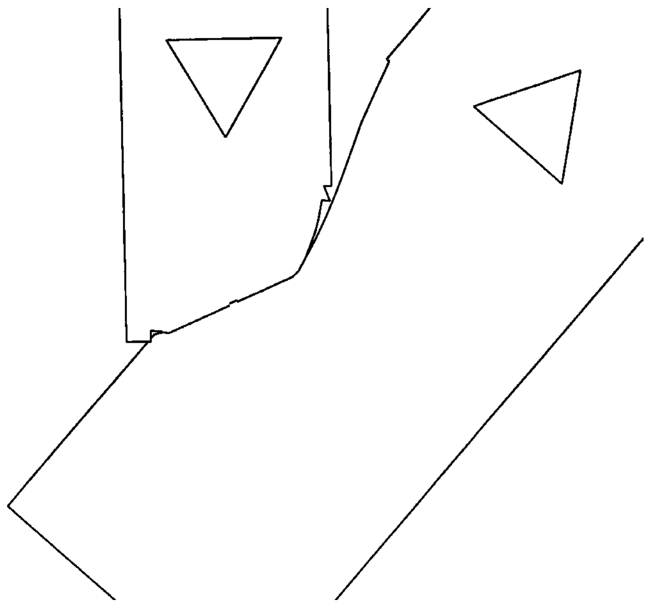

Figure 6 Close-up detail of variation of the X location of the center of collision interface origin to avoid perpendicular vectors (0.14 sec after initial impact)

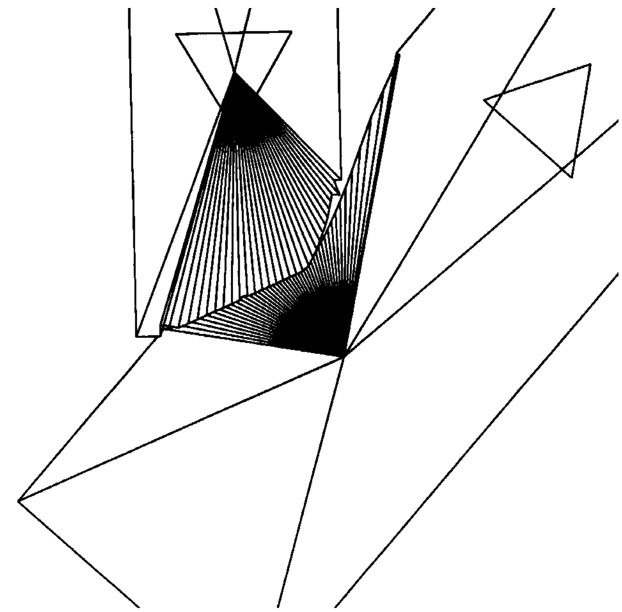

Figure 7 Close-up detail, including radial vectors

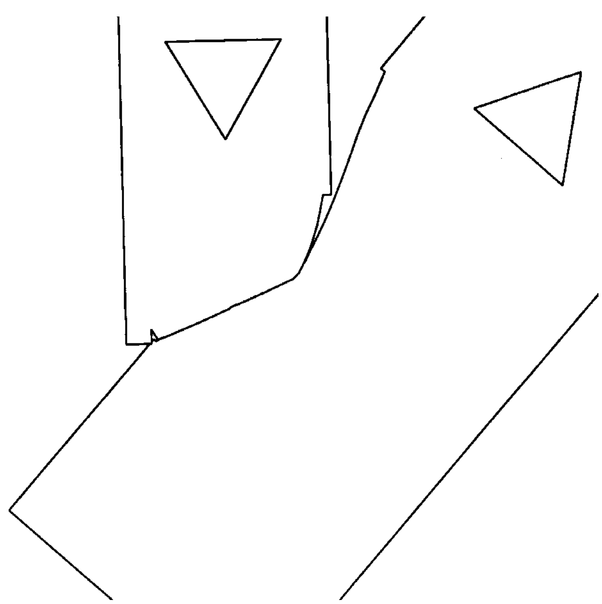

Figure 8 Close-up detail of variation of the X and Y location of the center of collision interface origin to avoid perpendicular vectors (0.140 sec after initial impact)

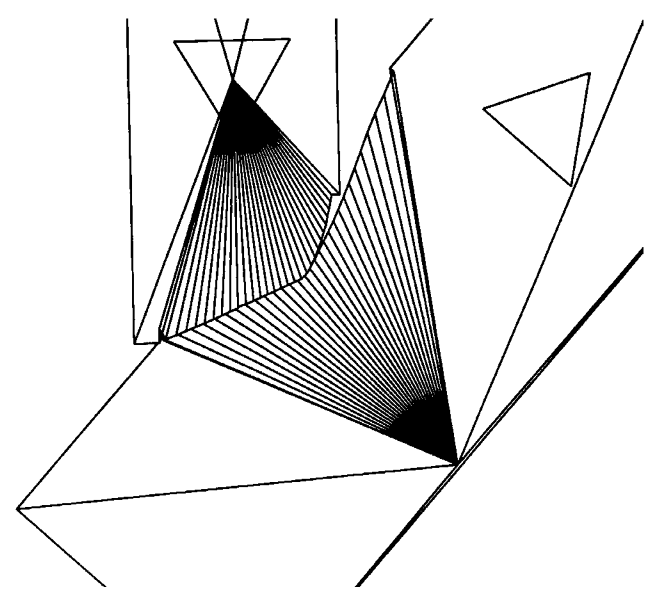

Figure 9 Close-up detail, including radial vectors

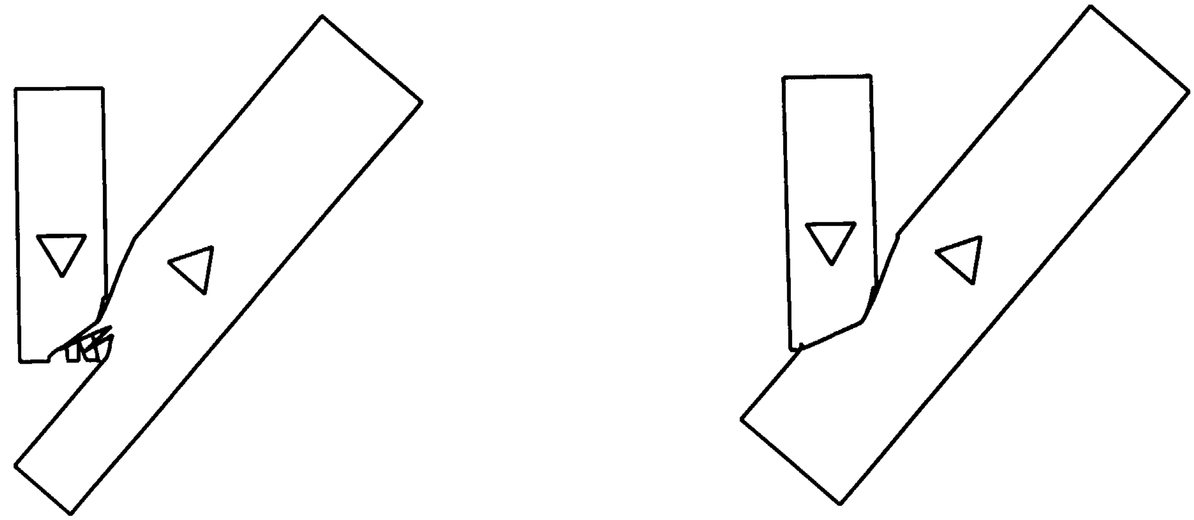

Figure 10 Comparison of predicted damage of original SMAC (EDSMAC) and revised SMAC (0.14 sec after initial impact)

A comparison of the effects of moving the origin of the collision interface from the CG is displayed in **Figure 10**. The results of the car/bus impact presented in **Figure 1** also indicate an incorrect value for the impact speed-change of the automobile. The EDSMAC program indicated an impact speed-change of 13.8 MPH for the automobile, whereas the correct value is 31.5 MPH (The impact velocities were 43 mph for the automobile and 15 mph for the bus).

The long vehicle example dramatically demonstrates problems which can occur with perpendicular vectors. Users of the original SMAC (EDSMAC) should also be aware that to a lesser degree, dependent on the impact configuration and severity level, normal length vehicles may occasionally encounter perpendicular vector problems. The problem is dramatically demonstrated on a smaller scale when users attempt to simulate a pole or small tree impact by using a small rectangular or square object. The original SMAC (EDSMAC) program is not valid for the simulation of pole and/or small tree impacts. The fundamental problem of pole impact simulations with the original SMAC(EDSMAC) (i.e., non-homogeneous crush properties for small contact areas) is increased by the perpendicular vector problem when the pole and/or small tree impact location is offset from the vehicle center of gravity. A separate research report will include discussion of revisions to SMAC to accommodate pole and/or small tree impacts[**23**]

The original form of SMAC can also produce application problems in reconstructions in which the equilibrium interface approaches the center of gravity of one of the vehicles. Therefore, lateral movement of the origin of the collision interface vectors may be required for simulations of severe side impacts where the collision interface can approach and/or exceed the ½ width of the vehicle. In the original SMAC (and EDSMAC) program these types of collisions normally produce either a program error or an effective softening of the crush characteristics (e.g., [**11**]).

The present discussion should not be interpreted as an indication that valid results can be obtained at very high severity levels. Rather, the related modifications of SMAC are aimed at minimizing the effects of artifacts, in the computer implementation of the analytical relationships, on the predicted results. Evaluations of the ranges of validity of a mathematical technique should not, of course, be obscured by the presence of significant effects of artifacts.

Research is underway to establish a generalized fix to automatically locate the origin of the collision interface vectors on the basis of impact configuration and severity. An automatic adjustment of the origin is considered to be highly desirable from the viewpoint of eliminating any possibility of related deviations from uniform interpretations of evidence. In the existing revised version of the SMAC program an option is presently included to permit the user to move the origin, where appropriate.

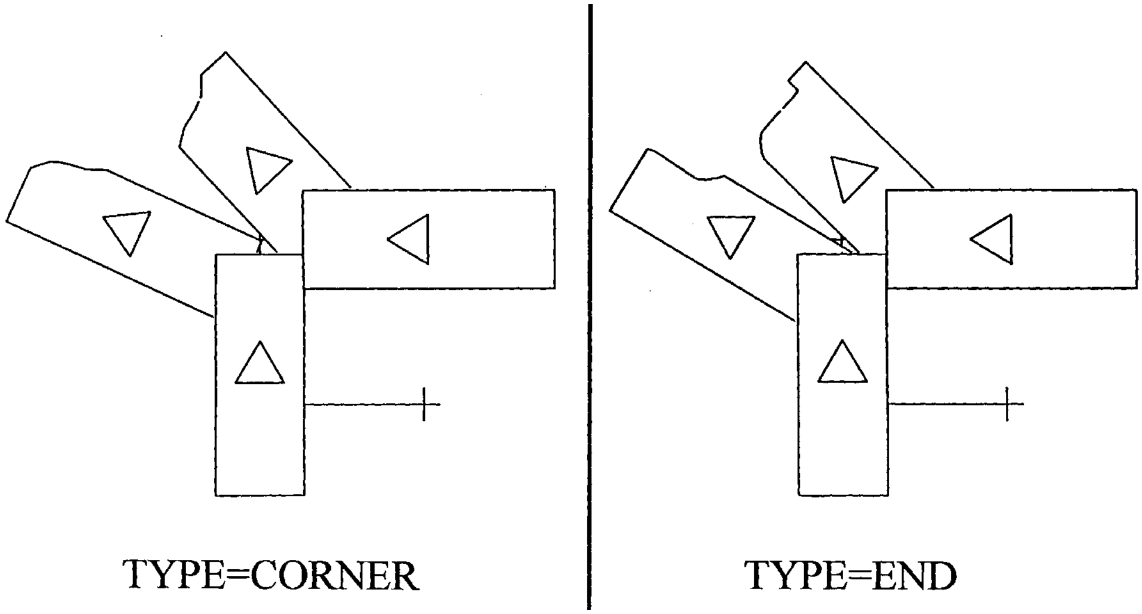

Figure 11 Demonstration of effects of 1" change in Y of vehicle produces different definition for type of impact configuration and therefore different damage profiles.

COLLISION TYPE SPECIFICATION

In the original SMAC (EDSMAC) program, the collision interface handles three types of impact configuration: End, Side, and Corner. Logic in the program calculates the extent of collision contact overlap at the instant of contact and determines which of the three types of configuration logic to use for calculation of the collision forces. Occasionally the program may exhibit a disproportionate sensitivity to minor changes in a particular impact configuration which is near a "logic" transition point. Minor changes in the impact configuration can cause the program to switch between the different types of collision force logic (e.g., Figure 11). Research is underway to update the logic associated with determination of the impact type as part of a general fix of the collision logic to avoid this phenomenon. To avoid sensitivity problems a manual override of the automatic logic is suggested and has been provided in the revised SMAC program. The manual override of the impact configuration logic eliminates the sensitivity and provides for a manual check of the effects of changing the designated impact configuration type.

SUPPLEMENTARY IMPULSIVE CONSTRAINTS ON RELATIVE MOTION

There are some impact configurations for which the simple combination of compressive forces and coulomb friction of the original SMAC program are inadequate. The actual structural interactions between colliding vehicles can include significant tensile forces and/or moment constraints on relative rotation in addition to the primary compressive interaction. Also, significant alternative load paths can occur which do not produce sheet metal crush. In such cases, supplementary impulsive constraints on relative motions can be applied without detracting from the principles of conservation of linear and angular momentum in relation to trajectory analyses. In other words, such impulsive constraints on relative motions of the two vehicles continue to conserve the linear and angular momentum of the two-body system with regard to interactions between the two vehicles. Any benefits derived in the form of improvements in the match of the position and heading at rest of vehicle#1 will have equal and opposite effects on the predicted position and heading at rest of vehicle#2. If both simulated vehicles can be brought into acceptable matches of their positions and headings at rest by means of such supplemental impulsive constraints on relative motions, the required pre-impact linear and angular momentum of the two vehicle system will be unaffected and the approximation of initial speeds and impact speed-changes can proceed as usual.

It should be noted that supplementary impulsive constraints on relative motions can have the effect both in reconstructed accidents and in actual collision evidence of disturbing the relationship between sheet metal crush and the corresponding ΔV. For example, in a small-overlap offset frontal collision, interlocking front wheels can support large interaction forces with only a limited extent of sheet metal crush. Also, a pocketing sideswipe can include a major load path (e.g., wheel/axle/suspension) that does not produce corresponding crushing of sheet metal.

It is therefore necessary for the reconstructionist to evaluate the role of alternative load paths when interpreting sheet metal crush. In those cases where alternative load paths play a major part in the vehicle interactions it is necessary to place greater emphasis on scene evidence as opposed to sheet metal crush and, in the case of SMAC applications, to make use of supplementary impulsive constraints.

To work around the indicated form of shortcoming of the original SMAC program some of the RICSAC reconstructions performed by Jones [**24**] and some users of EDSMAC made use of a value of the inter-vehicle friction coefficient substantially greater than 1.0 attempting to compensate for the lack of tensile forces and/or moment constraints on relative rotation. The problem with the high friction approach is two-fold.

First, the inter-vehicle friction coefficient of the SMAC collision model is based on coulomb friction which is independent of the sliding velocity and has a coefficient value less than or equal to 1.0. During the collision, as relative sliding of the surfaces occurs, the magnitude of the inter-vehicle friction force depends on the existence and magnitude of the collision normal force. Supplemental tensile forces and/or moment constraints occur in vehicles as the vehicles begin the separation phase when the normal force may be very small or zero. After the primary collision, as a result of the impact configuration, the vehicle contact area and/or the vehicle component contacted, intermeshed components of the two vehicles can offer additional resistance to separation in the absence of the normal forces required for coulomb friction. Using a value for the inter-vehicle friction coefficient greater than the recommended range (normal value 0.55, recommended range 0.3-1.0) may unrealistically and/or adversely affect the primary impact phase, since the additional forces and moments produced by the elevated friction can act to redirect the forces and moments during the primary impact.

A secondary problem which may occur with original SMAC (EDSMAC) use of a high value of inter-vehicle friction can occur in the post-processing program which may not be able to "match" the accelerations to the damage region. As a result invalid ΔV values and clock direction may be reported. An EDSMAC application summary page (used by an expert witness as an exhibit to deposition testimony) which contains invalid ΔV values for the collision partners was produced by the use of a value for the inter-vehicle friction coefficient of 2.0 and is shown in **Figure 12.** (Note that $m_1\Delta V_1 \neq m_2\Delta V_2$. In the original SMAC a supplementary page included diagnostics which report all of the speed changes calculated in a given run to permit a check of the values reported by the post-processing routine. This auxiliary page appears to have been omitted in the EDSMAC program.).

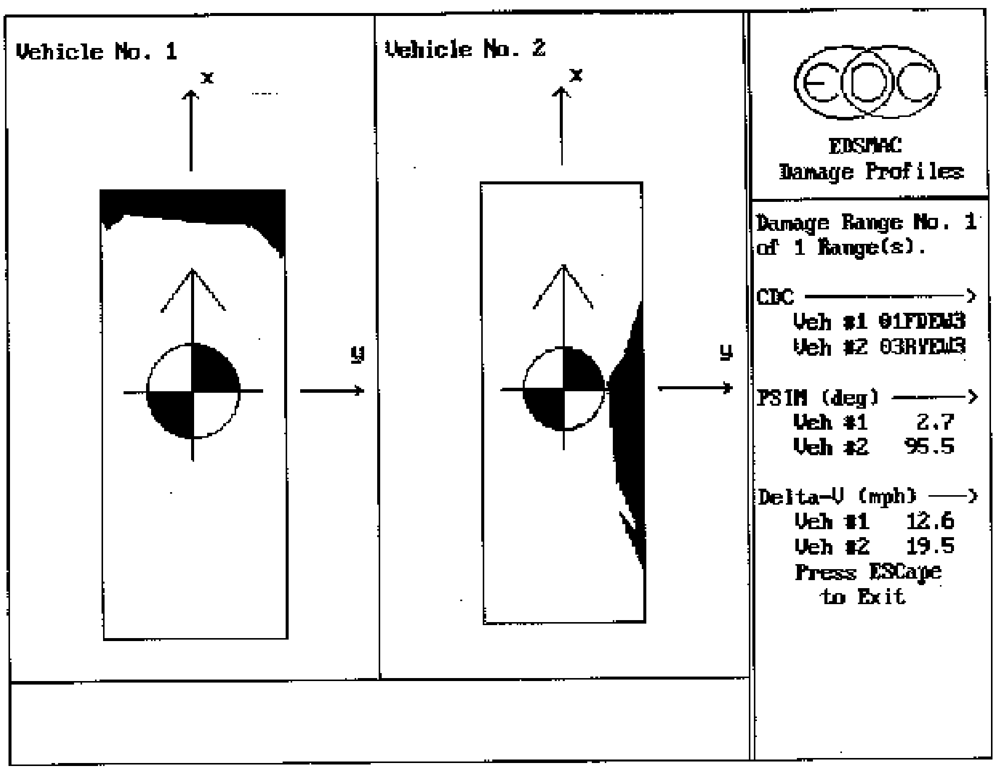

Figure 12 Example usage of invalid inter-vehicle friction coefficient of 2.0 which produces invalid results (Weight1=3226 lb., Weight2=3953 lb.) Therefore $m_1\Delta V_1 \neq m_2\Delta V_2$.)

Revisions to the SMAC program to model supplementary impulsive constraints include the impulsive-constraint "SNAG" option as previously presented in [**19**]. In **Figure 13** the original SMAC program does not adequately simulate an impact on the LR wheel of vehicle #1. The impact on the LR wheel in the investigated accident produced a 180 CCW rotation of vehicle #2 due to a momentary snagging of the LR wheel of vehicle #1 on the front of vehicle #2. In

Figure 14 two different impulsive constraints ("SNAG") are applied to the vehicles in the area of the left rear wheel of vehicle #1. The results indicate that applying a 1000 lb.-sec impulse is adequate to spin vehicle #2 180 degrees and, thereby, it constitutes a reasonable approximation of the magnitude of the actual snagging of the vehicle structures.

Efforts are being directed toward the development of automatic calls for impulsive constraints and for standardized related input values on the basis of the impact configuration and the closing speed. Prior to completion of that development the timing and the magnitudes of any impulsive constraints should be reported along with corresponding reconstruction results.

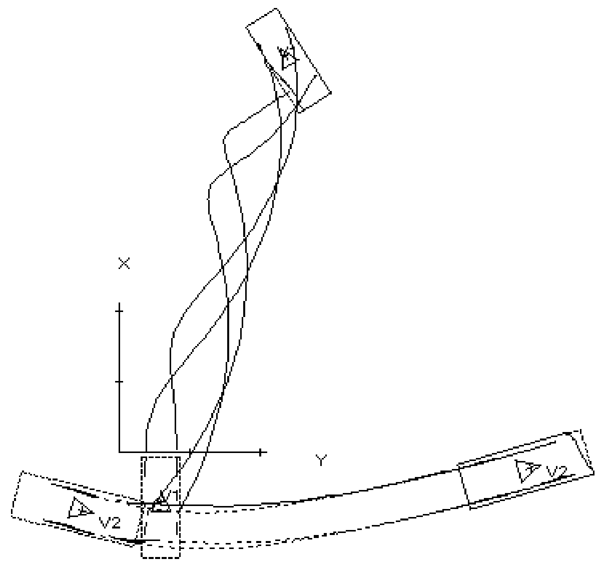

Figure 13 Original SMAC Simulated Impact on LR wheel of Vehicle No. 2

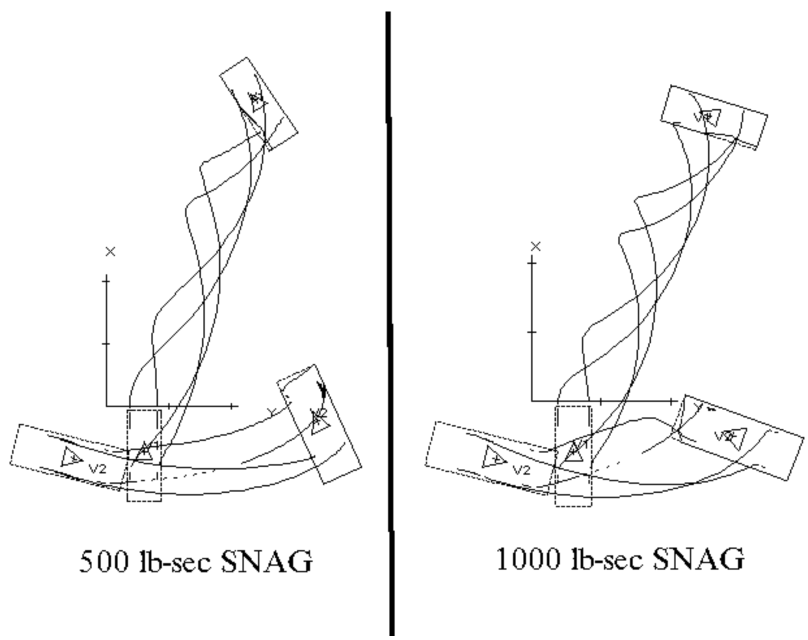

Figure 14 Revised SMAC simulated impact with 500 lb-sec and 1000 lb-sec impulsive constraint applied

VEHICLE PROXIMITY AND COLLISION DETECTION LOGIC

In the SMAC program, each vehicle is represented by a rectangular box with the length and width dimensions of the simulated vehicle. Collision detection is accomplished by continually checking the corners of each vehicle “box” to determine if it is within the periphery of the other vehicle “box”. Once a corner point is found to be in contact, the program begins calling the collision routine to use the collision model radial vectors to scan for interference and contacts and to calculate the associated collision forces. The program also changes the integration time increment to the user specified collision integration interval (DTCOLL, normally 0.001 seconds). The end of the collision event is assumed when a fixed number of time increments have passed wherein the accelerations for each vehicle is below 1 g-unit. The program flags the system into a separation mode and utilizes the separation time increment (DTCOLT, normally 0.005 seconds). In the original form of the SMAC program, the separation time increment was utilized for a fixed number of increments (originally 100). It was the intent of the separation time increment to catch side-slaps, etc. while the program was still in a relatively small time increment. If the fixed number of DTCOLT time increments are passed without any accelerations greater than 1 g-unit then the program shifts to the trajectory time increment (DTTRAJ, normally 0.01 seconds) for the remainder of the simulation run.

Problems have been found with applications of the EDSMAC program where the program missed the accelerations associated with “side-slap” impacts. The reasons for the problems with the EDSMAC program have been found to be mainly due to the choice of time increment size.

The recommended time increment sizes for use of the SMAC (or EDSMAC) program are as follows:

DTTRAJ, Trajectory time increment, not to exceed 0.01 seconds.

DTCOLT, Separation time increment, not to exceed 0.005 seconds

DTCOLL, Collision time increment, not to exceed 0.001 seconds.

These time increments should be assumed to be absolute maximums. With the speed of modern day Pentium computers, a complete SMAC ten second simulation run of an impact and spinout can be performed in less than 10 seconds of real time with all time increments set to 0.001 seconds. EDSMAC documents recommend the use of 0.01 for the DTCOLT separation time increment, 0.05 for the DTTRAJ trajectory time increment, 0.001 for the DTCOLL collision time increment [**25**]. These suggested times must have been based on suggested times for mainframe applications from 1974 contained in [**26**].

A problem with larger time-increments is the fact that they may reduce the accuracy of the predicted results. Also, when simulating a collision which may include a side-slap secondary collision, the program may miss the forces and moments associated with the side-slap event. After a primary collision event, once the SMAC (EDSMAC) program has changed to the EDSMAC recommended large DTCOLT or DTTRAJ time increments, the occurrence of a sideslap may not be detected or detected so late that the sideslap event is over and no associated accelerations are developed in the simulation due to the sideslap. The logic in the original SMAC (EDSMAC) associated with sideslap detection does not return to the DTCOLL small time-increment until the acceleration on either of the vehicles exceed 1 g-unit.

The following illustrates what occurred in an application of the EDSMAC program (used by an expert witness as an exhibit to deposition testimony). The impact configuration is displayed in **Figure 15** and the EDSMAC output damage page is contained in **Figure 16.** The damage display contains sideslap "damage" for which the accelerations associated with the sideslap “damage” were not simulated. The time history of the acceleration which 'misses' the side-slap is contained in **Figure 17** while the time-history of the corrected simulation is contained **Figure 18**. The differences which may occur between the incorrect simulation (which missed the accelerations associated with the sideslap) and the corrected simulation (which included the sideslap) are significant differences in the total amount of rotation and direction of travel to rest.

Revisions to the SMAC program have been implemented to make the post-impact interval where the program stays in DTCOLT a fixed *duration* of 0.30 seconds rather than a fixed number of time steps. In this manner, when the user sets the DTCOLT increment to 0.001 the program will continue to scan for greater than the 100 time steps . It is recommended that in accidents which include a sideslap collision that users use a DTCOLT of 0.001 seconds.

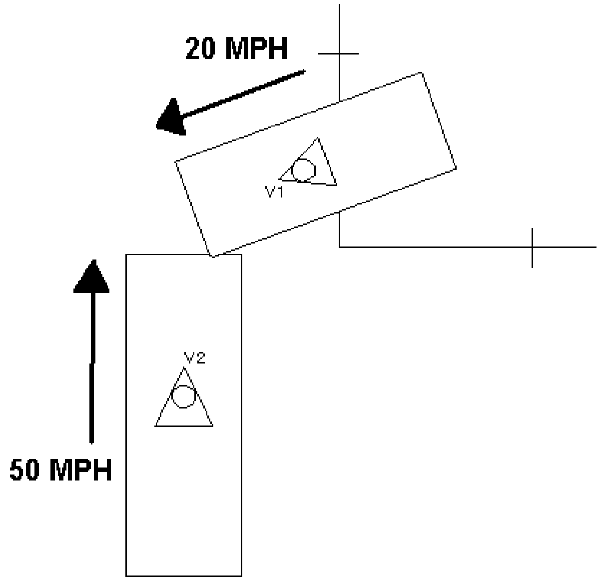

Figure 15 Impact Configuration which produces side-slap

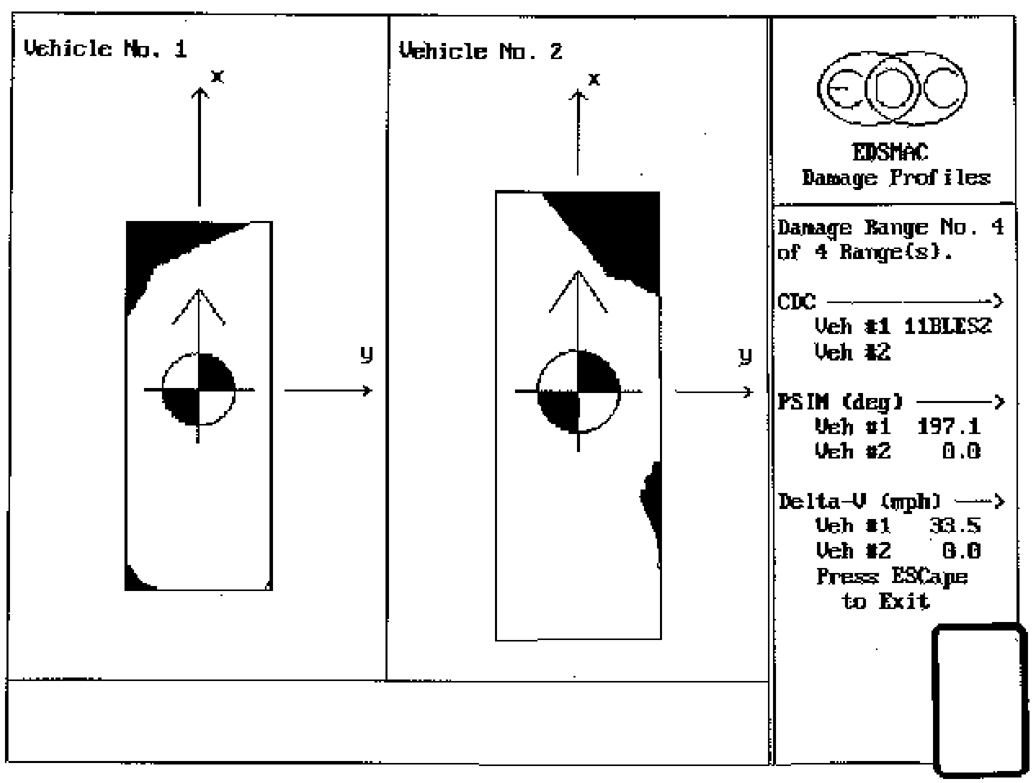

Figure 16 Example instance where EDSMAC program misses a side-slap event (no accelerations)

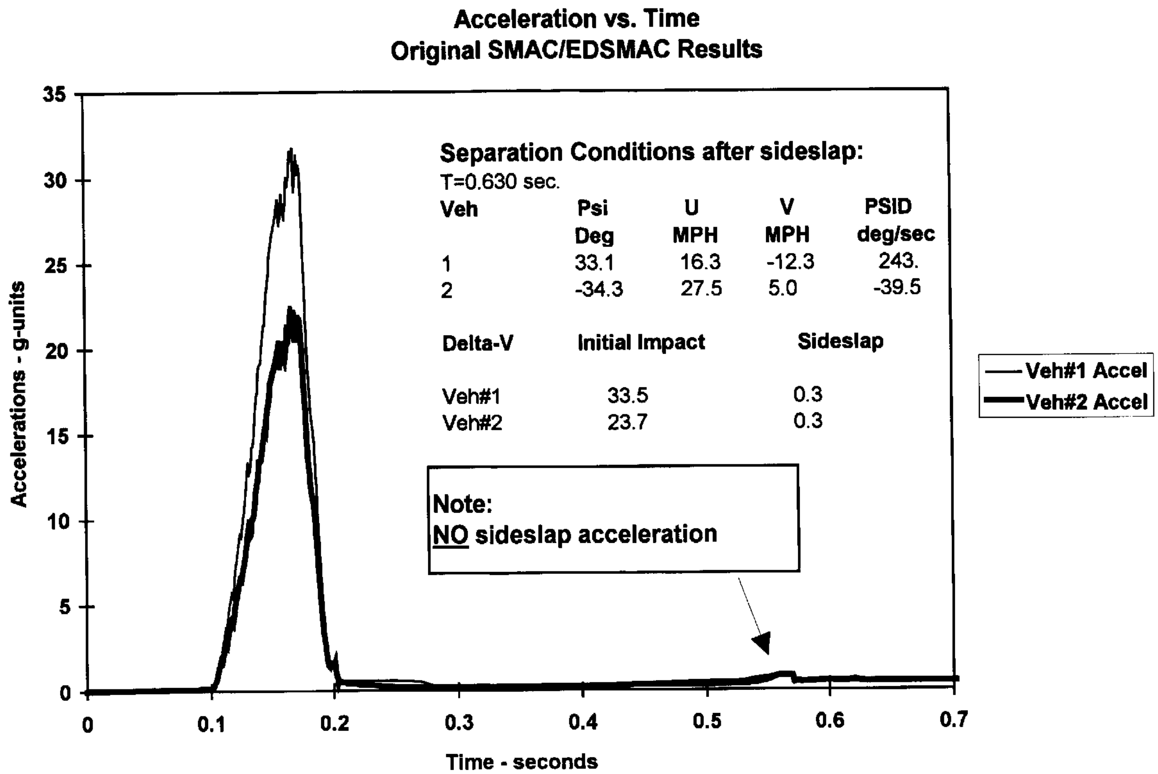

Figure 17 Acceleration time-history of example EDSMAC run which misses the side-slap

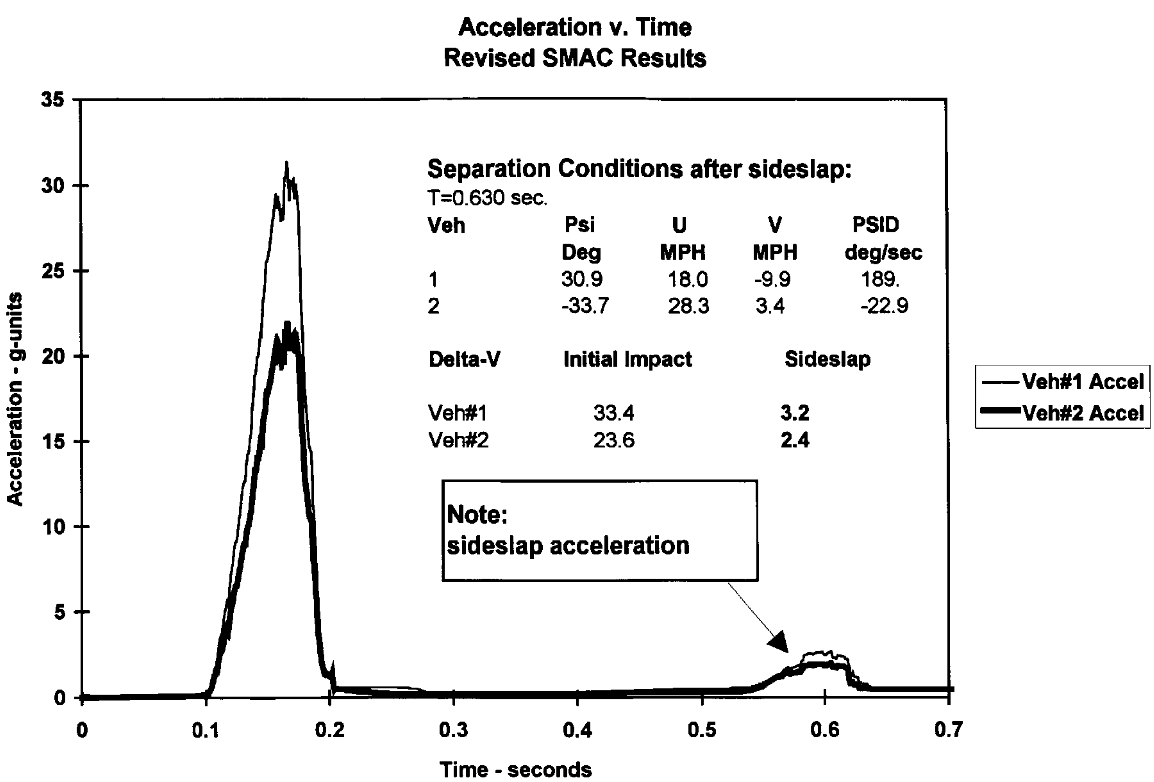

Figure 18 Acceleration time-history of example EDSMAC run on revised SMAC program which includes simulation of the side-slap impact

SUMMARY

With the rapidly changing capabilities and capacities of modern day computers, computer programs in general and accident reconstruction computer programs in particular require continuing efforts to check and refine results while critically evaluating the underlying simplifying assumptions. This paper has presented some areas of needed refinement in the original SMAC collision algorithm.

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