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CRASH-97

Refinement of the Trajectory Solution Procedure

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ABSTRACT

The *trajectory solution procedures* of the original CRASH program included both the SPIN routine and an exploratory *trajectory simulation option* to approximate and refine the linear and angular velocities at separation. The resulting separation speeds were then used to determine the impact speeds by means of application of the principle of conservation of linear momentum .

This paper presents a detailed review of the logic, rationale and limitations of the trajectory solution procedures of the original CRASH program and discusses a number of refinements including: incorporation of the principle of conservation of angular momentum, approximations of the effects of changes during collision in the positions and orientations of the two vehicles and of the effects of external forces and moments that act on the two-body system during the collision, and adaptations of optimization techniques for error reduction and convergence in iterative solutions.

The overall effects of the refinements to the CRASH trajectory algorithm on reconstruction results are illustrated by direct comparisons of results with SMAC reconstructions of full scale collision tests.

INTRODUCTION

The original form of the CRASH [**1**, **2**, **3**, **4**][1] computer program, which culminated in the CRASH3 version, was not intended to be a detailed, highly accurate reconstruction program. Rather, it was developed to serve as a simple preprocesser for the SMAC program. While the results of CRASH3 applications can be useful in providing approximate measures of accident severity for use in statistical studies, where the average error is most important, it has been demonstrated in validation tests to produce results which when compared to those of full-scale crash tests can include individual errors as great as 45%[**4**]. The possible error levels of the CRASH3 computer program are also generally applicable to the EDCRASH [**5**, **6**, **7**] computer program, since the CRASH3 program and the widely distributed EDCRASH clone are essentially identical. No significant analytical refinements have been made to the trajectory solution or trajectory simulation procedures of EDCRASH. The EDCRASH program, while claiming to be “within -6 to +7 percent of the combined impact speeds at a 95 percent level of confidence”[**6**] is subject to errors in individual speeds as great as 43.5% (Table 2, case 12, vehicle No. 1 [**6**]). Any “improvement” of the EDCRASH results over CRASH3 is mainly due to the “optimization” of the inputs to EDCRASH (to produce better correlation with known results) and modification of the error reporting techniques [**6**].

This paper presents refinements to the trajectory procedure of the CRASH3 program, herein referred to as the ‘***refined CRASH3***’ program. Refinements to the CRASH3 trajectory routine include the approximation of separation speeds through automatic iteration of the trajectory *simulation option*, inclusion of angular momentum equations, and inclusion of an approximation of the effects of the external forces (i.e., tire forces) which occur during the collision, in the CRASH3 trajectory *solution procedure*. Also to be presented is a discussion of the adaptation of optimization techniques for error reduction and convergence in the iterative solutions.

One of the problems associated with the development and refinement of any accident reconstruction technique and therefore with our research related to CRASH3 is that of demonstrating correlation with full-scale tests. The RICSAC tests [**8**, **9**, **10**] were specifically designed to serve as standards for such comparisons. Unfortunately, during review and utilization of the results (e.g., [**11**, **12**, **13**]), and particularly in prior studies which included evaluating the correlation of computer codes with RICSAC (e.g.,[**6**, **14**, **15**, **16**, **17**]) there have been various levels of interpretation and acceptance of the measured results. As a part of many of the cited projects, questions have been raised as to the validity of some of the reported RICSAC test results.

Since there has been no consensus on the interpretation of some of the results of the RICSAC tests, an intensive independent effort has been applied toward achieving proper and generally acceptable interpretations of the RICSAC test data. That research is being performed as part of a separate project reported in [**18**].

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

To permit a continuation of refinements of the CRASH3 computer code, which required comprehensive comparisons for validation, the approach reported herein has been to make use of the SMAC [**19**,**20**] computer program to generate "test results" data. The SMAC program has been demonstrated to correlate well with full-scale test results **[10] [17].** It has been generally accepted that, in the absence of significant external forces, the SMAC program correctly conserves linear and angular momentum of the two-body system. For example, **Figure 1** and **Figure 2** demonstrate comparisons of the linear and angular momentum and kinetic energy for two different RICSAC test configurations simulated on test track friction (mu=0.87) and on a frictionless surface (mu=0.0).

In the SMAC program the simulated vehicles are set up to run into each other at impact locations, orientations and speeds which are identical with those of the corresponding RICSAC tests. The response data generated by SMAC includes ΔV values for the centers of gravity, including effects of vehicle rotation and external forces, separation velocities and positions of rest. Use of the SMAC results for preliminary comparisons of the effects of refinements of computer codes avoids the complications which can occur when utilizing "raw" full-scale test data due to sensor locations and test measurement variations. The SMAC program also provides a means of refining imprecise definitions in the reported test data for such items as the effective drag at the individual wheels (e.g., driveline drag for automatic or manual transmissions in gear, rubbing of damaged sheet metal on rotating wheels) and steer angles. The refinement of the items can be achieved with SMAC on the basis of matching the positions and headings at rest between SMAC and the full-scale test results.

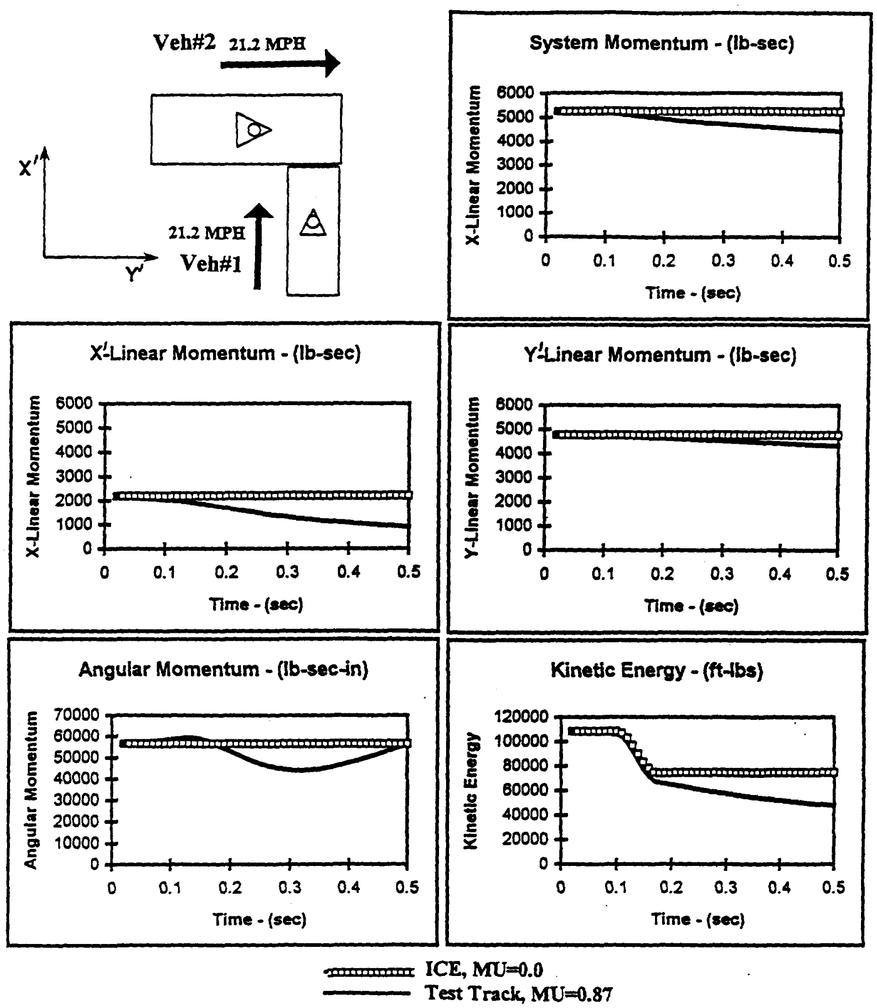

Figure 1: RICSAC Test 9: Comparison of SMAC generated System Momentum and Kinetic Energy time-histories for Test Track Friction and No Friction (note: impact at 0.10 sec, separation at 0.208 sec) (Veh#1 1975 Honda Civic,2270 lbs., Veh#2, 1974 Ford Torino, 4930 lbs.)

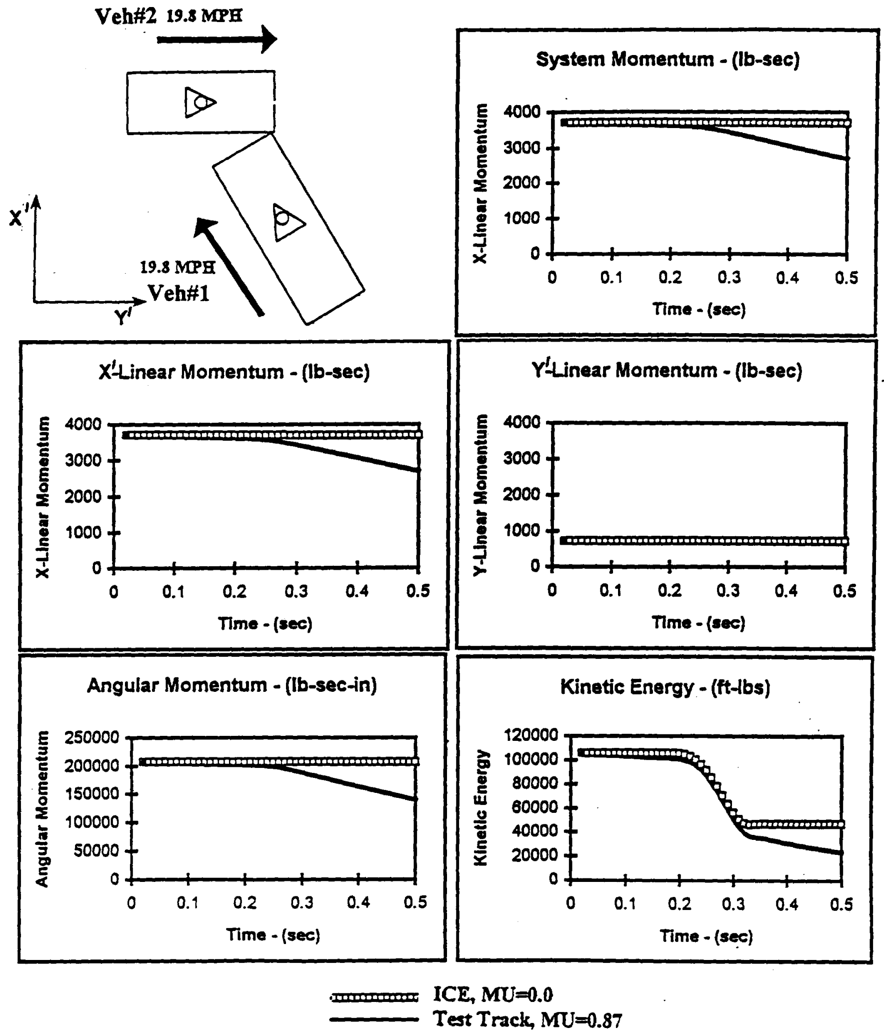

Figure 2: RICSAC Test 1- Comparison of SMAC generated System Momentum and Kinetic Energy time-histories for Test Track Friction and No Friction (note: impact at 0.18 sec, separation at 0.343 sec) (Veh#1 1974 Chevrolet Chevelle, 4650 lbs., Veh#2 1974 Ford Pinto, 3110 lbs.)

The inputs used in the present study for the SMAC runs were very similar to those that have been used in relation to SMAC validation [**10, 17**]. However, some of the cited prior SMAC inputs were found to be questionable (e.g., in some, the drag factor and steer angles at individual wheels were arbitrarily varied over time) or clearly erroneous (e.g., some had incorrect weights, tire cornering stiffness, intervehicle friction coefficient, etc.). The adjustment procedure for the SMAC inputs in the present research project was to initially check and correct any erroneous inputs and then to calculate a constant value for the wheel steer and drag factors based on the values reported in [**10, 17**]. The SMAC reconstructions were then re-run to determine the correlation of the SMAC "test results" with the full-scale test positions and orientations at rest. Minor refinements were then made, as required, to the constant values for the wheel steer angles and drag factors to achieve an approximate match of the SMAC reconstructed "test results" vehicle positions of rest with the RICSAC measured positions of rest [**21**].

Table 1 is a summary of the SMAC reconstructions of the RICSAC full-scale tests. This summary of the RICSAC tests represents a "best information" set of mathematically correct SMAC reconstructions for the individual RICSAC full-scale crash test conditions and results. The "best information" for the reconstruction results was derived from a review of the full-scale test reports [**8, 9, 22**], and a review of the reported results by Smith and Noga [**11**] to guide the SMAC reconstructions. Test numbers 1 through 12 were run at Calspan [**8, 9**]. Test number 14 is Test 3 run at Texas Transportation Institute [**22,** also see **23**].

While the wheel drag factors and steer can be varied over time in the SMAC program, "validation" datasets should be representative of what can be achieved in real world applications. For normal reconstructions a constant value is generally required since detailed time-history information is not available. The intent of the refinements to the SMAC input datasets performed for this project was to create without undue delay a representative collection of mathematically correct "test results" for comparison with CRASH predicted results. A more comprehensive review and refinement of the SMAC inputs will be performed as a part of the research reported in [**18**].

A set of input datasets for CRASH3 were then prepared which were derived from the SMAC "test results". The inputs for CRASH3 consisted of the SMAC impact and rest positions and headings, the SMAC steer angles and drag factors and the SMAC vehicle specifications (weights and dimensions) (see **Appendix 2** for the CRASH3 input datasets used**)**. No further adjustments or refinements were made to the CRASH3 or SMAC input datasets as part of this project.

These inputs were then run with the CRASH3/EDCRASH programs and the results are depicted in **Figure 3** and **Figure 4.** These figures represent the starting point for the ***refined CRASH3*** research project and they demonstrate the general inability of the CRASH3/EDCRASH programs to consistently reconstruct the mathematically correct SMAC predicted "test results".

Table 1: Summary of RICSAC Tests Impact conditions and SMAC ΔV reconstructions

RICSAC Test No.	RICSAC TEST Impact Speed Veh 1	Veh 2	SMAC Delta-V Veh 1	Veh 2
1	19.8	19.8	14	20
2	31.5	31.5	21	30
3	21	0	10	15
4	38.7	0	16	25
5	39.1	0	15	27
6	21.5	21.5	9	14
7	29.1	29.1	13	20
8	20.8	20.8	14	12
9	21.2	21.2	20	7.7
10*	33.3	33.3	36	16
11	20.4	20.4	28	17.5
12	31.5	31.5	40	27
14	26	38.5	18.9	19.8

***Note: The ΔV for Test #10 is the sum of the primary and secondary (side-slap) ΔV.**

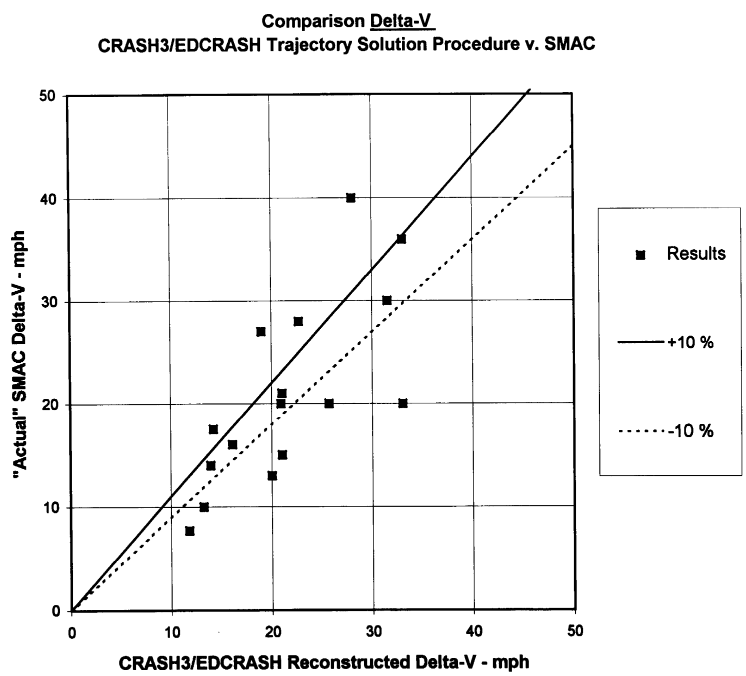

Figure 3 Initial comparison of reconstructed ΔV of CRASH3/EDCRASH Trajectory Solution vs. SMAC

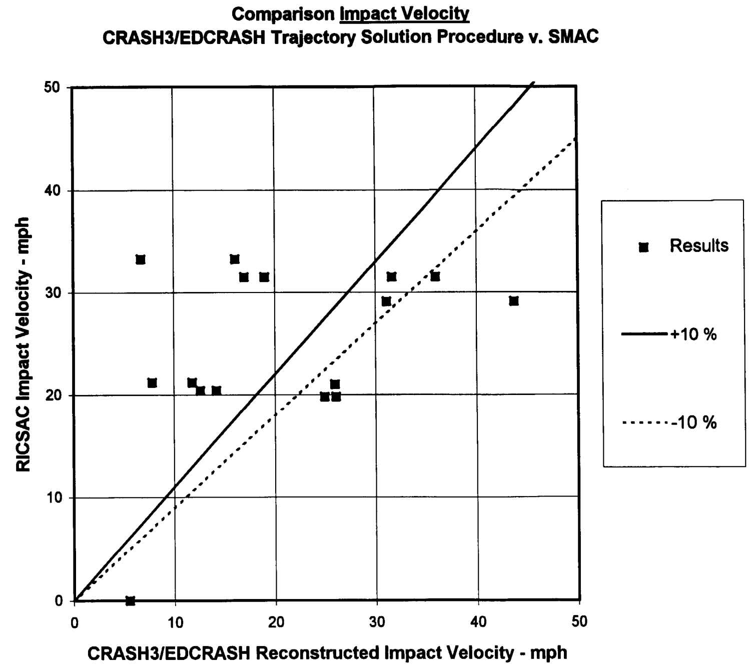

Figure 4 Initial comparison of reconstructed Impact Velocity of CRASH3/EDCRASH Trajectory Solution vs. RICSAC Test Results

BACKGROUND

When vehicles separate after a collision, they move to rest positions against resistance forces produced primarily by tire-ground friction. Analysis of the total energy dissipated as the vehicles travel from separation to their positions of rest and determination of their corresponding linear and angular velocities at separation constitute the essence of a *trajectory-based* reconstruction of a collision. The principles of conservation of linear and/or angular momentum are applied to the directions and magnitudes of the system momentum at separation to determine the velocities which must have existed prior to the collision.

In simple spinout motions, the actual paths traveled from separation to rest can be approximated, with reasonable accuracy, by straight lines between the separation and rest positions. The separation velocities can then be estimated on the basis of the total work done by each vehicle against tire-terrain friction forces between separation and rest. The rate of energy dissipation by tire forces is dependent on the heading direction of the vehicle in relation to its direction of motion, the rate of yawing rotation, and the extent of rotational resistance at the individual tires. For example, in a broadside slide, all tires produce full-friction resistance forces. In forward or backward motion, only those tires with applied brakes, damage effects, large steer angles or driveline braking produce significant drag forces. For the case of linear motion combined with angular rotation about a vertical axis (i.e., yawing rotation) a vehicle alternates between the two conditions of resistance of motion.

The CRASH3 program includes a simplified analytical procedure for approximating the linear and angular velocities of a vehicle subsequent to a collision. The developed procedure is referred to as SPIN2. A subcontract to refine SPIN2 undertaken in 1979 [**24**] (see **Appendix 1** for a discussion of SPIN2) led to the conclusion in [**24**]:

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

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

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

The purpose of the USMAC routine in CRASH3 was to serve as a check of the SPIN2 approximations of separation speeds. An optional iterative procedure was also included in the CRASH3 *trajectory simulation option* to automatically adjust the SPIN2 separation velocities in an attempt to reduce errors in the predicted vs. actual final rest positions. The initial form of the trajectory iteration routine was implemented merely to demonstrate feasibility and was not thoroughly tested and evaluated. The costs of a CRASH run increased ten-fold by the use of the exploratory iterative trajectory solution procedure (USMAC) (e.g., [**25**] , circa. 1976, p1.,"The computer costs … of the CRASH program …range from approximately $1.00 to $10.00 per case. The upper end of the indicated cost range corresponds to a run in which the option for testing and refining the trajectory analysis portion of the calculation has been exercised"). There was no further NHTSA sponsored development of the original exploratory implementation of the USMAC routine.

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

Effective refinements of the *trajectory simulation* procedure can substantially increase the usefulness of the simple "closed-form" CRASH3 accident reconstruction procedure by producing a general refinement of the *trajectory solution* procedure. The CRASH3 *trajectory solution* procedure requires a minimum amount of input information about the accident scene and vehicles. An effective improvement of the *trajectory solution* procedure can be expected to substantially improve the correlation or "validation" of the CRASH3 model when comparing the reconstruction results with full-scale test results. A 1989 study [**6**] concluded that the original form of the CRASH3/EDCRASH *trajectory simulation* option can actually degrade the *trajectory solution* results of the CRASH3 program.

A secondary task required in order to further refine and enhance the *trajectory solution* procedure of the CRASH3 program was a reactivation and refinement of the angular momentum solution procedure. The original CRASH program included conservation of linear momentum in the trajectory based solution to determine the impact speeds based on the separation velocities. A contract performed on CRASH2 to implement an angular momentum solution achieved mixed results [**26**]. A major hurdle for any procedure which includes an angular momentum solution is the need to approximate movement of the vehicles during the collision. In the CRASH2 formulation the impact and separation positions and headings were assumed to be identical. The research in [**26**] revealed that the accuracy of an angular momentum solution procedure for accident reconstruction which includes the assumption of no movement between impact and separation will produce unacceptable error levels (>>20%) in many cases.

Other analytical accident reconstruction techniques which include provision for an angular momentum solution procedure and/or which are based on conventional momentum analyses, include the somewhat subjective input requirement that either a vehicle-to-vehicle contact "point" [**27**], or a "point of maximum engagement" [**28**] or an "impact center" [**29**] be specified. The additional input is required to compensate for the cited solution procedure's lack of an independent determination of separation positions and orientations.

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

Figure 5 and **Figure 6** show representative changes in positions and orientations during the contact phase of collisions.

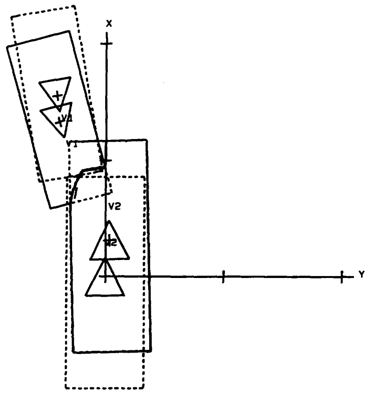

Figure 5 Impact and Separation Positions and Orientations for RICSAC Test #12

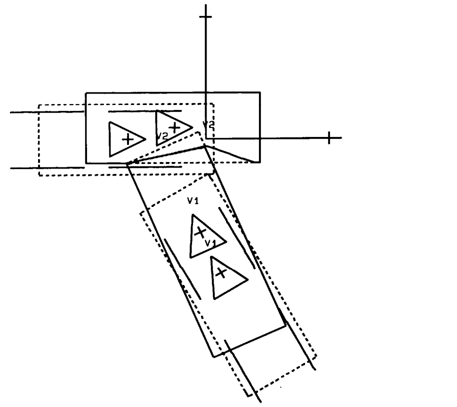

Figure 6 Impact and Separation Positions and Orientations for RICSAC Test #1

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

Other assumptions of the cited techniques [**27,28,29**] which may detract from the validity of their impact models for objective application to accident reconstruction are:

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

TIRE-TO-GROUND "EXTERNAL" FORCES: The effects of tire-ground forces must be considered in a motor vehicle collision reconstruction. During the early development of the SMAC program [**19, 20**] tests were performed to determine the effects of external tire forces on the collision solution procedure. It was concluded that “The conventional assumptions that the effects of vehicle deformations and of tire forces can be neglected in analytical reconstructions of collisions can lead to significant errors. This is particularly true for intersection-type collisions at low to moderate vehicle speeds, in which prolonged or multiple contacts and significant movements of the involved vehicles occur” and that "therefore it is essential in a general procedure for reconstruction calculations that both the collision and tire forces be considered simultaneously."

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

The importance of the inclusion of external forces in collision analysis and use of a finite time increment for the impact duration has also been reiterated more recently by Fonda [**30**].

RESEARCH APPROACH

The refinement of the trajectory solution procedure of CRASH3 required the following two basic tasks:

1. **Refinement of the trajectory *simulation option*** to improve the prediction of separation velocities.
2. **Refinement of the trajectory *solution procedure*** to include implementation of an angular momentum solution procedure and to include provisions for vehicle movement and external forces during the collision.

REFINEMENT OF THE TRAJECTORY *SIMULATION OPTION*

The refinement of the trajectory *simulation option* of CRASH3 began with determination of what constitutes the minimal information required for a trajectory based reconstruction. The minimum information required for a trajectory based reconstruction is contained in **Table 2**.

Table 2: Minimum Information Required for a trajectory based reconstruction:

1. Impact and rest positions and headings.
2. Approximations of wheel steer and drag.
3. Vehicle specifications (weights, dimensions).

The CRASH3 program includes optional inputs for points on curve, end of rotation position and other inputs which were intended to permit use of such information when it is clearly indicated by physical evidence. However, the cited options have frequently been applied as arbitrary, subjective inputs. One intention in the reported improvement of the trajectory simulation routine has been to eliminate the need for any supplemental, sometimes subjective, inputs and to thereby create a reconstruction technique which will provide *uniform interpretations of physical evidence.* The use of sometimes arbitrary points-on-curves and end-of-rotation positions as inputs can detract from an objective analysis.

One major advantage of the present refinement of the trajectory simulation procedure for CRASH3 over the original development was the availability of essentially unlimited computer resources. The number of iterations of the trajectory algorithm for a given reconstruction is virtually unlimited on a PC. The only limitation is clock time and the feasibility of attaining a solution in a reasonable amount of time. There are no computer resource charges for execution of a simulation on a PC. Also, on a Pentium-60 or faster CPU, a 10 sec trajectory simulation of a vehicle spinout requires much less than 1 sec of real time. Therefore large numbers of iterations can be performed, if required. In the CRASH3 form of the trajectory simulation, computer resource concerns dictated an arbitrary limitation on iterations of 5 per run and in many instances, five iterations required more than 10 minutes real clock time to execute in a time-share computer environment [**31**].

The next phase in the refinement of the trajectory *simulation option* for CRASH3 was to determine how to create an iterative scheme which could converge on the separation speeds required to travel a given distance in a given direction and to match the extent of rotation. The only items of information to be provided to the routine were those listed in **Table 2**. The routine would then determine the required separation speed, course angle and angular velocity.

Figure 7 and **Figure 8** show representative results of iterative adjustments of the separation velocities by revised CRASH3 that produce convergence towards matching the positions and headings at rest.

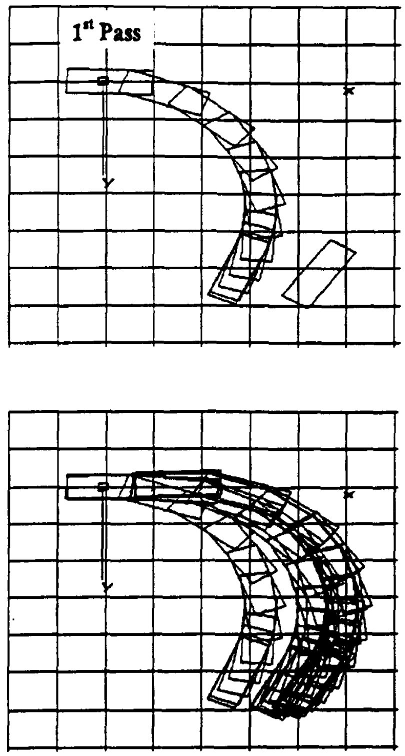

Figure 7 Sample of Revised CRASH3 Iterative Trajectory Simulation for RICSAC Test#4, Veh#1

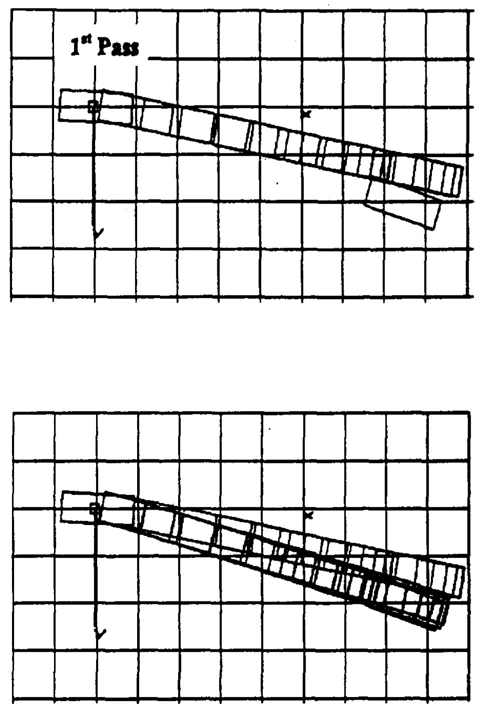

Figure 8 Sample of Revised CRASH3 Iterative Trajectory Simulation for RICSAC Test#7, Veh#1

Many different optimization and error minimization routines were investigated for convergence and optimization to a solution [**32**,**33**,**34**, **35**]. A fundamental problem with the use of many of the investigated control algorithms was the inherent requirement that the functions must be continuous and/or linear. The spinout trajectory of a vehicle can be a highly non-linear event. Minor variations in starting conditions (i.e., speed, course angle, angular velocity) can produce major changes in the resulting rest positions (X, Y, PSI) and discontinuities in the calculated error evaluation terms. For example, during the various “step” changes in the decelerations of the linear and angular velocities as a vehicle travels from separation to rest, at any instant when the velocity vector aligns with the longitudinal axis the vehicle may “shoot off” tangentially in what has been described as a “dog-leg” type of trajectory. Traditional function minimization techniques tested as part of this research which normally require the evaluation of some form of derivatives (e.g., Cramer's rule, Newton’s method) or include the assumption of a linear function (Powell’s method, Broyden’s method) were found to fail in many instances where step changes were produced in the "function" by minor alterations of the variables.

The choice of error terms and the relative magnitudes of the various calculated error terms can also cause iterative and optimization routines to fail. Within the reported research program error terms were developed which achieve a successful minimization of errors between predicted and actual positions of rest.

Problems encountered during the early formulation and comparisons of the revised CRASH trajectory simulation iteration procedure results (project USMAC2) with reported full-scale crash test results of RICSAC [**8**,**9**,**10**] revealed the need for an independent and separate task of evaluating the reported RICSAC test results. Most of the problems with comparisons were related to the values of separation conditions reported by Jones [**10**]. The reported values included some interpretation by Jones of the full-scale test results. In the full-scale tests, the separation velocities were not directly measured and required some additional calculations which included interpretation of accelerometer information for accelerometers not located at the vehicle centers of gravity. Also, the accelerometers in some of the tests were located in or very near to the crush zone and/or on possible flexible components of the vehicle. Therefore a separate task was undertaken to check the reported results of RICSAC independent of any validation efforts for a particular computer program [**18**].

The inputs for the ***refined CRASH3*** for the present project were derived from SMAC "test result" reconstructions (previously discussed in the introduction) and are contained in **Appendix 2**. The inputs consisted of the SMAC impact and rest positions and headings, the wheel steer angle and drag factors and the vehicle specifications (weights and dimensions).

A refined version of the original SPIN2 routine was utilized to determine starting values. The revised trajectory simulation routine, USMAC2, was then used to simulate the trajectory of each of the vehicles to positions of rest. Based on comparisons of the cited error terms, automatic adjustments were made to the separation conditions and the simulation was re-run. Once an acceptable "match" of the rest position and heading was achieved, the iterative procedure was stopped.

Table 3 contains SMAC generated separation conditions for the RICSAC full scale tests. The separation velocities are a direct output from the SMAC program and represent the first instance after the primary collision where the acceleration drops below 1 g-unit. **Table 4** contains a preliminary comparison of the USMAC2 with the SMAC generated separation conditions. Note that the comparison dataset does not include application of the angular momentum solution or external forces (these items are discussed in more detail below).

A review of the results reveal that most of the USMAC2 predicted separation speeds compare favorably with the SMAC "test result" generated separation speeds. However, some of the comparisons do not appear to agree very well. The reason for the differences is related to the assumptions regarding the time to separation. As a part of the ***refined CRASH*** trajectory solution procedure, a separation position is calculated. The calculation of a separation position requires assumption of a time to separation as well as reliance on the ***refined CRASH*** calculated impact speed. In order to provide for uniform interpretation in the ***refined CRASH*** results, a common assumption was made for the time to separation in the calculation procedure for the separation position and orientation. As more full scale tests become available (e.g., possibly the JARI crash test database which contains some 35 tests that are referenced in [**29**]) possible refinements of the technique will include modifications of the time to separation, etc. based on the impact configuration (e.g., a 90 degree side impact would be expected to have a longer time to separation than an offset frontal).

Another source of some discrepancy of the comparisons is related to the occurrence of secondary "side-slap" interactions. In tests 9 and 10 both the full-scale tests and SMAC reconstructions included secondary "side-slap" collisions. In test 10, a "side-slap" with magnitude greater than 5 mph on vehicle 1 occurred after the initial impact. The "side-slap" changed the magnitude and direction of the separation conditions. In test 9, subsequent to the initial contact the vehicles "side-slap" interacted at a lesser magnitude but for a longer time which produced re-direction of the initial separation velocities. The listed separation speeds in **Table 4** are the initial impact separation conditions which are different than the speeds and orientations after the occurrence of a "side-slap" collision.

The development of the trajectory *solution procedure*, discussed below, revealed that the cited comparison of SMAC and CRASH separation results, while not all within ±10%, were adequate when used with the refinements to the *trajectory solution* procedures to produce acceptable impact and ΔV predictions within ±10% of the corresponding SMAC results.

Table 3 SMAC generated separation conditions for 13 RICSAC tests

	Vehicle No. 1			Vehicle No. 2		
Test No.	**SDOT1 in/sec**	**GAMS1 deg**	**PSID1 deg/sec**	**SDOT2 in/sec**	**GAMS2 deg**	**PSID2 deg/sec**
1	125	-11.4	95	235	23.5	-12
2	210	-12	160	411	26	65
3	205	-6	-3	272	11	19
4	400	-6	3	432	13	40
5	435	-5	5	469	10	63
6	210	4	51	270	78	184
7	276	2	63	418	76	167
8	169	35	103	315	55	34
9	169	69	193	310	69	-44
10	282	64	357	488	67	-78
11	140	-29	-44	83	44	4
12	138	-30	-87	152	53	-27
14	282	49	-280	352	102	-200

Table 4: Comparison of USMAC2 predicted separation conditions with the SMAC generated separation results.

Test No.	Veh No.	SDOT in/sec	Error %	GAMS deg	Error deg	PSID deg/sec	Error deg/sec
1	1	108	-14	-11	0	103	8
2	1	227	8	-18	-6	147	-13
3	1	205	0	-12	-6	-1	2
4	1	439	10	-15	-9	29	26
5	1	431	-1	-5	0	7	2
6	1	198	-6	2	-2	36	-15
7	1	263	-5	1	-1	53	-10
8	1	138	-18	37	2	97	-6
9	1	274	62	57	-12	202	9
10	1	355	26	81	17	208	-149
11	1	118	-16	-34	-5	-42	2
12	1	129	-7	-35	-5	-93	-6
14	1	279	-1	46	-3	-270	10
1	2	257	9	25	2	7	19
2	2	422	3	29	3	59	-6
3	2	274	1	14	3	-32	-51
4	2	448	4	23	10	30	-10
5	2	508	8	8	-2	130	67
6	2	294	9	82	4	159	-25
7	2	419	0	78	2	159	-8
8	2	330	5	53	-2	42	8
9	2	269	-13	65	-4	6	50
10	2	494	1	63	-4	-30	48
11	2	82	-1	29	-15	11	7
12	2	157	3	46	-7	-23	4
14	2	322	-9	104	2	-198	2

REFINEMENT OF THE TRAJECTORY *SOLUTION PROCEDURE*

The primary task required to refine the trajectory *solution procedure* of CRASH3 was to implement an angular momentum solution. The implementation of the procedure required determination of separation positions and orientations. A secondary consideration was the implementation of effects of external tire forces during the impact phase.

The problems of approximation of positions and headings at separation are compounded by the fact that neither the impact nor the separation velocities are known. The ***refined CRASH*** trajectory *solution procedure* therefore had to be modified to include an iterative solution procedure.

A basic outline of the procedure used to determine the impact speeds for a combination linear and angular momentum solution was as follows:

1. The separation velocities are approximated on the basis of the vehicle travel from impact to rest.
2. The separation velocities are used with an application of conservation of linear momentum for an initial approximation of the impact velocities.
3. The separation positions and headings are approximated using the initial approximations of the impact and separation velocities.
4. With approximation of the separation positions and headings, the following steps are repeated to converge on a solution:

    4.1. The separation velocities are refined based on the vehicle travel from ***separation*** to rest.

    4.2. The refined separation velocity is used with an application of conservation of both linear and angular momentum for a refined approximation of the impact velocities.

An iterative procedure was developed to guide the iteration of step 4, until an "acceptable" solution was achieved. The task became both a choice of iterative schemes and determination of what constituted an "acceptable solution." It was hoped that once the solutions for the angular and linear solutions matched, an acceptable solution would result.

However, during the testing of various iteration schemes, the question became which solution procedure, linear or angular, should guide the iterative process. Some impact configurations are more suited to a linear momentum solution procedure and some are more suited to an angular momentum solution procedure. Also available to the CRASH program algorithm is a damage analysis procedure which can provide an additional discriminator to guide the iterative process. However, although included in initial testing, adequate approximations of the separation positions and orientations where achieved without the use of damage information.

Coincident with the investigation of iterative solution procedures was the implementation of terms to approximate the effects of external forces. Terms were developed and included in the momentum equations to approximate the forces and moments produced by the tire forces during the collision. The implementation included investigation of approximate values for the finite duration of the collision.

The successful inclusion of effects of external tire-forces and of a finite time for the collision momentum exchange in the ***refined CRASH*** solution procedure benefited from the outstanding resources afforded by modern day Pentium computers. Rather than being forced to perform iterations of individual runs for comparison tests of the effects of individual input variables, the whole collection of test cases could be iterated by control algorithms to quickly evaluate the effects of the assumptions on all of the validation comparison runs. A "suite" of tests was easily set up and the various variables tested. Some of the many assumptions and approximations tested and refined in this manner included:

- The approximation technique used for determining the separation positions and orientations.
- The approximate duration of the time to separation.
- The magnitude and duration of the forces and moments used to approximate the effects of external tire-forces during the collision.
- The various error evaluation terms and weighting functions used to guide the iteration and achieve an “acceptable” match.

RESULTS

A comparison of the ***refined CRASH3*** trajectory solution procedure with the time-forward SMAC simulation program for 13 of the RICSAC tests is presented in **Table 5** and in graphical form for ΔV in **Figure 9** and Impact Velocity in **Figure 10.** The results demonstrate that the “closed-form” ***refined CRASH*** program can reconstruct “open-form” SMAC generated “test results” within less than ±10% of the impact speeds and impact speed-changes.

When comparisons are made between a calculated value and a measured or “true” value, the magnitude of the error expressed as a percentage of the comparison with the “true” value of an estimated quantity appears to be the most meaningful engineering measure of accuracy. However, in the case of a very small or zero “true” value, the use of the actual magnitude of the error is more meaningful than a percentage. If it is assumed that ±1.0 MPH is an acceptable error range about a very small “true” value, then the transition from the actual magnitude of error to a percentage error can arbitrarily be made, for example, at a “true” value of 10 MPH. The error should be reported in both formats for “true” values in excess of 10 MPH. For lesser magnitudes, only the actual magnitude should be displayed (e.g., **Table 5,** note that “true” value for **Table 5** is the SMAC simulated “test result” reported in **Table 1.** The table gives a correlation of the predicted results of ***refined CRASH3*** with the “true” SMAC “test results”)

In the validation of EDSMAC contained in [**6**] the authors used the combined speeds of the two colliding vehicles (i.e., the closing speed of the collision) as a basis for calculating the error in the reconstructed impact speed. This technique was used to avoid the case where one vehicle was initially at rest and therefore had a “true” value of zero for its impact speed. The technique used appears to serve no useful purpose other than making the error appear smaller.

The SMAC "open-form" simulation is a widely used program that has been demonstrated to be a generally valid and accurate model of motor vehicle collisions. The primary drawback of the SMAC program is that it requires initial estimates and multiple iterations by the user to converge on an "acceptable" solution. Variations of what constitutes an "acceptable" solution for the SMAC simulation program are to some extent dependent on the individual users.

The ***refined CRASH3*** procedure achieves essentially the same results as the "open-form" SMAC computer program. The ***refined CRASH3*** "closed-form" approach eliminates differences in results for a given reconstruction that are produced by variations in the capabilities and perseverance of individual SMAC users.

CONCLUSIONS AND RECOMMENDATIONS

With regard to measures of reconstruction accuracy by means of comparison of reconstruction results with reliable test data, the distinction must be recognized between applications to statistical samples of cases and an application to an individual case.

In a large number of applications, the intercept and slope of the linear regression fit for actual measured data plotted against reconstruction estimates may be compared with the intercept of zero and slope of 1.00 corresponding to perfect correlation (e.g., see **Figure 9**, **Figure 10**). In this manner, measures of the average error may be obtained.

In an application to an individual accident, the maximum error in a comparison of reconstruction estimates with reliable test data constitutes the most significant measure of accuracy since it indicates the error that is possible with good data in any given application.

Subsequent to the research related to a review of the RICSAC tests [**18**], the ***refined CRASH3*** program will be compared directly with the refined RICSAC full-scale test results.

Further development of the ***refined CRASH*** program, which will follow the completion of work related to RICSAC [**18**] and the availability of additional full scale crash test results, should further improve the results of ***refined CRASH*** to be generally consistent with those of the SMAC simulation program. The preference for the CRASH program, particularly for case studies, is that it does not require any iterations by the user and, therefore, there should be little or no variation in reconstruction results obtained by different users.

Table 5 Summary of *refined CRASH3* reconstructions of RICSAC SMAC simulations:

RICSAC	Impact Speed						Delta-V					
TEST	Vehicle No. 1			Vehicle No. 2			Vehicle No. 1			Vehicle No. 2		
No.	Revised	Error		Revised	Error		Revised	Error		Revised	Error	
	crash	%	mph	crash	%	mph	crash	%	mph	crash	%	mph
1	19	-4	-.8	21.1	6.6	1.3	14.2	1.4	.2	19.9	-.5	-.1
2	33.4	6	1.9	32.1	1.9	.6	21.8	3.8	.8	31.5	5	1.5
3	20.8	-1	-.2	0		0	9.8	-2	-.2	15.6	4	.6
4	40.7	5.2	2	0		0	16.3	1.9	.3	25.5	2	.5
5	39.9	2	.8	0		0	15.9	6	.9	28.9	7	1.9
6	21	-2.3	-.5	22.8	6	1.3	9.8	8.9	.8	14.9	6.4	.9
7	28.7	-1.4	-.4	29.4	1	.3	13.8	6.2	.8	21.5	7.5	1.5
8	19.3	-7.2	-1.5	20.7	-.5	-.1	14.6	4.3	.6	12.1	.8	.1
9	21.9	3.3	.7	21.1	-.5	-.1	18.2	-9	-1.8	7.6	-1.8	-.1
10	34.1	2.4	.8	35.3	6	2	37	2.8	1	17.1	6.9	1.1
11	20	-2	-.4	19.9	-2.5	-.5	26.5	-5.4	-1.5	16.1	-8	-1.4
12	33.3	5.7	1.8	32.1	1.9	.6	39.1	-2.3	-.9	26.6	-1.5	-.4
14	25.9	-.4	-.1	36.5	-5.2	-2	19.6	3.7	.7	19.9	.5	.1

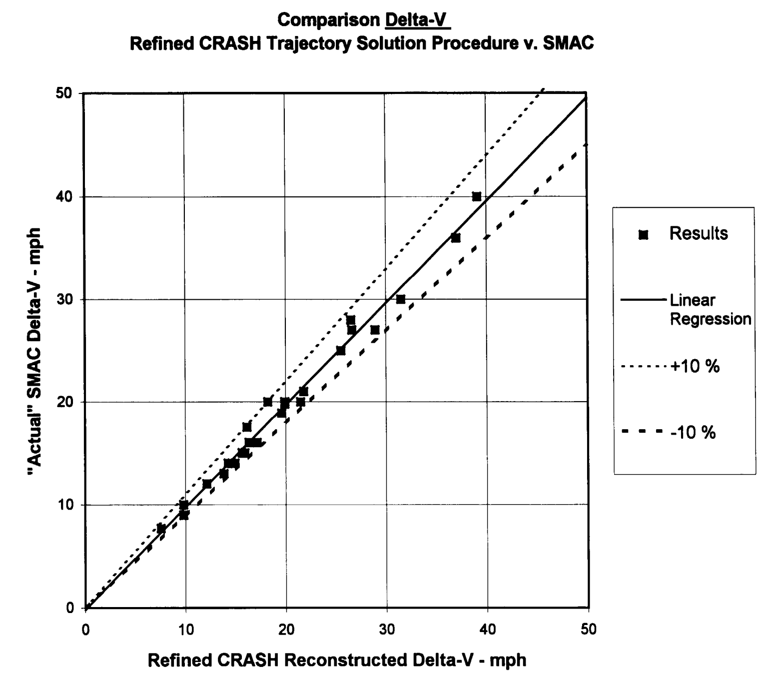

Figure 9 Comparison of reconstructed ΔV of *refined CRASH3* Trajectory Solution vs. SMAC

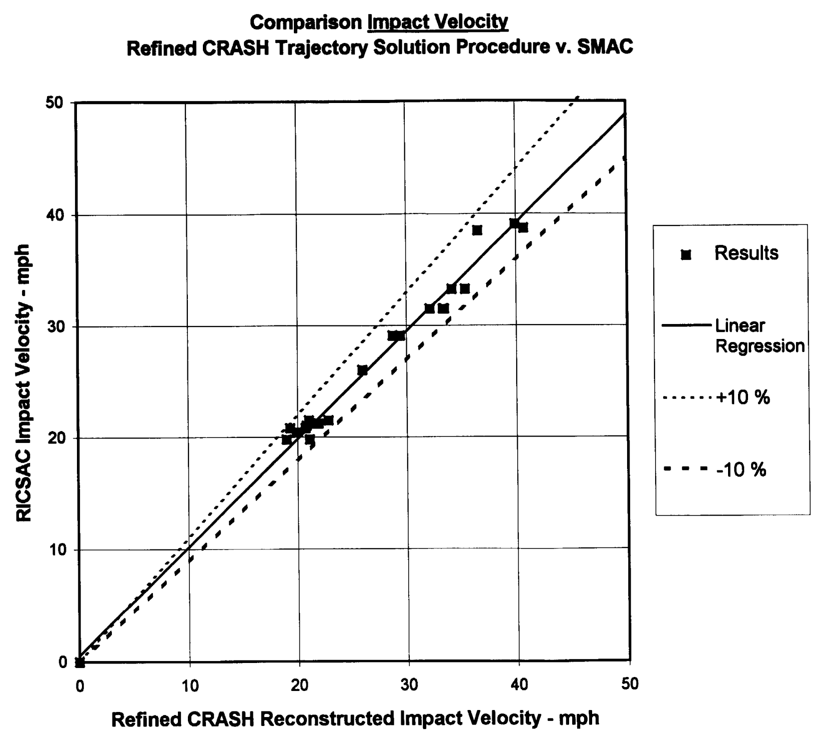

Figure 10 Comparison of reconstructed Impact Velocity of *refined CRASH3* Trajectory Solution vs. RICSAC Test Data

A secondary investigation is underway to determine internal tests and corresponding instructions that may be used to guide users if and when "bad" data are input. Since the results reported herein represent correlation of the predicted CRASH results with mathematically correct SMAC generated "test results", they indicate the 'best' correlation possible for the analytical technique. The next task is to test the procedure with "real world" data where problems may arise due to invalid or inconsistent inputs.

An auxiliary procedure developed during this project was a set of modifications for SMAC which automatically generates "evidence" for input to the ***refined CRASH3*** program. This routine provides a capability for further testing of the compatibility of results produced by the two programs. In tests performed to date, the ***refined CRASH3*** routine has consistently produced reconstruction results for the general case which are within ±15% of the speed inputs to the SMAC program and the corresponding impact speed-changes reconstructed by SMAC. Further testing and evaluation of the described routine and of the compatibility of the SMAC and CRASH program results will continue.

The final development of the ***refined CRASH3*** accident reconstruction procedure will incorporate previously defined refinements to the damage analysis procedure [**36**,**37**]. The utilization of damage information should assist in the analysis of real-world data and should dramatically improve the ability of the ***refined CRASH3*** to accurately reconstruct motor vehicle collisions while maintaining the original intent of the CRASH program to provide for *"uniform interpretation of accident evidence".*

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APPENDIX 1: DISCUSSION OF SPIN2

The SPIN2 procedure of the original CRASH program uses as a starting point the relationships developed by Marquard [**38**]. The Marquard procedure takes into account the fact that the linear and angular (i.e., yaw rotation) displacements of a four-wheeled vehicle subsequent to a collision each occur under conditions of intermittent deceleration when the wheels are free to rotate. By approximating the linear and angular deceleration rates of a vehicle with either (1) all wheels freely rotating or (2) all wheels locked during different phases of spinout motion, Marquard developed approximate relationships between the total linear and angular displacements during the travel from separation to rest and the corresponding linear and angular velocities of a vehicle at separation from its collision partner, for the two cited cases of rotational resistance.

In the CRASH program [**1**], the SPIN2 routine was developed to extend the relatively simple Marquard relationships to include the cases of partial braking and/or damage-locked individual wheels. Evaluations of the resulting, modified relationships by means of trial applications to spinout trajectories generated with SMAC [20] revealed several shortcomings of the initial SPIN2 relationships. First, a residual linear velocity frequently exists at the end of the rotational (i.e., yawing) motion. Next, the general shapes of plots of linear and angular velocity vs. time changed substantially as functions of the ratio of linear and angular velocity at separation from the collision. Finally, the transitions between the different deceleration rates of linear and angular motions were found to occur gradually rather than abruptly. Slope changes in the plots of linear and angular velocity vs. time were found to generally occur in the form of rounded "corners" in the curves.

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

The cited analytical developments, reported in [**2**], involved only limited efforts which were aimed primarily at demonstrating the feasibility of the CRASH concept. Polynomial functions to generate empirical coefficients were developed, on the basis of 18 single-vehicle SMAC runs with relatively high linear and angular velocities for starting (i.e., separation) conditions. In the more common, real-life accident case, a relatively small rotation (i.e., yawing) velocity may exist at separation. In such a case the initial direction of the velocity vector with respect to the longitudinal axis of the vehicle will obviously affect the sequence and the duration of the linear and angular deceleration rates of the vehicle.

In consideration of known shortcomings of the SPIN2 aspect of the CRASH program, a subcontract to refine SPIN2 was undertaken in 1979 [**24**]. A representative sample of actual accident cases was selected from the NCSS [**39**] files for use in the study. A total of 50 cases were selected and then reconstructed with the SMAC computer program. For each of the SMAC reconstructions, separation information was used to formulate a basis for a refinement of the SPIN2 empirical coefficients.

A careful examination of the time-history plots of linear and angular velocities for all of the cases in the sample revealed a significant number of cases in which the SMAC-predicted behaviour deviated from the analytical assumptions upon which the SPIN2 routine is based. Attempts were undertaken within the research project to discriminate characteristics of separation conditions. Unfortunately, only partial success was achieved in the attempts to accommodate deviations by means of the use of logic and discriminators. As a result, a realistic appraisal of residual scatter in the empirical fits led to the conclusion in [**24**]:

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

Subseqent work which has been performed on investigation and refinement of the SPIN empirical coefficients [**30**, **40**, **41**] and the corresponding modifications to CRASH is subject to the effects of ‘scatter’. Any proposed refinements of the SPIN empirical coefficients and any reconstruction techniques which are based on the refinements of the SPIN empirical approach will ultimately fail in some applications to individual case reconstructions due to the possibililty that the particular case being investigated may be characteristic of a "scatter" point. The research cited in this paper strongly supports the conclusion from 1981 that implementation of a trajectory solution procedure should utilize an iterative time-history simulation.

APPENDIX 2: CRASH INPUTS

The following are the inputs for the ***refined CRASH3*** reconstructions used for comparison with the SMAC program. Note that most inputs (where applicable) are from the SMAC reconstructions.

The following questions are all answered the same and therefore not repeated for the inputs for the ***refined CRASH3*** test preliminary RICSAC test runs:

```
 6. REST & IMPACT?.....................YES
 9. ANY SLIP ANGLES?...................NO
11. SUSTAINED CONTACT?.................NO
13. SKIDDING STOP BEFORE REST?.........NO
15. CURVED PATH?.......................NO
18. MORE THAN 360 DEG? ................NO
20. SKIDDING STOP BEFORE REST?.........NO
22. CURVED PATH?.......................NO
25. MORE THAN 360 DEG? ................NO
26. TIRE-GROUND FRICTION............... .870
27. ROLLING RESISTANCE OPTION..........1
32. TRAJECTORY SIMULATION?.............YES
35. TERRAIN BOUNDARY?..................NO
38. DAMAGE DIMENSIONS?.................NO
```

In the input listings, the input specs were input to the ***refined CRASH3*** program in the following form:

```
SMAC: 4:   A1,B1,TRW1,FMASS1,IZ1,XF1,XR1,YS1
SMAC: 5:   A2,B2,TRW2,FMASS2,IZ2,XF2,XR2,YS2
SMAC  6:   CSTF1, CSTF2, CSTF3, CSTF4
SMAC  7:   CSTF5, CSTF6, CSTF7, CSTF8
```

where:

A,B = distances from CG to front/rear axles
TRW = track width
FMASS1 = vehicle mass, lb-sec**2/in
IZ1 = Total vehicle yaw moment of inertia, lb-sec-in
XF = distance from CG to front end
XR = distance from CG to rear end
YS = ½ width of vehicle
CSTF = cornering stiffness, lb/rad

The individual inputs are as follows:

File s1j95

```
 1. TITLE..........sricsac1.bat test#1   7/15/95
 2. CLASS/WEIGHTS...................... 4 4650. 2 3100.
 3. CDC/PDOF # 1.......................12FDEW3  12.5
 4. CDC/PDOF # 2.......................02RDEW3  71.9
 5. V#1 & V#2 STIFFNESS CATEGORIES..... 4  2
 7. REST COORDINATES..................   -.8   5.5   -.7   8.5   6.9 100.3
 8. IMPACT COORDINATES................. -10.8   7.6 -30.0    .0    .0  90.0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1.......  .019  .019  .340  .340
29. ROLL. RES, INDIV. WHEELS # 2.......  .023  .023  .611  .611
33. STEER ANGLES #1....................   .0   .0   .0   .0
34. STEER ANGLES #2....................   .0   .0   .0   .0
35. TERRAIN BOUNDARY?..................NO
SMAC:4...   50.89   65.11   61.10   12.03 45019.0   90.99 -118.31   38.30
SMAC:5...   45.69   48.51   55.40    8.02 23676.0   83.19  -85.81   34.70
SMAC:6...-12338.0-12338.0-10991.0-10991.0
SMAC:7... -7547.0 -7547.0 -7108.0 -7108.0
```

File s2j95
1. TITLE.........sricsac2.bat test#2,7/26/95
2. CLASS/WEIGHTS...................... 4 4650. 2 3100.
3. CDC/PDOF # 1.......................11FDEW2 -17.3
4. CDC/PDOF # 2.......................02RDEW4 44.5
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 2
7. REST COORDINATES................... 6.7 6.9 67.5 21.4 14.3 158.0
8. IMPACT COORDINATES................. -11.0 7.7 -30.0 .0 -.5 90.1
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .270 .019 .250 .250
29. ROLL. RES, INDIV. WHEELS # 2....... 1.000 .020 .400 .400
33. STEER ANGLES #1.................... .0 .0 .0 .0
34. STEER ANGLES #2.................... .0 .0 .0 .0
35. TERRAIN BOUNDARY?..................NO
SMAC:4... 52.45 63.55 61.10 12.03 45019.0 92.45 -116.05 38.30
SMAC:5... 46.75 47.45 55.40 8.02 23676.0 84.75 -84.45 34.70
SMAC:6...-12338.0-12338.0-10991.0-10991.0
SMAC:7... -7547.0 -7547.0 -9086.0 -9086.0

File s3j95.c15
1. TITLE.........sricsac3.bat test#3, 7/26/95
2. CLASS/WEIGHTS...................... 4 4980. 2 3140.
3. CDC/PDOF # 1.......................12FZEW1 6.2
4. CDC/PDOF # 2.......................06BZEW1 179.0
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 2
7. REST COORDINATES................... 111.2 -5.0 -4.8 183.3 -10.0 -22.8
8. IMPACT COORDINATES................. .0 .0 .0 16.2 3.6 10.0
12. SKIDDING OF # 1?...................NO
17. ROTATION DIRECTION #1..............N/A
19. SKIDDING OF # 2?...................NO
24. ROTATION DIRECTION #2..............N/A
28. ROLL. RES, INDIV. WHEELS # 1....... .019 .019 .077 .077
29. ROLL. RES, INDIV. WHEELS # 2....... .020 .020 .107 .107
33. STEER ANGLES #1.................... -.5 -.5 .0 .0
34. STEER ANGLES #2.................... -1.5 -1.5 .0 .0
35. TERRAIN BOUNDARY?..................NO
SMAC:4... 55.65 62.32 63.45 12.89 58878.0 101.48 -116.32 39.65
SMAC:5... 37.32 56.78 55.40 8.13 22602.0 74.92 -94.08 34.70
SMAC:6...-12386.0-12386.0-11251.0-11251.0
SMAC:7... -8793.0 -8793.0 -5956.0 -5956.0

File s4j95.c15
1. TITLE.........sricsac4.bat test#4, 7/26/95
2. CLASS/WEIGHTS...................... 4 4980. 2 3190.
3. CDC/PDOF # 1.......................12FZEW2 8.5
4. CDC/PDOF # 2.......................06BDEW4 180.0
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 2
7. REST COORDINATES................... 44.6 51.9 123.6 59.7 67.4 97.4
8. IMPACT COORDINATES................. .6 .0 .0 16.4 3.5 10.0
12. SKIDDING OF # 1?...................NO
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................NO
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .020 .019 .360 .360
29. ROLL. RES, INDIV. WHEELS # 2....... .020 .020 .460 .760
33. STEER ANGLES #1.................... 16.0 16.0 .0 .0
34. STEER ANGLES #2.................... 8.0 8.0 .0 .0
35. TERRAIN BOUNDARY?..................NO
SMAC:4... 55.90 62.10 63.45 12.89 56174.0 99.50 -115.90 38.40
SMAC:5... 35.70 58.80 55.40 8.26 22704.0 72.90 -96.10 33.25
SMAC:6...-12386.0-12386.0-11252.0-11252.0
SMAC:7... -8982.0 -8982.0 -5673.0 -5673.0

File s5j95.c15
1. TITLE.........sricsac5.bat test#5, 7/26/95
2. CLASS/WEIGHTS...................... 4 4600. 1 2530.
3. CDC/PDOF # 1.......................12FZEW1 .0
4. CDC/PDOF # 2.......................05BDEW8 170.0
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 1
7. REST COORDINATES................... 257.4 7.6 2.0 67.2 42.4 275.0
8. IMPACT COORDINATES................. .6 .0 .0 15.0 3.1 10.0
12. SKIDDING OF # 1?...................NO
17. ROTATION DIRECTION #1..............N/A
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .020 .020 .210 .210
29. ROLL. RES, INDIV. WHEELS # 2....... .000 .000 .410 .410
33. STEER ANGLES #1.................... .0 .0 .0 .0
34. STEER ANGLES #2.................... .0 .0 10.0 4.0
SMAC:4... 35.80 62.40 63.45 11.90 52177.0 99.20 -116.90 35.40
SMAC:5... 37.00 46.90 50.80 6.55 14000.0 68.00 -79.10 29.60
SMAC:6...-11615.0-11961.0 -8347.0 -8347.0
SMAC:7... -8560.0 -8560.0 .0 -6753.0

File s6j95
1. TITLE.........sricsac6.bat test#6, 7/26/95
2. CLASS/WEIGHTS...................... 4 4300. 2 2623.
3. CDC/PDOF # 1.......................11FZEW1 -20.0
4. CDC/PDOF # 2.......................01RDEW4 33.7
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 2
7. REST COORDINATES................... 52.1 7.3 9.0 14.1 21.3 250.9
8. IMPACT COORDINATES................. .7 .0 .0 12.4 .8 120.0
12. SKIDDING OF # 1?...................NO
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .010 .010 .200 .200
29. ROLL. RES, INDIV. WHEELS # 2....... .200 .200 .530 .020
33. STEER ANGLES #1.................... .0 .0 .0 .0
34. STEER ANGLES #2.................... .0 .0 .0 .0
SMAC:4... 50.50 60.50 62.00 11.20 35237.0 90.80 -113.70 38.30
SMAC:5... 40.30 54.60 56.00 6.83 15616.0 66.30 -88.67 30.50
SMAC:6...-11110.0-11110.0 -9266.0 -9266.0
SMAC:7... -7186.0 -7186.0 -5295.0 -5295.0

File s7j95
1. TITLE.........sricsac7.bat test#7, 7/26/95
2. CLASS/WEIGHTS...................... 4 4310. 2 2610.
3. CDC/PDOF # 1.......................12FDEW2 -3.0
4. CDC/PDOF # 2.......................02RDEW4 53.6
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 2
7. REST COORDINATES................... 75.7 20.3 17.4 19.3 43.4 258.6
8. IMPACT COORDINATES................. .4 .0 .0 12.5 .4 120.0
12. SKIDDING OF # 1?...................NO
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .010 .010 .230 .230
29. ROLL. RES, INDIV. WHEELS # 2....... .170 .170 1.000 .000
33. STEER ANGLES #1.................... .0 .0 .0 .0
34. STEER ANGLES #2.................... .0 .0 .0 .0
35. TERRAIN BOUNDARY?..................NO
SMAC:4... 50.50 60.50 62.00 11.20 46050.0 94.80 -113.70 38.30
SMAC:5... 39.70 55.30 56.00 6.75 15616.0 68.86 -90.44 30.50
SMAC:6...-11109.0-11109.0 -9265.0 -9265.0
SMAC:7... -7185.0 -7185.0 -5153.0 -5153.0

File s8j95

1. TITLE.........sricsac8.bat test#8, 7/26/95
2. CLASS/WEIGHTS...................... 4 4479. 4 4710.
3. CDC/PDOF # 1.......................12FDEW2 -20.0
4. CDC/PDOF # 2.......................03RYEW2 65.5
5. V#1 & V#2 STIFFNESS CATEGORIES..... 4 4
7. REST COORDINATES................... 1.7 7.8 28.5 1.0 23.0 145.0
8. IMPACT COORDINATES................. -10.8 1.7 .0 .0 .3 90.0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .010 .010 .400 .400
29. ROLL. RES, INDIV. WHEELS # 2....... .010 .010 .350 .350
33. STEER ANGLES #1.................... .0 .0 .0 .0
34. STEER ANGLES #2.................... .0 .0 .0 .0
35. TERRAIN BOUNDARY?..................NO

SMAC:4... 50.50 60.50 62.00 11.59 47654.0 94.80 -113.70 38.30
SMAC:5... 50.50 60.50 62.00 12.20 50121.0 94.80 -113.70 38.30
SMAC:6...-11062.0-11062.0-10117.0-10117.0
SMAC:7...-12008.0-10590.0-11157.0-10779.0

File s9j95

1. TITLE.........sricsac9.bat test#9, 7/26/95
2. CLASS/WEIGHTS...................... 1 2256. 4 4900.
3. CDC/PDOF # 1.......................11FDEW2 -31.0
4. CDC/PDOF # 2.......................02RFEW2 59.5
5. V#1 & V#2 STIFFNESS CATEGORIES..... 1 4
7. REST COORDINATES................... .8 37.8 119.2 -1.0 48.2 136.5
8. IMPACT COORDINATES................. .0 .0 .0 8.5 -5.4 90.0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................NO
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .300 .300 .010 .010
29. ROLL. RES, INDIV. WHEELS # 2....... .120 .010 .180 .180
33. STEER ANGLES #1.................... 5.0 5.0 .0 .0
34. STEER ANGLES #2.................... 9.0 9.0 .0 .0
35. TERRAIN BOUNDARY?..................NO

SMAC:4... 37.17 49.83 50.80 5.88 12281.0 62.77 -84.13 29.60
SMAC:5... 54.56 63.94 63.45 12.76 58000.0 100.29 -117.50 39.65
SMAC:6... -5959.0 -5959.0 -5446.0 -5446.0
SMAC:7...-12193.0-12193.0-10406.0-10406.0

File s10j95

1. TITLE.........sricsac10.bat test#10,7/26/95
2. CLASS/WEIGHTS...................... 1 2306. 4 4720.
3. CDC/PDOF # 1.......................10FDEW2 -65.0
4. CDC/PDOF # 2.......................01RFEW2 25.0
5. V#1 & V#2 STIFFNESS CATEGORIES..... 1 4
7. REST COORDINATES................... 1.5 59.1 89.0 -2.2 117.3 126.3
8. IMPACT COORDINATES................. .0 .0 .0 8.4 -6.7 90.0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CW
19. SKIDDING OF # 2?...................NO
24. ROTATION DIRECTION #2..............CW
28. ROLL. RES, INDIV. WHEELS # 1....... .340 .340 .010 .010
29. ROLL. RES, INDIV. WHEELS # 2....... .180 .180 .240 .240
33. STEER ANGLES #1.................... -3.0 -3.0 .0 .0
34. STEER ANGLES #2.................... 5.0 5.0 .0 .0
35. TERRAIN BOUNDARY?..................NO

SMAC:4... 36.37 50.63 50.80 6.00 10000.0 61.42 -85.48 29.60
SMAC:5... 55.38 63.12 63.45 12.29 50000.0 101.80 -116.00 39.65
SMAC:6... -6168.0 -6168.0 -4807.0 -4807.0
SMAC:7...-11598.0-11598.0-11025.0-11025.0

File s11j95

1. TITLE.........sricsac11.bat test#11,7/26/95
2. CLASS/WEIGHTS...................... 2 3041. 4 4850.
3. CDC/PDOF # 1.......................12FYEW3 -5.0
4. CDC/PDOF # 2.......................12FYEW3 -13.0
5. V#1 & V#2 STIFFNESS CATEGORIES..... 2 4
7. REST COORDINATES................... 23.6 -7.5 167.0 7.1 .7 .4
8. IMPACT COORDINATES................. 15.4 -4.1 170.0 .3 .0 .0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............N/A
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............N/A
26. TIRE-GROUND FRICTION............... .870
28. ROLL. RES, INDIV. WHEELS # 1....... .010 .010 .470 .470
29. ROLL. RES, INDIV. WHEELS # 2....... .010 .010 .185 .185
33. STEER ANGLES #1.................... -6.0 -6.0 .0 .0
34. STEER ANGLES #2.................... .0 .0 .0 .0
35. TERRAIN BOUNDARY?..................NO

SMAC:4... 49.45 47.50 55.20 7.92 22394.0 87.80 -84.40 32.70
SMAC:5... 54.40 63.60 63.45 12.63 56546.0 100.40 -117.40 39.65
SMAC:6... -6876.0 -6876.0 -7151.0 -7151.0
SMAC:7...-12056.0-12056.0-10314.0-10314.0

File s12j95

0 1. TITLE.........sricsac12.bat test#12,7/26/95
2. CLASS/WEIGHTS...................... 2 3130. 4 4512.
3. CDC/PDOF # 1.......................12FYEW4 -7.0
4. CDC/PDOF # 2.......................12FYEW4 -10.4
5. V#1 & V#2 STIFFNESS CATEGORIES..... 2 4
6. REST & IMPACT?.....................YES
7. REST COORDINATES................... 21.9 -9.4 140.6 7.6 2.4 -12.2
8. IMPACT COORDINATES................. 15.1 -4.4 170.0 .0 .0 .0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CCW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CCW
28. ROLL. RES, INDIV. WHEELS # 1....... .010 .440 .233 .233
29. ROLL. RES, INDIV. WHEELS # 2....... .010 .480 .240 .240
33. STEER ANGLES #1.................... 10.0 10.0 .0 .0
34. STEER ANGLES #2.................... 12.0 19.0 .0 .0
35. TERRAIN BOUNDARY?..................NO

SMAC:4... 47.20 49.58 55.20 8.15 23044.0 84.20 -88.00 32.70
SMAC:5... 55.62 62.38 63.45 11.75 52604.0 102.70 -115.10 39.65
SMAC:6... -7380.0 -7380.0 -7610.0 -7610.0
SMAC:7...-11002.0-11002.0-10628.0-10628.0

File s14j95

1. TITLE..........sricsac14.bat Texas A&M test#3 9/14/95
2. CLASS/WEIGHTS...................... 3 3820. 3 3820.
3. CDC/PDOF # 1.......................11FDEW4 -20.0
4. CDC/PDOF # 2.......................01FDEW5 40.0
5. V#1 & V#2 STIFFNESS CATEGORIES..... 3 3
7. REST COORDINATES................... 27.4 14.6-257.0 1.2 28.3 -80.0
8. IMPACT COORDINATES................. 5.2 -1.1 .0 8.4 -11.7 120.0
12. SKIDDING OF # 1?...................YES
17. ROTATION DIRECTION #1..............CCW
19. SKIDDING OF # 2?...................YES
24. ROTATION DIRECTION #2..............CCW
26. **TIRE-GROUND FRICTION............... .750**
28. ROLL. RES, INDIV. WHEELS # 1....... .020 .020 .400 .130
29. ROLL. RES, INDIV. WHEELS # 2....... .130 .250 .130 .130
33. STEER ANGLES #1.................... .0 .0 .0 .0
34. STEER ANGLES #2.................... .0 .0 .0 .0
35. TERRAIN BOUNDARY?..................NO

SMAC:4... 43.50 68.50 60.00 9.89 30255.0 84.00 -119.00 36.50
SMAC:5... 43.50 68.50 60.00 9.89 30255.0 84.00 -119.00 36.50
SMAC:6...-10200.0-10200.0-10200.0-10200.0
SMAC:7...-10200.0-10200.0-10200.0-10200.0