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ABSTRACT

The accuracy of the SMAC computer program was evaluated in terms of its ability to predict the correct paths and damage profiles for vehicles involved in a crash. A comparison of the results from SMAC and EDSMAC were presented along with measured results from twelve staged collisions. Statistical analysis of those results revealed the average path error was 25 to 29 percent and the average damage profile error was 109 to 287 percent. A procedure was presented for improving the match between simulated and measured paths. After using this procedure, the average path error was reduced to -2 to 7 percent and the average damage profile error was 54 to 186 percent. CDC predictions were very good. Damage profile errors, which did not reduce the program's overall effectiveness, were the result of the way the program computes inter-vehicle forces, leading to a recommendation that the algorithm be reformulated to include an initial force coefficient. The findings also led to a discussion of how the term 'accuracy' was defined for crash simulation programs.

THE SMAC COMPUTER PROGRAM was developed during the early seventies as a means to help improve the process of accident investigation. Originally developed by CALSPAN [1,2]* under contract to the National Highway Traffic Safety Administration (NHTSA), its use was limited by two factors. First, the computational costs were high (approximately $20 per run). Second, SMAC (Simulation Model of Automobile Collisions) required estimates of impact speed; good estimates were difficult to obtain. Thus, several trial and error runs were required, increasing the cost per accident even further. Ultimately, NHTSA changed its approach and selected the CRASH program for its statistical research studies. No further NHTSA-sponsored work has been undertaken on the SMAC program since 1979.

* Numbers in brackets designate references found at the end of the paper.

Over the next few years, SMAC continued to see limited use by field accident investigators, primarily in forensic applications. SMAC was attractive in forensic work because, among other things, it produced a graphic display of the vehicle motion during the entire accident sequence. Investigators found these graphic results very useful when describing an accident to lay persons. In May of 1985, a PC version called EDSMAC [3] was introduced. Because of the availability of a PC version and SMAC's attractive features, its current level of usage has increased considerably.

This paper describes a study used to validate the SMAC and EDSMAC computer programs. This research is an extension of the work originally conducted by CALSPAN, called Research Input for Computer Simulation of Automobile Collisions (RICSAC, [4,5,6,7]). In that 1978 study, 12 two-car collisions were staged. Each vehicle was instrumented and the collisions were filmed using high speed cameras. These measured results were used as a basis for comparison to SMAC and CRASH2.

Several extensions and refinements to the SMAC program were produced during the development of EDSMAC. However, no validation study of these improvements has been published [8]. The purpose of this paper is to compare the actual staged collision results with the results from SMAC and EDSMAC. These comparisons provide an assessment of each program's validity.

HISTORICAL OVERVIEW

The RICSAC study represented the world's largest single attempt to determine the accuracy of any reconstruction tool. It was conducted under contract with NHTSA, which intended to use the CRASH and SMAC programs for various statistical studies [9,10]. The RICSAC test procedure is summarized below.

RICSAC Study

The RICSAC study was an analysis and reconstruction of 12 two-car staged collisions. The collisions were conducted at CALSPAN's Vehicle Experimental Research Facility (VERF) between November, 1977 and July, 1978.

Table 1. RICSAC Staged Collisions.

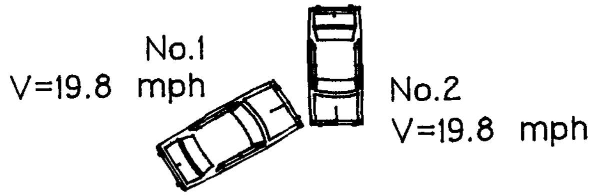
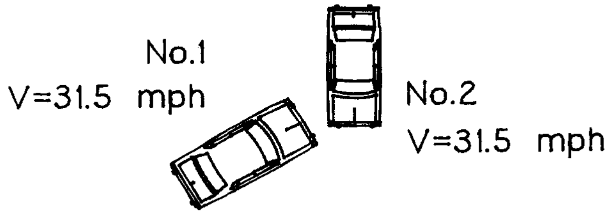
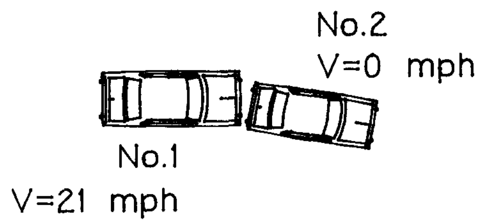
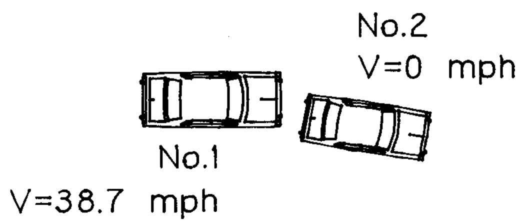
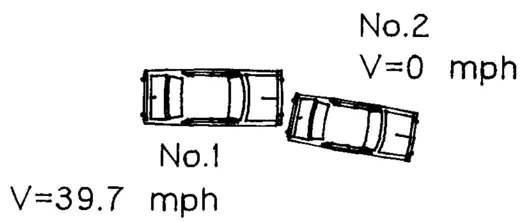
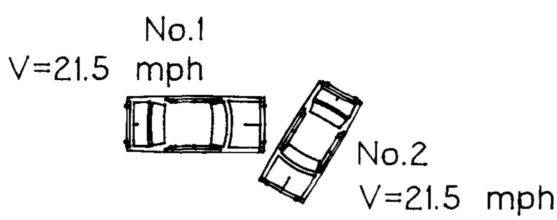
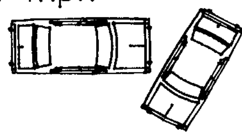
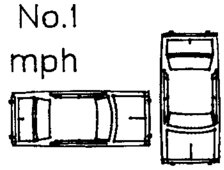
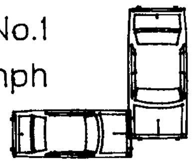
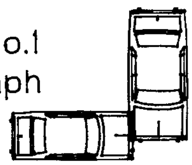
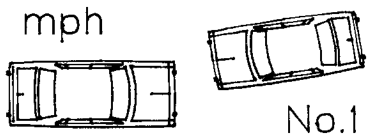
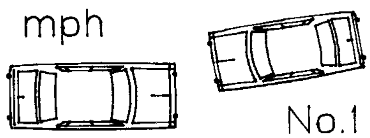
TEST No.	VEHICLES	COLLISION TYPE	CONFIGURATION at IMPACT
1	No. 1 - '74 Chevelle Malibu No. 2 - '74 Ford Pinto	Oblique	
2	No. 1 - '74 Chev Chevelle No. 2 - '74 Ford Pinto	Oblique	
3	No. 1 - '74 Ford Torino No. 2 - '74 Ford Pinto	Collinear	
4	No. 1 - '74 Ford Torino No. 2 - '74 Ford Pinto	Collinear	
5	No. 1 - '74 Ford Torino No. 2 - '74 Honda Civic	Collinear	
6	No. 1 - '74 Chev Chevelle No. 2 - '75 VW Rabbit	Oblique	

Table 1. RICSAC Staged Collisions (continued from previous page).

TEST No.	VEHICLES	COLLISION TYPE	CONFIGURATION at IMPACT
7	No. 1 - '74 Chev Chevelle No. 2 - '75 VW Rabbit	Oblique	No.1 V=29.1 mph  No.2 V=29.1 mph
8	No. 1 - '74 Chev Chevelle No. 2 - '74 Chev Chevelle	Oblique	No.1 V=20.8 mph  No.2 V=20.8 mph
9	No. 1 - '74 Honda Civic No. 2 - '74 Ford Torino	Oblique	No.1 V=21.2 mph  No.2 V=21.2 mph
10	No. 1 - '74 Honda Civic No. 2 - '74 Ford Torino	Oblique	No.1 V=33.3 mph  No.2 V=33.3 mph
11	No. 1 - '74 Chev Vega No. 2 - '74 Ford Torino	Collinear	No.2 V=20.4 mph  No.1 V=20.4 mph
12	No. 1 - '74 Chev Vega No. 2 - '75 Ford Torino	Oblique	No.2 V=31.5 mph  No.1 V=31.5 mph

The surface at the facility had a tested friction coefficient of 0.87 (ASTM E-274 [11]).

Impact Configurations - Several impact configurations were tested (see Table 1). These configurations represented those typical of most real-world accidents, and included head-on, rear-end and intersection-type collisions. Head-on and rear-end collisions were termed *collinear*, because the directions of their pre-impact velocity vectors are within 10 degrees of parallel; the remaining range was termed *oblique*.

Instrumentation - Each vehicle was fitted with a complete instrumentation package described in reference 5. The minimum package for measuring time-histories included:

- a triaxial accelerometer mounted on the firewall (vehicle position, velocity, acceleration).
- linear stroke potentiometers mounted on steering linkage (wheel steer angles).
- electric tachometers on at least three wheels (wheel spin velocity for percent lock-up).
- Teledyne Geotech Model 35500 crash recorders for recording the data.
- a minimum of ten high-speed cameras, including two hand-held cameras, eye-level cameras and cameras mounted on portable towers, for filming each crash test.
- marker paint sprayed from nozzles (two per vehicle) mounted on the unsprung mass approximately 1 inch above ground level for directly identifying each vehicle's path.

Post-crash Inspection - After the collision, the site evidence was documented by CALSPAN's professional accident investigation team. This evidence included:

- wheel positions at impact and rest
- locations of debris, skids, gouges and spilled fluids
- vehicle trajectory (spray paint)

See reference [5] for a complete description of the test procedures.

Evaluation by SMAC - As part of the original RICSAC study, the accident site and vehicle inspection results for each of the 12 staged collisions were reduced into SMAC input data sets, and the SMAC-simulated results were produced for comparison with the measured results [7].

Validation Procedure

Since the original RICSAC study, no comparison between the staged collisions and the results produced by EDSMAC has been published. As part of the current research, the same 12 data sets from the original RICSAC study were fed into SMAC and EDSMAC to obtain the results from both programs.

The measured data reported in this paper were obtained from references 4 through 7 and supplemented by analysis of the high-speed film performed subsequently by NHTSA [12]. The SMAC results were obtained on an Amdahl V8 computer using source code purchased from McDonnell Douglas Automation Company (McAuto was a computer service bureau under contract to NHTSA) in 1981. The EDSMAC results were obtained using Version 2.3 on a Compaq Deskpro 286 PC.

The remainder of this paper deals with a comparison of the measured staged collision results with the results predicted by SMAC and EDSMAC.

Program Differences

During the development of EDSMAC and its subsequent enhancements, the original mainframe version of SMAC was modified. These modifications included changes to the overall program design. SMAC was a batch-oriented, mainframe computer program, whereas EDSMAC was designed to take advantage of the interactive PC environment; see figures 1 and 2. Other modifications included changes and corrections to the calculation procedures themselves. These changes were made in the following areas:

- Driver input tables
- Terrain boundary
- Correction to COLL subroutine
- Correction to DAMAGE subroutine
- Correction to RANGDAM subroutine

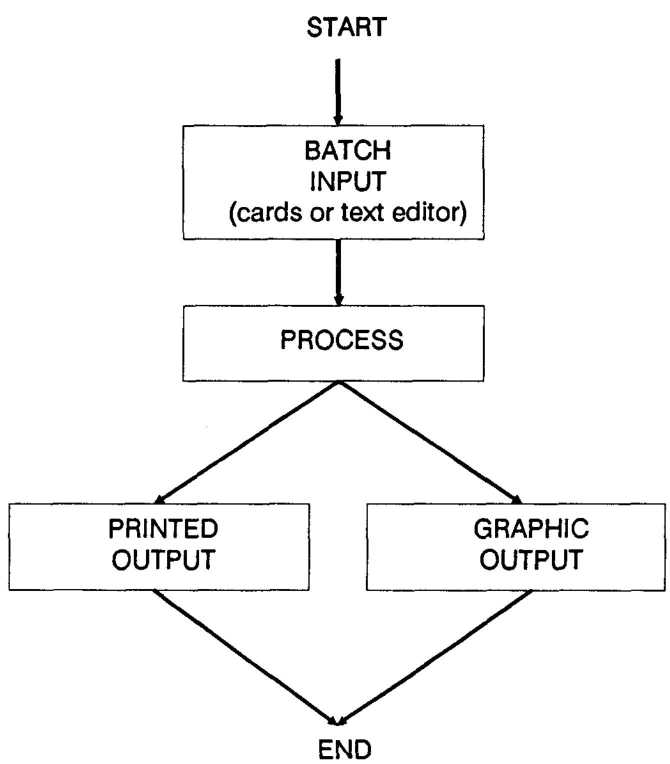


Figure 1 - Flow chart for SMAC

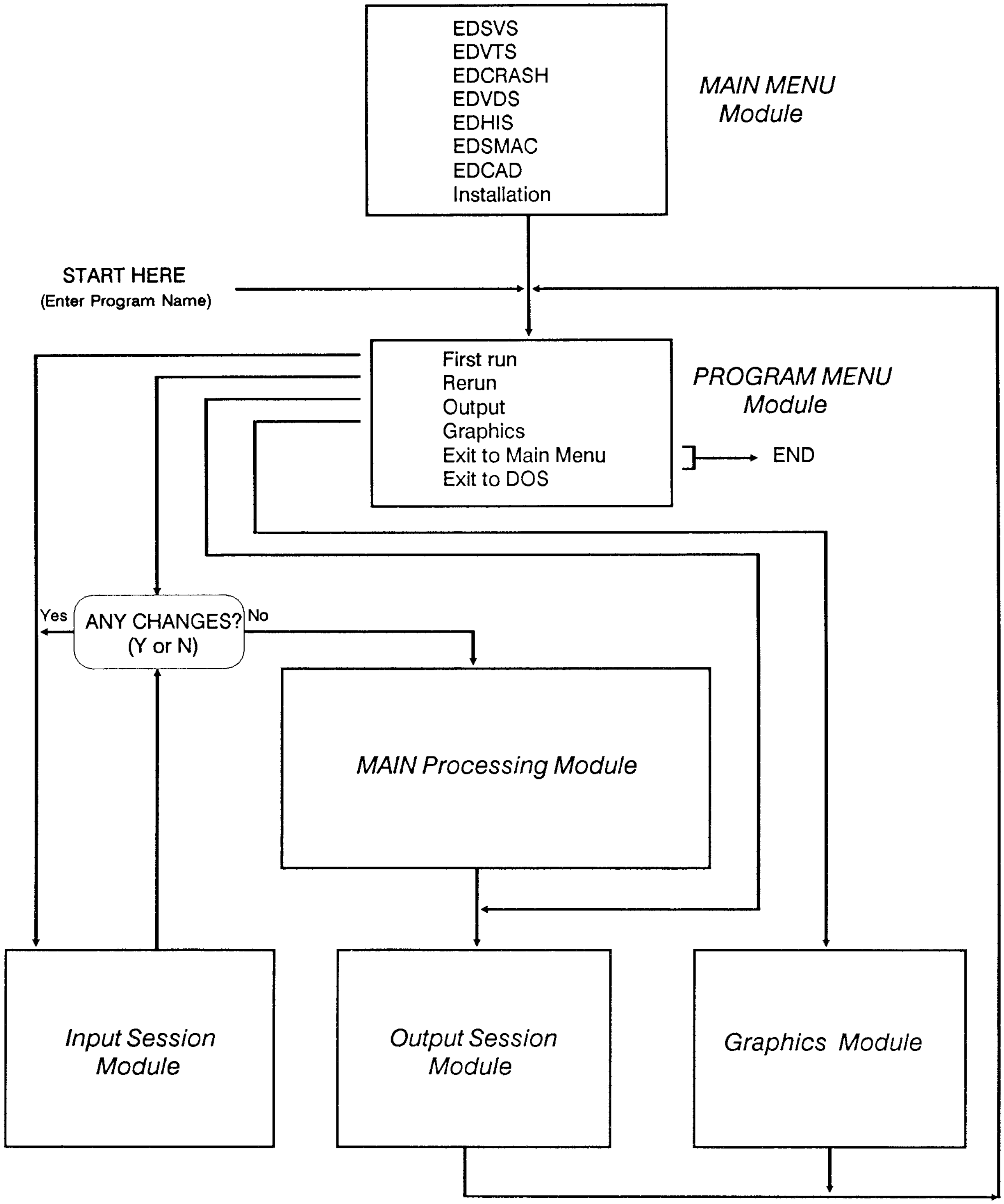


Figure 2 - Flow chart for EDSMAC

Each of these changes was described in reference 13. The source code for EDSMAC, showing the exact details of each change, can be found in reference 14.

VALIDATION RESULTS

During the original RICSAC study, SMAC input data sets were prepared for each of the twelve staged collisions [7]. These data sets were fed into SMAC and EDSMAC and output files were produced. The results of interest were:

- Path (rest) positions
- Damage profiles
- Collision Deformation Classification (CDC)
- Delta-V

Table 2 shows the rest path positions, CDCs and delta-Vs for both programs, along with the measured test results. Table 3 shows the corresponding damage results.

PROGRAM ACCURACY

The term 'accuracy', when applied to simulation programs, described how well the program predicted the outcome of the event. The outcome was the data shown in Table 2 (path, CDC and delta-V) and Table 3 (damage profiles). The accuracy of the data was analyzed differently, depending on the nature of the results.

Path Positions

Path position errors were analyzed according to the distance from the predicted rest position to the measured rest position, as shown in Figure 3 (this was also the procedure used to calculate the error scores for the trajectory simulation option in CRASH [15]). For the difference in (X,Y) coordinates (*range* error), the error was

$$\text{ERROR }(\%) = \Delta(X,Y)/L_{act}*100$$

where

$$\Delta(X,Y) = \text{difference between predicted and measured rest position}$$

$$= \sqrt{(X_{pred}-X_{act})^2 + (Y_{pred}-Y_{act})^2} \quad \text{(ft)}$$

$$L_{act} = \text{actual path length}$$

$$= \sqrt{(X_{rest}-X_{imp})^2 + (Y_{rest}-Y_{imp})^2} \quad \text{(ft)}$$

pred ≡ predicted value
act ≡ actual (measured) value
rest ≡ rest coordinate
imp ≡ impact coordinate

For the difference in heading angle, the error was

$$\text{ERROR }(\%) = (\Delta\psi_{pred} - \Delta\psi_{act})/360$$

where

$$\Delta\psi_{pred} = (\psi_{rest} - \psi_{imp})_{pred}$$
$$\Delta\psi_{act} = (\psi_{rest} - \psi_{imp})_{act}$$

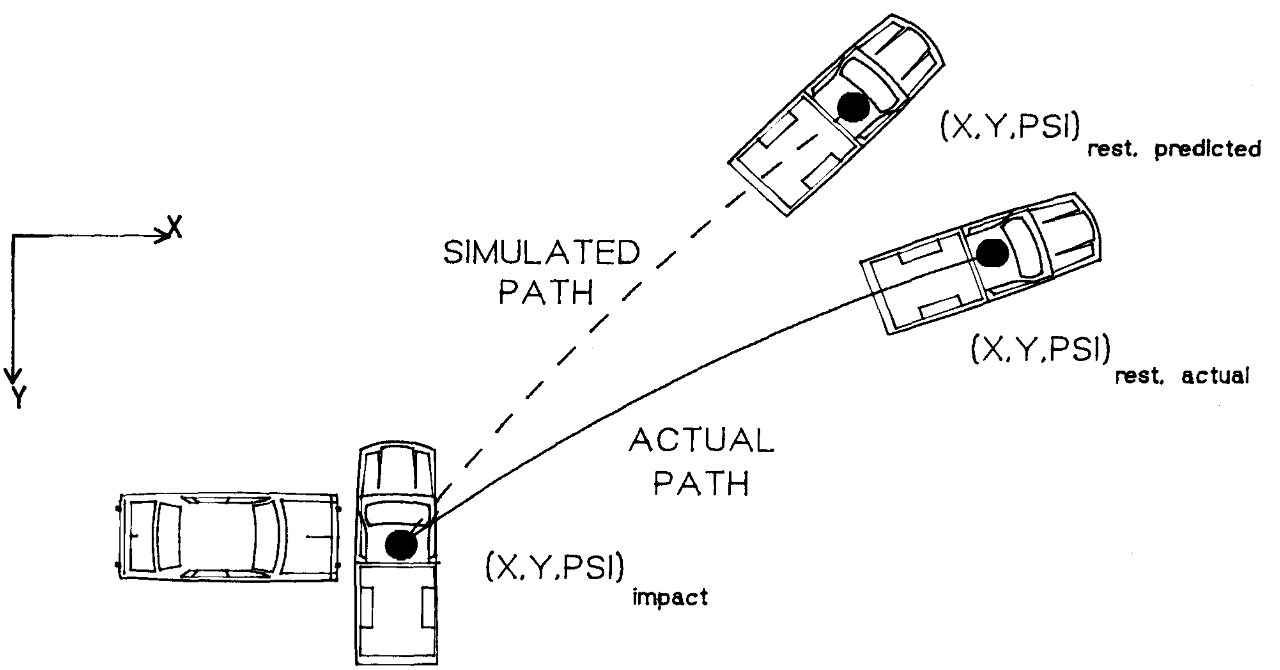


Figure 3 - Path error analysis

Table 2. Validation results for rest position, CDC and delta-V. Measured test data and results from SMAC and EDSMAC.

TEST No.	METHOD	REST POSITION Veh #1 X (ft)	REST POSITION Veh #1 Y (ft)	REST POSITION Veh #1 PSI (deg)	REST POSITION Veh #2 X (ft)	REST POSITION Veh #2 Y (ft)	REST POSITION Veh #2 PSI (deg)	CDC Veh #1	CDC Veh #2	DELTA-V Veh #1 (mph)	DELTA-V Veh #2 (mph)
1	*MEASURED*	*-1.0**	*5.4**	*-1.5*	*8.5**	*7.8**	*105.0*	*11FZEW2*	*01RDEW3*	*12.2*	*15.6*
	SMAC	*-1.0*	*5.5*	*1.3*	*8.7*	*7.2*	*91.9*	*11FDEW2*	*03RDEW3*	*14.3*	*20.6*
	EDSMAC	*-1.0*	*5.5*	*1.3*	*8.8*	*7.2*	*92.1*	*12FDEW2*	*03RDEW3*	*14.2*	*20.5*
2	*MEASURED*	*11.0*	*9.4*	*55.0*	*23.6*	*12.5*	*134.0*	*11FDEW2*	*02RDEW4*	*19.6*	--
	SMAC	*0.0*	*3.6*	*49.9*	*40.7*	*16.6*	*191.3*	*11FDEW2*	*01RDEW5*	*24.8*	*35.4*
	EDSMAC	*4.4*	*3.5*	*78.5*	*22.2*	*14.9*	*177.6*	*11FDEW1*	*02RDEW5*	*20.9*	*29.6*
3	*MEASURED*	*111.4*	*2.0*	*-4.0*	*181.5*	*-6.3*	*-19.0*	*12FZEW1*	*06BZEW1*	*9.5*	*15.8*
	SMAC	*119.8*	*3.6*	*-4.7*	*191.1*	*-0.1*	*-22.1*	*12FZEW2*	*06BYEW2*	*9.9*	*15.7*
	EDSMAC	*118.2*	*3.7*	*-4.6*	*192.5*	*-0.6*	*-22.5*	*12FZEW2*	*06BYEW2*	*9.9*	*15.8*
4	*MEASURED*	*42.8*	*54.5*	*137.5*	*63.9*	*62.5*	*88.0*	*12FZEW3*	*05BYEW5*	*18.7*	*22.2*
	SMAC	*47.7*	*43.6*	*103.5*	*73.6*	*66.7*	*69.5*	*12RFEW2*	*06BDEW4*	*16.9*	*26.1*
	EDSMAC	*36.4*	*58.1*	*137.5*	*79.4*	*60.1*	*54.6*	*12FZEW4*	*06BDEW4*	*16.0*	*24.9*
5	*MEASURED*	*252.0**	*0.0*	*0.0*	*59.0**	*35.0**	*282.0*	*12FZEW1*	*05BDEW2*	*16.3*	*25.1*
	SMAC	*175.4*	*-31.6*	*-11.2*	*83.0*	*30.6*	*242.1*	*12RFEW2*	*06BYEW5*	*14.9*	*26.4*
	EDSMAC	*175.6*	*-30.0*	*-10.6*	*83.4*	*30.5*	*243.5*	*12FZEW4*	*06BYEW5*	*14.9*	*26.5*
6	*MEASURED*	*60.0*	*11.0*	*15.0*	*20.0*	*21.0*	*242.0*	*11FZEW1*	*02RDEW3*	*9.2*	*11.9*
	SMAC	*35.4*	*17.3*	*32.4*	*20.8*	*29.0*	*245.4*	*12FDEW3*	*01RDEW5*	*10.8*	*16.9*
	EDSMAC	*35.1*	*17.7*	*33.2*	*20.7*	*28.5*	*244.8*	*12FDEW1*	*01RDEW5*	*10.8*	*16.8*
7	*MEASURED*	*84.5*	*18.2*	*16.5*	*22.9*	*41.4*	*262.0*	*11FDEW1*	*02RDEW4*	*12.0*	*16.5*
	SMAC	*96.3*	*7.4*	*5.0*	*0.3*	*51.6*	*287.3*	*12FDEW3*	*02RDEW4*	*8.4*	*12.3*
	EDSMAC	*96.2*	*7.3*	*5.0*	*2.3*	*47.1*	*285.3*	*12FDEW3*	*02RDEW4*	*8.4*	*12.3*
8	*MEASURED*	*0.0**	*10.8**	*45.0**	*6.3**	*19.2**	*130.0**	*12FDEW1*	*03RYEW2*	*15.3*	*10.7*
	SMAC	*0.7*	*10.8*	*42.2*	*3.8*	*22.5*	*133.2*	*11FDEW2*	*03RDEW3*	*18.0*	*13.6*
	EDSMAC	*0.7*	*10.8*	*41.9*	*3.8*	*22.0*	*133.7*	*11FDEW2*	*03RDEW3*	*17.5*	*13.6*
9	*MEASURED*	*4.0*	*35.5*	*104.0*	*-5.0*	*49.5*	*152.0*	*11FDEW2*	*02RFEW2*	*21.4*	*8.9*
	SMAC	*7.7*	*16.8*	*73.5*	*-17.8*	*57.5*	*166.9*	*11FLEE2*	*02RYEW3*	*20.2*	*8.6*
	EDSMAC	*7.7*	*16.9*	*73.8*	*-17.9*	*57.4*	*166.9*	*11FDEW4*	*02RYEW3*	*20.2*	*8.6*
10	*MEASURED*	*5.0*	*43.0*	*87.0*	*0.0*	*99.5*	*128.5*	*10FDEW2*	*01RFEW2*	*35.1*	*14.1*
	SMAC	*-4.8*	*27.1*	*141.4*	*5.0*	*103.2*	*118.1*	*11FLEE3*	*02RYEW3*	*36.2*	*15.2*
	EDSMAC	*-4.5*	*25.7*	*148.5*	*5.5*	*103.2*	*117.8*	*11FDEW5*	*02RYEW3*	*36.1*	*15.2*
11	*MEASURED*	*25.6*	*-6.4*	*170.0*	*8.6*	*0.4*	*0.0*	*12FYEW3*	*12FYEW3*	*24.0*	*15.7*
	SMAC	*23.2*	*-7.4*	*167.1*	*6.9*	*0.7*	*0.3*	*12FYEW3*	*12LFEW2*	*28.7*	*17.6*
	EDSMAC	*23.2*	*-7.4*	*167.2*	*6.8*	*0.7*	*0.2*	*12FYEW3*	*12FYEW4*	*28.6*	*17.6*
12	*MEASURED*	*22.3*	*-5.5*	*118.0*	*6.8*	*2.6*	*-12.0*	*12FDEW4*	*12FYEW4*	*40.1*	*26.4*
	SMAC	*21.3*	*-6.5*	*148.7*	*8.8*	*1.6*	*-1.8*	*12FDEW4*	*12LFEW3*	*40.9*	*27.6*
	EDSMAC	*21.2*	*-6.5*	*148.6*	*8.9*	*1.6*	*-1.7*	*12FDEW4*	*12FYEW3*	*40.7*	*27.5*

* These measured data were inconsistent with reference materials [7]. The source of the inconsistencies could not be identified.

Table 3. Validation results for vehicle damage (damage areas not available for SMAC)

TEST No.	METHOD	DAMAGE AREA Veh #1 (in^2)	DAMAGE AREA Veh #2 (in^2)
1	MEASURED	330	1050
	EDSMAC	704	1015
2	MEASURED	498	1930
	EDSMAC	684	3760
3	MEASURED	56	159
	EDSMAC	495	517
4	MEASURED	265	984
	EDSMAC	532	1350
5	MEASURED	53	1330
	EDSMAC	484	916
6	MEASURED	71	1100
	EDSMAC	679	1370
7	MEASURED	188	1297
	EDSMAC	840	1610
8	MEASURED	263	529
	EDSMAC	698	1800
9	MEASURED	293	218
	EDSMAC	547	821
10	MEASURED	475	288
	EDSMAC	771	1040
11	MEASURED	571	661
	EDSMAC	773	964
12	MEASURED	871	743
	EDSMAC	1220	1610

Path errors for each case are tabulated in Table 4. The average and standard deviation for all runs are also shown. These results revealed an average range error of approximately 24 to 29 percent and average heading error of approximately 0 to 2 percent. The differences between programs and the differences between vehicle #1 and #2 were not significant at a 95 percent level of confidence.

An allowable error of 10 percent was established as a permissible limit for path errors. This limit was selected because of its use as the convergence test criterion for the trajectory simulation in CRASH [15]. Inspection of the results revealed only 11 of the 24 total paths met this criterion for range error; 22 of the 24 rest positions met the criterion for heading error.

The path errors were associated with a variety of sources, both from the simulations as well as from the test data itself.

On tests 4, 5, 6, 7, 9 and 10, one of the vehicles was still moving at the end of the simulation. Thus, a meaningful comparison for these cases required rerunning them with longer simulation times.

Review of the staged collision results [7] revealed in test no. 5, vehicle #1 was brought to rest prematurely by its data cable. During test no. 10, vehicle #2 was brought to rest prematurely when it struck a metal transformer. During test no. 10, a metal bar extending from the rear of vehicle #1 contacted vehicle #2, thus affecting the separation conditions for both vehicles. These problems limited the use of these tests in a validation study where rest position was of key interest.

Simulation nos. 4, 6, 7 and 9 were rerun with longer simulation times. Error analysis of the results revealed no significant improvement. In fact, the average range error actually increased from 24.6 percent to 29.6 percent when these simulations were allowed to run to completion. The lack of improvement may have been the unintended result of optimizing the original data sets to the shortened run times.

Damage Profiles

Measured and predicted damage profiles were compared by computing the difference in the damage areas, as shown in figure 4. Using this approach, the damage error was

$$\text{ERROR}\ (\%) = (A_{pred} - A_{act})/A_{act}$$

where

A_{pred} = Area of simulated damage (in^2)
A_{act} = Area of measured damage (in^2)

Damage profile errors are shown in Table 4. The average and standard deviation are also shown. Inspection of these results revealed EDSMAC significantly overestimated the vehicle damage, the average error being approximately 109 to 287 percent. The difference in the average error between vehicles was not statistically significant. However, the data scatter, as indicated by the standard deviation, was significantly less for vehicle 2 than for vehicle 1. This suggested perhaps the collision algorithm, COLL, tended to produce more consistent results for vehicle #2 than for vehicle #1. (Prior in-house validations of SMAC and EDSMAC [16] have confirmed slightly different results are obtained for the same accident when the vehicles are swapped and the simulation is rerun.)

It was apparent from these results that the SMAC DAMAGE algorithm significantly overestimated crush depth for the RICSAC cases. Inspection of the individual cases revealed the error was greatest for cases involving minor crush depths. Increasing the crush stiffnesses by a factor of two did not substantially reduce the error for these cases. A possible reason is presented in the *Discussion* section of this paper.

Table 4. Path and damage profile errors

TEST No.	METHOD	PATH ERROR								DAMAGE PROFILE ERROR *	
		Veh #1				Veh #2				Veh #1 (%)	Veh #2 (%)
		RANGE		HEADING		RANGE		HEADING			
		(ft)	(%)	(deg)	(%)	(ft)	(%)	(deg)	(%)		
1	*SMAC*	*0.1*	*1.0*	*2.8*	*0.8*	*0.6*	*5.5*	*-13.1*	*-3.6*	--	--
	EDSMAC	*0.1*	*1.0*	*2.8*	*0.8*	*0.7*	*5.8*	*-12.9*	*-3.6*	*113.3*	*--3.3*
2	*SMAC*	*12.4*	*56.0*	*-5.1*	*-1.4*	*17.6*	*65.8*	*57.3*	*15.9*	--	--
	EDSMAC	*8.9*	*39.8*	*23.5*	*6.5*	*2.8*	*10.4*	*43.6*	*12.1*	*37.4*	*94.8*
3	*SMAC*	*8.6*	*7.7*	*-0.7*	*-0.2*	*11.4*	*6.9*	*-3.1*	*-0.9*	--	--
	EDSMAC	*7.0*	*6.3*	*-0.6*	*-0.2*	*12.4*	*7.4*	*-3.5*	*-1.0*	*783.9*	*225.2*
4	*SMAC*	*12.0*	*17.2*	*-34.0*	*-9.4*	*10.6*	*13.9*	*-18.5*	*-5.1*	--	--
	EDSMAC	*7.3*	*10.6*	*0.0*	*0.0*	*15.7*	*20.7*	*-33.4*	*-9.3*	*100.8*	*37.2*
5	*SMAC*	*82.9*	*32.9*	*-14.2*	*-3.9*	*24.4*	*45.0*	*-39.9*	*-11.1*	--	--
	EDSMAC	*82.1*	*32.6*	*-13.6*	*-3.8*	*24.8*	*45.7*	*-38.5*	*-10.7*	*813.2*	*-31.1*
6	*SMAC*	*25.4*	*41.6*	*17.4*	*4.8*	*8.0*	*39.5*	*3.4*	*0.9*	--	--
	EDSMAC	*25.8*	*42.3*	*18.2*	*5.1*	*7.5*	*37.0*	*2.8*	*0.8*	*856.3*	*24.6*
7	*SMAC*	*16.0*	*18.5*	*-11.5*	*-3.2*	*24.8*	*62.2*	*25.3*	*7.0*	--	--
	EDSMAC	*16.0*	*18.5*	*-11.5*	*-3.2*	*21.4*	*53.6*	*23.3*	*6.5*	*346.8*	*24.1*
8	*SMAC*	*0.7*	*5.3*	*-2.8*	*-0.8*	*4.1*	*22.5*	*3.2*	*0.9*	--	--
	EDSMAC	*0.7*	*5.3*	*-3.1*	*-0.9*	*3.8*	*20.4*	*3.7*	*1.0*	*165.4*	*240.3*
9	*SMAC*	*19.1*	*53.4*	*-30.5*	*-8.5*	*15.1*	*26.5*	*14.9*	*4.1*	--	--
	EDSMAC	*19.0*	*53.1*	*-30.2*	*-8.4*	*15.1*	*26.5*	*14.9*	*4.1*	*87.0*	*276.6*
10	*SMAC*	*18.7*	*43.1*	*54.4*	*15.1*	*6.2*	*5.9*	*-10.4*	*-2.9*	--	--
	EDSMAC	*19.7*	*45.6*	*61.5*	*17.1*	*6.6*	*6.3*	*-10.7*	*-3.0*	*62.3*	*261.1*
11	*SMAC*	*2.6*	*25.5*	*-2.9*	*-0.8*	*1.7*	*20.1*	*0.3*	*0.1*	--	--
	EDSMAC	*2.6*	*25.5*	*-2.8*	*-0.8*	*1.8*	*21.2*	*0.2*	*0.1*	*35.4*	*45.8*
12	*SMAC*	*1.4*	*20.9*	*30.7*	*8.5*	*2.2*	*30.7*	*10.2*	*2.8*	--	--
	EDSMAC	*1.5*	*22.0*	*30.6*	*8.5*	*2.3*	*31.9*	*10.3*	*2.9*	*40.1*	*116.7*
AVG	*SMAC*	*16.6*	*26.9*	*0.3*	*0.1*	*10.6*	*28.7*	*2.5*	*0.7*	--	--
	EDSMAC	*15.9*	*25.2*	*6.2*	*1.7*	*9.6*	*23.9*	*0.0*	*0.0*	*286.8*	*109.3*
STD.DEV.	*SMAC*	*21.5*	*17.7*	*23.6*	*6.6*	*8.0*	*19.9*	*23.1*	*6.4*	--	--
	EDSMAC	*21.5*	*17.7*	*23.6*	*6.6*	*7.8*	*15.1*	*21.8*	*6.0*	*317.3*	*107.2*

* Damage profiles were unavailable for SMAC.

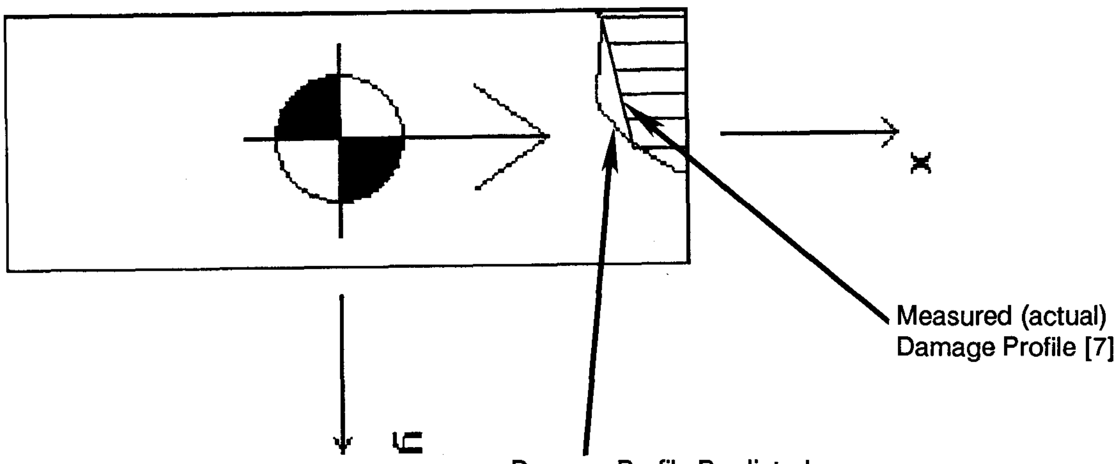


Figure 4 - Damage error analysis

CDC

The Collision Deformation Classification (CDC) is a 7-character code representing the location and extent of vehicle damage. Because it is a code, it has no numeric value amenable to calculation. Therefore, a rigorous error analysis could not be performed. However, an assessment was performed by observing the number of differences between the assigned (measured) characters and the predicted characters. Using this approach, the error in each coding entry (PDOF, General Damage Area, Specific Damage Area, Damage Elevation, Damage Distribution, and Damage Extent) was computed for each of the 24 assigned CDCs as follows:

$$\text{ERROR (\%)} = (\text{\# of errant predictions}/24)*100$$

Table 5 shows the results for each coding entry. Inspection of these results revealed the following:

PDOF - The measured and predicted values for the principal direction of force (PDOF), as indicated by the clock direction in the CDC, disagreed for both SMAC and EDSMAC in 41.7 percent of the cases. Because accurate field measurements of PDOF are difficult to establish, it was quite possible the SMAC and/or EDSMAC results were better than the "measured" values. The difference between SMAC and EDSMAC results for Case No. 1, Veh #1 could not be identified, but were probably the result of computer round-off. The difference for Case No. 2, Veh #2 was attributed to the error in SMAC's COLL routine which was corrected in EDSMAC (see reference 13).

General Damage Area - The measured and predicted damage areas (3rd character of the CDC) disagreed for 16.7 percent of the cases in SMAC. The disagreement was traced to an error in the DAMAGE routine [13]. EDSMAC agreed with the measured values in all 24 cases.

Specific Damage Area - The difference between measured and predicted specific areas of damage (4th character of CDC) was quite significant in both programs (58.3 percent in SMAC; 33.3 percent in EDSMAC). Corrections to the DAMAGE routine logic [13] were responsible for the improvement in EDSMAC. However, the specific zones, which are set constant in both SMAC and EDSMAC, actually vary from vehicle to vehicle due to differences in design and styling. Small improvements might be gained by modifying the programs' zone constants. However, it is doubtful the improvement would be justified for all vehicles: Although some cases might show improvement, other cases would probably become worse.

Damage Elevation - All the staged collisions had damage elevations below the beltline. Thus, the 5th character was always *E*. In SMAC and EDSMAC, the 5th character is set to *E* (and is a constant). Therefore, SMAC and EDSMAC were in agreement with the measured values for all collisions.

Damage Distribution - The measured and predicted damage distributions (6th character of CDC) disagreed in 8.3 percent of the cases for SMAC. The disagreement was traced to the error in the DAMAGE routine (see reference 12). EDSMAC agreed with the measured values in all 24 cases.

Extent of Damage - The damage extents (7th character of CDC) showed the poorest agreement between measured and predicted character values (70.8 percent error for SMAC; 75.0 percent for EDSMAC). Corrections to the COLL and DAMAGE routines actually *reduced* the agreement between EDSMAC and the measured values. These differences were found to be the result of several factors. The primary cause was similar to the cause of differences between predicted and computed 4^{th} characters: the specific extent zones, which are set constant in both SMAC and EDSMAC, actually varied from vehicle to vehicle due to differences in design and styling. Because no attempt has been made to fine-tune the zones for each individual vehicle, such differences should be expected.

Another factor was traced to the COLL routine. Inspection of the damage profiles revealed the algorithm tended to over-predict vehicle crush at the corners. Thus, the predicted crush extents were greater than measured.

Delta-V

Several studies published since 1978 have attempted to use the RICSAC delta-V data as a basis for validation of CRASH, SMAC and other programs [7,17,18,19]. In many cases, researchers found significant differences between delta-Vs computed by the programs and the delta-Vs measured during the RICSAC study. This has led some researchers to question the accuracy and usefulness of these programs. However, the original research [5,6,7] clearly stated there were problems with the sophisticated data acquisition systems aboard the vehicles. One of the major problems encountered during the study was the fact that the accelerometer data were not taken at the center of gravity (CG), but rather, at the firewall. Thus, any rotation during impact would cause *some* error (the amount depending on the actual rotation rate and distance from the CG to the firewall) in the measured separation velocities and, therefore, the delta-V.

Subsequent to the original study, analysis of the high-speed film was used to improve the test data. However, the high-speed film was not analyzed for all the staged collisions. In this paper, the high-speed film results were used where available [12]. Analysis of the best available staged collision results revealed the delta-Vs were not inversely proportional to the vehicle masses (this should be approximately true for a collision when tire forces are small compared to impact forces). It was felt the error in the test data might be in the same order of magnitude as the error in the computer programs.

Because of the problems with the RICSAC data for separation velocity and delta-V, the accuracy of these data could not be properly evaluated. Previous program evaluations which used the RICSAC data as a means of validation for delta-V are suspect. The program estimates may be better (or worse) than reported.

Table 5. CDC errors

Character(s)	METHOD	ERROR (percent)
1,2	*SMAC*	*41.7*
	EDSMAC	*41.7*
3	*SMAC*	*16.7*
	EDSMAC	*0.0*
4	*SMAC*	*58.3*
	EDSMAC	*33.3*
5	*N/A*	*N/A*
6	*SMAC*	*8.3*
	EDSMAC	*0.0*
7	*SMAC*	*70.8*
	EDSMAC	*75.0*

OPTIMIZATION

The level of error produced by the original RICSAC data sets was felt to be unacceptable. Therefore, the data were modified and rerun.

When simulating a crash, the goal was to have the predicted results match the actual results. Since only a few of the input parameters were actually known with great precision, the usual approach was to vary one or more of the estimated parameters until a satisfactory match was achieved. This process was termed *optimization*.

Optimization Process

The optimization process required skill, experience and good intuitive logic. Over the years, a procedure has been developed which helped to quicken the process of achieving a satisfactory match between predicted and actual results. This procedure began with the following steps:

- Identify the difference(s) between the predicted and measured results. Usually, the results of interest are (a) rest position and heading and (b) damage profiles.
- Identify the unknown or estimated input parameters and their associated possible ranges. Eliminate the remaining parameters from consideration.
- Identify those unknown or estimated parameters which have the greatest effect on the identified differences. Eliminate the remaining parameters from consideration.

As a result of the above procedure, a list was developed containing only those parameters which were capable of effecting the desired changes. Next came the process of improving the match between the predicted and actual paths and damage profiles. This process is outlined below:

- First, select one of the parameters. Modify its value and identify its effect on the results. By reducing or increasing its value, determine if the match was improved or made worse.

- Second, if the match was not suitably improved, select a second parameter and repeat the process.

- Third, if necessary, repeat the process for all the significant parameters until a satisfactory match is achieved.

Input parameters affecting the impact phase were always tested first. This was necessary because changes to these parameters affected the separation conditions. For example, if the post-impact steering and braking were modified first, any subsequent changes to the crush stiffness, inter-vehicle friction or restitution would alter the separation conditions, thus requiring further changes to the post-impact steering and braking.

It was absolutely *essential* to vary only one parameter at a time. Otherwise, the necessary cause-effect relationship could not be established. When finished, several parameters may have been changed during the matching process. The key point is that only one parameter was changed at a time.

Sensitivity of Selected Variables

For efficient use of time, it was also important to recognize the most significant parameters for producing the desired change. This problem was approached by recognizing which results represented the poorest match and then changing the appropriate input parameters.

Table 6 illustrates the effect of changing certain input parameters on the results of interest (path length, heading change and crush depth). For example, increasing the inter-vehicle friction tended to decrease path lengths, increase heading change and did not significantly affect crush depth. It should be noted that the effects shown in Table 6 were only the *major* effects associated with changing a variable. Other minor effects also occurred. In addition, changing certain combinations of variables could have a compounding or counteracting effect.

Example of Optimization

The above optimizing procedures were applied to the RICSAC cases in an effort to improve the match between the predicted and actual vehicle paths and damage profiles. Because the RICSAC collisions were staged, the initial speeds were known. Thus, the most dominant simulation input parameter (i.e., initial speed) was eliminated from the list of significant parameters.

The optimization process for test no. 3 is described below. The original simulation results provided a reasonable match with the measured paths and damage profiles.

Table 6. Effect of changing selected parameters on the simulated vehicle paths and damage profiles.

INCREASING THIS...	...CAUSES THIS
IMPACT CONDITIONS	
CG Offset	↓ *Path Length* ↑ *Heading Change* ↓ *Crush Depth*
Linear Velocity	↑ *Path Length* ↑ *Heading Change* ↑ *Crush Depth*
Angular Velocity	↓ *Path Length* ↑ *Heading Change* ↔ *Crush Depth*
VEHICLE PARAMETERS	
Weight	↕ *Path Length* ↓ *Heading Change* ↑ *Crush Depth*
Yaw Moment of Inertia	↔ *Path Length* ↓ *Heading Change* ↔ *Crush Depth*
Crush Stiffness	↕ *Path Length* ↑ *Heading Change* ↓ *Crush Depth*
Inter-vehicle Friction	↓ *Path Length* ↑ *Heading Change* ↔ *Crush Depth*
Restitution	↕ *Path Length* ↕ *Heading Change* ↓ *Crush Depth*
ENVIRONMENTAL PARMS	
Tire-ground Friction	↓ *Path Length* ↓ *Heading Change* ↔ *Crush Depth*
DRIVER PARAMETERS	
Wheel Forces (+/-)	↑/↓ *Path Length* ↔ *Heading Change** ↔ *Crush Depth*
Steering	↔ *Path Length* ↑ *Heading Change* ↔ *Crush Depth*

Legend:
↑ - Result tends to increase
↓ - Result tends to decrease
↕ - Result may increase or decrease
↔ - Result tends to remain constant

* Assumes balanced braking

Table 7. Validation results for rest position, CDC and delta-V after optimizing

TEST No.	METHOD	REST POSITION						CDC		DELTA-V	
		Veh #1			Veh #2			Veh #1	Veh #2	Veh #1 (mph)	Veh #2 (mph)
		X (ft)	Y (ft)	PSI (deg)	X (ft)	Y (ft)	PSI (deg)				
1	MEASURED	-1.0	5.4	-1.5	8.5	7.8	105.0	11FZEW2	01RDEW3	12.2	15.6
	EDSMAC	-0.3	5.1	-3.5	8.6	7.9	101.0	12FDEW2	01RDEW3	14.1	19.9
2	MEASURED	11.0	9.4	55.0	23.6	12.5	134.0	11FDEW2	02RDEW4	19.6	--
	EDSMAC	9.6	10.9	54.5	22.4	14.1	159.2	12FDEW2	02RDEW4	21.1	30.7
3	MEASURED	111.4	2.0	-4.0	181.5	-6.3	-19.0	12FZEW1	06BZEW1	9.5	15.8
	EDSMAC	111.5	1.6	-6.8	181.6	-6.2	-22.7	01FZEW1	07BYEW1	10.9	17.5
4	MEASURED	42.8	54.5	137.5	63.9	62.5	88.0	12FZEW3	05BYEW5	18.7	22.2
	EDSMAC	43.5	52.2	130.2	64.2	64.8	88.5	12FZEW4	06BDEW4	15.8	24.4
5	MEASURED	252.0	0.0	0.0	59.0	35.0	282.0	12FZEW1	05BDEW2	16.3	25.1
	EDSMAC	--	--	--	67.3	27.7	268.1	01FZEW4	06BYEW4	13.8	25.4
6	MEASURED	60.0	11.0	15.0	20.0	21.0	242.0	11FZEW1	02RDEW3	9.2	11.9
	EDSMAC	58.3	12.6	13.7	19.8	20.7	210.6	12FZEW1	02RYEW4	11.8	18.2
7	MEASURED	84.5	18.2	16.5	22.9	41.4	262.0	11FDEW1	02RDEW4	12.0	16.5
	EDSMAC	85.0	20.8	15.7	18.8	43.4	259.7	11FDEW1	02RDEW5	13.3	20.4
8	MEASURED	0.0	10.8	45.0	6.3	19.2	130.0	12FDEW1	03RYEW2	15.3	10.7
	EDSMAC	0.6	11.5	46.0	4.2	22.7	130.6	12FDEW2	03RDEW3	16.2	6.5
9	MEASURED	4.0	35.5	104.0	-5.0	49.5	152.0	11FDEW2	02RFEW2	21.4	8.9
	EDSMAC	4.8	35.2	105.3	-4.7	49.9	147.2	11FDEW3	02RYEW2	19.9	8.5
10	MEASURED	5.0	43.0	87.0	0.0	99.5	128.5	10FDEW2	01RFEW2	35.1	14.1
	EDSMAC	--	--	--	--	--	--	11FDEW5	02RYEW3	36.1	15.2
11	MEASURED	25.6	-6.4	170.0	8.6	0.4	0.0	12FYEW3	12FYEW3	24.0	15.7
	EDSMAC	25.6	-7.8	169.9	7.7	0.7	-0.1	12FYEW3	12FYEW4	28.5	17.5
12	MEASURED	22.3	-5.5	118.0	6.8	2.6	-12.0	12FDEW4	12FYEW4	40.1	26.4
	EDSMAC	21.2	-6.5	148.6	8.9	1.6	-1.7	12FDEW4	12FYEW3	40.7	27.5

Inspection of Tables 2 and 3 revealed the following differences for the simulation of vehicle #1:

- it travelled too far after impact (range error)
- it rotated too little after impact (heading error)
- it was damaged too much

Similarly, the following differences were observed for the simulation of vehicle #2:

- it travelled too far after impact (range error)
- it was damaged too much

Based on the observed differences, Table 6 was used to identify the key input variables to effect the desired changes. Accordingly, the following changes were made, *in the following order*, to the input:

- To reduce the amount of simulated crush, the stiffness was increased for each vehicle. This change was made first because it would affect the post-impact path lengths. As a result of this change, vehicle #1 no longer travelled far enough after impact; vehicle #2 travelled an even greater distance.

Table 8. Validation results for vehicle damage after optimizing

TEST No.	METHOD	DAMAGE AREA Veh #1 (in^2)	DAMAGE AREA Veh #2 (in^2)
1	*MEASURED*	*330*	*1050*
	EDSMAC	*623*	*1320*
2	*MEASURED*	*498*	*1930*
	EDSMAC	*779*	*2260*
3	*MEASURED*	*56*	*159*
	EDSMAC	*413*	*525*
4	*MEASURED*	*265*	*984*
	EDSMAC	*626*	*1020*
5	*MEASURED*	*53*	*1330*
	EDSMAC	*249*	*562*
6	*MEASURED*	*71*	*1100*
	EDSMAC	*312*	*890*
7	*MEASURED*	*188*	*1297*
	EDSMAC	*520*	*1720*
8	*MEASURED*	*263*	*529*
	EDSMAC	*531*	*1240*
9	*MEASURED*	*293*	*218*
	EDSMAC	*490*	*443*
10	*MEASURED*	*475*	*288*
	EDSMAC	*N/A*	*N/A*
11	*MEASURED*	*571*	*661*
	EDSMAC	*732*	*700*
12	*MEASURED*	*871*	*743*
	EDSMAC	*1220*	*1610*

- To correct the path lengths, the wheel forces for vehicle #1 were reduced and the wheel forces for vehicle #2 were increased. After these changes, the rollout distances were correct, but the path directions were slightly off.

- To correct the directions, the amount of steering was changed for each vehicle. The degree of steering was increased for consecutive runs until it became clear that the time of steering had to be changed as well. Thus, the onset of steering was delayed until the desired match was achieved.

The above procedures were applied to the remaining cases. Tables 7 and 8 show the results after optimization. The associated errors are shown in Table 9. In comparison with Table 4, the average path range error was reduced from approximately 25 percent to 9 percent. The average heading error was reduced from approximately 1 percent to 0 percent. The damage profile error was reduced from approximately 200 percent to 120 percent. The error in the 7th character of the CDC (see Table 10) improved from 75 percent to 54 percent. Standard deviations for all results were also reduced significantly - an indication the results were more consistent and scatter was reduced.

The primary improvements were observed in the path errors. CDC errors, already felt to be reasonable given the simplifying assumptions, were not significantly affected. However, after optimizing, the damage profile errors were still significant.

DISCUSSION

The term 'accuracy' is felt to be somewhat misleading when applied to simulation programs used for accident reconstruction. This is true for several reasons. The investigator normally is interested in the accuracy of speed estimates. However, accident simulations require speed estimates as an *input* quantity. The true purpose of simulations is to predict the outcome of an event - in this case, vehicle paths and damage profiles. Given sufficient time, an investigator can adjust the program parameters until the simulated paths and damage profiles match the measured results nearly perfectly. One then must address the accuracy of the individual input parameters (some of which are rather crude estimates) used to achieve such a match. The most logical and useful inference is that, by using a physical

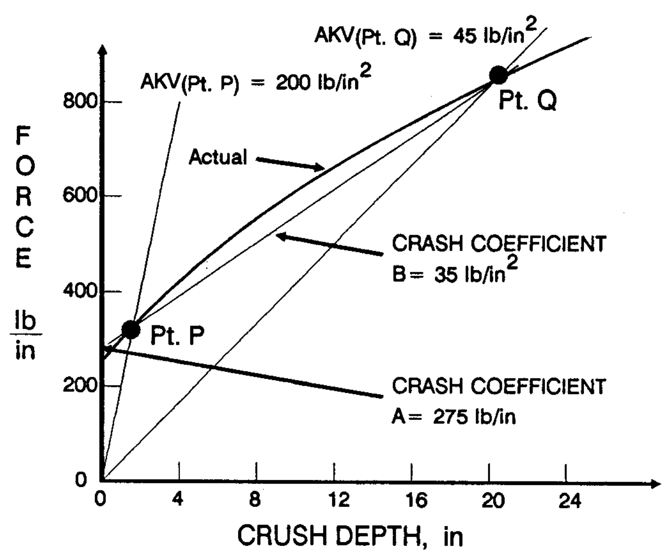


Figure 5 - Force vs deflection curves. Comparison of a typical vehicle with the CRASH and SMAC models. This example illustrates why extremely high stiffness coefficients must sometimes be used with the SMAC model.

Table 9. Path and damage profile errors after optimization.

TEST No.	METHOD	PATH ERROR								DAMAGE PROFILE ERROR	
		Veh #1				Veh #2				Veh #1 (%)	Veh #2 (%)
		RANGE		HEADING		RANGE		HEADING			
		(ft)	(%)	(deg)	(%)	(ft)	(%)	(deg)	(%)		
1	EDSMAC	0.1	1.0	2.8	0.8	0.6	5.5	-13.1	-3.6	91.5	25.7
2	EDSMAC	2.1	9.2	-0.5	-0.1	2.0	7.5	25.2	7.0	56.4	17.1
3	EDSMAC	0.4	0.4	-2.8	-0.8	0.1	0.1	-3.7	-1.0	637.5	230.2
4	EDSMAC	2.4	3.5	-7.3	-2.0	2.3	3.1	0.5	0.1	136.2	3.7
5	EDSMAC	--	--	--	--	11.1	20.4	-13.9	-3.9	369.8	-57.7
6	EDSMAC	2.3	3.8	-1.3	-0.4	0.4	1.8	-31.4	-8.7	339.4	-19.1
7	EDSMAC	2.6	3.1	-0.8	-0.2	4.6	11.4	-2.3	-0.6	176.6	32.6
8	EDSMAC	0.9	6.9	1.0	0.3	4.1	22.2	0.6	0.2	101.9	134.4
9	EDSMAC	0.9	2.4	1.3	0.4	0.5	0.9	-4.8	-1.3	67.2	103.2
10	EDSMAC	--	--	--	--	--	--	--	--	--	--
11	EDSMAC	1.4	13.7	-0.1	0.0	0.9	11.0	-0.1	0.0	28.2	5.9
12	EDSMAC	1.5	22.0	30.6	8.5	2.3	31.9	10.3	2.9	40.1	116.7
AVG	EDSMAC	1.5	7.3	1.8	0.5	2.6	10.1	-2.1	-0.6	185.9	53.9
STD.DEV.	EDSMAC	0.7	6.1	9.9	2.7	3.0	10.1	13.2	3.7	180.1	79.3

simulation model which duplicates (or nearly so) all the known accident evidence, any unknown parameters (e.g., vehicle speeds) must be nearly duplicated by the simulation as well. Stated another way, if one is able to match the evidence using simulation, and if one agrees with all the data used to achieve the match, then one should agree a priori with the speeds used to achieve the match.

A match between simulation and scene measurements can normally be achieved using a variety of data combinations. Therefore, if speed is an issue, a range of speed estimates should be examined and matches should be attempted. The minimum and maximum limits of the speed range are found when the known evidence can no longer be matched.

What is an acceptable match? The authors feel this is a difficult question to answer. The requirements will vary from crash to crash. However, the following example may provide some insight: After RICSAC test no. 3 was optimized (i.e., a satisfactory match was achieved between simulated and measured results; see Table 7), a test was performed, wherein the impact speed of the striking vehicle was reduced from 21.3 to 19.3 mph and the simulation was rerun. The resulting paths were shortened for vehicles #1 and #2 by 19 feet and 27 feet, respectively. Next, the impact speed was increased from 21.3 to 23.3 mph. The resulting paths were 22 and 27 feet longer, respectively. The sensitivity of rest positions to impact speed, suggested by this finding, is of major importance to the investigator using simulations. It means the investigator may not need to spend a great deal of time creating a "perfect" match in order to draw reasonable conclusions about impact speeds. For the above RICSAC case, a ±2 mph speed range required matching rest positions only to within about 20 feet.

The above observation ignores the effect of changing several variables simultaneously. For example, if the impact speed were reduced by another 2 mph while simultaneously reducing the rolling resistances (wheel lock-ups), the path lengths could be made to match the measured lengths.

During the optimization process, the vehicle crush stiffnesses had to be increased significantly (in some cases over 100 lb/in^2) to improve the match between measured and simulated damage profiles. This was especially true for crashes resulting in minor frontal damage. The explanation for this requirement is illustrated by comparing the SMAC collision model with a real vehicle. In the model, the force vs deflection curve begins at the origin. This implies the vehicle begins crushing as soon as an external force is applied. The front of a real vehicle can resist a significant force before crushing begins. In this regard, the CRASH algorithm, which contains an 'A' stiffness coefficient to represent this initial force, is more realistic. Figure 5 shows a force vs. deflection curve typical of an actual vehicle, along with idealized curves for CRASH and SMAC. Two crush depths are considered. Point P has a 2 inch crush depth, while point Q has a 20 inch crush depth. The CRASH model, using A = 275 lb/in and B = 35 lb/in^2, fits both points quite well. The SMAC model requires a significantly different stiffness value, either 200 lb/in^2 or 45 lb/in^2, depending on the crush depth. As shown in Figure 5, the SMAC stiffness coefficient must be increased substantially for minor crush to overcome the lack of an initial force.

The primary goal when using SMAC is to match the measured and predicted vehicle paths. During the optimization process, a broad range of stiffness coefficients were tried (typically between 40 and 100 lb/in^2). This range generally produced the expected change in the damage profiles, but produced only slight changes in the vehicle paths. Thus, the large damage profile errors shown in Table 8, while important academically, should not be used to criticize the use of the program by accident investigators.

The definitions of error (and implied degree of accuracy) used in this paper are somewhat arbitrary. While several approaches were considered for each type of result (path, damage and CDC), none worked well for all results and none was perfectly objective. This suggests further research is required to standardize a procedure for assessing the error in simulation programs used for accident reconstruction.

The assessment of damage profile error was particularly pessimistic. The poor quality of the results in part reflected the way error was computed, coupled with the fact that the simulations always over-predicted crush depth for minor damage. Lost in this assessment was the fact that the location and shape of damage profiles were always predicted quite well. However, further research may provide a better algorithm for computing simulated crush depth.

Table 10. CDC errors after optimizing

Character(s)	METHOD	ERROR (percent)
1,2	*EDSMAC*	*41.7*
3	*EDSMAC*	*0.0*
4	*EDSMAC*	*33.3*
5	*N/A*	*N/A*
6	*EDSMAC*	*0.0*
7	*EDSMAC*	*54.2*

CONCLUSIONS

1. The term 'accuracy' had little meaning when applied to accident reconstruction simulations because, given sufficient time, nearly any desired level of accuracy could be achieved.

2. The RICSAC test data set was an extremely valuable set of input for validation studies. However, the results must be used carefully because of problems with the test data. In particular:

- The rest positions for test 5, vehicle #1 and test 10, vehicle #2 were invalid and should not be used.

- The data sets for test nos. 4, 5, 6, 7, 9 and 10 were invalid because the length of simulation was too short; for each case, one of the vehicles was still in motion at the end of the simulation. These data sets were useful after increasing the maximum simulation time.

- The measured delta-Vs were not of acceptable accuracy for use in a validation study because the motion transducers were placed at the vehicle's firewall, rather than at the CG. This problem might be improved or eliminated by re-analyzing the original data with software which included a transformation matrix.

Because of the above problems, several of the original SMAC data sets were useful for comparing SMAC runs with EDSMAC runs, but not useful for comparing either program's results with the actual staged collision results.

3. In six of the twelve test cases (run nos. 1, 5, 8, 9, 11 and 12), EDSMAC and SMAC produced virtually identical results. Any differences were only traceable to the different machines on which the simulations were run.

4. In the remaining cases, EDSMAC and SMAC produced different results. The path and delta-V differences were due to an error in SMAC subroutine COLL, which computed the inter-vehicle force. The CDC differences were due to logic errors in SMAC subroutine DAMAGE, which computed the CDC.

5. After optimizing, the match between measured and simulated path positions and headings was very good (9 and 0 percent average errors, respectively).

6. After optimizing, the match between measured and simulated CDCs was generally very good. The 4th character (specific damage location) and 7th character (damage extent) showed room for improvement.

7. After optimizing, the match between measured and simulated damage profiles was still poor for minor damage. The match could be improved by changing the algorithm to include an initial force coefficient similar to that used in CRASH.

8. Cases which produced airborne vehicle rotation were the most difficult to simulate. This was due to the assumption that tire forces existed at all times. Load transfer, especially significant for these cases, was also ignored.

9. The appropriate crush stiffness coefficients for SMAC and EDSMAC varied according to the crush depth. Shallow crush required significantly higher coefficients than deeper crush.

10. The optimization process required changing one variable at a time to monitor the cause-effect relationship. Thus, because of the trial-and-error process, optimization required a significant amount of time. A powerful PC (286- or 386-based system with a coprocessor) was quite helpful.

11. An individual simulation could be varied to show a variety of results, each being consistent with the input. Thus, the investigator should study a variety of possible scenarios and present the associated range of results.

12. Small changes in some inputs (i.e., initial velocities) produced very large changes in rest positions, thereby adding confidence to the validity of the simulation, even if the simulated rest positions were only reasonably close to the actual rest positions.

13. Sensitivity studies could be used to determine how close the simulated path must match the actual path achieve the desired accuracy. This technique greatly reduced the amount of time required to reach an acceptable match.

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