MATHEMATICAL RECONSTRUCTION OF ACCIDENTS - SCENE MEASUREMENT AND DATA PROCESSING SYSTEM

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16. Abstract

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Results of the third year of effort are presented and discussed. They include the results of field testing by a local police agency as well as by Calspan personnel.

It is concluded that development of the prototype system has reached a point where it can be routinely applied to many highway accidents. Proposed modifications and extensions, aimed at greater ease of application and at increased generality, are presented and discussed.

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FOREWORD

This report summarizes results achieved in the third year continuation of the development and field testing of a measurement and data processing system for use in investigation of highway accidents. The reported research was performed under Task A of Contract No. DOT-HS-053-3-658 with the National Highway Traffic Safety Administration, U. S. Department of Transportation.

The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the National Highway Traffic Safety Administration.

This report has been reviewed and is approved by:

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- Software Development

  Camille F. Bainbridge
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- Field Testing

  Amherst Police Department, Amherst, New York
  Robert F. Wantuck
  Robert J. Hochreiter

- Initial Planning of System Hardware

  William Jenney

SUMMARY

A computer program and an associated optical measurement system have been developed to aid the investigation of highway accidents. They provide a capability of processing and evaluating scene data, via radio contact with a remote computer, while the investigators are at the accident scene.

Results of the third year of effort are presented and discussed. They include the results of field testing by a local police agency as well as by Calspan personnel.

It is concluded that development of the prototype system has reached a point where it can be routinely applied to many highway accidents. Proposed modifications and extensions, aimed at greater ease of application and at increased generality, are presented and discussed.

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1.0 INTRODUCTION

The overall objective of the reported research (References 1, 2, 3) has been to develop, validate and demonstrate a computer system that will process measured scene data and provide an on-scene reconstruction capability for automobile accidents. A further objective has been to process indirect evidence (i.e., data not directly used in reconstruction calculations) to complete the definition of all phases of the accident sequence.

The specific objectives of the third year have been (1) to complete the development and field testing of a prototype system and (2) to perform a pilot study application of the developed reconstruction technique to the task of calibration of anthropometric dummy responses for injury interpretations on the basis of actual, injury producing highway accidents. The latter task (Task B of the research contract) has been completed and the results have been reported separately in Reference 3.

The presently reported research was performed under Task A of the contract. While developmental difficulties with the investigation vehicle curtailed the total time available for field testing, the system was made fully operational and successful field tests were performed.

Conclusions and recommendations based on results of the third year efforts of this research are presented in Section 2.0. The results of the research are summarized in Section 3.0.

References are listed in Section 4.0. Detailed material to supplement the discussion of results in Section 3.0 is presented in Appendices 1 through 8.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

2.1.1 The feasibility of detailed, on-scene reconstruction of highway accidents by trained police personnel using the developed prototype system has been clearly established.

> A persistent question during the three year development of the SMAC program and the associated measurement and computer systems has been if these advanced tools can be provided in a form such that non-technical personnel, such as police investigators, can successfully use them. The development of the computerized accident investigation vehicle and its successful use by police officers shows conclusively that the software package coupled with the automatic SMAC iteration reconstruction capability provide a total accident investigation system that can be successfully applied, with minimum training, by any working accident investigator.
>
> The limited extent of field testing of the system at actual accidents did not permit a definitive evaluation of the relative value of a capability for on-scene, as compared with off-scene, reconstruction. However, it is anticipated that an on-scene reconstruction capability, which insures that the measured evidence will permit an acceptable reconstruction before the investigators leave the scene, will ultimately prove to be of significantly greater value. For example, experience in other areas of accident investigation has shown that, when undertaking an accurate off-scene reconstruction of a particular accident with the SMAC program via manual iterations, questions often arise which could have been answered accurately at the scene but which must be resolved on the basis of memory or by use of intelligent guess work.

2.1.2 The START routine (Appendix 2), which was developed to generate initial estimates of collision speeds for use in iterative applications of the SMAC program, constitutes an advance in the state of the art of closed solution forms (i.e., single step solutions, as opposed to step-by-step time histories) for accident reconstruction.

> The START routine was initially aimed at the generation of gross estimates with which the SMAC program could be automatically started in a series of iterative runs. The high degree of success in generating accurate speed estimates that has been achieved with this relatively simple routine (see Section 3.3) indicates a potential for separate applications in large-scale studies of accident reports, in which its low operating cost would be particularly attractive.

2.1.3 The Simulation Model of Automobile Collisions (SMAC) computer program also constitutes an extremely useful aid in off-scene applications to reported accident evidence.

> Many of the existing Multi Disciplinary Accident Investigation (MDAI) cases have been found to be inadequately reported to permit definitive reconstructions. This is also frequently true for accident cases that are the subject of litigation. The Simulation Model of Automobile Collisions (SMAC) computer program does not, of course, require more complete evidence than other reconstruction techniques. Rather, it permits one to utilize more complete data when they are available.
>
> The SMAC program has been found to be quite useful for evaluating fragmentary evidence. It generates complete track, damage and rest position data for each iterative run, and the fragmentary bits of real evidence can be compared with corresponding portions of the overall analytical reconstruction.

The SMAC program can serve to extend the capabilities of inexperienced investigators and analysts. It faithfully applies the laws of mechanics for any selected impact conditions within the constraints of the simplifying assumptions, regardless of the quality of the selections. In fact, the relative economics of labor and computer costs (approximately $20 for a complete SMAC run) have approached the point where groping for the "best fit" impact conditions on a superficial basis can be less expensive than carefully evaluating the results of each iterative run. In view of the included analytical details, SMAC is also expected to yield improvements in the uniformity of evidence interpretations made by more experienced analysts.

2.1.4 The optical data acquisition system for scene measurements, if modified to incorporate a range finder (see Recommendation 2.2.1), can provide major advantages over other existing measurement techniques, whether or not an on-scene reconstruction system is in use.

The capability of automatically producing an on-board, scaled display of the measured data at any point in the data acquisition process is a particularly attractive feature of the developed system. The speed and accuracy of measurements and the reduced interference with other activities at the accident scene are also very attractive features. The digitized format of the measured data lends itself to data processing in reconstruction calculations and/or statistical studies of accidents.

2.1.5 With relatively minor extensions and refinements of the iteration procedure (e.g., see Section 3.3.1) the majority of adequately reported accidents could be automatically reconstructed to provide estimates of travel speeds and collision speed changes with a high degree of accuracy.

Although the automated version of the SMAC program, i.e., the START-SMAC-ITERATE package, should be considered as still under development, the potential of the system has been successfully demonstrated in the field trials.

2.2 Recommendations

2.2.1 The present technique of range measurement, which makes use of the change in elevation angle corresponding to a known vertical dimension, should be replaced with a commercially available range finder (e.g., Hewlett Packard Model 3805A Distance Meter).

> The sensitivity to sighting errors in the range determination of the present measurement system tends to become unacceptable for distances greater than approximately 120 feet. While the problem can be overcome by movement of the investigation vehicle whenever the measurement distances exceed 100 feet, the required frequency of movement in representative accident cases would be excessive. A range finder can reduce the number of sightings to one per data point and it can also overcome difficulties with maintaining the two sighting lights on the stadia rod within the field of view at all times (e.g., points on other side of damaged vehicle).

2.2.2 Development and refinement of the SMAC program and of the auxiliary routines for generating initial speed estimates (START, Appendix 2) and for adjusting the speed estimates to reduce errors (ITERATE, Section 3.3) should be continued.

> Possible improvements to the system have been suggested in Section 3.3. In providing an efficient automatic reconstruction scheme, emphasis should be placed on developing the START routine so that the initial velocities of each vehicle can be determined to a known degree of accuracy. This would allow further development of the ITERATE procedure to include checks on the relative positions and orientations of the vehicles in addition to optimizing their velocities.
>
> In the course of performing off-scene applications of SMAC, a number of minor refinements which would improve the convenience of applications and the accuracy of results have been identified.

For example, the present single friction boundary limits the ability of the user to traverse a terrain patch which has a different friction coefficient. The use of terrain table definitions similar to those in the HVOSM program* would ease the application task.

The effects of longitudinal weight transfer on yaw responses should be approximated to improve prediction accuracy.

The existing collision subroutine is not suitable for collisions with very narrow obstacles (e.g., sign posts, small trees). Also, it does not include a capability for simulating tensile forces. The collision subroutine should be supplemented by an impulsive load capability.

The coefficients of restitution of the two colliding bodies should be separately specified.

The effects of aligning torques on the front wheel steer angles during skidding should be added in the form of a simplified steer degree of freedom.

2.2.3 The existing evidence of the validity of the SMAC program should be extended to include results achieved by means of automatic iteration of the initial conditions (i.e., using an extended version of Subroutine ITERATE, which is described in Section 3.3).

The degree of correlation of reconstructed and measured collision conditions obtained via manual iteration of initial conditions in the SMAC program reflects, to some extent, the expertise and perseverance of the individual program users. Thus, a general level of confidence in results cannot be rigorously established unless it is related to the nature and the magnitudes of final discrepancies between reconstructed and measured items of evidence. With automatic iteration of the initial conditions of SMAC, the results become independent of the individual program user. The high degree of success achieved with the relatively simple initial version of Subroutine ITERATE makes this approach very attractive from the viewpoint of establishing general levels of confidence for the results of SMAC reconstructions.

*Highway Vehicle Object Simulation Model computer program (Reference 17).

In any new validation experiments, the instrumentation should include crash recorders, to permit a comparison of the extent and quality of information obtained via SMAC reconstruction and via on-board recorders.

2.2.4 The post-processing routine in the SMAC program which generates the vehicle damage index (VDI) should be used as a starting point for improving the clarity of definitions within the SAE recommended practice (Reference 16).

The existing form of SAE J224a permits a range of interpretations in its application. This fact was made abundantly clear at the NHTSA meeting of air bag case investigation teams on 4 October 1974. A flow chart of the existing SMAC computer routine logic could serve to guide language changes and/or definition changes that will clarify intended meanings. A logical flow chart of the end product of an intensive review and revision would be expected to be helpful in applications.

3.0 DISCUSSION OF RESULTS

3.1 Field Tests

3.1.1 Accident Scene for System Tests

For the purposes of initial field testing of the complete scene measurement and data processing system by Calspan personnel and training of police personnel in its use, a durable accident scene was created on the Calspan Vehicle Experimental Research Facility (VERF) to permit repeated investigations. The selected accident case was a staged, intersection type of collision from Reference 18 (see Figure 3.1.1). The primary basis for this selection was the relatively extensive track data for measurement exercises (see Figure 3.1.2).

Figures 3.1.2 and 3.1.1, respectively, show SMAC-predicted and experimental kinematics of the vehicles in the selected intersection-type collision. It should be noted that the predicted tire tracks and the final positions and orientations displayed in Figure 3.1.2 include a time interval of 2.0 seconds after initial contact. In Figure 3.1.1, the experimental kinematics of vehicle #2 are shown only for 1.0 second after initial contact, and vehicle #1 is shown in its rest position at an unspecified time greater than 2.0 seconds. A further comparison of the predicted and experimental kinematics in this case is presented in Figure 3.1.3. In general, the correlation of predicted and experimental kinematics is considered to be very good. The minor discrepancies are considered to be within the probable range of repeatability of the experiments.

Since SMAC predictions include complete definitions of the individual tire tracks and indications of points at which sliding of the individual wheels occurs, as depicted in the display shown in Figure 3.1.2 (solid lines indicate sliding tires), a complete SMAC run to the points of rest of the two vehicles was used to generate comprehensive track data. The resulting definitions of the vehicle positions and orientations at impact and at rest and the tire track data were painted on the VERF skid pad, as shown in Figure 3.1.4.

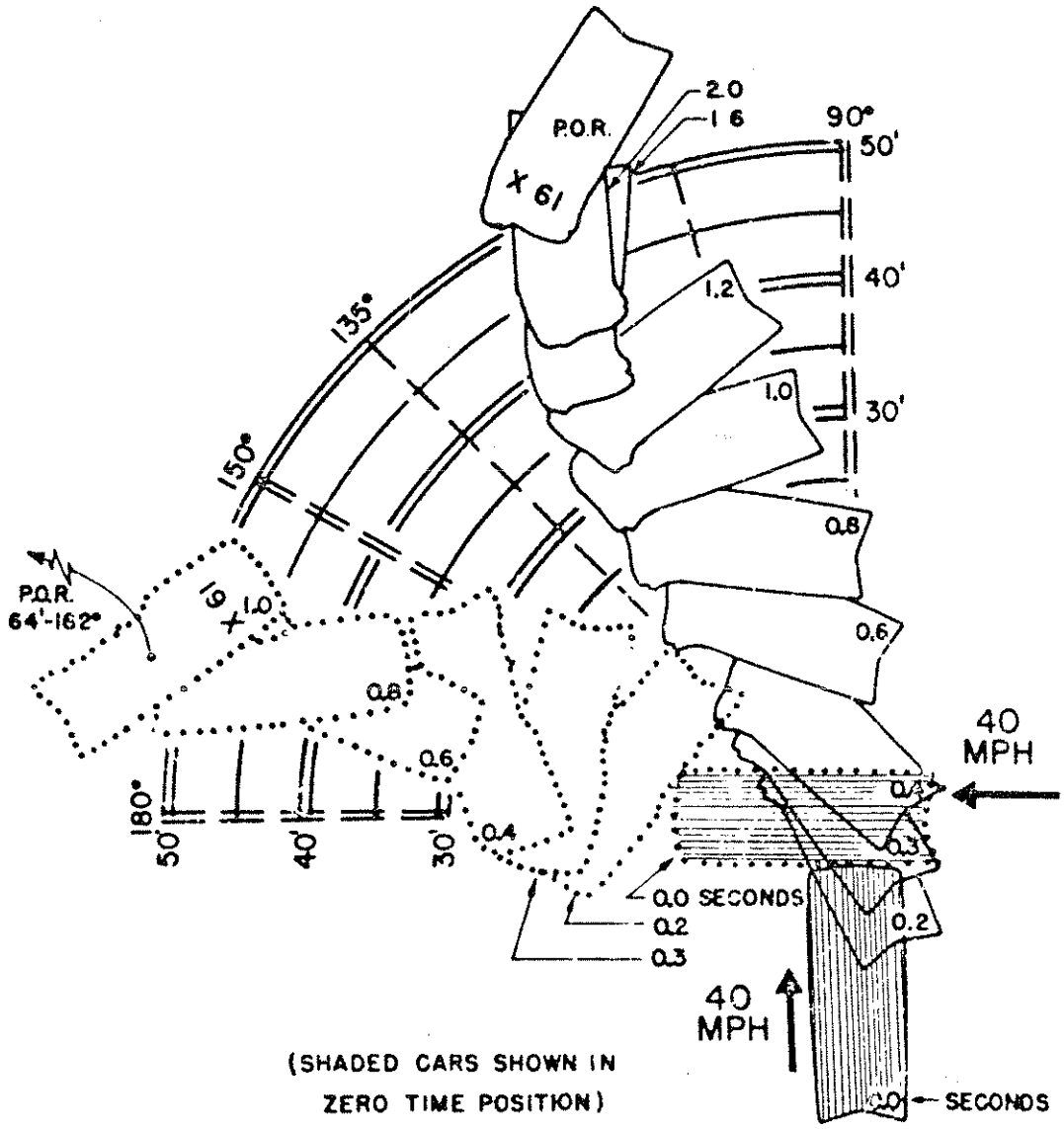


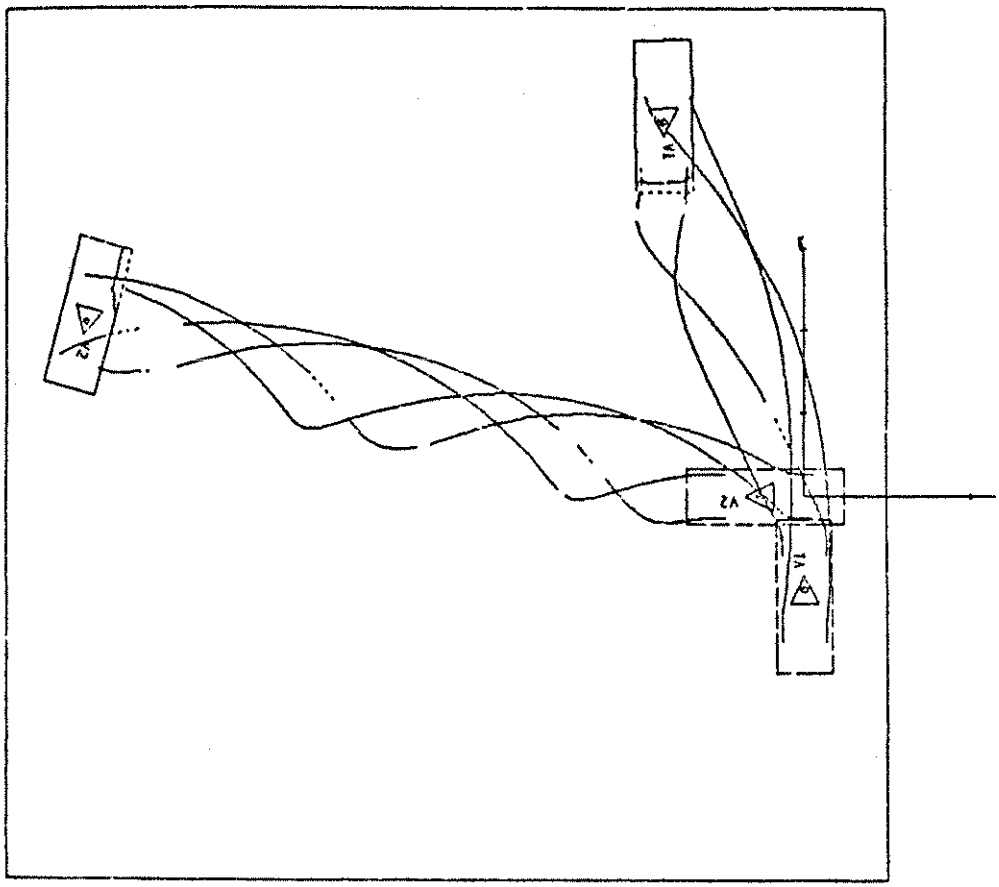
Figure 3.1.1 EXPERIMENTAL DATA FROM REFERENCE 18 – REAR-SIDE IMPACT AT 40 MPH

Figure 3.1.2

GRAPHIC DISPLAY OF OUTPUTS OF ACCIDENT RECONSTRUCTION

COLLISION AND TRAJECTORY

REAR-SIDE IMPACT AT 40 MPH



AXIS INTERVALS ARE 10. FEET

	RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT						DISPLAYED FINAL POSITIONS				VEHICLE DAMAGE INDICES
	C.G. POSITION		HEADING				C.G. POSITION		HEADING	REMARKS	
	XCI	YCI	PSII	FWD	LATERAL	ANGULAR	XCIF	YCIF	PSIIF		
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT.	DEG.		
VEHICLE # 1	-11.1	-0.0	-0.0	40.0	0.0	-0.1	45.0	-16.2	-180.9	IN MOTION AT 2.0 SEC AFTER INITIAL CONTACT	D I F D E H 2
VEHICLE # 2	0.0	-5.2	-90.0	40.0	0.0	-0.1	21.0	-84.8	-525.0	IN MOTION AT 2.0 SEC AFTER INITIAL CONTACT	1 0 L Z E H 3

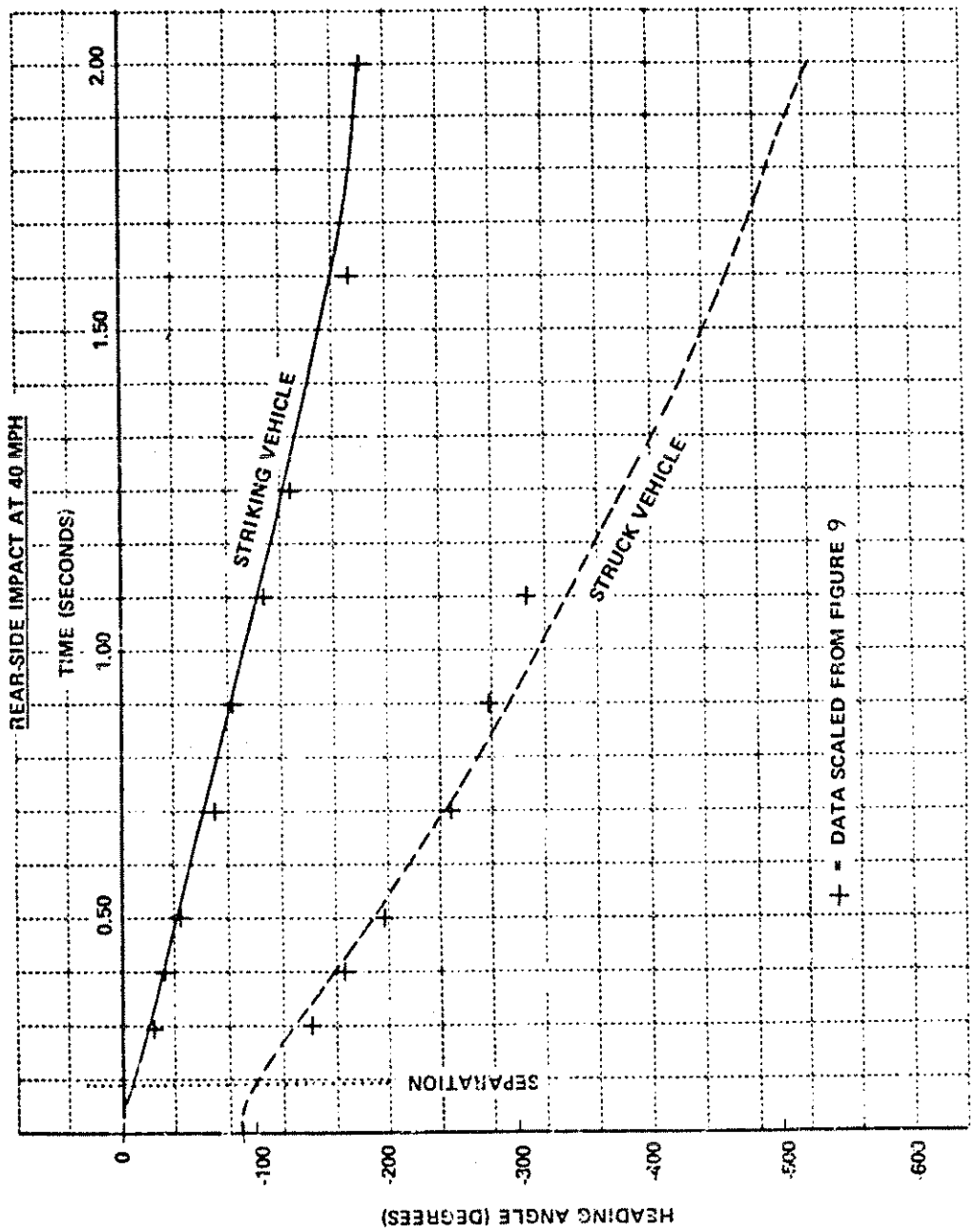


Figure 3.1.3 HEADING ANGLES VS TIME

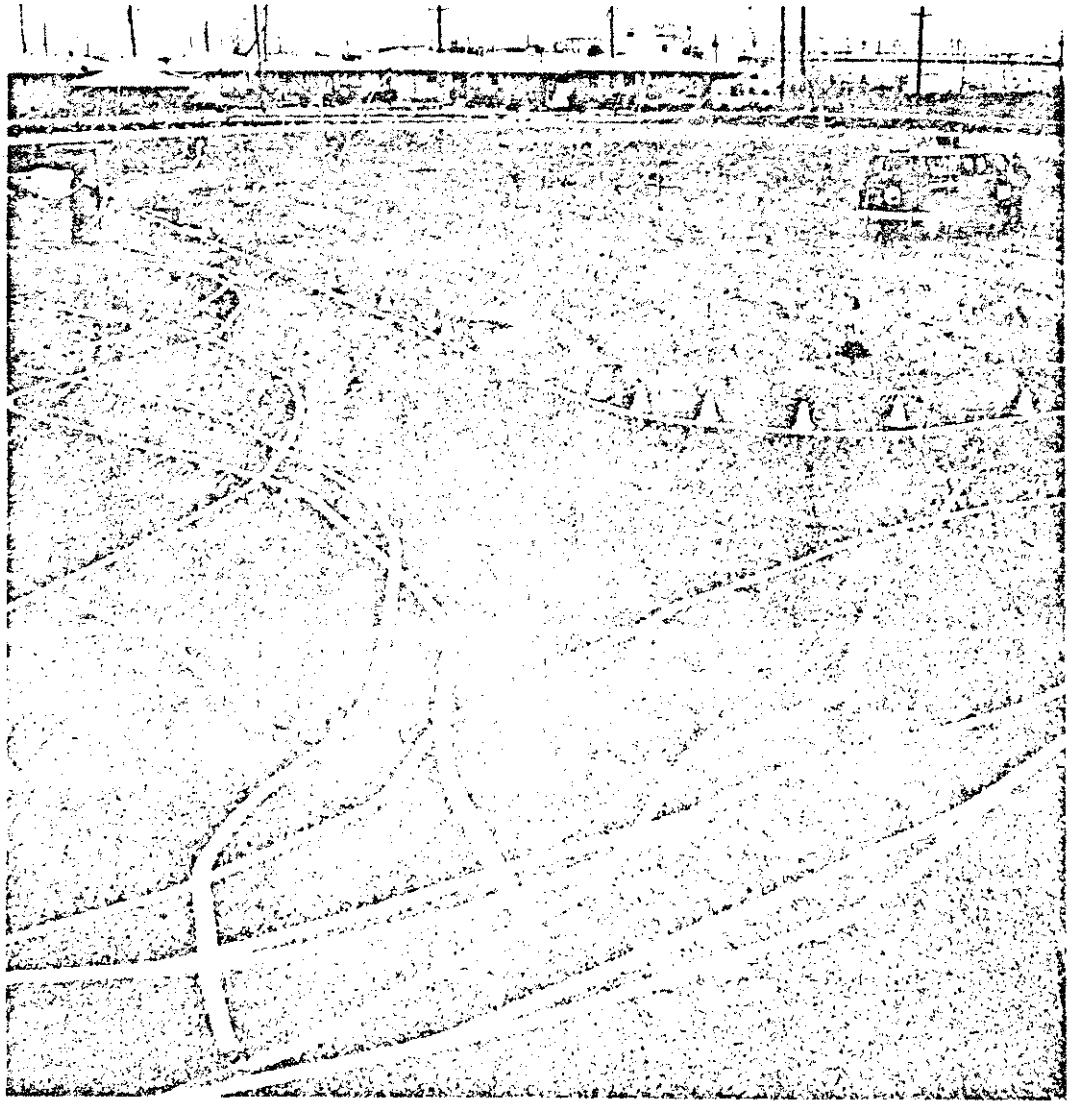


Figure 3.1.4 ACCIDENT SCENE ON VERF SKID PAD

This accident scene was measured, by Calspan and Amherst police personnel, a number of times with the Calspan accident investigation vehicle located in different positions. The results of the measurements were transmitted via radio-telephone to a remote digital computer facility for reconstruction by the SMAC program. The results of these field trials are discussed in the following paragraphs.

3.1.2 Accident Van Field Experience

Four full-scale field trials were conducted with the accident investigation vehicle before time ran out. They were:

A) Practice Session #1 - November 26, 1974 with Calspan personnel at the practice accident scene

B) Practice Session #2 - December 11, 1974 with Amherst Police personnel at the practice accident scene

C) Practice Session #3 - December 17, 1974 with Calspan personnel at the practice accident scene

D) On-Site Case #1 - December 18, 1974 with Amherst Police at actual fatal accident in Amherst, New York.

The purpose of the field trials was to uncover problems and gain experience. Inspection of each of the session results will show that both objectives were met.

3.1.3 Practice Session #1

On Tuesday, November 26, 1974, a complete systems shakedown was performed by Calspan personnel (James Lynch and Robert Wantuck). Eliminating all non-investigative activities, the time spent was:

Setup Time	- 15 minutes	
Scene Survey Time	- 60 minutes	(140 sightings)
Reconstruction Time	- 15 minutes	

Figure 3.1.5 shows the results of sighting the origin, X-axis point, and picture boundary points. The size of the box enclosing the scene is determined from the largest boundary span in the X or Y directions.

Figure 3.1.6 shows the results of sighting the rest and impact wheelpoints (the impact positions are presently not displayed in the scene survey). The measured wheelpoints are averaged and related to the wheelbase to determine the c.g. positions and orientations. A table lookup procedure is used to determine the proper vehicle rectangular outline and this outline is transformed and plotted at the correct rest location.

Figure 3.1.7 shows a simple pavement edge intersection having been sighted. Note the bad data point in the 3rd quadrant. In Section 3.2 of this report, the sensitivity of the stadia rod ranging technique is discussed and it is shown to be very sensitive to mis-sightings, which can result in significant range errors. This appears to be the case in this point and some others to follow.

Figures 3.1.8 and 3.1.9 show the sighting of the skidmarks of vehicle 1 and vehicle 2. Note a bad sighting in the left front track of vehicle 2 similar to the bad sighting on the road edge. Also note that the orientation of vehicle 2 is about 20° in error. This was caused by a communications

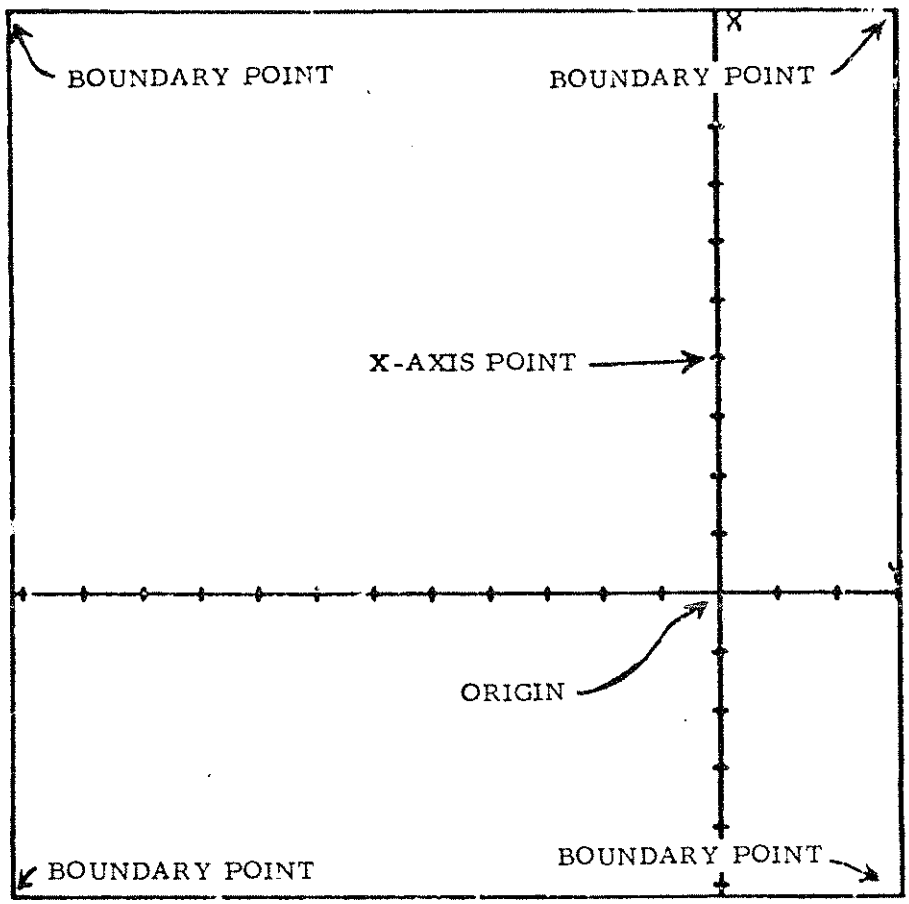


Figure 3.1.5 ORIGIN AND BOUNDARIES DEFINED

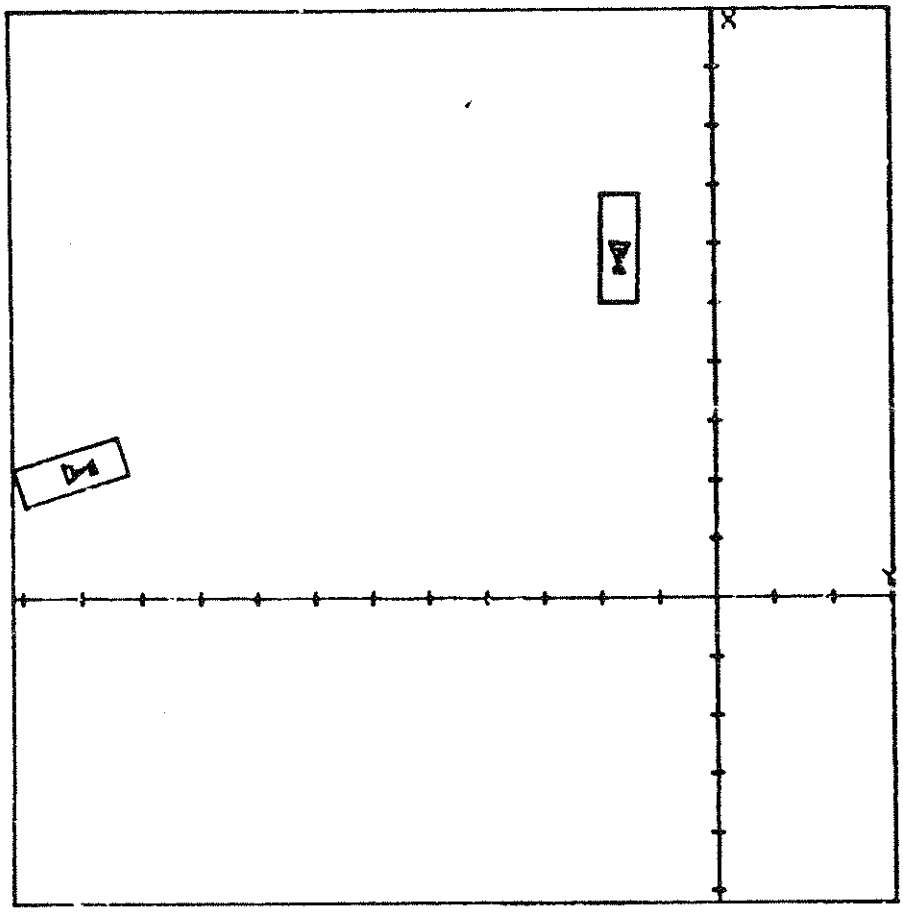


Figure 3.1.6 REST AND IMPACT WHEELPOINTS SIGHTED

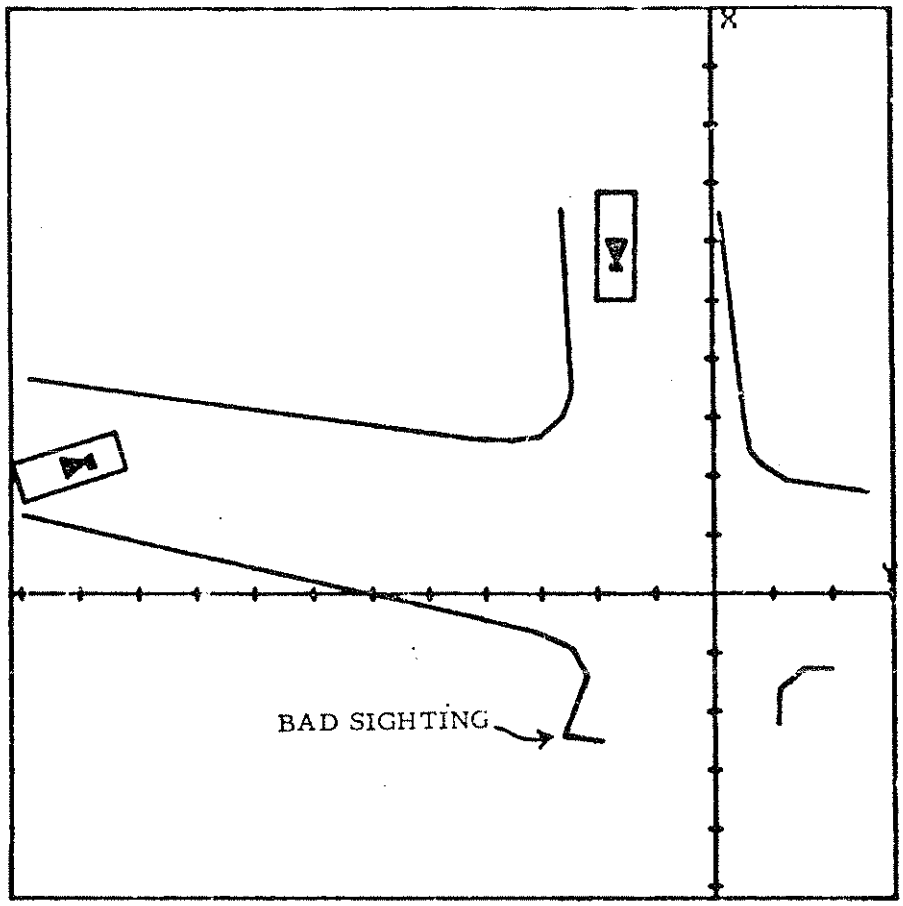


Figure 3.1.7 ROAD EDGES SIGHTED

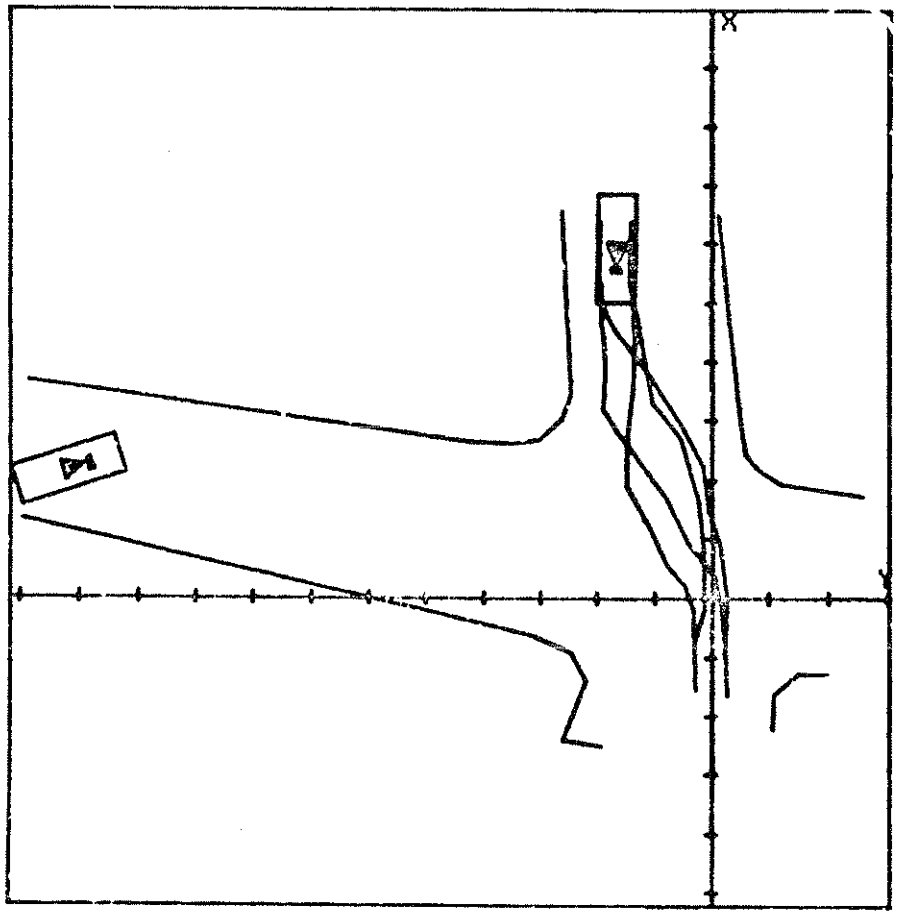


Figure 3.1.8 VEHICLE #1 TIRE TRACKS SIGHTED

NOTE: V2 REST ORIENTATION IN ERROR
RF AND LF WHEELPOINTS INADVERTENTLY MADE EQUAL

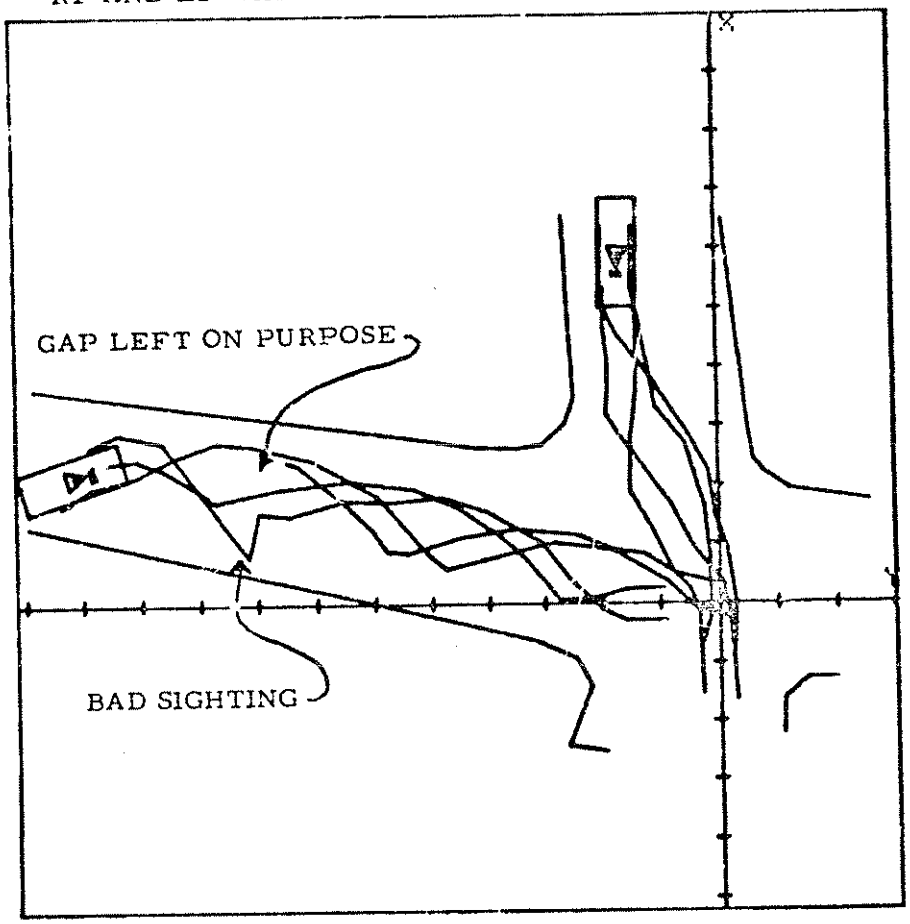


Figure 3.1.9 VEHICLE #2's TIRE TRACKS SIGHTED

foulup between the investigator and the transit operator. Both the right front and left front wheelpoints were sighted as the same point. The problem could have been resolved by resighting the wheelpoints, but this was not attempted because of the lateness of the hour.

Figure 3.1.10 shows the display of the transmission of the measured information to the Computersearch timesharing computer via radio-telephone. Note that Computersearch assigned a job number of 00ED to the SMAC reconstruction. Figure 3.1.11 is a printout of the standard SMAC input card deck as generated by the START program from accident van measured data. Figure 3.1.12 is a display of the status checking capability whereby the operator can have the on-board minicomputer find out if the SMAC program is completed. Figure 3.1.13 is the display of the 5 minute data transfer of the SMAC results back to the accident van. The data is transmitted in twenty-two 360 character blocks. The dollar sign indicates a successful reception of the block (a checksum error detection method is used). If the block is not read in perfectly (a question mark would be displayed), then the entire 360 character block is retransmitted.

Figure 3.1.14 displays a plot of the initial results obtained from the reconstruction program while Figure 3.1.15 is the single page printed summary. This reconstruction is a single pass run without any iteration capability (i.e., direct application of START results only). Note that the vehicle speeds are too high and V2 spins out of the boundary area, causing various graphic software blowups. Figure 3.1.16 is a plot with manually expanded scale that keeps the data within the screen limits. Note the orientation error of V2, which was traced to improper operation of the sine/cosine routine in the negative 4th quadrant. Note also the smoothness of the reconstruction generated tiremarks (each track has 35 points). The impact positions are plotted with dashed outlines, and a damage outline is included in the rest outlines.

The first practice session was very fruitful in that several software bugs were uncovered and the need for an iteration capability in SMAC applications was clearly demonstrated.

```
**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

**** COMPUTERSEARCH IS RUNNING THE START PROGRAM ****


**** CARD # 1 TRANSMITTED ****
*

**** CARD # 2 TRANSMITTED ****
*

**** CARD # 3 TRANSMITTED ****
*

**** CARD # 4 TRANSMITTED ****
*

**** CARD # 5 TRANSMITTED ****
*


**** START PROGRAM HAS COMPLETED ****

**** SMAC RECONSTRUCTION PROGRAM RUNNING ****
JOB ID = AAAA
**** HANG UP RADIOTELEPHONE ****

**** HIT CARRIAGE RETURN TO RETURN TO SMAC MENU ****
```

Figure 3.1.10 TRANSMITTING DATA TO COMPUTERSEARCH

```
COPY SMACINPUT 20 MS
SIMULATION MODEL OF AUTOMOBILE COLLISIONS (SMAC)
PRACTICE SESSION 1    REAR-SIDE IMPACT      NOVEMBER 26,1974
0.0      3.0      0.025    0.001    .01     0.001     5.0      2.0      2.0                1
 -143.00    -1.60    -2.40       .00   620.23      .00                                     2
   -5.40   -52.42   267.02       .00   867.53      .00                                     3
   60.50    63.00    63.1044563.00    12.420.0        100.50 -119.60    39.60              4
   60.50    63.00    63.1044563.00    12.420.0        100.50 -119.60    39.60              5
 -11572. -11572. -11113. -11113.                                                            6
 -11572. -11572. -11113. -11113.                                                            7
0.125    0.175    0.01      .0                                                              8
0.0        0.0        0.0          -851.52   -851.52   -851.52
0.0        0.0        0.0          -851.52   -851.52   -851.52
0.0        0.0        0.0          -817.73   -817.73   -817.73
0.0        0.0        0.0          -817.73   -817.73   -817.73
0.125    0.175    0.01      .0                                                              9
0.0        0.0        0.0          -851.52   -851.52   -851.52
0.0        0.0        0.0          -851.52   -851.52   -851.52
0.0        0.0        0.0          -817.73   -817.73   -817.73
0.0        0.0        0.0          -817.73   -817.73   -817.73
0.0      0.30     0.10     1.0                                                              10
0.0      0.30     0.10     1.0                                                              11
-2400.   2400.    2400.    2400.    0.60     0.60     0.0                                   12
2.0      0.2      15.0     5.0        50.00    50.00    0.55                                13
0.00423 3.5417-34.7301-5                                                                    14
                                                                                            9999

IDYE

CPU = .1622 CORE 103 INT = 8
```


Figure 3.1.11 SMAC INPUT DATA AS SUBMITTED BY THE START PROGRAM

```
**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

SMAC JOB STATUS BEING CHECKED

**** SMAC JOB RUNNING ****
**** TRY AGAIN IN A FEW MINUTES ****
**** HIT CARRIAGE RETURN TO LOG OFF ****
```

Figure 3.1.12 CHECKING ON THE STATUS OF THE RECONSTRUCTION

```
**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

SAAC DATA TRANSFER PROGRAM REQUESTED
SAAC DATA TRANSFER PROGRAM STARTED

BLOCK #  1 IN PROGRESS   $
BLOCK #  2 IN PROGRESS   $
BLOCK #  3 IN PROGRESS   $
BLOCK #  4 IN PROGRESS   $
BLOCK #  5 IN PROGRESS   $
BLOCK #  6 IN PROGRESS   $
BLOCK #  7 IN PROGRESS   $
BLOCK #  8 IN PROGRESS   $
BLOCK #  9 IN PROGRESS   $
BLOCK # 10 IN PROGRESS   $
BLOCK # 11 IN PROGRESS   $
BLOCK # 12 IN PROGRESS   $
BLOCK # 13 IN PROGRESS   $
BLOCK # 14 IN PROGRESS   $
BLOCK # 15 IN PROGRESS   $
BLOCK # 16 IN PROGRESS   $
BLOCK # 17 IN PROGRESS   $
BLOCK # 18 IN PROGRESS   $
BLOCK # 19 IN PROGRESS   $
BLOCK # 20 IN PROGRESS   $
BLOCK # 21 IN PROGRESS   $
BLOCK # 22 IN PROGRESS   $

ALL BLOCKS READ IN SUCCESSFULLY

**** HANG UP RADIO-TELEPHONE ****
```

Figure 3.1.13 RECEIVING THE RECONSTRUCTION FROM COMPUTERSEARCH

NOTE: RECONSTRUCTED V2 REST POSITION OUT OF BOUNDARY AND OFF SCREEN EDGE. PLOTTING SOFTWARE BLOWS UP.

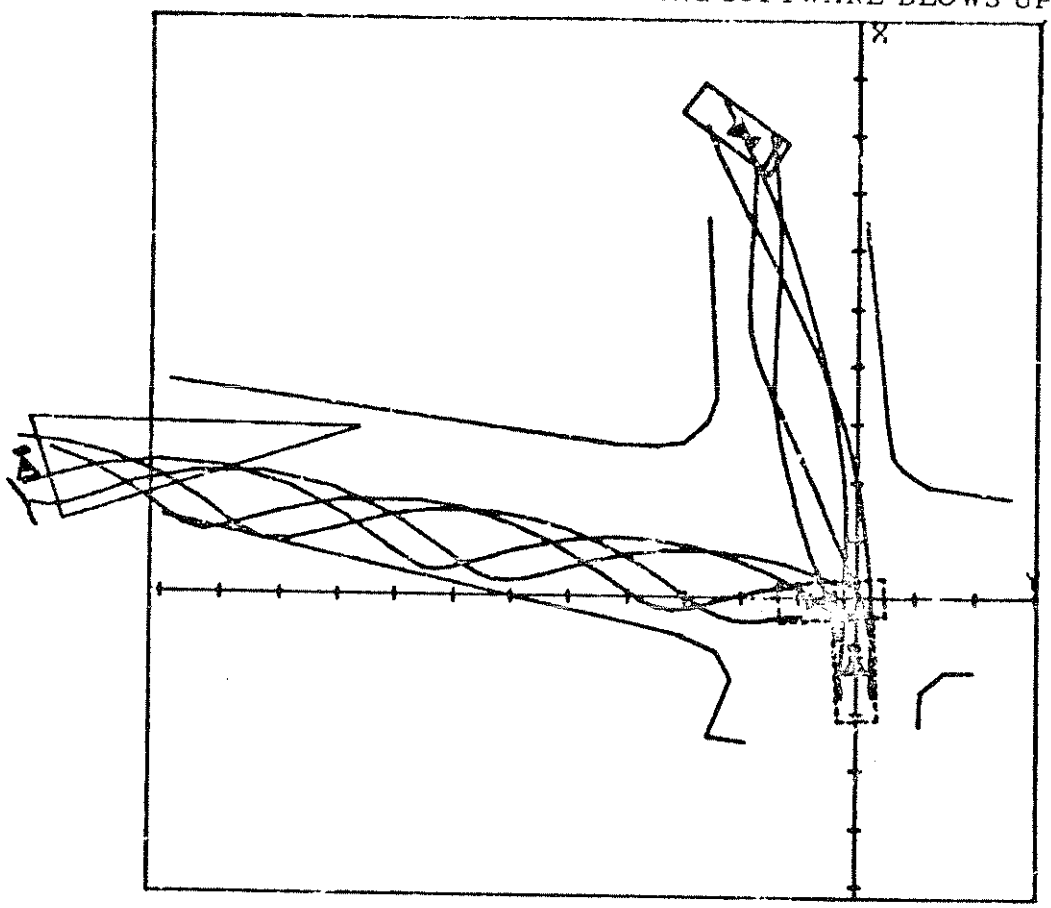


Figure 3.1.14 RECONSTRUCTED ACCIDENT (SAME SCALE)

**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

++++ SMAC RECONSTRUCTION RESULTS ++++

PRACTICE SESSION 1 REAR-SIDE IMPACT NOVEMBER 26,1974

IMPACT CONDITIONS	VEHICLE # 1		VEHICLE # 2	
X-COORDINATE	-11.30	FEET	-.49	FEET
Y-COORDINATE	-.18	FEET	-5.13	FEET
HEADING ANGLE	-2.46	DEGREES	267.01	DEGREES
FORWARD SPEED	46.59	MPH	49.25	MPH
LATERAL SPEED	.00	MPH	.00	MPH
ANGULAR VELOCITY	.00	DEG/SEC	.00	DEG/SEC
IMPACT SPEED CHANGE	11.55	MPH	11.17	MPH
	.00	MPH	.00	MPH
	.00	MPH	.00	MPH
VEHICLE DAMAGE INDICES	01FDEW3		10LZEW4	
	E		E	
	E		E	

REST CONDITIONS	VEHICLE # 1		VEHICLE # 2	
X-COORDINATE	80.72	FEET	20.67	FEET
Y-COORDINATE	-20.71	FEET	-142.31	FEET
HEADING ANGLE	-234.78	DEGREES	-342.51	DEGREES
REMARKS	IN MOTION		IN MOTION	

Figure 3.1.15 PRINTED RECONSTRUCTION SUMMARY

NOTE: V2 RECONSTRUCTED REST ORIENTATION IN ERROR
SOFTWARE BUG IN SINE/COSINE ROUTINE WAS THE CAUSE

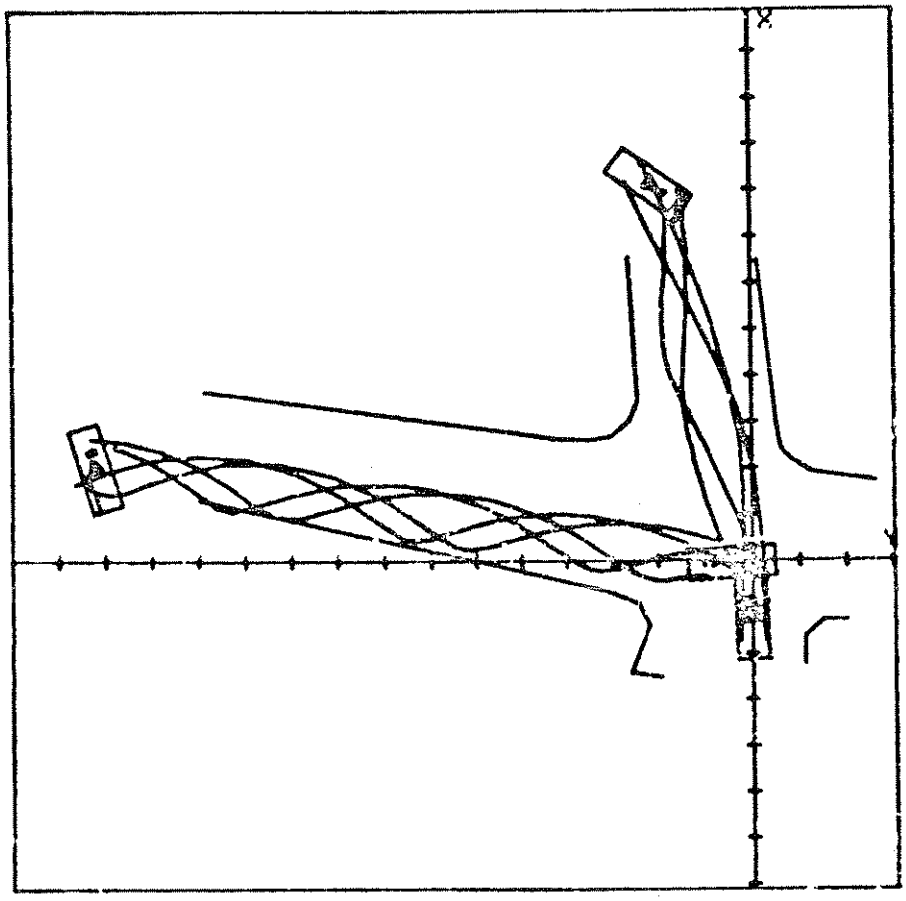


Figure 3.1.16 RECONSTRUCTED ACCIDENT (EXPANDED SCALE)

3.1.4 Practice Session #2

Six members of the Accident Investigation Unit of the Amherst, New York, police force were given an intensive training session at Calspan on December 11, 1974. Since this was a tutorial session, not as much data was sighted as in the previous practice session. The police officers, all assigned to traffic accident investigation duties, had no trouble starting the computer, understanding the codes, or doing the sighting. Figure 3.1.17 shows the practice accident scene as sighted by the police officers, i.e., rest positions and road edges. Note that one of the road edges (i.e., painted line on VERF skid pad) was sighted as a curb (the double line). Several points in the upper right road edge were in serious error - these were later traced to a loose cable connector in the transit control box. Figures 3.1.18 and 3.1.19 are photographs of the vehicle #1 tire marks being sighted. Figure 3.1.20 is the final scene sketch showing one tiremark having been sighted. In Figures 3.1.21 through 3.1.23 the listing provided by the Data Acquisition Program print option is presented - it shows all the information sighted except the road edges.

Figure 3.1.24 is the reconstruction sketch and Figure 3.1.25 is the associated single page summary. This is the first field test with the automatic SMAC iteration capability included, this particular run being the result of 3 iterative passes. Note that V2 still spins out too far and both speeds are still not quite correct (from Severy's test (Reference 18), both speeds are known to be 40 MPH). The relatively slow rate of convergence of the iterative procedure was traced to the initial use, for simplicity, of a velocity adjustment that was directly proportional to the magnitude of the rest position error term. A simple change to the more rational square root of the position error substantially improved the convergence rate (see Section 3.3). Some difficulty was experienced in using the radio-telephone during the police training session. In one instance, the 5 minute data transfer between the timesharing computer and the van was "disconnected" three times. This was later found to be a problem in the Bell System radio-telephone equipment. No major accident van software bugs were discovered and the reconstruction results prompted a change in the iteration software.

NOTE: THESE ERRONEOUS SIGHTINGS CAUSED BY SINE/COSINE RESOLVER CONNECTOR PROBLEMS

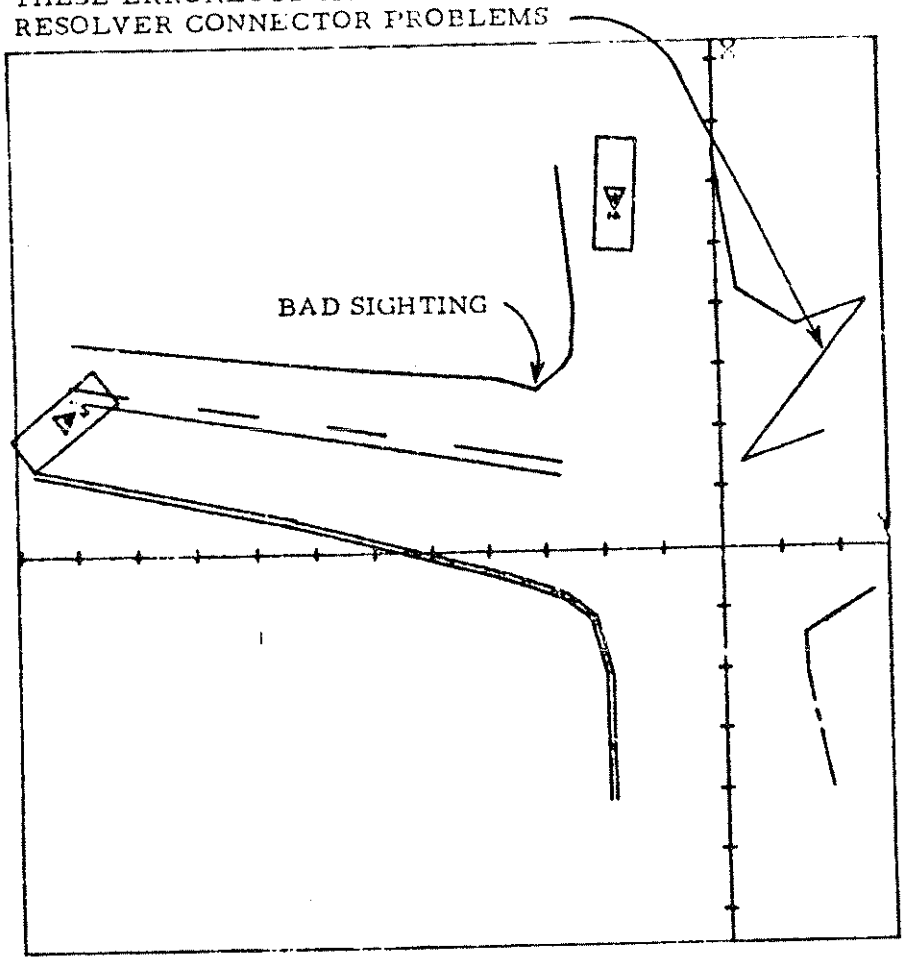


Figure 3.1.17 SIGHTING OF REST POSITIONS AND ROADWAY BY POLICE INVESTIGATORS

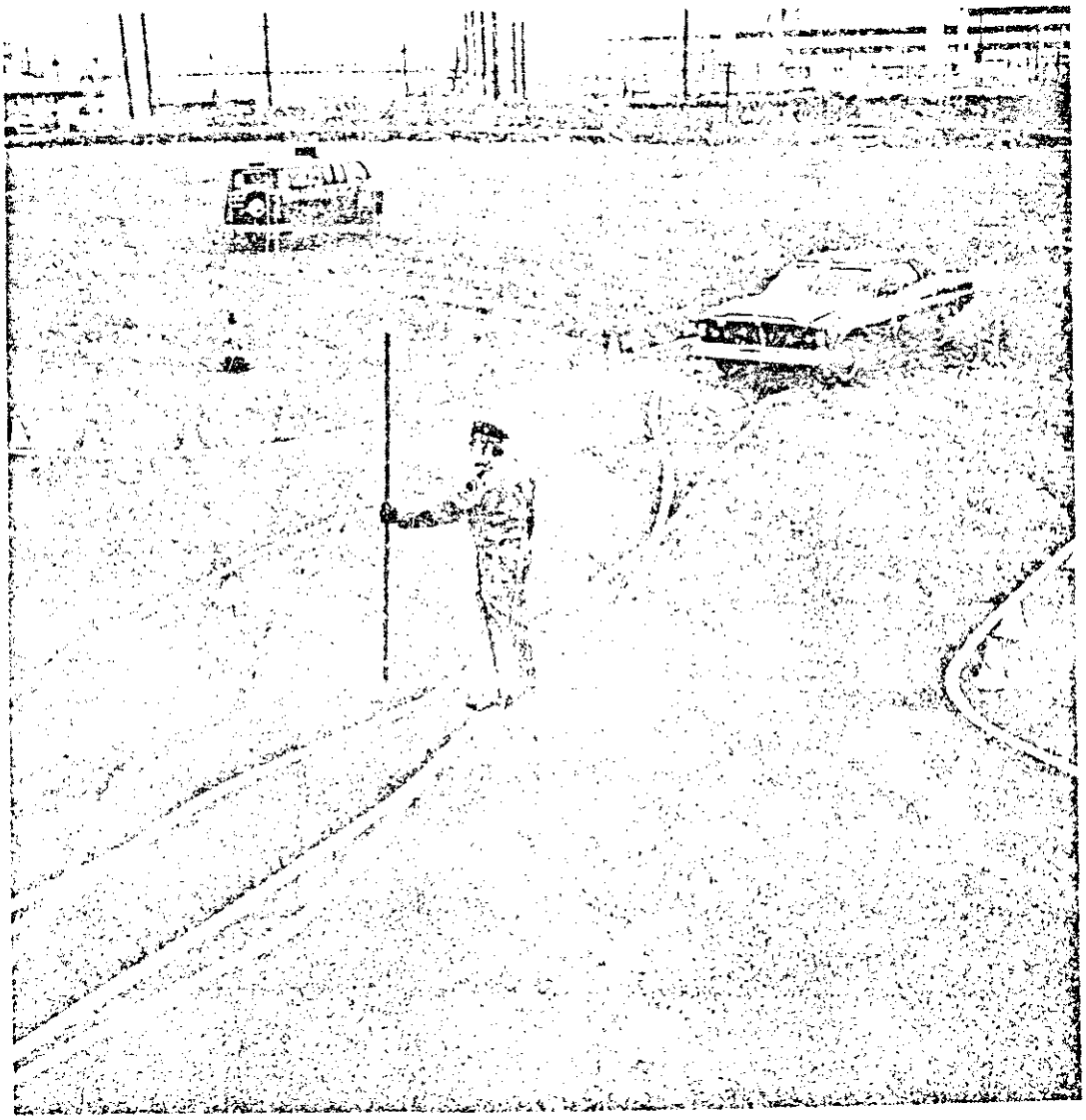


Figure 3.1.18 SIGHTING PRACTICE ACCIDENT SCENE -- TIRE MARKS

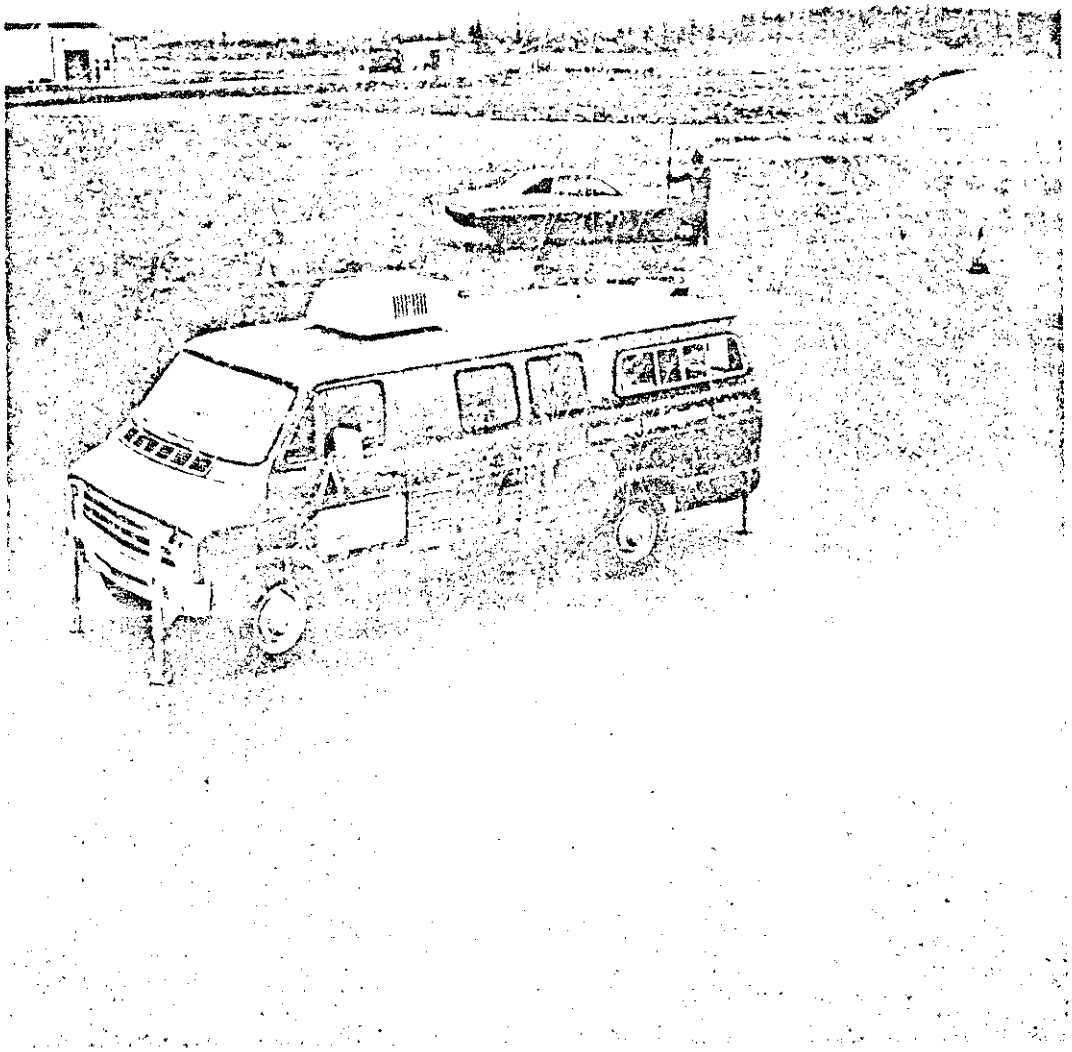


Figure 2.1.19 SIGHTING PRACTICE ACCIDENT SCENE – WHEEL POINTS

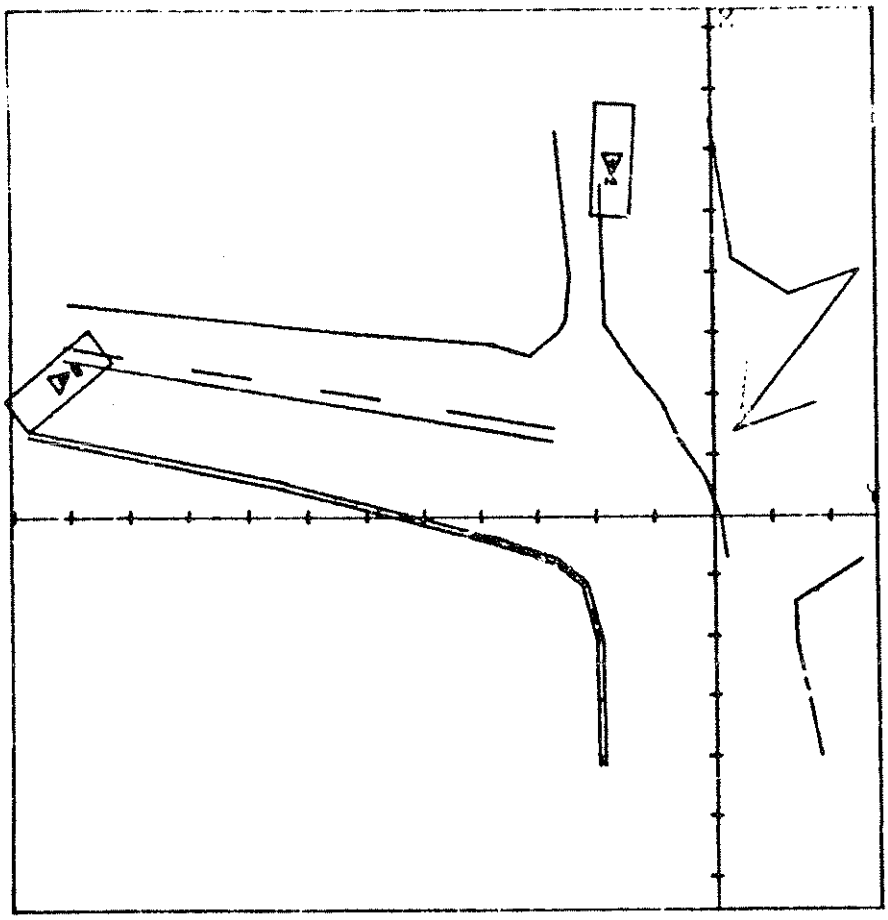


Figure 3.1.20 FINAL SCENE SKETCH BY POLICE INVESTIGATORS

**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

COORDINATE SYSTEM DEFINITION POINTS

POINT	X'	Y'	
1	.00	.00	(ORIGIN)
2	22.03	-.00	(POINT ON THE + X-AXIS)

PICTURE BOUNDARY POINTS

POINT	X'	Y'
1	65.17	27.93
2	-47.47	24.83
3	49.86	-109.73
4	9.79	-120.66

**** HIT CARRIAGE RETURN TO CONTINUE ****

Figure 3.1.21 PRINTOUT OF DATA COLLECTION RESULTS, PART 1

**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

VEHICLE REST POSITIONS

WHEEL POINT	VEHICLE # 1 X	VEHICLE # 1 Y	VEHICLE # 2 X	VEHICLE # 2 Y
1	53.69	-18.86	23.81	-105.99
2	51.32	-14.98	27.89	-109.21
3	64.47	-18.74	17.17	-113.93
4	64.79	-13.48	21.59	-117.40

VEHICLE IMPACT POSITIONS

WHEEL POINT	VEHICLE # 1 X	VEHICLE # 1 Y	VEHICLE # 2 X	VEHICLE # 2 Y
1	-6.89	2.63	2.40	-9.22
2	-6.93	-2.66	-2.58	-8.84
3	-17.46	2.46	2.86	1.33
4	-17.07	-3.09	-2.31	1.66

**** [illegible] CARRIAGE RETURN TO CONTINUE ****

Figure 3.1.22 PRINTOUT OF DATA COLLECTION RESULTS, PART 2

```
**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

                    VEHICLE NO.  1
      WHEEL NO.  1                          WHEEL NO.  2
  X'        Y'                            X'       Y'
 -7.03     2.28  S B          ****************
  -.51     1.34  C B          ****************
  5.95     -.87  C B          ****************
 13.17    -6.13  C B          ****************
 18.19    -8.35  C B          ****************
 23.96   -12.93  C B          ****************
 31.38   -18.30  C B          ****************
 37.74   -18.37  C B          ****************
 54.07   -18.83  E B          ****************

**** HIT CARRIAGE RETURN TO CONTINUE ****
```

Figure 3.1.23 PRINTOUT OF DATA COLLECTION RESULTS, PART 3

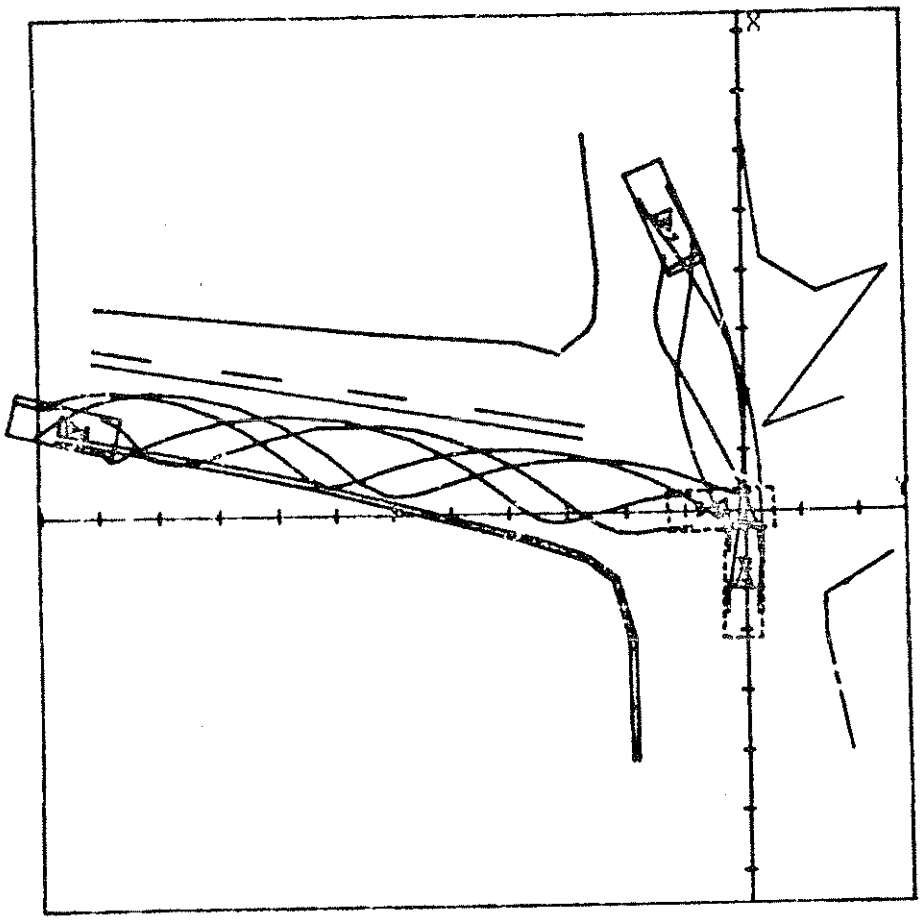


Figure 3.1.24 RECONSTRUCTION SKETCH - PRACTICE SESSION #2

**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

++++ SMAC RECONSTRUCTION RESULTS ++++

POLICE PRACTICE SESSION 1 12/11/74 CALSPAN 3PAS

IMPACT CONDITIONS	VEHICLE # 1		VEHICLE # 2	
X-COORDINATE	-11.37	FEET	.06	FEET
Y-COORDINATE	-.15	FEET	-4.62	FEET
HEADING ANGLE	1.66	DEGREES	268.04	DEGREES
FORWARD SPEED	36.23	MPH	42.38	MPH
LATERAL SPEED	.00	MPH	.00	MPH
ANGULAR VELOCITY	.00	DEG/SEC	.00	DEG/SEC
IMPACT SPEED CHANGE	10.57	MPH	10.20	MPH
	.00	MPH	.00	MPH
	.00	MPH	.00	MPH
VEHICLE DAMAGE INDICES	01FDEW2		10LZEW3	

REST CONDITIONS	VEHICLE # 1		VEHICLE # 2	
X-COORDINATE	46.15	FEET	15.22	FEET
Y-COORDINATE	-12.43	FEET	-115.18	FEET
HEADING ANGLE	-203.16	DEGREES	-256.38	DEGREES
REMARKS	AT REST		AT REST	

Figure 3.1.25 RECONSTRUCTION SUMMARY - PRACTICE SESSION #2

3.1.5 Practice Session #3

Practice Session #3 on December 16, 1974, was the last run-through of the practice accident scene by Calspan personnel (Lynch and Wantuck again) before releasing the vehicle for on-site field trials at actual accidents. For this session, the purpose was to sight each point very carefully and to correct those few bad sightings by the "check-pointing" method described in Part 3 of this final report (Reference 19).

The elapsed time in this practice session was as follows:

Setup Time	- 15 minutes	
Scene Survey	- 90 minutes	(151 points)
Reconstruction	- 20 minutes	

It should be noted that the reconstruction time varies during the day as a function of the workload of the timesharing computer.

Figure 3.1.26 shows the complete scene measurement sketch. Note that the intersection is bounded on three sides by curb lines, and on one side by a curb/pavement edge combination. This side also has a guardrail line sighted while the pavement edge across the intersection is bounded by a shoulder edge line. One of the roads has a lane divider line, defined by only two sightings, running down its center. These additional details demonstrate the flexibility and utility of the measurement system.

Figure 3.1.27 shows the reconstruction sketch while Figure 3.1.28 gives the single page reconstruction printed results. Note the accuracy of the 3-pass reconstruction, both in impact speeds and final rest positions. The modification of the iterative routine that is cited in the preceding section greatly improved the extent of convergence in the 3 iterations. A very nice feature of this display is the retention of scale factors and terrain descriptions from the scene measurement data for use in the reconstruction sketch. This represents a useful enhancement over the previous version of the System/370 SMAC graphics display, which had no such capability.

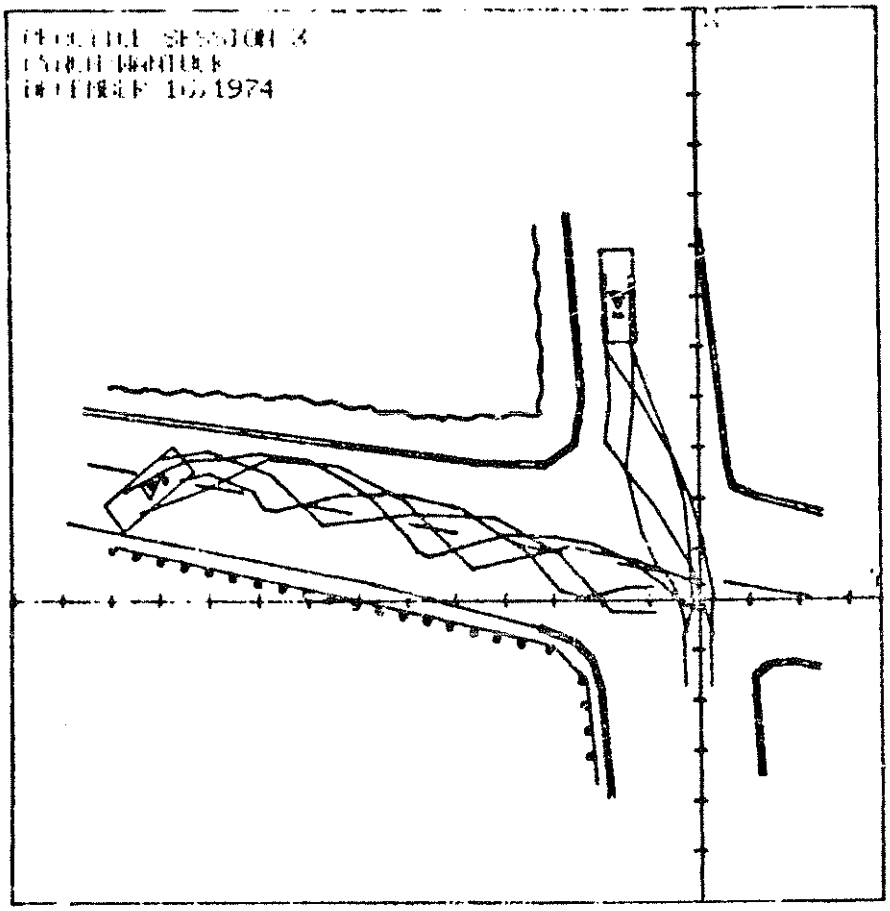


Figure 3.1.26 SCENE SKETCH - PRACTICE SESSION #3

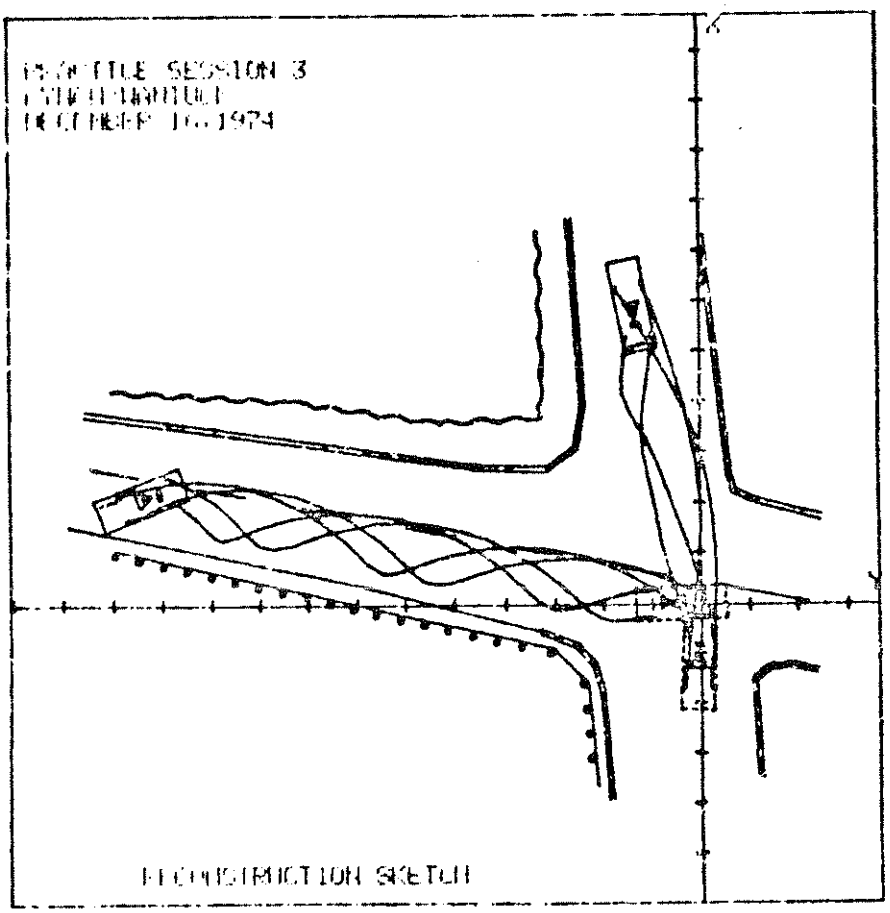


Figure 3.1.27 RECONSTRUCTION SKETCH - PRACTICE SESSION #3

FMVSS GENERAL ACCIDENT INVESTIGATION SYSTEM ****

**** SMAC RECONSTRUCTION RESULTS ****

PRACTICE SESSION 3 LYNCHBURG DECEMBER 16,1974 CHL PARCEL

IMPACT CONDITIONS	VEHICLE # 1		VEHICLE # 2	
X-COORDINATE	-11.42	FEET	- 13	FEET
Y-COORDINATE	- .25	FEET	-4 66	FEET
HEADING ANGLE	1 98	DEGREES	307 72	DEGREES
FORWARD SPEED	40 26	MPH	41.02	MPH
LATERAL SPEED	.00	MPH	00	MPH
ANGULAR VELOCITY	.00	DEG/SEC	00	DEG/SEC
IMPACT SPEED CHANGE	10.97	MPH	10 64	MPH
	.00	MPH	.00	MPH
	.60	MPH	.00	MPH
VEHICLE DAMAGE INDICES	01FDEW3		1PDCEN2	

REST CONDITIONS	VEHICLE # 1		VEHICLE # 2	
X-COORDINATE	58.14	FEET	20 00	FEET
Y-COORDINATE	-13.28	FEET	-11 49	FEET
HEADING ANGLE	-192 03	DEGREES	-204 84	DEGREES
REMARKS	AT REST		AT REST	

Figure 3.1.28 RECONSTRUCTION SUMMARY - PRACTICE SESSION #3

It should be pointed out that the practice accident scene represents a worst case with regard to complexity of the physical evidence to be recorded. While it might take a couple of hours to sight this much data, the job is finished when the last sighting is taken. The plot is readily available, there is no homework to do at the office. In truth, the van does achieve the objective of permitting the investigator to spend all his time investigating and locating physical evidence; he spends no time in bookkeeping. The measured information is also digitized, which implies that it can be put on casette or transmitted by telephone to a central data bank. Thus, many features of this system of investigation are new concepts, that were never before available.

3.1.6 Calspan/Amherst Police On-Site Case #1

The accident investigation vehicle was made available to the Amherst, New York Police Department from December 19 to December 25, the completion date of this research effort. During this period, the van was called out to only one accident - a fatal collision between a 1975 Chevrolet station wagon and a 1971 Subaru.

This accident occurred the previous day on Tuesday, December 17, 1974 at 2:22 p.m. during a snow storm. The Subaru was attempting to make a left turn from Millersport Highway into North Forest going east. The Subaru turned into the path of the oncoming Chevrolet Suburban wagon which was going north on Millersport Highway. The car-to-car impact was not severe, as the station wagon was able to drive into the florist shop parking lot. The impact spun the Subaru around and it impacted quite violently into a signal pole, killing the passenger-side occupant. The police accident report is shown in Figure 3.1.29.

Figure 3.1.29 POLICE REPORT OF CHEVY/SUBARU ACCIDENT

Figure 3.1.29 POLICE REPORT OF CHEVY/SUBARU ACCIDENT

State of New York – Department of Motor Vehicles

POLICE ACCIDENT REPORT

DMV COPY

FATAL (1)

INJ (1)

(A)

(1)

Tues

75 Chev.

Subu

293

71 Subaru

4dsd

Erie

Millersport

Millersport Hwy

N Forest Rd

Car #1 was going North, Car #2 was waiting to make left turn & suddenly turned in front of Car #1. Car #1 struck Car #2 in middle of right side. Car #2 then spun around & hit pole.

WITNESS –

a	1	1	4	1	27	M	—	—	—	—	—
b	2	1	1	1	60	F	11	12	6	PCL	1401
c	2	3	1	1	62	M	10	9	6	POL	1401

ZQ-5341-V-2

The accident van was used the following day to investigate this accident. Since the accident occurred during a snow storm, there were no tire marks or any indication of the point of impact - so reconstruction with the current system would be fruitless and no attempt was made to do same.

Figure 3.1.30 is the physical evidence sketch while Figure 3.1.31 is the summary of the Indirect Supporting Evidence Report. The total time spent was 2 hours and 35 minutes, but much of this period included the resighting of bad lines, getting warm, and breaking for lunch. The actual time sighting the plotted evidence was closer to 1 hour.

The accident van was parked in the florist's shop parking lot. Much difficulty was experienced in sighting the pavement edges on the south side of North Forest. Sighting errors caused the two bad points in the southeast edge, and the southwest edge required 3 resightings. The distance was over the 100 foot arbitrary limit and vibrations from passing trucks (this is a very busy truck route) were probably coupling through the jacks into the surveyor's transit. It was concluded that a high vibration environment makes it difficult to be always precise in sighting with this two-point stadia rod method and that the measurement technique needs to be upgraded to a single point, rangefinder method that will be less sensitive to minor sighting errors. Additional software developments would be desirable to make the error correction methods more efficient.

While it was intended to include more real-world accidents, the experience from these 4 sessions has proved the usefulness of the concept and pointed out some desirable system design changes.

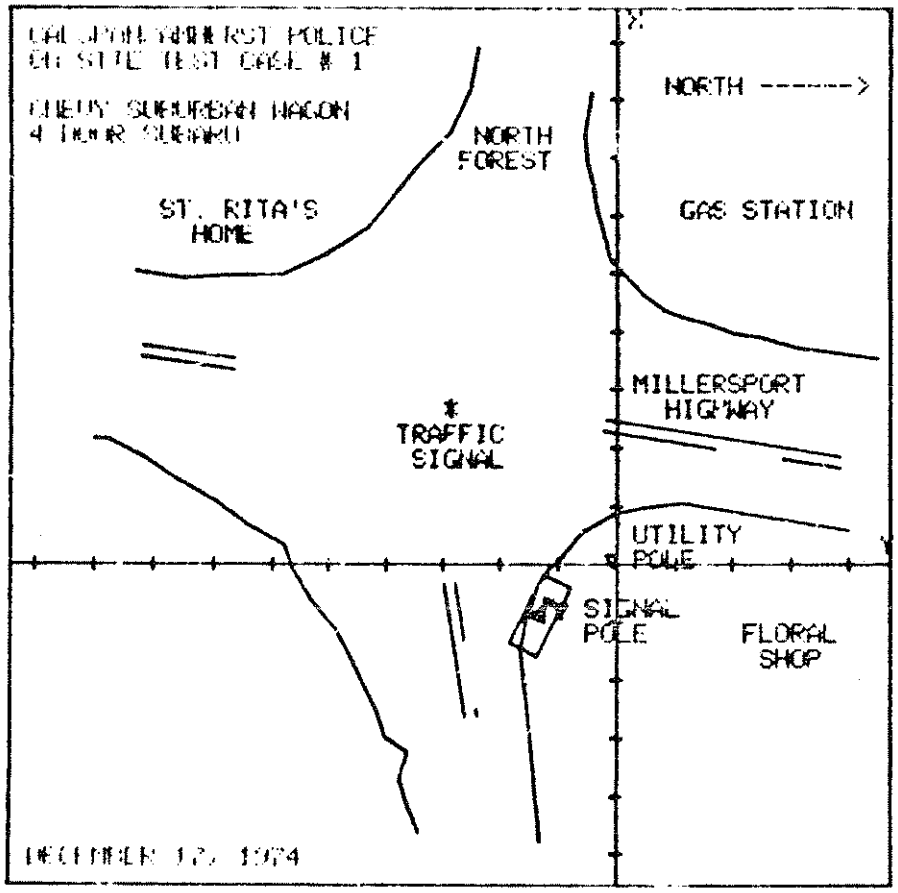


Figure 3.1.30 SCENE SKETCH - ON-SITE CASE #1

**** CALIFORNIA ACCIDENT INVESTIGATION SYSTEM ****

INDIRECT SUPPORTING EVIDENCE REPORT

DECEMBER 17, 1974 2:22 P.M.

SUMMARY OF HOW ACCIDENT HAPPENED
ACCIDENT OCCURRED AT INTERSECTION OF MILLERSPORT HWY AND N. FOREST.
VEHICLE 2 (SUBARU) WAITING TO MAKE LEFT TURN - TURNED SUDDENLY IN FRONT
OF VEHICLE 1 (CHEVY) WHICH WAS GOING NORTH ON MILLERSPORT HIGHWAY.
V1 STRUCK V2 IN MIDDLE OF RIGHT SIDE, V2 SPUN AROUND AND HIT SIGNAL POLE

SPEED LIMITS IN FORCE
MILLERSPORT HIGHWAY 55 MPH N. FOREST 35 MPH
UPHAN

WEATHER CONDITIONS AT TIME OF ACCIDENT
MODERATE SNOWFALL

ROAD CONDITION AT TIME OF ACCIDENT
ICY

VISIBILITY
MEDIUM TO GOOD VISIBILITY

Figure 3.1.31 INDIRECT SUPPORTING EVIDENCE REPORT

3.1.7 Police Comments Based on Field Tests

Comments on the prototype investigation van were prepared by the Amherst Police Department. They are presented on the following page.

POLICE DEPARTMENT

H. E. ZIMMERMAN, CHIEF

AREA CODE 716
832-1110

TOWN OF AMHERST • ERIE COUNTY

5565 MAIN STREET
WILLIAMSVILLE, N. Y. 14221

January 6, 1975

Calspan Corporation
4455 Genesee Street
Cheektowaga, New York 14225

ATTENTION: Edward Pitcher

This letter is in response to your request for comments on your computer van. The officers who had attended the class wrote up short summaries and some suggestions on how this computer van could be more versatile and advantageous to them in their job of investigating accidents.

Taking into consideration that this vehicle is still in the prototype stage, our men feel that it will be, in the future, very advantageous in the investigation of accidents. They do feel, however, that some changes are necessary in order for them to use this vehicle to their advantage.

The following are the suggestions our men submitted regarding changes necessary in your computer van:

1) The measuring turret should be designed to take in a greater scanning area to eliminate positioning of the unit various times for the purpose of collecting data.

2) The hydraulic leveling device should be turned in such a manner as to be operated from inside the vehicle or from the outside with the doors closed. Considering the sensitivity of the computer, changes in temperature would impede the operating capabilities of the unit.

3) The installation of a small electric pump to take the place of the manual jacking system would be very advantageous.

4) It appears heavy truck traffic affected the unit adversely, as the lines came out jagged on several tries to make them curve according to the road structure.

We would like to take this opportunity to thank you for giving the men of our department the opportunity to attend the classes and operate the equipment you have devised. We look forward to continued good relations in working with Calspan Corporation.

Very truly yours,

Kenneth J. Braun

Kenneth J. Braun
Captain

KJB/ss

ZQ-5341-V-2

3.2 The Calspan Accident Investigation Vehicle

The Calspan Accident Investigation Vehicle is a mobile computerized system which enables accident investigators to perform a total scientific analysis of the accident at the scene. Figure 3.2.1 is a photograph of the prototype accident van. A minicomputer system powered by an on-board generator is coupled to an instrumented surveyor's transit to optically locate and record key accident physical evidence, such as rest and impact positions, skid marks, curb edges, and so forth. The minicomputer is also connected by radio-telephone to a larger time-sharing computer which uses the optically gathered information to mathematically reconstruct the accident events via the Simulation Model of Automobile Collisions (SMAC) program. The minicomputer system also aids the investigators in compilation of an accident report. A graphics display terminal and hard copy unit allow printouts of the report and schematic drawings of the accident scene, both measured and reconstructed, to be provided. The system is easy to operate and requires no knowledge of computers or electronics to run. This system substantially extends the capability of accident investigators to determine the exact cause of the accident at the scene and it forces adherence to proper investigative procedures and formats. The computerization of this data will permit statistical studies that can have a positive influence on the efforts of Federal, State, and local agencies to make policy decisions concerning highway safety.

3.2.1 Specifications

Vehicle - 1973 Dodge Maxivan

Stabilizer Jacks - 4 Hellstar leveling jacks (manually operated)

Generator - Onan Model LK, 2500 watts, 120 volts, 20.8 amps

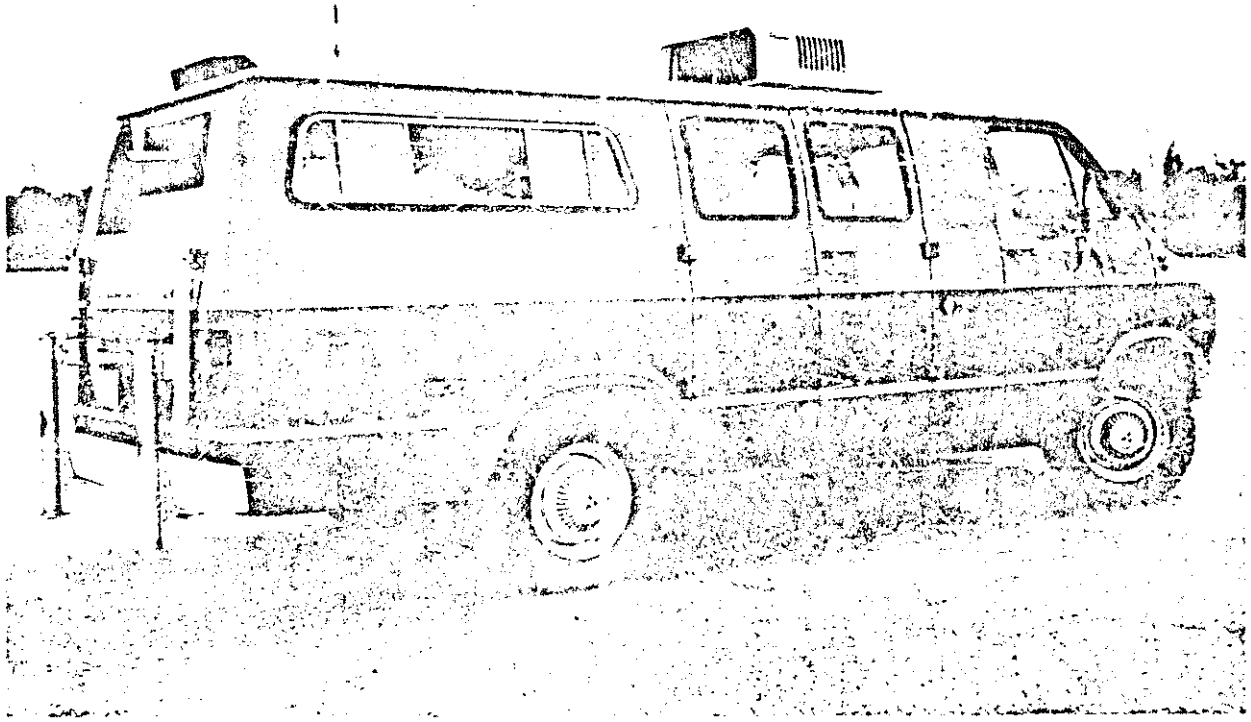


Figure 3.2.1 CALSPAN ACCIDENT INVESTIGATION VEHICLE

Optics - K&E surveyors transit

Astrosystems sine/cosine resolvers (.01 degree)

Astrosystems digital angle readout

Calspan Corporation minicomputer interface

Radio-telephone - Bell system radio-telephone

General Electric TDM-115 acoustic coupler

Walkie-Talkie - Realistic TRC-24B C.B. tranceiver (in van)

Fanon T404 walkie-talkie (in field)

Minicomputer - Texas Instruments 960-A computer with:

Extended arithmetic option

24 K of memory

Interval timer

2 - RS-232 interfaces

Diablo Model 32 disc memory

Tektronix 4010 graphic display unit

Tektronix 4016 hard copy unit

Texas Instruments PAM/D operating system

3.2.2 Description of Equipment

Referring to Figure 3.2.2, the salient components of the accident investigation minicomputer system are:

1. Texas Instrument 960A Minicomputer

An on-board processor used to collect and store optically measured transit data and provide prints and plots of same, assist the operator in preparation of an accident report, and communicate via radio-telephone to the time-sharing computer for reconstruction operations.

2. Diablo Model 30 Disc Memory Unit

Used by the minicomputer for bulk storage of programs and data. The disc memory incorporates a removable disc platter and is the principal non-volatile storage method in the computer system.

3. Tektronix 4010 Graphics Display Unit

Incorporates a keyboard and storage screen display to allow the van operator to communicate with the minicomputer system and observe results and plots on the screen.

4. Tektronix 4610 Hard Copy Unit

Produces a hard copy of whatever is displayed on the display screen. The hard copy unit is used to make permanent records of the accident scene evidence plots and reconstruction results, as well as other reports.

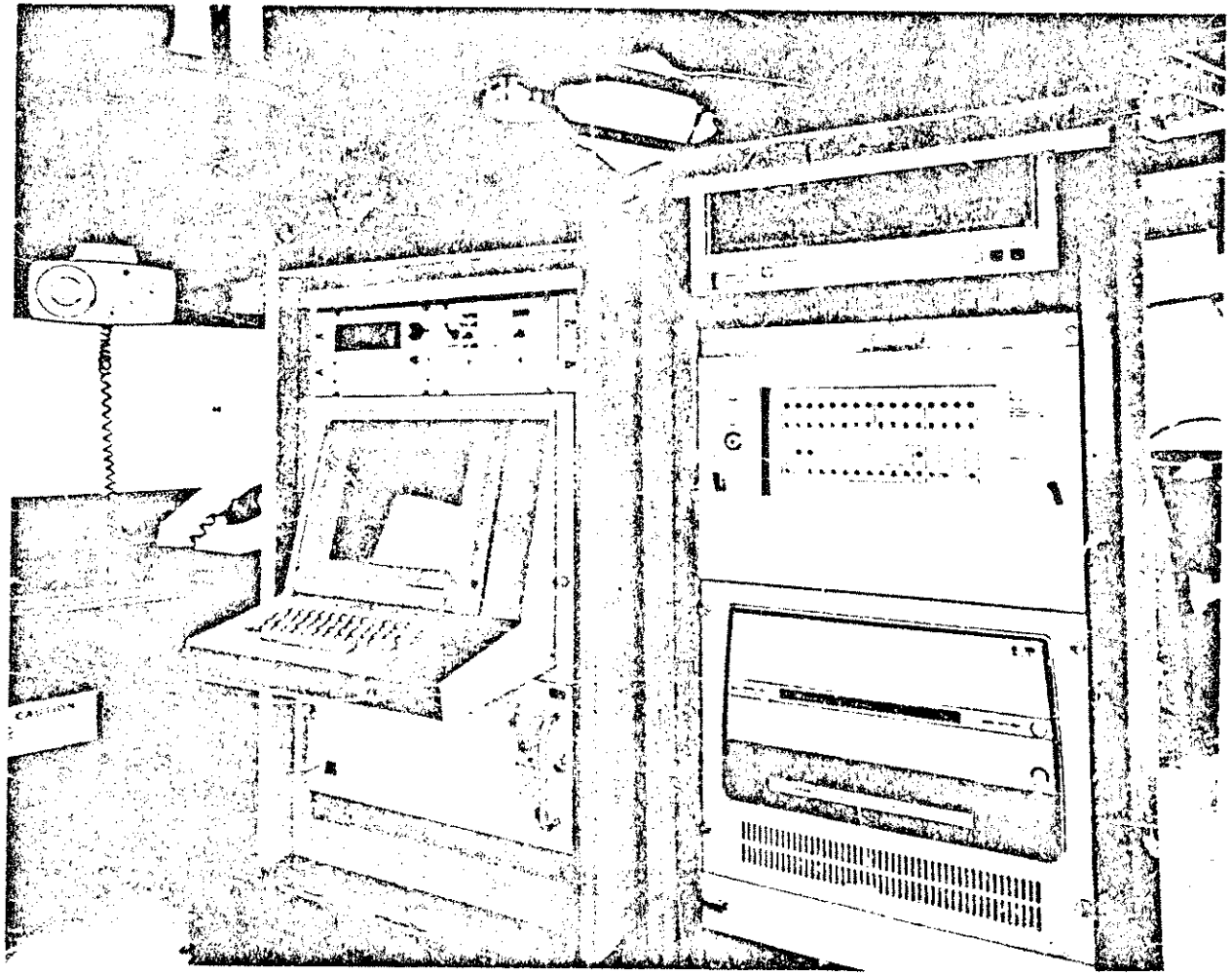


Figure 3.2.2 ACCIDENT INVESTIGATION COMPUTER SYSTEM

5. Astrosystems Shaft Angle Encoder

Converts the sine/cosine resolver signals from the transit into digital numbers representing shaft angle degrees suitable for input to the minicomputer. Guaranteed accuracy of this device is .01 degrees.

6. Talspan Electronic Transit Interface

Prepares and formats transit angles and identification codes into suitable RS-232 teletype format for transmission to the minicomputer.

7. Bell System Radio-Telephone

Provides a mobile telephone link for connection to the time-sharing computer.

8. General Electric Acoustic Coupler

Connects the telephone directly to the van minicomputer.

Referring to Figure 3.2.3, the components of the transit station are:

9. Instrumented Transit

This device includes a K&E Surveyor's Transit and two sine/cosine resolvers to measure azimuth and elevation angles. The transit is weighted so that when the gimbal locks are loosened, it will generally flop down into a level condition.

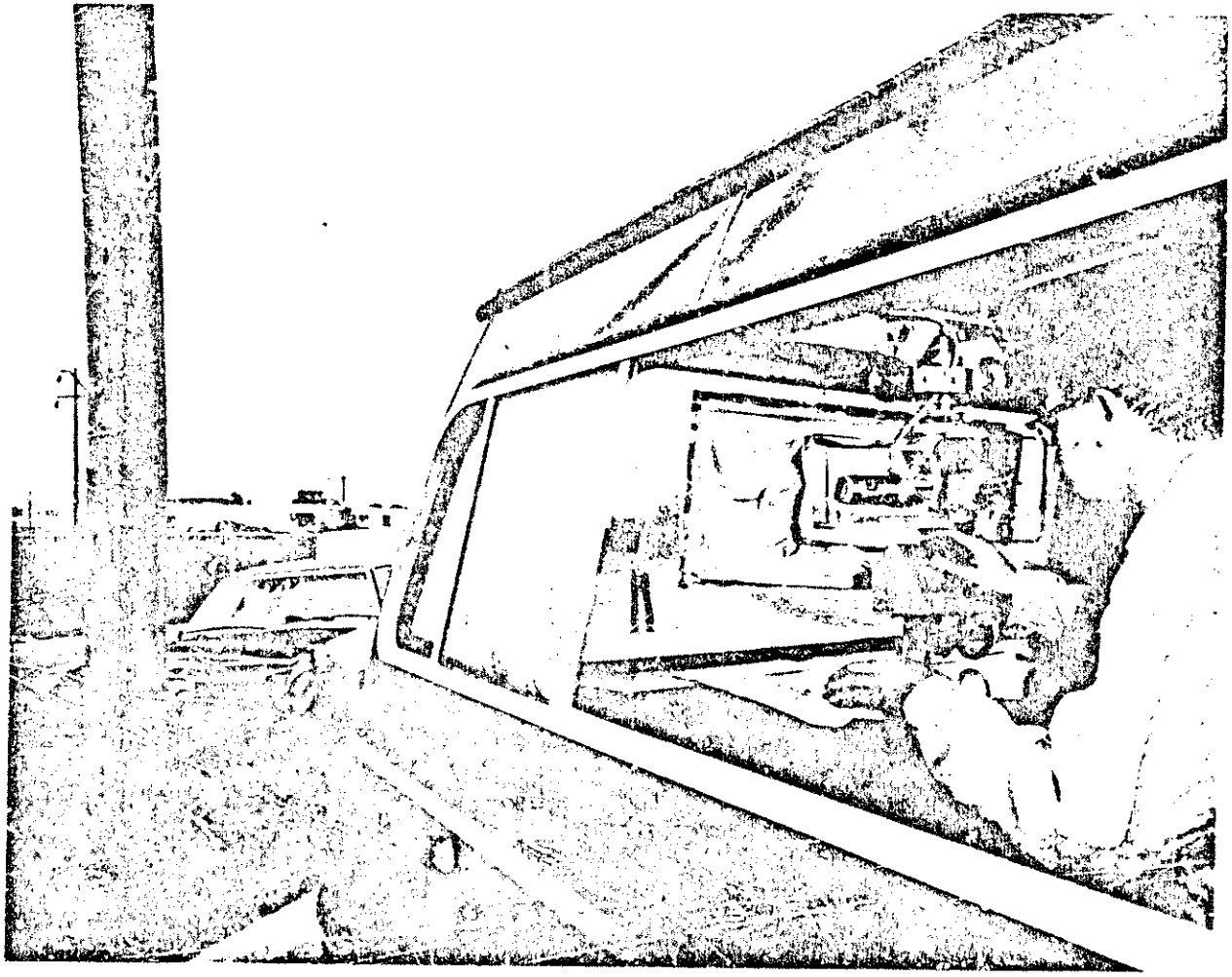


Figure 3.2.3 TRANSIT CONTROL STATION

10. Transit Control Box

This console includes a 5-digit thumbwheel switch assembly to identify the nature of the transit sightings, a pushbotton to take a sighting, and lights to indicate an out-of-level condition and which target on the stadia rod to sight.

11. Stadia Rod (seen through the back window)

This is an 8-foot high tube with two lightbulbs 7 feet apart serving as targets. Sighting the top and bottom light on this rod provides a triangle that the minicomputer can solve to resolve the rod location into an appropriate reference frame.

Figure 3.2.4 is a schematic diagram showing the major components of the accident van minicomputer system.

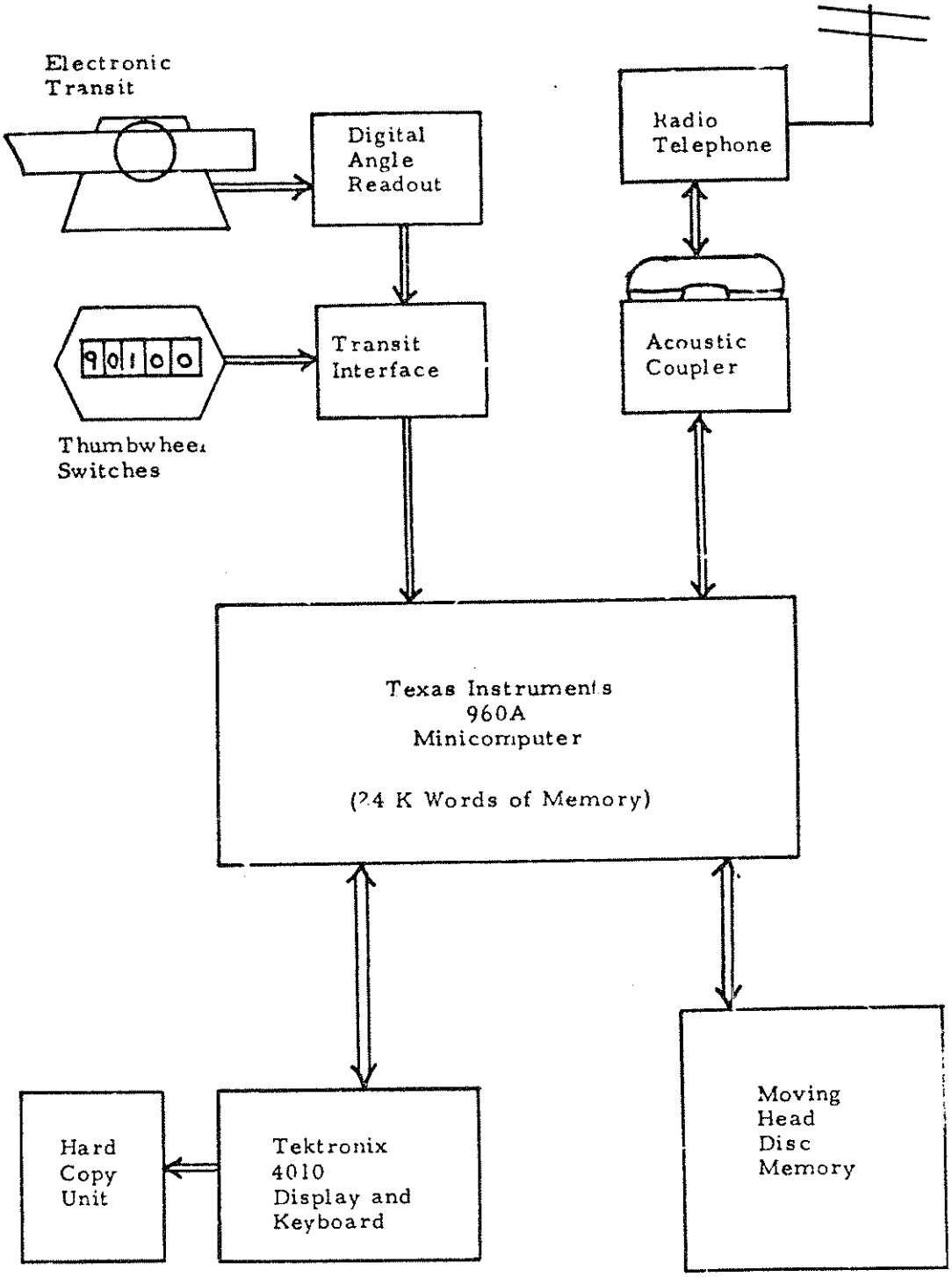


Figure 3.2.4 CALSPAN ACCIDENT INVESTIGATION VEHICLE MINICOMPUTER LAYOUT

3.2.3 Accident Investigation Software System

All investigation operations, both data collection and computer reconstruction, are under the direct control and supervision of the minicomputer software system. Much effort has been expended to make the software "idiot-proof". Even the most experienced programmer can inadvertently type in an incorrect entry to a minicomputer that can cause its programming to lock up (sometimes called a "crash"). All operator entries to the minicomputer, be they be from either the keyboard or instrumented transit, are extensively checked for validity. It is virtually impossible to type an input or take a sighting that will "crash" this system - if the operator makes a mistake, the minicomputer is programmed to recognize it, issue a diagnostic message, and request a resubmission of the input. The net result of all this effort is that a non-technical person can learn to operate this equipment in a couple of hours. The minicomputer operation is so tutorial by nature that the only item of any difficulty at all in this system is the transit identification codes which one must learn.

The keystone of the accident investigation software is the notion of a set of interconnected menus. A menu is a list of options with short descriptions displayed on the screen. To use a menu, the operator simply reads the list of options, selects and types one at the bottom of the screen, and hits the carriage return key. The minicomputer analyzes the response and, if legal, it takes the appropriate action. In many cases, selection of an option from one menu will bring up another menu.

3.2.4 System Menu

Once the minicomputer has been started, the Main System Menu is displayed. This menu allows the operator to select the major software subsystems provided in the accident investigation vehicle. The accident scene data acquisition program (DAP) is the subsystem that controls all operations involved with the sighting and plotting of physical evidence. The accident reconstruction program (SMAC) is the subsystem

that communicates via radio-telephone to the SMAC program on the time-sharing computer system. The indirect supporting evidence (ISE) aids in the compilation and printing of a police-type accident report. The KEEP subsystem allows the accident data to be stored or retrieved from the disc memory unit. The user assistance service (HELP) provides tutorial information on such items as transit codes, starting the computer, vehicle damage indices and the like. Figure 3.2.5 is an example of the system menu display. To select an option, the operator merely types its name followed by a carriage return.

```
                    CALSPAN ACCIDENT INVESTIGATION SYSTEM

THE FOLLOWING IS A LIST OF THE CURRENTLY IMPLEMENTED SOFTWARE

NAME                    DESCRIPTION

DAP        ACCIDENT SCENE DATA ACQUISITION PROGRAM
SMAC       ACCIDENT RECONSTRUCTION PROGRAM
ISE        INDIRECT SUPPORTING EVIDENCE
KEEP       SAVE OR RECOVER THE SYSTEM DATA AREA FROM DISC
HELP       USER ASSISTANCE SERVICE
QUIT       TERMINATE THE PROCEEDINGS
PAM/D      FALL THROUGH TO THE PAM/D MONITOR

TYPE IN ONE OF THE ABOVE NAMES

DAP
```

Figure 3.2.5 SYSTEM MENU

3.2.5 Collection of Physical Evidence Using the DAP Subsystem

The Data Acquisition Program (DAP) subsystem is controlled by its own DAP menu. Options in this menu include clearing the memory of the previous accident, quizzing the operator about the vehicles involved, accepting sightings from the transit, and printing and plotting the current results. One option, of course, is a return to the system menu.

A 5000 word FORTAN common area, shared by all tasks, is always resident in the minicomputer's memory. This area is automatically cleared when the computer is started up and when the DAP CLEAR option is selected. It is in this area that all physical evidence and reconstruction information is stored. The KEEP option in the system menu allows fresh copies of this area, called the system data area, to be either stored or retrieved in a similar area on the disc memory. Saving this information on disc provides a secure, non-volitile way to hold the accident data that is impervious to power downs, etc.

The QUIZ option asks the name of each vehicle and requests the operator to classify it as to subcompact, compact, intermediate, or full size. This information is used to draw the rectangular vehicle outlines on the accident scene diagram and is later transmitted to the SMAC program.

3.2.6 Scene Data Measurement System

In taking a sighting of a piece of evidence, the operator enters the code in the code switches, sights the top bulb on the stadia rod and hits the transmit button, then sights the bottom bulb and hits the transmit button. The sequence of data transmitted is as follows: 5 digits of identification code, comma, 5 digits of top bulb elevation, comma, 5 digits of top bulb azimuth, comma, 5 digits of bottom bulb azimuth, comma, 5 digits of bottom bulb elevation, carriage return.

The geometrical relationships involved in converting the angles of the top/bottom sightings into X-Y coordinates are quite simple. Using the elevation angles, the horizontal range is calculated; from this, the azimuth angle provides the X and Y values using standard coordinate transformations.

Figure 3.2.6 shows the geometrical relationships involved in the range calculation.

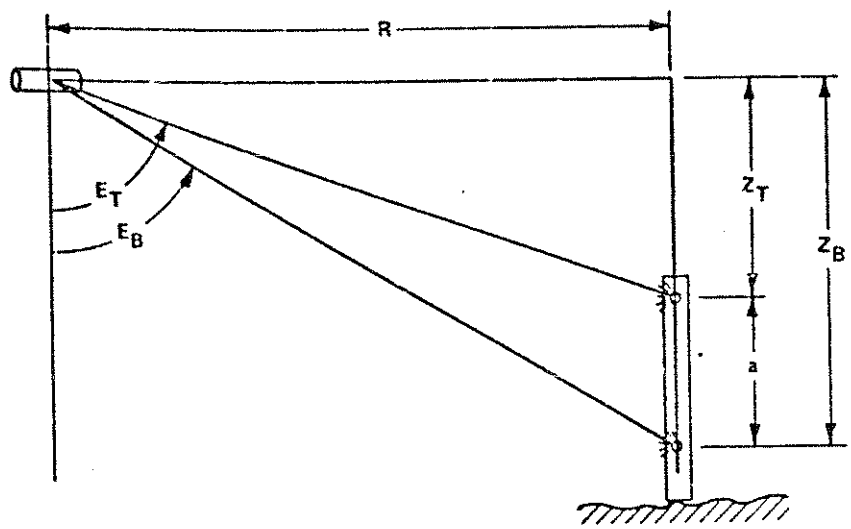


Figure 3.2.6 GEOMETRY OF RANGE DETERMINATION

The expression for the range is:

$$R = \frac{7.\ \mathrm{Sin}(e_T)\,\mathrm{Sin}(e_b)}{\mathrm{Sin}(e_T - e_b)}$$

The range is converted into X and Y values using the azimuth angle and these coordinates, being defined for a transit-fixed reference frame, must be transformed into a scene defined coordinate system.

An interesting side issue is the sensitivity of this measurement system to angular errors, be they the resolution of the angle encoders or operator pointing accuracy. An expression for the absolute error in range as a function of the absolute errors in the elevation angles is:

$$\delta R = \frac{\partial R}{\partial e_T}\,\delta e_T + \frac{\partial R}{\partial e_b}\,\delta e_b$$

where $$\frac{\partial R}{\partial e_T} = \frac{7.\ \mathrm{Sin}(e_b)\,\mathrm{Cos}(e_T)}{\mathrm{Sin}(e_T - e_b)} + \frac{7.\ \mathrm{Sin}(e_T)\,\mathrm{Sin}(e_b)}{\mathrm{Sin}^2(e_T - e_b)}\,\mathrm{Cos}(e_T - e_b)$$

$$\frac{\partial R}{\partial e_b} = \frac{7.\ \mathrm{Sin}(e_T)\,\mathrm{Cos}(e_b)}{\mathrm{Sin}(e_T - e_b)} + \frac{7.\ \mathrm{Sin}(e_T)\,\mathrm{Sin}(e_b)}{\mathrm{Sin}^2(e_T - e_b)}\,\mathrm{Cos}(e_T - e_b)$$

The worst case is when the signs of the angular errors are opposite (that is, when the top bulb is sighted above by some angular error and the bottom bulb is sighted below with some angular error). A plot of this situation for both .01° error (the basic resolution of the sine/cosine angle resolvers) and .05° error (a very typical operator error which includes the encoder resolution error and an accidental "jiggle" of the transit) is given in Figure 3.2.7.

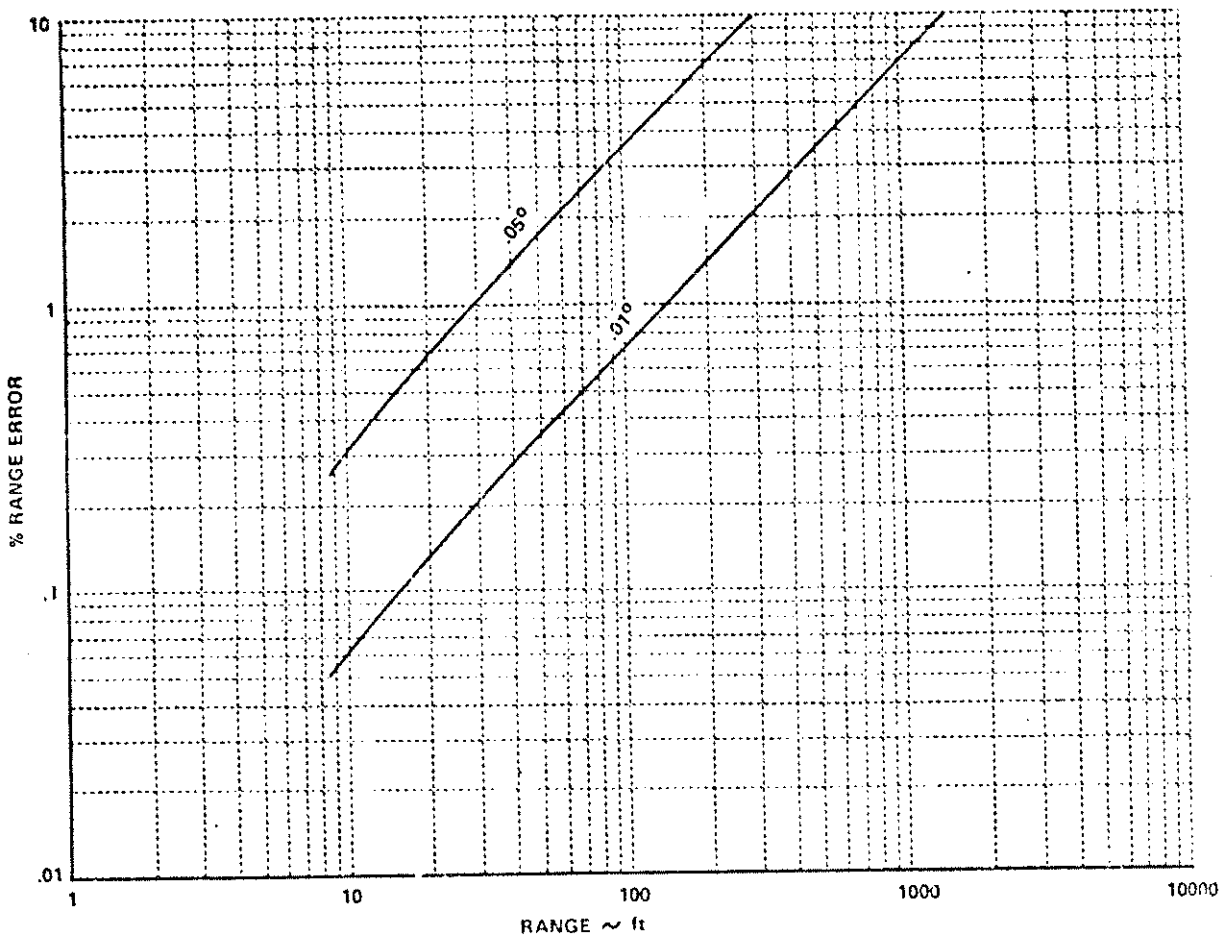


Figure 3.2.7 PREDICTED RANGE ERRORS

As can be seen, at ranges above 100 feet very precise sighting by the operator is required. Any sighting errors will be amplified by this system. It is possible, however, to move the van to keep all sightings within the 100 foot range.

3.2.7 Sighting Methodology

After arriving at the scene of the accident, the operators must make a preliminary walkthrough to note the total span of evidence that is pertinent. They must decide on a location to park the accident van so that the optical measurement system can sight all of this evidence. Once the van has been parked, the jacks lowered, the generator started, the transit leveled, and the minicomputer system started, the investigators may begin to record evidence.

The sighting procedure is quite straightforward. The investigator in the field holds the stadia rod vertical over the item of interest. The operator inside determines the proper identification code and enters it in the thumbwheel switches. Centering the telescope crosshairs over the top stadia target bulb, he punches the "transmit" button - this causes the code, azimuth and elevation angles to be sent to the minicomputer. Doing the same for the botton target causes the azimuth and elevation angles and a "carriage return" to be sent to the minicomputer to complete the sighting.

The first point sighted must be an origin. This origin should be a recognizible physical object such as a street sign or fire plug. The next point is an X-axis point used to define the direction of the X-axis (it should also be recognizible). If for any reason the van must be moved, then resighting the origin and X-axis point will allow the minicomputer to compute all new sightings in the originally defined axis system.

The investigator then sights four boundary points. These four points tend to "box in" the accident scene and are used primarily to calculate scale factors for plotting the data. The minicomputer "squares up" this box and once defined, a plot of the current data can be made at any point in the collection process. Figure 3.2.8 is a schematic showing these reference points.

Items of physical evidence at the accident scene are classified into two general types - single points and line structures. Items that are sighted as single points are rest and impact wheelpoints, individual terrain items like stop signs, and the origin, etc. Line structure items include tire marks, curb edges, guardrails and the like. In identifying a line structure like a pavement edge, the field investigator takes enough sightings along the edge so that when the minicomputer connects these points on the screen, a suitable curve is generated. When coding a line structure, the point being sighted must be identified as a start, continuation, or end point.

What the minicomputer does with these sightings is very interesting. In the case of a line structure, the minicomputer connects the sighted points with a line structure that identifies the line type. For example, if a shoulder edge was sighted with 5 points, the minicomputer would connect these points on the display screen with a wavy line - the standard designation. For the case of a single point, such as a utility pole, the minicomputer looks up the stored line drawing of a utility pole (a circle with a line through it) and plots it at the appropriate spot on the display screen. It is these types of operations that speed up the total investigation job.

Part 3 of this final report entitled, "Accident Investigation Vehicle - Operational Manual", which has been separately submitted, provides a complete description of the transit codes and explains how to use them.

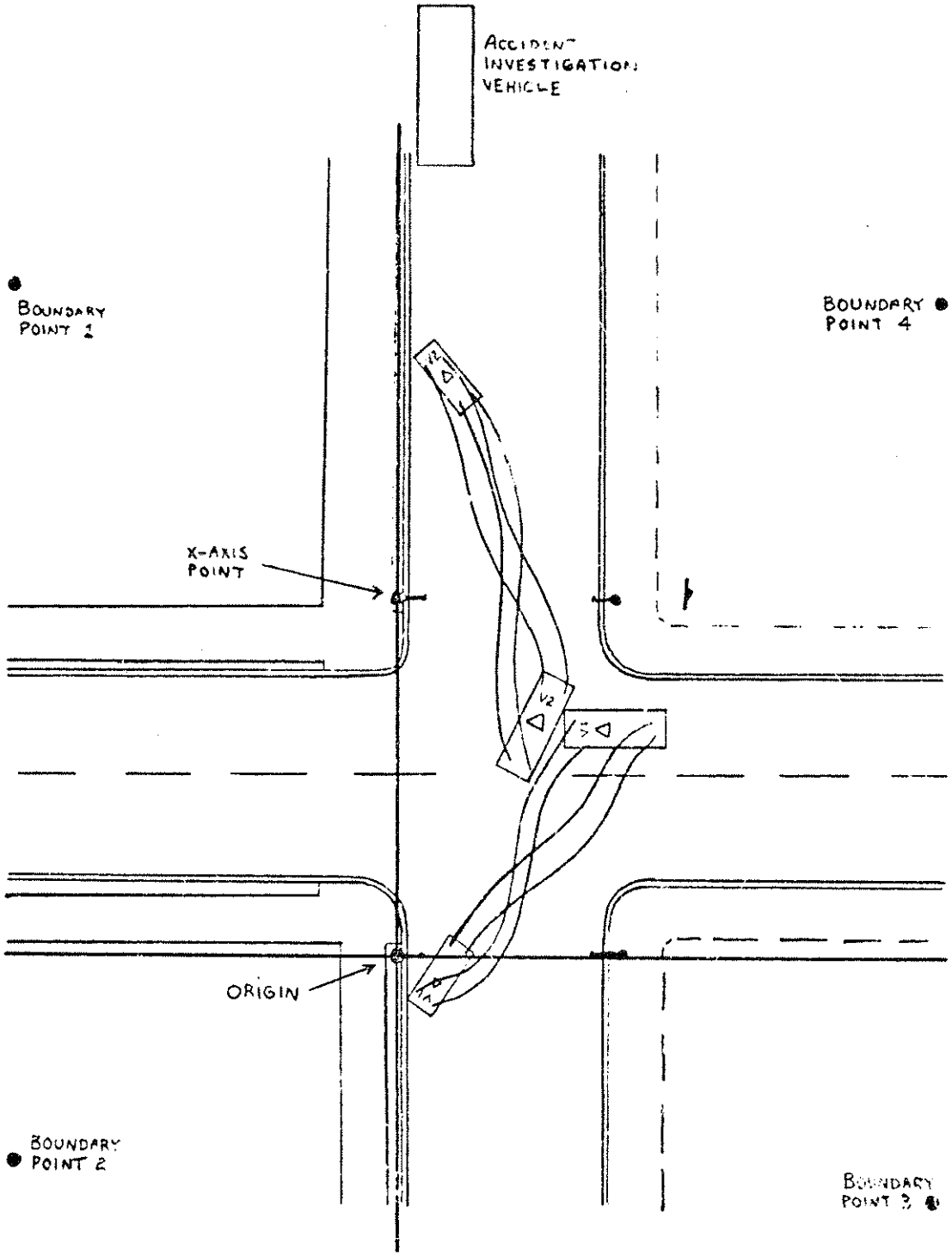


Figure 3.2.8 ACCIDENT SCENE AXIS DEFINITION POINTS

3.2.8 SMAC Reconstruction System

The on-board minicomputer has neither the processing power nor the memory capacity to support the SMAC program. Hence, the SMAC program, the START "first guess" program, and various data transfer programs have been installed on the Computersearch timesharing system. These programs may be used by the accident van minicomputer via the radio-telephone linkup.

All operations involving the reconstruction process are controlled by the SMAC menu. Options include a quiz to determine the VDI's of the vehicles and similar information, the START option which transmits the measured data to Computersearch and submits the START program's "first guess" to the SMAC program, the CHECK option which inquires about the status of the SMAC reconstruction, the DATA option which transmits the extensive reconstruction results back to the accident van, and the PRINT and PLOT options which provide the visual reconstruction results.

Readers familiar with timesharing computer operations know that extensive operator knowledge of language protocols, commands, and formats is required. With the SMAC software subsystem developed for the accident van, all of this complexity is eliminated by programming both computers to do all the "talking". The minicomputer requests the operator to dial the telephone number of Computersearch - this is the only human intervention required. The minicomputer handles sending the charge number, submitting the proper commands to START programs, reading characters of data coming back from the reconstruction program, and all other operations normally assigned to the operator. Thus, the reconstruction process with Computersearch over the radio-telephone is "hands-off" and fully automatic. Extensive error checking and correction software has been developed for both computers so that the system may recover from a noise burst. The complete disconnection of the radio FSK link is a special case, however, which there is no current software protection.

The operator, using the QUIZ option, may override the measured rest and impact positions, modify the VDI's, change the post-collision rotation and wheel lockup indicators, and vary the title. The PLOT option uses the same scale factors and terrain description as the DAP version, but the rest and impact vehicle outlines, tire marks, and damage outlines are as supplied by the SMAC program. The PRINT option is a single page synopsis that is similar in content to the System/370 graphics version.

3.2. Investigation Procedure

The following is a summary of the automobile accident investigation procedure using the accident van system:

1. Set up van.

2. Bring up computer system.

3. Select DAP subsystem.

   A. Clear previous accident.

   B. Take DAP quiz.

   C. Select TRANSIT option.

      1. Sight origin, X-axis point, and 4 picture boundaries.

      2. Sight rest and impact wheel points.

      3. Sight road edges.

      4. Sight tire marks.

      Note: periodically plot and save good data

      5. When finished, get hard copy of plot and printout.

4. Select SMAC subsystem.

   A. Take SMAC quiz.

   B. Select START option to start reconstruction.

   C. Check on reconstruction status using CHECK option.

   D. Bring results back in with the DATA option.

   E. Get hard copy of result and PRINT and PLOT option.

5. Select ISE subsystem to make report summary.

3.3 Extensions and Refinements of SMAC

3.3.1 Development of the START Routine and Automation of the Reconstruction Routine

Part of the overall objective of this research has been to make the system "user oriented" so that users without an engineering background can operate it with ease. Present users of the IBM 370 version of SMAC have to make either an intelligent guess or use the more standard approximate reconstruction techniques to estimate the initial velocities of the vehicles, rotations, etc. They must also provide the necessary vehicle and tire data for each of the vehicles involved.

To overcome this problem with the accident van/SMAC program a START routine was developed to generate the 14 input cards that the SMAC program requires and then to run the program automatically. The common area from the Data Acquisition Program (DAP) is used to furnish the coordinates of the impact and rest positions for the two vehicles. Note that this can be overridden manually to allow alternative values to be submitted. The remaining information required by the START program is obtained from DAP and SMAC via their QUIZ programs (see accident van users manual for details) as follows.

Size of each vehicle, i.e., whether it is full size, intermediate, compact or subcompact; obtained from the DAP QUIZ program.

Direction of rotation of each vehicle between impact and rest positions, whether any of the wheels were locked up during this spinout motion and the primary vehicle damage index for each vehicle; obtained from the SMAC QUIZ program.

The program then automatically generates the 14 card input including estimates of the speeds at impact for each vehicle.

3.3.1.1 Approximate Speed Estimates in START

To estimate the speeds prior to collision, the impact and spinout phases are treated separately in the START program.

To calculate the linear and angular velocities of each vehicle immediately after impact, i.e., at the start of the spinout phase, expressions developed by Marquard (Reference 4) are used. Analyzing in detail the spinout for various different wheel configurations, e.g., rolling without braking, rolling with braking, etc., Marquard has shown that very good approximations can be obtained with piecewise linear solutions of the equations of motion. Providing the number of wheels which are locked up can be specified, the velocities which have been dissipated during a given spinout can be reliably estimated. If the linear and angular velocities of each vehicle immediately after impact is known, their velocity prior to impact can be estimated using impulsive force techniques (Reference 5); implicit in their use is the assumption that displacements during impact are negligible.

Having obtained the velocities at the start of the spinout, the vehicle damage index of each vehicle is examined to decide the type of collision. This is necessary because different expressions are used in START for head-on or rear-end collisions than for intersection collisions. In head-on or rear-end collisions the extent of damage to each vehicle is used to determine the energy absorbed during the impact. This is used along with the principle that linear momentum is conserved, to calculate the velocities prior to impact. For intersection collisions it is merely necessary to apply the principle of conservation of momentum to determine these velocities.

Finally, a check is made to see if the vehicles are in contact for the impact positions specified by the user; if the SMAC program is started with the vehicles in contact, the initial values generated by the collision force routine are generally in error. If contact is detected in START the vehicles are each "backed up" slightly and the coordinates of the impact positions adjusted accordingly.

For comparison purposes, Table 3.3.1 shows the velocities predicted by the START program together with those taken from the "best fit" SMAC run for each of 11 accident reconstructions. It can be seen that in general the agreement is quite good and large errors only occur in cases where there is significant displacement during the collision (e.g., Case CA73231) or where spinouts diverge markedly from a straight line trajectory.

These "START" values are then used in the first run of the SMAC program. On completion of this run an iterative routine designed to optimize the input values of velocities to provide a "best fit" reconstruction to the available scene data is called. This routine compares the predicted rest positions of the vehicles with the actual rest positions. If the agreement is within 5 percent the run is accepted and no further reconstruction attempts are made. When the errors are unacceptable the program computes correction terms for each vehicle which are used to update the START velocity estimates. A second SMAC run using these new velocities is then submitted automatically. This iteration process is continued for a user specified number of SMAC runs unless agreement between actual and predicted rest positions is reached in an earlier run. The "best fit" solution of these iterative runs is then accepted as the final run. At present the iteration process has only been tested on a handful of actual reconstructions. However, reference to the highly successful example given in the field trials illustrates the potential of this system.

3.3.1.2 Iteration Procedure for Adjusting Impact Velocities

In the present iteration scheme as in the START program axial type collisions (i.e., head-on or rear-end) are treated separately from oblique or intersection type collisions.

Table 3.3.1

Initial Velocities Predicted by START Compared to Those Used in the "Best Fit" SMAC Runs

MDAI Case No.	Type of Collision	Velocity in MPH Predicted by START		Velocity in MPH Predicted by SMAC	
		Vehicle 1 MPH	Vehicle 2 MPH	Vehicle 1 MPH	Vehicle 2 MPH
CA73231	Intersection	56.0	47.0	43.0	28.0
-	Intersection	18.7	44.9	24.0	36.8
CB71055	Front corner intersection	8.1	23.6	10.8	25.0
AA00145	Direct head-on	25.7	33.5	17.0	26.3
CB70053	Offset head-on	60.9	24.1	53.0	43.0
SN71044	Offset head-on	14.8	1.7	12.5	0.0
TR00973	Offset head-on	28.9	24.4	40.0	38.1
GI00056	Head-on with a tree	0.0	27.1	0.0	32.0
CA71031	Head-on with a tree	0.0	40.6	0.0	35.0
CB70072	Head-on with a tree	24.0	0.0	25.2	0.0

Notation

$(X_{R1}' \; Y_{R1}' \; \Psi_{R1}')(X_{R2}' \; Y_{R2}' \; \Psi_{R2}')$ = Actual rest positions, vehicles 1 and 2

$(X_{R1}'' \; Y_{R1}'' \; \Psi_{R1}'')(X_{R2}'' \; Y_{R2}'' \; \Psi_{R2}'')$ = Predicted rest positions, vehicles 1 and 2

$(X_{C1}' \; Y_{C1}' \; \Psi_{C1}')(X_{C2}' \; Y_{C2}' \; \Psi_{C2}')$ = Contact positions, vehicles 1 and 2

U_{10}, U_{20} = Start values of forward velocities, vehicles 1 and 2

U_{1A}, U_{2A} = Adjusted values of forward velocities, vehicles 1 and 2

$K_{x1}, K_{y1}, K_{x2}, K_{y2}$ = Error terms for adjustment of forward velocities, vehicles 1 and 2

VDI1A, VDI2A = Actual VDI's for vehicles 1 and 2

VDI1P, VDI2P = Predicted VDI's for vehicles 1 and 2

1. Check to see if actual and predicted rest positions agree within 5 percent.

$$ERR1 = (X_{R1}' - X_{R1}'')/(X_{R1}' - X_{C1}') + (Y_{R1}' - Y_{R1}'')/(Y_{R1}' - Y_{C1}')$$

$$ERR2 = (X_{R2}' - X_{R2}'')/(X_{R2}' - X_{C2}') + (Y_{R2}' - Y_{R2}'')/(Y_{22}' - Y_{C2}')$$

If $(ERR1 + ERR2) < 0.1$ existing SMAC run accepted.

2. Determine type of collision.

$$\Delta\psi = (\psi'_{c_1} - \psi'_{c_2})$$

If $\left\{ \begin{array}{l} 170° \leq \Delta\psi \leq 190° \\ \text{or } -10° \leq \Delta\psi \leq +10° \end{array} \right\}$ The collision is considered to be head-on or rear-end.

The collision is considered to be oblique if it fails this test or if either of the vehicle VDI's indicates damage to the side of the vehicle.

3. Oblique Collisions.

$$K_{x1} = (X'_{R1} - X'_{c1}) / (X''_{R1} - X'_{c1})$$
$$K_{y1} = (Y'_{R1} - Y'_{c1}) / (Y''_{R1} - Y'_{c1})$$
$$K_{x2} = (X'_{R2} - X'_{c2}) / (X''_{R2} - X'_{c2})$$
$$K_{y2} = (Y'_{R2} - Y'_{c2}) / (Y''_{R2} - Y'_{c2})$$

Then the adjusted velocities for the next SMAC run are given by

$$U_{1A} = \sqrt{K_{x1}} \cdot U_{10} \cdot \cos^2 \psi'_{c1} + \sqrt{K_{y1}} \cdot U_{10} \cdot \sin^2 \psi'_{c1}$$

$$U_{2A} = \sqrt{K_{x2}} \cdot U_{20} \cdot \cos^2 \psi'_{c2} + \sqrt{K_{y2}} \cdot U_{20} \cdot \sin^2 \psi'_{c2}$$

4. Axial Type Collisions.

The predicted and actual extent of damage to the vehicles given by column 7 of the vehicle damage indices is first compared. This checks whether the relative velocity between the two vehicles is of the right magnitude and adjustments are made accordingly.

Total predicted damage = D_P = VDI1P(7) + VDI2P(7)

Total actual damage = D_A = VDI1A(7) + VDI2A(7)

$$U_{1A} = U_{10} \cdot D_P/D_A$$

$$U_{2A} = U_{20} \cdot D_P/D_A$$

Once agreement as to the extent of damage is reached, a routine similar to that for the oblique impact is used to optimize the velocities of each vehicle. Note that this alternative procedure was adopted because unlike intersection collisions the spinouts in head-on type collisions are usually very small. Thus, using the predicted rest positions as the only means of velocity adjustment would likely lead to inaccurate reconstructions.

3.3.1.3 Proposed Further Development of START/ITERATION Capability

The algorithm for generation of the speed estimates within the START routine was originally designed to provide values within about 10 percent of actual speeds. It has been demonstrated that the present very simple version is capable of this. Because of this success it is suggested that the algorithm could be developed, with the use of more sophisticated techniques, to provide a closed loop solution with which to obtain reliable speed estimates for a majority of accident types.

In the present version the reconstruction is divided into two parts; the collision phase and the spinout phase. The velocities at the start of the spinout phase are estimated using linearized equations of motion developed by Marquard (Reference 4). It is proposed that these spinout velocities should be optimized by providing a simple trajectory routine which "spins" the vehicles back to their rest positions. These predicted rest positions would then be compared to the actual rest positions and the spinout velocities adjusted with a simple iterative routine until an optimum solution is obtained.

Once the spinout velocities have been accurately determined they can be used to calculate the pre-collision velocities. Further work will be necessary to decide whether the present collision algorithm can be significantly improved. (However, initial indications are that where large errors occur in the velocity estimates they usually result from spinouts which deviate significantly from a straight line trajectory.) There are a number of techniques that could be used as alternatives to the present impulse-momentum approach (e.g., the energy approach of Reference 6) and the improvements that would result from their use should be determined.

It is anticipated that by revising the model in this manner, collision speeds could be predicted to within 5 percent. Such a system would obviously reduce the number of SMAC runs needed to reach a "best fit" solution and would possibly allow a more sensitive version of iterate (i.e., sensitive to a larger number of input parameters). For example, the existing version of iterate assumes that the user has assessed the orientation of the vehicles correctly and it adjusts the impact velocities to provide an optimum solution. However, if the velocities have a known degree of precision to start with, emphasis can be put on checking for errors incurred from incorrect positioning of the vehicles, etc. Such a system would also be the most efficient from an economic viewpoint since the extended START program would cost only a few dollars to run and the number of SMAC runs necessary to find a "best fit" solution would be reduced to a minimum.

The improved speed estimate algorithm could also find immediate application in other areas of research, particularly because of its low running cost. For example, it would become economically feasible to reconstruct large numbers of accidents. In those cases where the contact and rest positions are known, speed estimates could be obtained for Level 2 type accidents. At this level the number of cases should be large enough to determine the distribution of speeds for the various types of accident as well as begin to evolve injury levels as a function of the change in velocity that vehicles experience in these types of accident.

3.3.2 Velocity Change During Collision

In accordance with the recommendations of Reference 2, the SMAC output calculations were extended to include ΔV (see Figure 3.3.1).

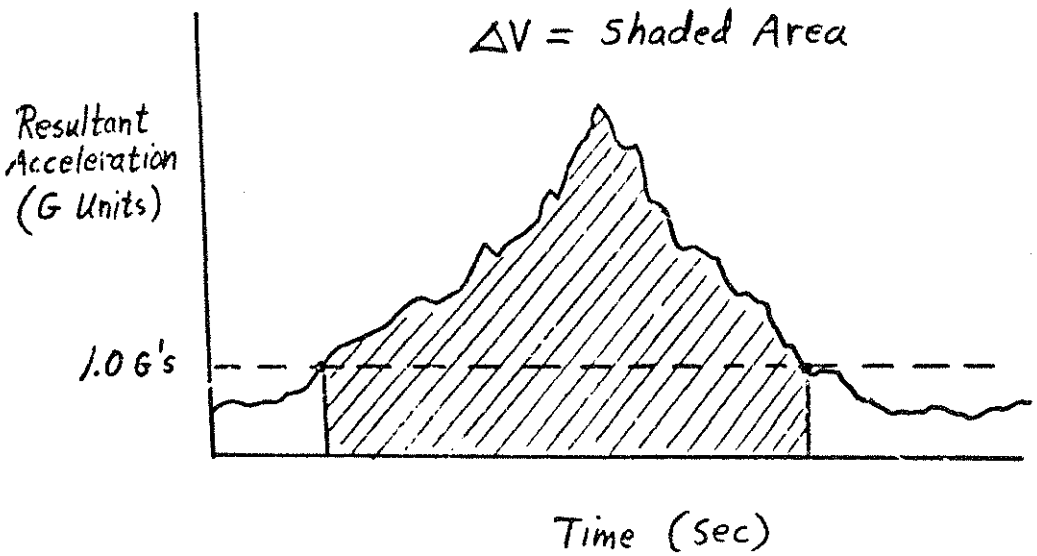


Figure 3.3.1 DEFINITION OF ΔV

As illustrated in Figure 3.3.1, ΔV is herein defined as the velocity change experienced by the passenger compartment during a collision. Its calculation is limited to those time periods during which the resultant acceleration exceeds 1.0 g's (i.e., the duration of a given collision contact). There is a separate ΔV associated with each VDI generated in the SMAC output.

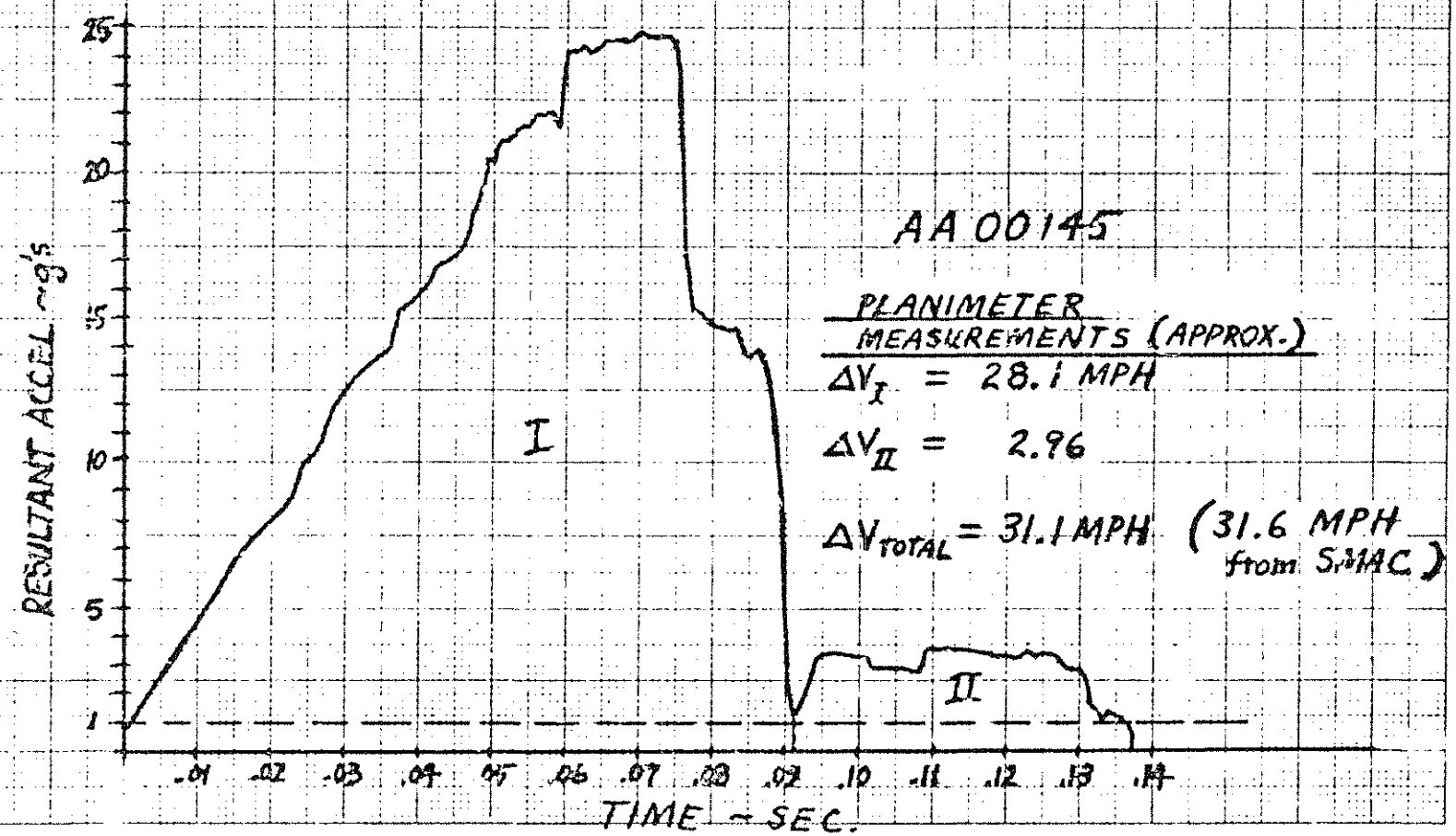
In the initial series of application runs with this output calculation, two forms of calculation difficulties were identified. It was found to be necessary to develop and incorporate corresponding extensions of the associated logic.

3.3.2.1 A Rapid Change in the Direction of Acceleration at the End of the Impulse

The resultant acceleration is, of course, always a positive quantity. That fact, combined with the discrete point form of the digital solution, makes it possible for a rapid reversal in the direction of acceleration at the end of the impulse to occur without any solution points being calculated for which the resultant acceleration is less than 1.0 g's (e.g., see Figure 3.3.2). The described error source was discovered in the application of SMAC to Case No. AA00145, in which the initial printout value for ΔV of Vehicle No. 2 (31.6 MPH) was recognized as being too large.

The initial logic in the ΔV calculation tested only the magnitude of the resultant acceleration. To overcome the described form of calculation difficulty, a sequence of tests of the acceleration components was incorporated. In the case of unequal magnitudes of the acceleration components at the start of a ΔV calculation, the sign of the initially larger component is tested at each point in time and the calculation of ΔV (i.e., the numerical integration of the resultant acceleration) is terminated if a sign change occurs. In cases where the magnitudes of the acceleration components are

Figure 3.3.2 ACCELERATION INCLUDING A RAPID CHANGE IN DIRECTION



nearly equal at the start of a ΔV calculation, the sign of the product of the two acceleration components is tested, and the allowed change in direction of the resultant is thereby limited to approximately $\pm 45°$. It should be noted that the direction of the resultant tends to remain relatively constant during the major portion of the impulse.

The tests of acceleration components are defined in the following listing. A flow chart for the tests is presented in Figure 3.3.3. The symbols a_x and a_y are used to denote the components of acceleration along the vehicle fixed X and Y axes. The symbols IND and $\emptyset$ represent indicators that are used only within the presented sequence.

TESTS OF ACCELERATION COMPONENTS

1.0 IF $\left(\sqrt{a_x^2 + a_y^2}\right) \leq$ 1.00, GO TO 14.0.

2.0 IF IND $\neq$ 0, GO TO 6.0.

3.0 IF 0.84 < $\left|\frac{a_y}{a_x}\right|$ < 1.23, SET IND = 1.00, SET SGN $\emptyset$ = SGN ($a_x a_y$), GO TO 13.0.

4.0 IF $\left|\frac{a_y}{a_x}\right|$ < 0.84, SET IND = 2.00, SET SGN $\emptyset$ = SGN (a_x), GO TO 13.0.

5.0 SET IND = 3.00, SET SGN $\emptyset$ = SGN (a_y), GO TO 13.0.

6.0 IF IND $\neq$ 1.00, GO TO 9.0.

7.0 IF SGN ($a_x a_y$) = SGN $\emptyset$, GO TO 13.0.

8.0 GO TO 14.0.

9.0 IF IND $\neq$ 2.00, GO TO 12.0.

10.0 IF SGN (a_x) = SGN $\emptyset$, GO TO 13.0.

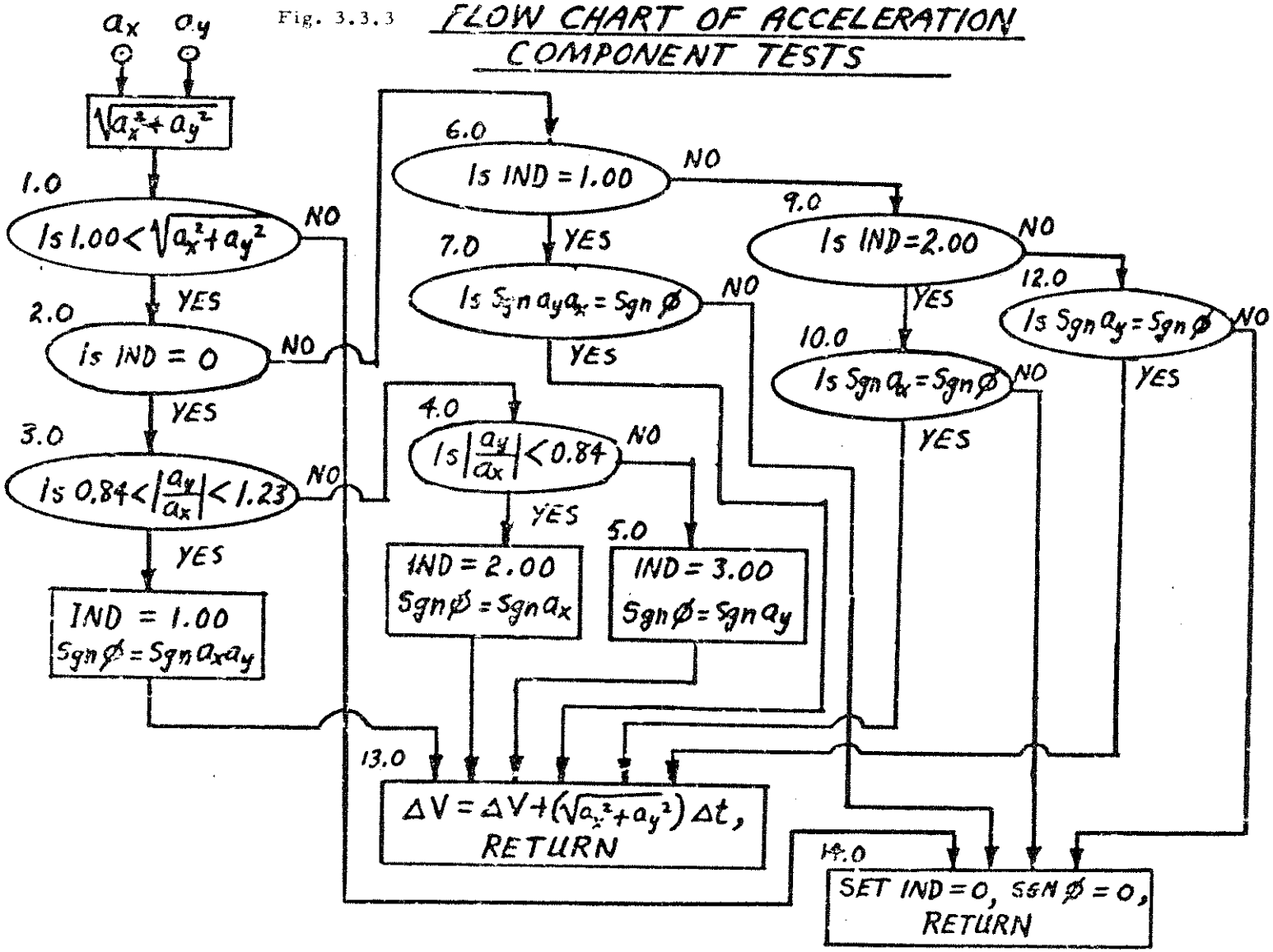
11.0 GO TO 14.0.

12.0 IF SGN (a_y) $\neq$ SGN $\emptyset$, GO TO 14.0.

13.0 $\Delta V = \Delta V + \left(\sqrt{a_x^2 + a_y^2}\right)\Delta t$, RETURN.

14.0 SET IND = 0, SGN $\emptyset$ = 0, RETURN.

Fig. 3.3.3 FLOW CHART OF ACCELERATION COMPONENT TESTS



3.3.2.2 Momentary Interruption of Acceleration

A second form of ΔV calculation difficulty was detected in the SMAC run for Case No. CB00053 (Figure 3.3.4). In this offset frontal collision, the lateral wedging action of the inclined collision interface produces lateral displacement that are sufficiently large to cause a momentary separation of the two vehicles. The continued longitudinal motions act to restore the contact. Thus, the interruption of acceleration in Figure 3.3.4 appears to be a realistic feature of the predicted responses.

In this case, it was necessary to develop logic to match the values of ΔV with the corresponding damage range(s) and to add any multiple ΔV values that occur during impacts involving a single damage range.

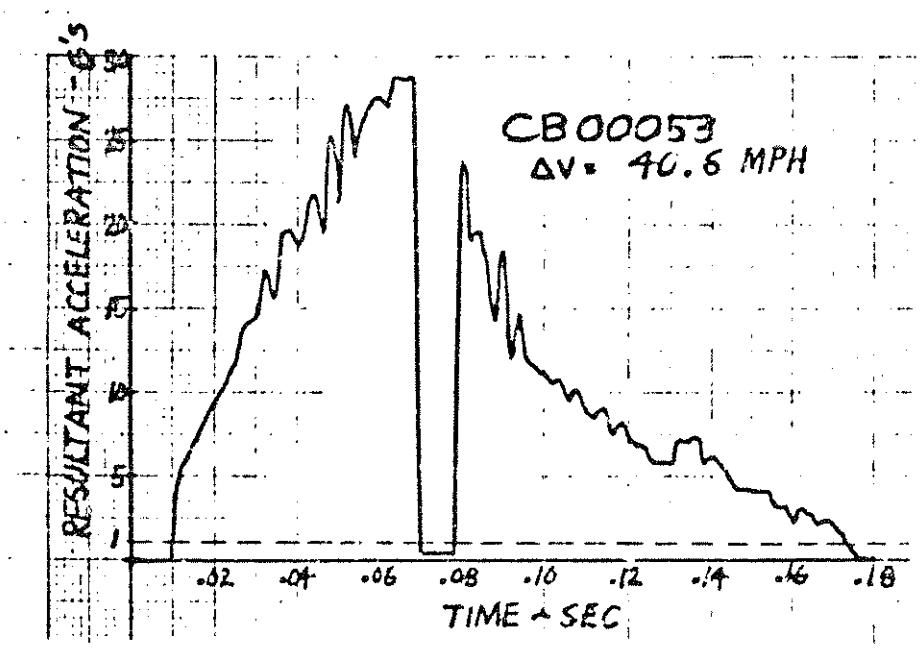


Fig. 3.3.4 MOMENTARY INTERRUPTION OF ACCELERATION

3.3.3 Extension of SMAC to Approximate Obstacle Contacts While Vehicles are Interacting

Applications of the SMAC computer program both within and outside the present contact effort (e.g., in relation to litigation cases) indicated a frequent need for a "third body" capability. In recognition of this need, a special version of SMAC was developed to provide the capability. However, the present version of the extended program requires a large increase in memory and it also substantially increases the running time. For these reasons, the simpler "two body" version is used with the accident van.

The general analytical approach is described in the following paragraphs.

Calculation Procedure

The obstacle is treated as "vehicle 3" in subroutine COLL to take advantage of the extensive development effort on that routine. Since vehicle 3 remains motionless, there are no additional equations of motion. The obstacle forces are added to the force summations in step 216 of COLL. A table for storing obstacle damage is provided.

New Inputs

Y_B' = Obstacle location, always parallel to X' axis with contact surface facing origin, inches.

K_{V3} = Load-deflection characteristic of obstacle, lb/in^2.

μ_B = Friction coefficient for vehicle-obstacle contact.

3.3.4 Minor Developmental Changes

Minor developmental changes were introduced to the SMAC program to achieve the following:

3.3.4.1 In frontal collisions, where complete separation of the original vehicle boundaries does not occur, operating costs of the SMAC program were made relatively high by retention of the collision time increment size (i.e., 0.001 sec.). Tests of the resultant accelerations of the two impacting bodies and associated logic that will increase the time increment size have been incorporated.

3.3.4.2 The VDI calculations previously used tests of the acceleration components as criteria for retention of a given peak value of acceleration. Difficulties encountered in the case of minor collisions made it necessary to apply the tests to the resultant acceleration (i.e., a resultant acceleration greater than 1.0 g's is interpreted as a collision for which a VDI should be calculated).

3.3.4.3 The combination in the collision routine of "discrete point" representations of the peripheral structures and numerical solutions tends to produce small erroneous lateral accelerations in direct hits. The resulting lateral "drift" velocities were abruptly resisted by the early form of discontinuous representation of intervehicle friction defined in step 24 on page 60 of Reference 1. This calculation problem also contributed to early problems with discrepancies in the first two columns of the VDI (i.e., the maximum lateral acceleration reflected an erroneous tangential force). While the program calculation change defined in Figure 3.3.5 was incorporated during 1972, it has not been previously documented in the series of technical reports on this research.

$$\gamma = \begin{cases} \mu \left(\dfrac{V_{T2} - V_{T1}}{\zeta_v} \right), & \text{for } |V_{T2} - V_{T1}| < \zeta_v \\ \mu \operatorname{sgn}(V_{T2} - V_{T1}), & \text{for } \zeta_v \leq |V_{T2} - V_{T1}| \end{cases}$$

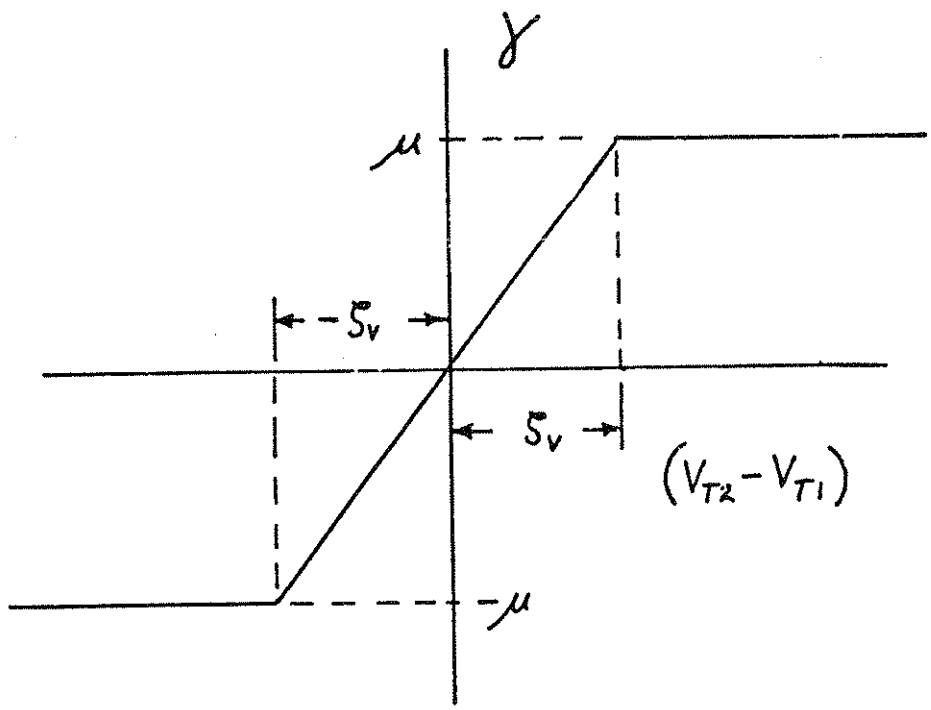


Figure 3.3.5 INTERVEHICLE FRICTION COEFFICIENT VS. RELATIVE VELOCITY

3.4 Indirect Supporting Evidence

An important aspect in the development program to provide a comprehensive accident reconstruction facility is the provision of computer routines which allow all phases of the collision sequence to be addressed.

To supplement the information provided by the measured and reconstructed accident data, a program has been developed which furnishes indirect supporting evidence.

Indirect supporting evidence information varies according to the type of investigation required, and the time that is allowed to collect the information. For example, much of the information recorded for an in-depth investigation would be surplus to requirements for a police investigation.

To make the reconstruction program as flexible as possible, a number of "indirect supporting evidence" program options should eventually be supplied (see paragraph 3.4.2). This will enable the investigator to select the option which is relevant to his requirements at the accident scene. Independent of the option selected, a primary supporting evidence program is used to obtain basic information about the accident. Only information which is readily available at the scene of the accident is requested. This includes exact location of the accident, time of day, weather, light and road surface conditions, registration particulars of the vehicles involved, information on the number of occupants in each vehicle and the severity of their injuries.

This program "quizes" the investigator via the visual display facility on-board the accident van and requires appropriate answers to be punched in. Data checks are incorporated to ensure that answers are punched in the correct format.

Having completed this primary program satisfactorily, secondary information programs can then be brought in depending on the particular option originally selected.

To illustrate the feasibility of the indirect supporting evidence option the primary program -supplementary scene data has been incorporated in the van software (see paragraph 3.4.1.1). Figure 3.4.1 shows a sample printout of the program which is displayed after the operator has selected this option and replied to the questions which are subsequently displayed. A hard copy of this display can then be made and combined with those obtained from the scene data display and SMAC reconstruction to provide a comprehensive report of the accident.

INDIRECT SUPPORTING EVIDENCE - POSSIBLE OPTIONS

3.4.1 Primary Supporting Evidence Program

The following information will be recorded as a minimum requirement: supplementary options may be requested.

3.4.1.1 Supplementary Scene Data

Time and date of the accident.

Location of the accident including type of locality.

Environmental Conditions

Type of road on which accident occurred, number of lanes and speed limit in force.

Type of road surface.

Horizontal and vertical alignment of the road.

Figure 3.4.1

**** CALSPAN ACCIDENT INVESTIGATION SYSTEM ****

INDIRECT SUPPORTING EVIDENCE REPORT

DECEMBER 17, 1974 2:22 P.M.

SUMMARY OF HOW ACCIDENT HAPPENED

ACCIDENT OCCURRED AT INTERSECTION OF MILLERSPORT HWY AND N. FOREST. VEHICLE 2 (SUBARU) WAITING TO MAKE LEFT TURN - TURNED SUDDENLY IN FRONT OF VEHICLE 1 (CHEVY) WHICH WAS GOING NORTH ON MILLERSPORT HIGHWAY. V1 STRUCK V2 IN MIDDLE OF RIGHT SIDE, V2 SPUN AROUND AND HIT SIGNAL POLE.

SPEED LIMITS IN FORCE

MILLERSPORT HIGHWAY 55 MPH N. FOREST 35 MPH
URBAN

WEATHER CONDITIONS AT TIME OF ACCIDENT

MODERATE SNOWFALL

ROAD CONDITION AT TIME OF ACCIDENT

WET

VISIBILITY

MEDIUM TO GOOD VISIBILITY

Road Conditions

Record of any defects in the road.

Surface condition, i.e., whether the surface was slippery and type of covering, e.g., dry, damp, wet, snow, etc.

Weather Conditions

Type and rate of precipitation.

Temperature.

Cross wind.

Visibility limitation (fog, smoke, glare, etc.).

Visibility obstruction (sign, bushes, tree, hill, curve in road, etc.).

3.4.1.2 Vehicle Particulars

To be reported for each vehicle involved.

Identification number and odometer reading.

Make and model.

Number of occupants in the vehicle and details of loading.

Record of any mechanical defect.

3.4.1.3 Occupant Information

To be reported for each occupant in all vehicles.

Record of which vehicle occupied and seat location.

Position and posture on seat.

Age and sex of occupant.

Type of restraint fitted for this occupant position, whether the restraint was worn by occupant and whether it was worn correctly.

Details of whether the occupant was ejected during the accident and area of ejection.

Preliminary occupant injury information, e.g., none, hospitalized, fatal at scene.

Driver's Ability Impaired

Record of ability impairment and cause of any of the drivers involved in the accident.

Record of any traffic violation and consequent legal action taken.

3.4.2 Secondary Options

The following are examples of secondary options which can be furnished to augment the basic information program.

3.4.2.1 Detailed Record of Vehicle Crash Performance

Case vehicle only.

Tire information: tread type, tread wear, profile, and carcass type.

Hood performance, e.g., whether hood remained on vehicle, performance of latches, etc.

Steering column performance, including details of engine compartment telescoping unit, steering wheel and steering wheel energy absorbing device.

Details of pillar and side rail damage.

Door latch and hinge performance.

Fuel tank performance, i.e., approximate fuel level at time of impact, whether tank was retained, damaged, etc.

Tailgate/trunk lid performance.

Passenger compartment damage, i.e., whether intrusion occurred and extent of damage.

Windshield performance including whether cracked or broken by occupant contact.

Performance of interior items, e.g., instrument panel, foot controls, rear view mirror, sunvisor, etc.

3.4.2.2 Detailed Information on Occupant Injury

Occupant injury is classified according to the following body regions: internal organs, brain, face, head, neck (cervical region), shoulder girdle, right upper trunk, left upper trunk, chest and upper back, lower back (lumbar region), abdomen, pelvic girdle, right

lower trunk, left lower trunk, whole body. The severity of the particular injury is recorded under the following classification; overall injury to body region, fracture, laceration, contusion, complaint of pain, abrasion, concussion, burn, hemorrhage, other.

3.4.2.3 Case Vehicle Drivers Record

Details of driver education together with previous violations, collisions and license suspensions. Information about the drivers origin and destination of the trip in which the accident occurred.

Psychological factors - these will include: mental state, occupation, permanent and transient physiological condition, any non-impact medical condition, evidence of stress on the day of the accident (e.g., argument with relatives or friends, etc.), pharmacological agents present but not necessarily causal, and blood alcohol level.

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APPENDIX 1

SMAC INPUT REQUIREMENTS AND FORMAT

A1.1 SMAC Input Requirements

A1.1.1 Initial Conditions

$\left.\begin{matrix} X'_{C10}, & Y'_{C10} \\ X'_{C20}, & Y'_{C20} \end{matrix}\right\}$ = Coordinates of initial position of vehicle center of gravity, inches.

ψ_{10}, ψ_{20} = Initial heading angle, degrees.

$\left.\begin{matrix} u_{10}, & v_{10} \\ u_{20}, & v_{20} \end{matrix}\right\}$ = Initial velocity components in vehicle coordinate system, inches/sec.

$\dot{\psi}_{10}, \dot{\psi}_{20}$ = Initial angular velocity, degrees/sec.

A1.1.2 Dimensional and Inertial Properties of Vehicles (see Appendix 5)

a, b = Distances along vehicle fixed X axis from the total vehicle center of gravity to the center lines of the front and rear wheels, respectively, inches (both entered as positive quantities).

T = Tread at front and rear wheels (average), inches.

I_1, I_2 = Moment of inertia of complete vehicle in yaw, lb-sec^2-in ($I = Mk^2$).

k^2 = Radius of gyration squared for complete vehicle in yaw, inches squared.

M_1, M_2 = Total vehicle mass, lb-sec^2/in.

$\left.\begin{matrix} X_{F1}, X_{R1} \\ X_{F2}, X_{R2} \end{matrix}\right\}$ = Distances along vehicle fixed X axis from the total vehicle center of gravity to the boundaries of the vehicle at the front and rear, respectively, inches (X_{R_i} is entered as a negative quantity).

Y_{S1}, Y_{S2} = Distance along vehicle fixed Y axis from the total vehicle center of gravity to the boundary of the vehicle at the side (i.e., one-half of the total vehicle width), inches.

A1.1.3 Tire Properties (see Appendix 6)

C_1, C_2, C_3, C_4 = Cornering stiffnesses of the tires at wheels 1, 2, 3, 4 for small slip angles, pounds/radian (entered separately to permit simulation of damaged tires).

A1.1.4 Tractive or Braking Forces, Rolling Resistance (see Appendix 6)

T_i = Tabular inputs of tractive or braking forces and/or rolling resistance at wheel i (positive for traction, negative for braking), pounds.

A1.1.5 Steer Angles

ψ_R = Rear axle angle produced by damage, deg.

ψ_1, ψ_2 = Tabular inputs of steer angles as functions of time to simulate steering or damage, degrees.

A1.1.6 Terrain Properties

X'_{Bj}, Y'_{Bj} = Points defining boundary between terrain zones (j = 1, 2), inches.

μ_1, μ_2 = Tire-terrain friction coefficients at zero speed.

C_μ = Coefficient of linear decrement of friction with tire speed (see Appendix 8).

A1.1.7 Calculation Constants

$\Delta\psi$ = Angular interval between radial vectors in contact determination, degrees.

λ = Acceptable error in pressure balance between the two bodies, lb/in (note that a constant height of the contact area is assumed). Also, for solution stability, ($K_{V1}\Delta\rho$, $K_{V2}\Delta\rho \leq \lambda$).

$\Delta\rho$ = Increment of change of radial vector length in iterative routine for achieving equilibrium, inches.

$\dot{S}_V$ = Minimum magnitude of relative velocity for which vehicle-to-vehicle friction forces are calculated, inches/sec.

A1.1.8 Properties of Deformable Layer of Vehicle Structure

K_{V1}, K_{V2} = Load-deflection characteristic of peripheral vehicle structure, lb/in^2 (corresponding to a given height of contact).

μ = Friction coefficient for tangential forces between the two interacting bodies.

C_0, C_1, C_2 = Constant coefficients in parabolic relationship fitted to approximate the "coefficient of restitution" as a function of deflection (see Appendix 7).

SMAC CARD NO. 1

PROGRAM CONTROL DATA

Field	Program Variable	Analysis Variable	Units	Definition
1	T0	-	Seconds	Start time.
2	TF	-	Seconds	End time.
3	DTTRAJ	-	Seconds	Interval of integration at beginning and ending of run.
4	DTCØLL	-	Seconds	Interval of integration during collision contact.
5	DTCØLT	-	Seconds	Interval of integration for 100 time increments subsequent to separation (i.e., during the time period when secondary contacts may occur).
6	DTPRN0	-	Seconds	Output time interval
7	UVMIN	-	Inches/Sec	Vector velocity test* for stop.
8	PSIDMN	-	Degrees/Sec	Angular velocity test* for stop.
9	IVEH0	-	-	Number of Simulated Vehicles (1.0 or 2.0).

*The program is stopped when the resultant linear velocity of each vehicle is less than UVMIN inches/sec and the angular velocity of each vehicle is less than PSIDMN degrees/sec.

SMAC CARD NO. 2

INITIAL CONDITIONS - VEHICLE NO. 1*

Field	Program Variable	Analysis Variable	Units	Definition
1	XCP10	X'_{c10}	Inches	Vehicle 1, X' coordinate (space-fixed system) of initial position of center of gravity.
2	YCP10	Y'_{c10}	Inches	Vehicle 1, Y' coordinate (space-fixed system) of initial position of center of gravity.
3	PSI10	ψ_{10}	Degrees	Vehicle 1, initial heading angle.
4	PSI1D0	$\dot{\psi}_{10}$	Degrees/Sec	Vehicle 1, initial angular (yaw) velocity.
5	U10	U_{10}	Inches/Sec	Vehicle 1, component of initial velocity along vehicle-fixed X axis.
6	V10	V_{10}	Inches/Sec	Vehicle 1, component of initial velocity along vehicle-fixed Y axis.

*The smaller vehicle should always be entered as Vehicle #1. The collision forces are calculated in a clockwise sweep of Vehicle #1. The force calculation is less accurate in the vicinity of a narrow intrusion; therefore, accuracy is improved when Vehicle #1 is the smaller vehicle.

SMAC CARD NO. 3

INITIAL CONDITIONS - VEHICLE NO. 2*

Field	Program Variable	Analysis Variable	Units	Definition
1	XCP20	X'_{c20}	Inches	Vehicle 2, X' coordinate (space-fixed system) of initial position of center of gravity.
2	YCP20	Y'_{c20}	Inches	Vehicle 2, Y' coordinate (space-fixed system) of initial position of center of gravity.
3	PSI20	ψ_{20}	Degrees	Vehicle 2, initial heading angle.
4	PSI2D0	$\dot{\psi}_{20}$	Degrees/Sec	Vehicle 2, initial angular (yaw) velocity.
5	U20	U_{20}	Inches/Sec	Vehicle 2, component of initial velocity along vehicle-fixed X axis.
6	V20	V_{20}	Inches/Sec	Vehicle 2, component of initial velocity along vehicle-fixed Y axis.

*The smaller vehicle should always be entered as Vehicle #1. The collision forces are calculated in a clockwise sweep of Vehicle #1. The force calculation is less accurate in the vicinity of a narrow intrusion; therefore, accuracy is improved when Vehicle #1 is the smaller vehicle.

SMAC CARD NO. 4

DIMENSIONS AND INERTIAL PROPERTIES - VEHICLE NO. 1

(see Appendix 5)

Field	Program Variable	Analysis Variable	Units	Definition
1	A1	a_1	Inches	Vehicle 1, distance along vehicle-fixed X axis from the total vehicle center of gravity to the front wheel centerline (+).
2	B1	b_1	Inches	Vehicle 1, distance along vehicle-fixed X axis from the total vehicle center of gravity to the rear wheel centerline (+).
3	TR1	T_1	Inches	Vehicle 1, average of tread at front and rear wheels.
4	FIZ1	I_{z1}	Lb-Sec^2-In	Vehicle 1, moment of inertia of complete vehicle in yaw.
5	FMASS1	M_1	Lb-Sec^2/In	Vehicle 1, total vehicle mass.
6	PSIR10	ψ_{R1}	Degrees	Vehicle 1, rear axle steer angle produced by damage (clockwise = +).
7	XF1	X_{F1}	Inches	Vehicle 1, distance along vehicle-fixed X axis from the total vehicle center of gravity to the front boundary (+).
8	XR1	X_{R1}	Inches	Vehicle 1, distance along vehicle-fixed X axis from the total vehicle center of gravity to the rear boundary (—).
9	YS1	Y_{S1}	Inches	Vehicle 1, distance along vehicle-fixed Y axis from the total vehicle center of gravity to the side boundary (i.e., one-half of the total vehicle width) (+).

SMAC CARD NO. 5

DIMENSIONS AND INERTIAL PROPERTIES - VEHICLE NO. 2

(see Appendix 5)

Field	Program Variable	Analysis Variable	Units	Definition
1	A2	a_2	Inches	Vehicle 2, distance along vehicle-fixed X axis from the total vehicle center of gravity to the front wheel centerline (+).
2	B2	b_2	Inches	Vehicle 2, distance along vehicle-fixed X axis from the total vehicle center of gravity to the rear wheel centerline (+).
3	TR2	T_2	Inches	Vehicle 2, average of tread at front and rear wheels.
4	FIZ2	I_{Z2}	Lb-Sec^2- In	Vehicle 2, moment of inertia of complete vehicle in yaw.
5	FMASS2	M_2	Lb-Sec^2/in	Vehicle 2, total vehicle mass.
6	PSIR20	ψ_{R2}	Degrees	Vehicle 2, rear axle steer angle produced by damage (clockwise = +).
7	XF2	X_{F2}	Inches	Vehicle 2, distance along vehicle-fixed X axis from the total vehicle center of gravity to the front boundary (+).
8	XR2	X_{R2}	Inches	Vehicle 2, distance along vehicle-fixed X axis from the total vehicle center of gravity to the rear boundary (−).
9	YS2	Y_{S2}	Inches	Vehicle 2, distance along vehicle-fixed Y axis from the total vehicle center of gravity to the side boundary (i.e., one-half of the total vehicle width) (+).

SMAC CARD NO. 6

TIRE PROPERTIES - VEHICLE NO. 1

(see Appendix 6)

Field	Program Variable	Analysis Variable	Units	Definition
1	CSTF1(1)	C_{11}	Pounds/Radian	Vehicle 1, RF Tire Cornering Stiffness*.
2	CSTF1(2)	C_{12}	Pounds/Radian	Vehicle 1, LF Tire Cornering Stiffness.
3	CSTF1(3)	C_{13}	Pounds/Radian	Vehicle 1, RR Tire Cornering Stiffness.
4	CSTF1(4)	C_{14}	Pounds/Radian	Vehicle 1, LR Tire Cornering Stiffness.

*Cornering stiffness is defined as the partial derivative of lateral force with respect to slip angle, measured at zero slip angle.

SMAC CARD NO. 7

TIRE PROPERTIES - VEHICLES NO. 2

(see Appendix 6)

Field	Program Variable	Analysis Variable	Units	Definition
1	CSTF2(1)	C_{21}	Pounds/Radian	Vehicle 2, RF Tire Cornering Stiffness*.
2	CSTF2(2)	C_{22}	Pounds/Radian	Vehicle 2, LF Tire Cornering Stiffness.
3	CSTF2(3)	C_{23}	Pounds/Radian	Vehicle 2, RR Tire Cornering Stiffness.
4	CSTF2(4)	C_{24}	Pounds/Radian	Vehicle 2, LR Tire Cornering Stiffness.

*Cornering stiffness is defined as the partial derivative of lateral force with respect to slip angle, measured at zero slip angle.

SMAC CARD NO. 8

TRACTIVE OR BRAKING FORCES - VEHICLE NO. 1

Field	Program Variable	Analysis Variable	Units	Definition
1	TBTQ1	-	Seconds	Initial time for torque inputs, Vehicle 1.
2	TETQ1	-	Seconds	Final time for torque inputs, Vehicle 1.
3	TINCQ1	-	Seconds	Time increment for torque inputs, Vehicle 1.
4	NTBLQ1	-	-	If $\neq 0.0$, do not read table.

Note: If TBTQ1 > TO (control inputs starting in the middle of a run), the first three values in the input tables must be zero to provide zero control inputs between TO and TBTQ1. Also, if TETQ1 < TF (control inputs ending in the middle of a run), the control inputs between TETQ1 and TF are determined by quadratic interpolation of the last three values in the control input tables. Hence, if a constant control input is desired between TETQ1 and TF, the last three tabular values must be equal.

SMAC CONTROL INPUT TABLES
FOLLOWING CARD NO. 8

(THESE CARDS ARE NOT NUMBERED
IN COLUMNS 79 AND 80)

(1) Table of Traction (+) or Braking (-) Force at RF Wheel, Vehicle 1 Card Format 7F10.0, use three to two hundred and one values for each wheel. The number of entries for each wheel is computed as

$$\frac{TETQ1 - TBTQ1}{TINCQ1} + 1.$$

Start the entries for each wheel on a new card. Seven entries per card.

(2) Table of Traction (+) or Braking (-) Force at LF Wheel, Vehicle 1

(3) Table of Traction (+) or Braking (-) Force at RR Wheel, Vehicle 1

(4) Table of Traction (+) or Braking (-) Force at LR Wheel, Vehicle 1

Note that Subroutine TRAJ, statements 62 and 74, limits the maximum value of tractive or braking force that is actually applied at wheel i to the product $\mu_i \cdot W_i$, where

i = 1, 2, 3, 4,

μ_i = tire-terrain friction coefficient at wheel i,

W_i = normal force at wheel i.

SMAC CARD NO. 9

TRACTIVE OR BRAKING FORCES - VEHICLE NO. 2

Field	Program Variable	Analysis Variable	Units	Definition
1	TBTQ2	-	Seconds	Initial time for torque inputs, Vehicle 2.
2	TETQ2	-	Seconds	Final time for torque inputs, Vehicle 2.
3	TINCQ2	-	Seconds	Time increment for torque inputs, Vehicle 2.
4	NTBLQ2	-	-	If $\neq 0.0$, do not read table.

Note: If TBTQ2 > TO (control inputs starting in the middle of a run), the first three values in the input tables must be zero to provide zero control inputs between TO and TBTQ2. Also, if TETQ2 < TF (control inputs ending in the middle of a run), the control inputs between TETQ2 and TF are determined by quadratic interpolation of the last three values in the control input tables. Hence, if a constant control input is desired between TETQ2 and TF, the last three tabular values must be equal.

SMAC CONTROL INPUT TABLES
FOLLOWING CARD NO. 9

(THESE CARDS ARE NOT NUMBERED
IN COLUMNS 79 AND 80)

(1) Table of Traction (+) or Braking (-) Force at RF Wheel, Vehicle 2 Card format 7F10.0, use three to two hundred and one values for each wheel. The number of entries for each wheel is computed as

$$\frac{TETQ2 - TBTQ2}{TINCQ2} + 1.$$

Start the entries for each wheel on a new card. Seven entries per card.

(2) Table of Traction (+) or Braking (-) Force at LF Wheel, Vehicle 2

(3) Table of Traction (+) or Braking (-) Force at RR Wheel, Vehicle 2

(4) Table of Traction (+) or Braking (-) Force at LR Wheel, Vehicle 2

Note that Subroutine TRAJ, statements 62 and 74, limits the maximum value of tractive or braking force that is actually applied at wheel i to the product $\mu_i W_i$, where

i = 1, 2, 3, 4,

μ_i = tire-terrain friction coefficient at wheel i,

W_i = normal force at wheel i.

SMAC CARD NO. 10

STEERING CONTROL INPUTS - VEHICLE NO. 1

Field	Program Variable	Analysis Variable	Units	Definition
1	TBPSF1	-	Seconds	Initial time for steer inputs, Vehicle 1.
2	TEPSF1	-	Seconds	Final time for steer inputs, Vehicle 1.
3	TINCP1	-	Seconds	Time increments for steer inputs, Vehicle 1.
4	NTBLP1	-	-	If $\neq 0.0$, do not read table.

Note: If TBPSF1 > TO (control inputs starting in the middle of a run), the first three values in the input tables must be zero to provide zero control inputs between TO and TBPSF1 Also, if TEPSF1 < TF (control inputs ending in the middle of a run), the control inputs between TEPSF1 and TF are determined by quadratic interpolation of the last three values in the control input tables. Hence, if a constant control input is desired between TEPSF1 and TF, the last three tabular values must be equal.

SMAC CONTROL INPUT TABLES
FOLLOWING CARD NO. 10

(THESE CARDS ARE NOT NUMBERED
IN COLUMNS 79 AND 80)

(1) Steer Table (degrees) for RF Wheel, Vehicle 1
(2) Steer Table (degrees) for LF Wheel, Vehicle 1

} Clockwise = +

Card Format 7F10.0, use three to two hundred and one values for each wheel. The number of entries for each wheel is computed as

$$\frac{TEPSF1 - TBPSF1}{TINCP1} + 1.$$

Start the entries for each wheel on a new card. Seven entries per card.

SMAC CARD NO. 11

STEERING CONTROL INPUTS - VEHICLE NO. 2

Field	Program Variable	Analysis Variable	Units	Definition
1	TBPSF2	-	Seconds	Initial time for steer inputs, Vehicle 2.
2	TEPSF2	-	Seconds	Final time for steer inputs, Vehicle 2.
3	TINCP2	-	Seconds	Time increments for steer inputs, Vehicle 2.
4	NTBLP2	-	-	If $\neq 0.0$, do not read table.

Note. If TBPSF2 > TO (control inputs starting in the middle of a run), the first three values in the input tables must be zero to provide zero control inputs between TO and TBPSF2. Also, if TEPSF2 < TF (control inputs ending in the middle of a run), the control inputs between TEPSF2 and TF are determined by quadratic interpolation of the last three values in the control input tables. Hence, if a constant control input is desired between TEPSF2 and TF, the last three tabular values must be equal.

SMAC CONTROL INPUT TABLES
FOLLOWING CARD NO. 11

(THESE CARDS ARE NOT NUMBERED
IN COLUMNS 79 AND 80)

(1) Steer Table (degrees) for RF Wheel, Vehicle 2
(2) Steer Table (degrees) for LF Wheel, Vehicle 2

} Clockwise = +

Card format 7F10.0, use three to two hundred and one values for each wheel. The number of entries for each wheel is computed as

$$\frac{TEPSF2 - TBPSF2}{TINCP2} + 1.$$

Start the entries for each wheel on a new card. Seven entries per card.

SMAC CARD NO. 12

TIRE-TERRAIN FRICTION AND BOUNDARY

Field	Program Variable	Analysis Variable	Units	Definition
1	XBP(1)	X'_{B1}	Inches	Points defining boundary between terrain zones.
2	YBP(1)	Y'_{B1}	Inches	
3	XBP(2)	X'_{B2}	Inches	
4	YBP(2)	Y'_{B2}	Inches	
5	*XMU1	μ_1	-	Tire-Terrain Friction Coefficient at Zero Speed (Zone 1).
6	XMU2	μ_2	-	Tire-Terrain Friction Coefficient at Zero Speed (Zone 2).
7	CMU	C_μ	-	Coefficient of linear decrement of friction with tire speed (see Appendix 8).

*μ_1 (Zone 1) is always on the same side of the friction boundary as the origin of the space-fixed coordinate system.

Note that the relationship of the space-fixed coordinate system and the friction boundary should be selected so that potential difficulties with a "mirror image" of the boundary on the opposite side of the origin will be avoided. Toward this end, the boundary should be located as far as possible away from the origin and the vehicle trajectories should, to the greatest extent possible, remain on the same side of the origin as the friction boundary.

SMAC CARD NO. 13

CALCULATION CONSTANTS AND PERIPHERAL STRUCTURE

(see Appendix 5)

Field	Program Variable	Analysis Variable	Units	Definition
1	DELPS0	$\Delta\psi$	Degrees	Interval between radial vectors.
2	DELRØ0	$\Delta\rho$	Inches	Increment of change in radius vector.
3	*ALAMB	λ	Lb/Inches	Acceptable error in equilibrium.
4	ZETAV	ζ_V	Inches/Sec	Minimum relative velocity for friction.
5	AKV(1)	K_{V1}	Lb/In^2	Load-deflection characteristic, Vehicle 1.
6	AKV(2)	K_{V2}	Lb/In^2	Load-deflection characteristic, Vehicle 2.
7	AMU	μ	-	Intervehicle friction coefficient.

* $K_{V1}\Delta\rho,\ K_{V2}\Delta\rho \leq \lambda$

SMAC CARD NO. 14

COEFFICIENT OF RESTITUTION

(see Appendix 7)

Field	Program Variable	Analysis Variable	Units	Description
1	C0	C_0	-	Coefficients in assumed parabolic relationship between the extent of recovery of structural deflection and the magnitude of the maximum deflection.*
2	C1	C_1	-	
3	C2	C_2	-	

$$^{*}C = \begin{cases} C_0 - C_1\,\delta + C_2\,\delta^2, & \text{for } 0 < \delta < \dfrac{C_1}{2C_2} \\ 0, & \text{for } \dfrac{C_1}{2C_2} \leq \delta \end{cases}$$

where $C = 1.00 - \dfrac{\text{final deflection}}{\text{maximum deflection}}$, and

δ = maximum deflection of individual radius vector, inches.

{Note that $C = 1.00 - \sqrt{1 - \epsilon^2}$, where ϵ = conventional coefficient of restitution.}

INPUT DATA FORM

SIMULATION MODEL OF AUTOMOBILE COLLISIONS (SMAC)

RUN TITLE : _____

DATE : _____

FIELD NUMBER

CARD NO.	1	2	3	4	5	6	7	8	9
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									

APPENDIX 2

SUBROUTINE START

SUBROUTINE START - a routine for generating the 14 card input required by SMAC.

The following information must be furnished; impact and rest positions for both vehicles, their size, vehicle damage indices, which wheels are locked up after impact and the direction of rotation of each vehicle between the impact and rest position. The format for each of 3 input cards are given below. Card 1 refers to vehicle 1, card 2 to vehicle 2, and card 3 is a general title card. All these cards must be furnished for the program to run.

Card 1 10 inputs each of field width 8

Start in Column No.	Program Variable	Units or Coding Option	Definition
1	XC1	inches	x-coordinate of vehicle 1 at impact
9	YC1	inches	y-coordinate of vehicle 1 at impact
17	PSI1	radians	heading angle of vehicle 1 at impact
25	IROT1	clockwise = +1 anticlockwise = -1	describes direction of rotation of vehicle 1 between impact and rest
33	XC1F	inches	x-coordinate of vehicle 1 at rest
41	YC1F	inches	y-coordinate of vehicle 1 at rest
49	PSI1F	radians	heading angle of vehicle 1 at rest
57	IVDI1		vehicle damage index - 7 digit entry

Card 1 (continued)

Start in Column No.	Program Variable	Units or Coding Option	Definition
65	L1W1	free wheel = 0 locked wheel = 1	4 digit entry specifying locked wheel* after impact
73	J1TYP	1 = subcompact 2 = compact 3 = intermediate 4 = full size	specify size of vehicle 1, single digit entry

*Wheels must be entered in this order; right front, left front, right rear, left rear.

Card 2 10 inputs each of field width 8

Start in Column No.	Program Variable	Units or Coding Option	Definition
1	XC2	inches	x-coordinate of vehicle 2 at impact
9	YC2	inches	y-coordinate of vehicle 2 at impact
17	PSI2	radians	heading angle of vehicle 2 at impact
25	IROT2	clockwise = +1 anticlockwise = -1	describes direction of rotation of vehicle 1 between impact and rest
33	XC2F	inches	x-coordinate of vehicle 2 at rest
41	YC2F	inches	y-coordinate of vehicle 2 at rest
49	PSI2F	radians	heading angle of vehicle 2 at rest
57	IVDI2		vehicle damage index - 7 digit entry

Card 2 (continued)

Start in Column No.	Program Variable	Units or Coding Option	Definition
65	L2WI	free wheel = 0 locked wheel = 1	4 digit entry specifying locked wheel* after impact
73	J2TYP	1 = subcompact 2 = compact 3 = intermediate 4 = full size	specify size of vehicle 2, single digit entry

*Wheels must be entered in this order; right front, left front, right rear, left rear.

Card 3 Title Card specifying title to appear on the SMAC run - limited to 80 digits

Once this information has been specified the program automatically generates the 14 input cards for SMAC. Representative values of the vehicle parameters required by SMAC are selected from a parameter matrix which incorporates the values given in Table A5.1 for full size, intermediate, compact and subcompact cars. For simplicity it is assumed that steering inputs are zero and brake inputs are calculated as specified by the wheel lockup inputs. The time for wheel lockup is fixed, specified as the end of impact. Options allowing the user to specify wheel lockup time and steering inputs could be incorporated. However, it was felt that these options would detract from the simplicity of the START input requirements.

The output format varies according to the version of START used. Two versions of the program have been developed, one for incorporation with the accident van software and the other for use with the IBM 370 version of SMAC. The accident van version writes the SMAC inputs to a disc file on the timeshare computer which is then read as input by the SMAC program. The other version punches out 14 Fortran cards which can then be used to run the SMAC program.

Collisions With Fixed Objects

Although SMAC was originally designed to simulate two-vehicle collisions, it has been shown that impacts with poles, trees, etc. can be simulated by including the object as a very stiff vehicle with a large mass and moment of inertia. Such an option is available with the START program and is requested by furnishing the VDI of vehicle 1 as zero.

Approximate Speed Estimate in START

In running the SMAC program, initial estimates of the collision speeds of each vehicle are required. Using the rest and impact positions of each vehicle, the speeds immediately prior to impact are estimated using the following procedure. The impact and spin-out phases are processed separately. To calculate the linear and angular velocities of each vehicle immediately after impact, i.e., at the start of the spin-out phase, expressions developed by Marquard (Reference 4) are used. Analyzing in detail the spin-out for various different wheel configurations, e.g., rolling without braking, rolling with braking, etc., Marquard has shown that very good approximations can be obtained with linearized equations of motion. Providing the number of wheels which are locked up can be specified, the velocities which have been dissipated during a given spin-out can be reliably estimated using the following routine.

Spin-out Calculation

INPUTS:

$X'_{cR}, Y'_{cR}, \psi'_R$ = Rest position and orientation (feet and degrees)

X'_{cs}, Y'_{cs}, ψ_s = Position and orientation at separation (feet and degrees)

$a+b$ = Wheelbase, inches

K^2 = Radius of gyration squared for complete vehicle in yaw, in^2

μ = Nominal tire-ground friction coefficient

θ = Decimal portion of full deceleration, $0 \leq \theta \leq 1.000$

g = Acceleration of gravity
= 386.4 inches/sec^2

1.0 $S = 12\sqrt{(X'_{cR} - X'_{cs})^2 + (Y'_{cR} - Y'_{cs})}$ inches

Straight line distance from point of separation to point of rest.

2.0 $\Delta\psi = \frac{(\psi_R - \psi_s)}{57.3}$ radians

Change in orientation.

3.0 $\gamma_s = \arctan\left(\frac{Y'_{cR} - Y'_{cs}}{X'_{cR} - X'_{cs}}\right)$

Orientation of path with respect to coordinate axis.

4.0 If $0.02 < |\Delta\psi|$ and $\theta < 1.000$, go to 10.0.

5.0 $PR = \dfrac{|\Delta\psi|(a+b)}{2S}$ (path ratio)

6.0 $\phi_\psi = \begin{cases} 0.78\,(PR) - 0.16\,(PR)^2 & \text{, for } PR < 1.50 \\ 0.80, \text{ for } 1.50 \leq PR \end{cases}$

7.0 $\phi_V = \begin{cases} 1.00 - 0.10\,(PR) - 0.28\,(PR)^2 & \text{, for } PR < 1.50 \\ 0.20, \text{ for } 1.50 \leq PR \end{cases}$

8.0 $\dot{\psi}_S = 57.3 \left\{ \sqrt{\left(\dfrac{\phi_\psi (a+b)\mu g}{K^2}\right)(|\Delta\psi|)} \right\} \mathrm{Sgn}(\Delta\psi)$ deg/sec

9.0 $\dot{S} = \sqrt{2\phi_V \theta \mu g S}$ inches/sec

Go to 12.0.

10.0 $\dot{\psi}_S = 57.3 \left\{ \sqrt{\dfrac{\mu g (\Delta\psi)^2}{\left[\frac{K^2(1-\theta)}{a+b}\right]\left[|\Delta\psi| + \frac{S}{1.70}\right]}} \right\} \mathrm{Sgn}(\Delta\psi)$ deg/sec

11.0 $= 1.70 \left[\dfrac{57.3\,\mu g (\Delta\psi)}{\dot{\psi}_S} - \dfrac{K^2(1-\theta)(|\dot{\psi}_S|)}{57.3(a+b)} \right]$ inches/sec

12.0 $U_S = \dot{S} \cos(\gamma_S - \psi_S)$ inches/sec

13.0 $V_S = \dot{S} \sin(\gamma_S - \psi_S)$ inches/sec

14.0 Return with values for the post impact velocities.

U_S inches/sec

V_S inches/sec

$\dot{\psi}_S$ degrees/sec

Then once the velocity and angular velocity of each vehicle immediately after impact is known, their velocity prior to impact can be estimated using impulsive force techniques, implicit in their use is the assumption that displacements during impact are negligible.

Having obtained the velocities at the start of the spin-out, the vehicle damage index of each vehicle is examined to decide the type of collision. This is necessary because different expressions are used in START for head-on or rear-end collisions than for oblique or intersection type collisions. To determine the type of collision, the angle between the trajectories of the vehicles at the moment of impact is calculated.

$\Delta\psi = \psi_{1c} - \psi_{2c}$ where ψ_{1c}/ψ_{2c} are the heading angles at impact.

If $\left\{ \begin{array}{l} 170° \leq \Delta\psi \leq 190° \\ \text{or } -10 \leq \Delta\psi \leq +10 \end{array} \right\}$ The collision is considered to be head-on or rear-end.

The collision is considered to be oblique if it fails this test or if either of the vehicle VDI's indicates damage to the side of the vehicle.

Head-on or Rear-end Collision

If the collision is assumed to be inelastic, then the velocity change of vehicle 1 = $\frac{m_2}{m_1+m_2}(u_1 - u_2)$.

Where m_1 = mass of vehicle 1
m_2 = mass of vehicle 2
u_1 = velocity pre-impact of vehicle 1
u_2 = velocity pre-impact of vehicle 2.

Velocity change of vehicle 2 = $\frac{m_1}{m_1+m_2}(u_1 - u_2)$.

Energy absorbed in inelastic impact = $\frac{1}{2} K_1 d_1^2 + \frac{1}{2} K_2 d_2^2 = \frac{1}{2} \cdot \frac{m_1 m_2}{m_1 + m_2} \cdot (u_1 - u_2)$

Where K_1 = stiffness vehicle 1 d_1 = deformation of vehicle 1

K_2 = stiffness vehicle 2 d_2 = deformation of vehicle 2.

Then $$u_1 - u_2 = \Delta V = \sqrt{\frac{m_1 + m_2}{m_1 m_2} \left(K_1 d_1^2 + K_2 d_2^2 \right)}$$

So that $$u_{10} = u_{1S} + \Delta V \cdot \frac{m_2}{m_1 + m_2}$$

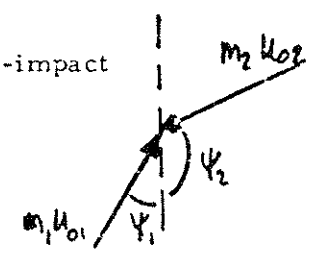
$$u_{20} = u_{2S} + \Delta V \frac{m_1}{m_1 + m_2}$$

Where u_{1S} and u_{2S} are the velocities at separation.

Oblique Impact

To calculate the velocities, pre-impact, the principle of conservation of linear momentum are used. The use of the vehicle damage is not necessary because unlike head-on type collisions, the components of velocity in the x- and y-direction are large enough to define the change of velocity to each vehicle (in head-on impacts the y-velocities are usually very small and their use produces large errors in computing ΔV).

Pre-impact



Post-impact

Forward velocity = u_{S1}, u_{S2}

Lateral velocity = V_{S1}, V_{S2}

Angular velocity = $\dot{\psi}_{S1}, \dot{\psi}_{S2}$

Orientation = ψ_{S1}, ψ_{S2}

Then $$u_{01} = \frac{A \sin \psi_2 - B \cos \psi_2}{m_1 \cdot \sin(\psi_2 - \psi_1)}$$

$$u_{02} = \frac{A \sin \psi_1 - B \cos \psi_1}{m_2 \sin(\psi_1 - \psi_2)}$$

Where $A = u_{s_1} m_1 \cos \psi_{s_1} - v_{s_1} m_1 \sin \psi_{s_1} + u_{s_2} m_2 \cos \psi_{s_2} - v_{s_2} m_2 \sin \psi_{s_2}$

$B = u_{s_1} m_1 \sin \psi_{s_1} + v_{s_1} m_1 \cos \psi_{s_1} + u_{s_2} m_2 \sin \psi_{s_2} + v_{s_2} m_2 \cos \psi_{s_2}$

Finally, a check is made to see if the vehicles are in contact for the impact positions specified by the user; if the SMAC program is started with the vehicle in contact, the initial values generated by the collision force routine are generally in error. If contact is detected in START the vehicles are "backed up" and the coordinates of the impact positions adjusted accordingly.

APPENDIX 3

SMAC OUTPUT FORMAT

In the IBM 370 version of SMAC, the following five-page output format is used.

VEHICLE NO. 1 Page 1

Time (sec)	C. G. Position (ft)		Heading Angle (deg)	Velocities (ft/sec)		Angular Velocity (deg/sec)	Acceleration (g units)		
	X_{c1}'	Y_{c1}'		Fwd.	Lat		a_{x1}	a_{y1}	Σa
t	$X_{c1}'/12$	$Y_{c1}'/12$	$57.296\ \psi_1$	$u_1/12$	$v_1/12$	$57.296\ \dot{\psi}_1$	$\frac{\dot{u}_1 - v_1\dot{\psi}_1}{386.4}$	$\frac{\dot{v}_1 + u_1\dot{\psi}_1}{386.4}$	$\frac{\sqrt{a_{x1}^2 + a_{y1}^2}}{386.4}$
0.00	0000.0	0000.0	000.00	000.00	000.00	0000.0	000.00	000.00	000.00

VEHICLE NO. 1 Page 2

Time (sec)	Velocity Vector (deg) γ_i	Tire Tracks (Ft)*							
		RF		LF		RR		LR	
		X_1'	Y_1'	X_2'	Y_2'	X_3'	Y_3'	X_4'	Y_4'
t	arctan (v_1/u_1)	$X_1'/12$	$Y_1'/12$	$X_2'/12$	$Y_2'/12$	$X_3'/12$	$Y_3'/12$	$X_4'/12$	$Y_4'/12$
0.00		0000.0	0000.0	0000.0	0000.0	0000.0	0000.0	0000.0	0000.0

*If $3 \leq |\bar{\beta}_i|$ and/or ($\mu_i W_i$ -1.00 lb) < F_{c_i}' , this information is made available, along with the wheel locations, in order that the tracks can be displayed as skids (i.e., solid lines). Otherwise, the tracks are dotted lines in the graphic display. The printout is marked with an asterisk to indicate skidding.

VEHICLE NO. 2

Page 3

Time (sec)	C. G. Position (ft)		Heading Angle (deg)	Velocities (ft/sec)		Angular Velocity (deg/sec)	Acceleration (g units)		
	X'_{c2}	Y'_{c2}		Fwd	Lat		a_{x2}	a_{y2}	Σa
t	$X'_{c2}/12$	$Y'_{c2}/12$	$57.296\psi_2$	$u_2/12$	$v_2/12$	$57.296\dot{\psi}_2$	$\frac{\dot{u}_2 - v_2\dot{\psi}_2}{386.4}$	$\frac{\dot{v}_2 + u_2\dot{\psi}_2}{386.4}$	$\frac{\sqrt{a_{x2}^2 + a_{y2}^2}}{386.4}$
0.00	0000.0	0000.0	000.00	000.00	000.00	0000.0	000.00	000.00	000.00

VEHICLE NO. 2

Page 4

Time (sec)	Velocity Vector (deg) γ_2		Tire Tracks (Ft)*							
			RF		LF		RR		LR	
			X'_1	Y'_1	X'_2	Y'_2	X'_3	Y'_3	X'_4	Y'_4
t	Arctan (v_2/u_2)		$X'_1/12$	$Y'_1/12$	$X'_2/12$	$Y'_2/12$	$X'_3/12$	$Y'_3/12$	$X'_4/12$	$Y'_4/12$
0.00	0.000	0.000	0000.0	0000.0	0000.0	0000.0	0000.0	0000.0	0000.0	0000.0

*See footnote on preceding page.

DAMAGE SUMMARY
(DISPLACED POINTS)

VEHICLE 1		VEHICLE 2	
X_1	Y_1	X_2	Y_2
$\rho_{B1} \cos \psi_{B1}$	$\rho_{B1} \sin \psi_{B1}$	$\rho_{B2} \cos \psi_{B2}$	$\rho_{B2} \sin \psi_{B2}$
000.0	000.0	000.0	000.0
(Corresponding to of Table 1)	ρ_{B1}, ψ_{B1}	(Corresponding to of Table 2)	ρ_{B2}, ψ_{B2}

Vehicle Damage Indices (Reference 16)

Delta V MPH (see Section 3.3)

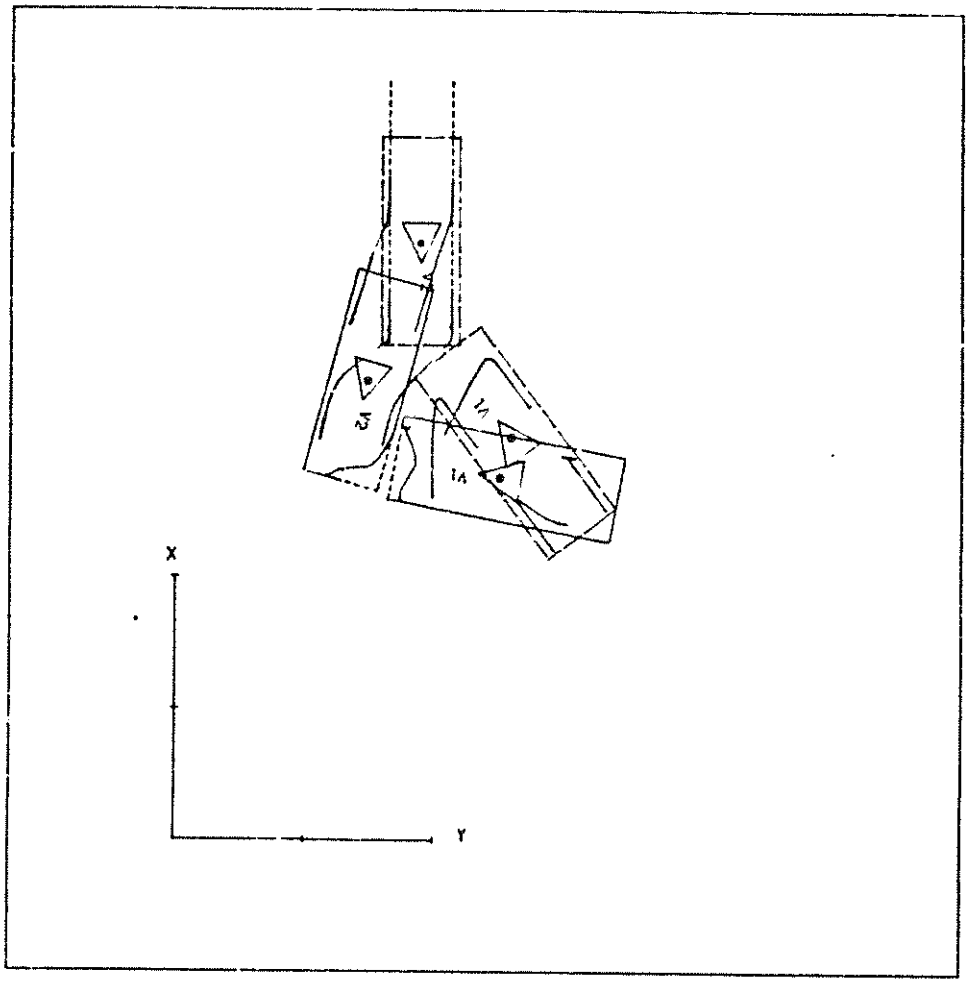
In the accident van system, the output format is limited to the data required to complete a summary display such as that shown in Figure A3.1 (i.e., the time history data are omitted).

Figure A3.1

GRAPHIC DISPLAY OF OUTPUTS OF ACCIDENT RECONSTRUCTION

COLLISION AND TRAJECTORY

CASE NO. 71-558 MDHI NO. CH71055



AXIS INTERVALS ARE 10. FEET

RECONSTRUCTED POSITIONS AND VELOCITIES AT IMPACT							DISPLAYED FINAL POSITIONS				VEHICLE DAMAGE INDICES	ΔV
	C.G. POSITION		HEADING				C.G. POSITION		HEADING	REMARKS		
	XCI	YCI	PSII	FWD	LATERAL	ANGULAR	XC1F	YC1F	PS11F			
	FT.	FT.	DEG.	MPH	MPH	DEG/SEC	FT.	FT.	DEG.			MPH
VEHICLE # 1	30.8	25.8	-37.0	10.8	0.0	0.0	27.8	25.0	-79.5	VEHICLE AT REST	1 2 F D E W 2	16.9
VEHICLE # 2	45.4	18.9	180.0	25.0	0.0	-0.1	34.9	14.9	195.5	VEHICLE AT REST	1 1 L F E W 2	18.6

APPENDIX 4

I STOP MESSAGES FOR THE ACCIDENT VAN/SMAC PROGRAM

The numeration of the I STOP messages for the accident van/SMAC program is consistent with that for the IBM 370 version of SMAC. There are, however, five additional stops, three which result from checks in the ITERATE routine and two from checks in the Transfer program, "TRANSI" which transfers the SMAC output to the van. It should also be noted that the software in CALVAN is programmed to stop operations if any I STOP message other than zero is encountered.

The I STOP messages which are passed to the van are those which actually stop the program in the collision, trajectory or iterate routines. The remaining I STOP messages from the post processing part of SMAC are printed but not passed to the van as they affect the VDI only and do not cause the program to stop.

I STOP values occurring in the collision and trajectory processing:

	ERROR	SUBROUTINE
I STOP = 1	FVEH0<0.9 OR FVEHO>2. USER SHOULD SET FVEH0 = 1. OR 2.	INPUT
I STOP = 2	FMOVIE SHOULD BE ZERO USER SHOULD SET FMOVIE=0.	INITIAL
I STOP = 3	RHOBIT .LE. 0.	COLL
I STOP = 4	WRONG INDEX IN LOOKUP OF TPSIB FOR J	COLL
I STOP = 5	MISTAKE IN REARRANGEMENT OF ACCELERATION MAXIMA.	SAVMAX
I STOP = 6	DT = 0.0	MAIN PGM
I STOP = 7	TOO MANY TRIALS IN PRESSURE BALANCE (I PRES. GE. 200)	COLL
I STOP = 9	TOO MANY ENTRIES IN TABLE 3 (IB3. GT. 100) USER SHOULD USE LARGER DELPSI	COLL
I STOP = 10	RHOBIC. LE. 0. RESULT OF PRESSURE BALANCE	COLL
I STOP = 15	INDXB 0, USER SHOULD CHECK INPUT FOR TERRAIN BOUNDARIES.	TRAJ

I STOP values occurring in the iteration routine:

I STOP = 12 GOOD MATCH OF POSITIONS, DO NOT ITERATE.
I STOP = 13 NO VDI COL 7
I STOP = 14 DISCREPANCY IN VDI COL 3 AND ORIGINAL ORIENTATION.

I STOP values occurring in 'TRANSI', the transfer program from SMAC output to van:

I STOP = 20 FAILURE IN READING SMACOUT, OR IN PREPARING I BUF
I STOP = 21 AN 'ILLEGAL' STOP HAS BEEN INTERPRETED.

'POST-PROCESSING' I STOP values:

RNGDAM I STOP=30 MIDPOINT OF DAMAGE RANGE DOES NOT MATCH
DIRECTION OF PRINCIPAL ACCELERATION.
CHOOSE FIRST (GREATEST) ACCELERATION.
COLS 1,2 OF VDI

DAMAGE I STOP = 41,42,43,44,45,46,47,49,
51,54,56,57,59,
61,62,63,64,65,66,67

NCOLDV (I STOPP) LEADS TO SETTING I STOP = 70,71 IN OUT2

DAMAGE AND NCOLDV SET COLS 3,4,6,7 OF VDI

'POST-PROCESSING' in subroutine OUT2 saves the value of I STOP at entry to OUT2, prints the I STOP message for the above I STOP set in RNGDAM, DAMAGE, and NCOLDV, and then restores the previous I STOP value.

I STOP Messages for the IBM 370 Version of the SMAC Program

There are two types of I STOP messages; those which actually stop the program in the collision and trajectory routines and those resulting from checks in the post processing routines. The latter are, in general, warnings to alert the user to possible inconsistencies in the vehicle damage indices, for example, I STOP = 30 occurs when the program fails to match the clock direction of the maximum force and the midpoint of the predicted damage.

In using the program the user will rarely encounter stops apart from I STOP = 7 and STOP = 9 which usually occur from a poor choice of inputs. I STOP = 7 warns the operator that in seeking equilibrium to create the collision interface the number of increments of $\Delta\rho$ the increment of change in radions vector has exceeded 200; the usual fix is to increase the value of $\Delta\rho$. I STOP = 9 indicates that the 100 point capacity of the interface table has been exceeded; an increase in the value of $\Delta\psi$ the interval between radial vectors reduces the detail in the definition of the equilibrium interface and the amount of storage required.

The following values of I STOP cause the program to stop.

I STOP	Subroutine	Statement	Error
5	SAVMAX	41 I STOP=5	Mistake in search for max accel in loop for rearranging.
15	TRAJ	35 I STOP=15	Use of terrain boundary. INDXB neg. Failure is due to mistaken input on Card 12.
	COLL		
3		111 I STOP=3	RHOBIT zero.
		143 I STOP=4	Picked wrong value from TPSIB table on J index.
		1452 I STOP=11	There is not a good value in TSPSIB, TCPSIB tables at this index. Should not have reached st 145.
7		173 I STOP=7	IPRES > 200, indicates that more than 200 increments, $\Delta\rho$, have been used in selecting equilibrium (step 172 of COLL). An increase in $\Delta\rho$ (e.g., to 0.30 inches) reduces required number of increments. Note that $K_{v1}\Delta\rho, K_{v2}\Delta\rho \leq \lambda$ for SOLUTION STABILITY.
9		1800 I STOP=9	Indicates that the 100 point capacity of Table 3 (equilibrium interface used in calculation of collision force, step 180 of COLL) is being exceeded. Increasing $\Delta\psi$ (to say 3. degrees) reduces detail in the interface definition and the amount of data storage in Table 3.
10		193 I STOP=10	RHOBIC zero ("damaged" radius)
50	OUTPUT	50 I STOP=50	Page count wrong. Mix-up in logic, say, for MOVIE version.

The following values of I STOP do not stop the program since they occur in 'post-processing' routines. NOTE: These values may overwrite each other. Some are printed as part of the intermediate messages in post-processing. Otherwise, the value printed at very end of output represents the LAST setting.

I STOP	Subroutine	Statement	Error
70	OUT2	67 I STOP=70	Subr NCOLDV has returned non-zero ISTOPP for vehicle No. 1. (Inconsistency in setting NCOL2, second digit of clock direction for VDI.)
71		86 I STOP=71	Same as I STOP=70, but for vehicle No. 2.
51		50 I STOP=51	Page count wrong.
30	RNGDAM	62 I STOP=30	No match for clock direction of max force and damage midpoint. As default, use first clock direction, as it corresponds to the largest max. This message is printed.
	DAMAGE		
41		241 I STOP=41	PSD1 > 2 π } Endpoints of damage
42		245 I STOP=42	PSK2 > 2 π } after adjustment.
43		249 I STOP=43	PSIMT > 2 π Midpoint from adjusted endpoints.
44		3119 I STOP=44	
45		3126 I STOP=45	
46		3201 I STOP=46	
47		3210 I STOP=47	
49		3220 I STOP=49	Inconsistency for checks on PSD1,
51		3301 I STOP=51	PSD2, PSIMT when setting NCOL4,
52		3310 I STOP=52	fourth column of VDI
54		3320 I STOP=54	
56		3401 I STOP=56	
57		3412 I STOP=57	
59		3422 I STOP=59	

Error Messages (continued)

I STOP	Subroutine	Statement	Error
61		4150 I STOP=61	DIS negative, trying to set NCOL6, sixth column of VDI from whole damage arrays (not adjusted endpoints).
67		4204 I STOP=67	NCOL3 should have character F, R, B, L but does not.
62		4250 I STOP=62	DIS neg, trying to set NCOL6 as for I STOP=61.
63		5005 I STOP=63	NCOL3 should have character F, R, B, L but does not.
64 65 66		5011 I STOP=64 5022 I STOP=65 5031 I STOP=66	EXT $\leq$ 0, trying to set NCOL7, seventh column of VDI.

APPENDIX 5

REPRESENTATIVE VEHICLE PARAMETERS

In the interest of simplicity and convenience, the SMAC computer program includes provision for the optional use of "typical" parameters for the different categories of vehicle size rather than actual parameters for the specific vehicles. Vehicles representative of four different size categories were selected to provide a basis for "typical" parameters. The following vehicles were included in the different categories.

1. Subcompact

   Volkswagen Beetle
   Toyota 1200
   Datsun 1200
   Vega
   Pinto
   Fiat 850

2. Compact

   Maverick
   Camero
   Dart
   Hornet

3. Intermediate

   Chevelle
   Torino
   Coronet
   Matador
   Skylark

4. Full Size

   Chevrolet
   Galaxie
   Polara
   Ambassador
   Monterey
   LeSabre
   New Yorker
   Fleetwood
   Continental

On the basis of available dimensional and shipping weight information, and with allowances made for both liquid weight and two passenger loading, the following "typical" parameters have been either directly derived or estimated from available measured values for similar vehicles.

Table A5.1

TYPICAL DIMENSIONAL, INERTIAL AND CRUSH PARAMETERS FOR 1971-72 AUTOMOBILES

Parameter	1 Subcompact	2 Compact	3 Intermediate	4 Full Size	Units
a	44.7	52.7	57.3	60.5	Inches
b	46.6	54.8	59.7	63.0	Inches
T	51.2	57.7	60.0	63.1	Inches
k^2	1963.	2635.	2998.	3588.	$Inches^2$
M	5.71	8.51	9.86	12.42	$Lb\text{-}Sec^2/In$
X_F	74.7	85.7	94.8	100.5	Inches
X_R	-83.5	-100.0	-110.8	-119.6	Inches
Y_S	31.1	35.7	38.4	39.6	Inches
K_V	59.	70.	51.	56.	$Lb/Inch^2$

The symbols used in Table A5.1 are defined in Appendix 1.

The basis for the values of K_V in Table A5.1 is discussed in the following paragraphs.

In an earlier report on this research (Reference 2), a value for K_V of 50 lb/in^2 for full size vehicles was found, in exploratory computer runs, to yield good agreement with the damage and accelerations measured in staged collisions. In the referenced report it was pointed out that the predicted vehicle responses are relatively insensitive to minor changes in K_V, since the extent of deflection of a linear spring for a given amount of energy absorption varies inversely with the square root of the stiffness:

$$E = \frac{1}{2} K \delta^2 \quad , \quad \delta = \sqrt{\frac{2E}{K}} \tag{1}$$

In the SMAC collision calculations, the specific crush properties that are assumed do not, of course, affect the conservation of momentum. By producing a finite time duration for the application of forces, the simulated crush permits relative motions of the colliding bodies to occur during the reconstructed collision. The time-varying values for the magnitudes, positions and orientations of collision forces that are obtained with relatively gross approximations of crush properties have been found to yield results that are significantly more realistic than those of simple impulse-momentum calculations in which the effects of crush are neglected.

In References 6 and 7, experimental test data for residual crush vs. impact speed are presented. In each of the references, a linear fit to the experimental data is made to provide a means of interpreting the damage encountered in accident investigations. The fits in each reference include non-zero intercepts for the impact speed corresponding to zero residual crush. The present form of the SMAC program cannot accommodate such non-zero intercept data. Therefore, the actual data points were reviewed in References 6 and 7 to find the slopes of linear fits that pass through the origin of the coordinates (i.e., zero impact speed for zero residual crush).

In each case, when attention is focused on the first 40 inches of crush, the data points in Figures 1 and 2 of both Reference 6 and Reference 7 do not strongly support a non-zero intercept.

With linear fits through the origin, the following results were obtained.

$$V = A\delta \text{ miles per hour,} \tag{2}$$

where δ = residual crush, inches.

Data Source	A Compact	A Full Size
Campbell (Reference 6)	1.35	1.11
Mason and Whitcomb (Reference 7)	1.52	1.32

The data in Reference 6 include the effects of adjustment to "standard" test weights, which explains at least part of the discrepancies between the two sources. The following makes use of the Reference 6 data.

On the basis of sinusoidal responses, the above values of A can be interpreted in terms of the full frontal load deflection properties.

$$V_o = \frac{1}{17.6}\sqrt{\frac{K}{M}}\,\delta = A\delta \text{ miles per hour.} \tag{3}$$

Solving (3) for K,

$$K = (17.6A)^2 M \text{ lb/inch, full frontal load-deflection rate.} \tag{4}$$

The crush stiffness per unit of contact width, as required by the SMAC program, is obtained from (4) as

$$K_V = \frac{(17.6A)^2 M}{2 Y_S} \quad \text{lb/in}^2 \tag{5}$$

where M is the "standard" mass used in the experimental determination of stiffness (Reference 6). Solution of equation (5) yields the following results.

	Std. Test Weight	A	K_V
	lbs	MPH/inch	lb/in^2
Full Size	4500	1.11	56
Intermediate	4000	1.11	51
Compact	3400	1.35	70
Subcompact	2500	1.35	59

It should be noted that the indicated greater crush resistance of the smaller vehicles in frontal collisions is probably the result of a smaller dimension between the front bumper and the front of the engine. The engine, of course, does not crush and the frontal resistance is, therefore, highly nonlinear. The linear approximations used in the present derivations reflect the effects of the relatively small resistance in the crush distance preceding engine contact. Crush resistance values for non-frontal collisions must be obtained from appropriate test data.

For the vehicle parameters in Table A5.2, representative values have been found but no refinement has yet been attempted for the different categories of vehicle size.

Table A5.2

REPRESENTATIVE VALUES OF VEHICLE PARAMETERS

Parameter	Value		Units
C_0	0.04606	see Appendix 7	-
C_1	1.7547×10^{-3}		-
C_2	1.6711×10^{-5}		-
μ	0.550		-
$\Delta\psi$	2.00, 3.00*		Degrees
$\Delta\rho$	0.20, 0.30**		Inches
λ	15.0		Lb/In
ζ_V	5.0		In/Sec

The symbols used in Table A5.2 are defined in Appendix 1.

*See Appendix 4, ISTOP = 9.

**See Appendix 4, ISTOP = 7.

Note that $K_{V1}\Delta\rho$, $K_{V2}\Delta\rho \leq \lambda$ for solution stability.

APPENDIX 6

REPRESENTATIVE TIRE PROPERTIES

It is difficult to find reliable generalizations regarding tire properties. Cornering stiffness and rolling resistance, which are required for the SMAC program, are very much dependent on tire construction. However, the present parameter data needs can be served by relatively gross approximations, in view of the generally short durations of simulated motions at small slip angles with unbraked wheels.

In Reference 8, Olley states that "the value of cornering coefficient on a flat dry road is ordinarily about 1/6, meaning that, at small slip angles and under normal loads, the cornering force per degree of slip angle is 16 to 17 percent of the load on the tire". Thus, for a first approximation,

$$C_{ji} \cong -(0.165)(57.3)(W_{ji})$$

$$\cong -9.455\ W_{ji} \quad \text{Lbs/Radian} \qquad (1)$$

On the basis of tire test data presented in References 9 and 10, the following gross approximations have been developed for "normal" rolling resistance and for the changes in cornering stiffness and rolling resistance at reduced inflation pressures.

Table A6. 1

EFFECTS OF INFLATION PRESSURE

	$\frac{C_{ji}}{-9.455\ W_{ji}}$	T_{ji}/W_{ji}
Normal Inflation	1.00	-0.009
Partial Inflation	0.80	-0.0125
Flat	0.20	-0.017

Application of the relationships defined by equation (1) and Table A6. 1 to the four different size categories of vehicles yields the results presented in Table A6. 2.

Table A6.2

REPRESENTATIVE VALUES OF TIRE PARAMETERS

		Size Category				
		01	02	03	04	
	Parameter	Subcompact	Compact	Intermediate	Full Size	
1	C_{j1}, C_{j2}	-5323.	-7923.	-9189.	-11572	Normal Inflation
2	T_{j1}, T_{j2}	-5.1	-7.6	-8.7	-11.0	
3	C_{j3}, C_{j4}	-5106.	-7620.	-8820.	-11113.	
4	T_{j3}, T_{j4}	-4.9	-7.3	-8.4	-10.6	
5	C_{j1}, C_{j2}	-4258.	-6338.	-7351.	-9258.	Partial Inflation
6	T_{j1}, T_{j2}	-7.0	-10.5	-12.1	-15.3	
7	C_{j3}, C_{j4}	-4085.	-6096.	-7056.	-8890.	
8	T_{j3}, T_{j4}	-6.8	-10.1	-11.7	-14.7	
9	C_{j1}, C_{j2}	-1063.	-1585.	-1838.	-2314.	Flat
10	T_{j1}, T_{j2}	-9.6	-14.3	-16.5	-20.8	
11	C_{j3}, C_{j4}	-1021.	-1524.	-1764.	-2223.	
12	T_{j3}, T_{j4}	-9.2	-13.7	-15.9	-20.0	

APPENDIX 7

COEFFICIENT OF RESTITUTION

Program inputs on Card No. 14 control the extent of recovery of vehicle structural deflections, as a function of the magnitude of deflection. For simplicity, the two colliding bodies are assumed to have identical recovery properties. Further, the load-deflection rate of each vehicle is assumed to be identical for loading and unloading (see Figure A7.1). For compatibility with the selected forms of load-deflection characteristic and control of recovery, the following relationship must be maintained:

$$C = 1.00 - \sqrt{1 - \epsilon^2} \tag{1}$$

where C = Program variable = $1.00 - \frac{\text{final deflection}}{\text{maximum deflection}}$

and ϵ = Conventional coefficient of restitution (i.e., the ratio of the relative velocity of separation to the relative velocity of approach)

In the SMAC program,

$$C = \begin{cases} C_0 - C_1 \delta + C_2 \delta^2, & \text{for } 0 \leq \delta < \frac{C_1}{2C_2} \\ 0, & \text{for } \frac{C_1}{2C_2} \leq \delta \end{cases} \tag{2}$$

where δ = Maximum deflection of individual radius vector, inches.

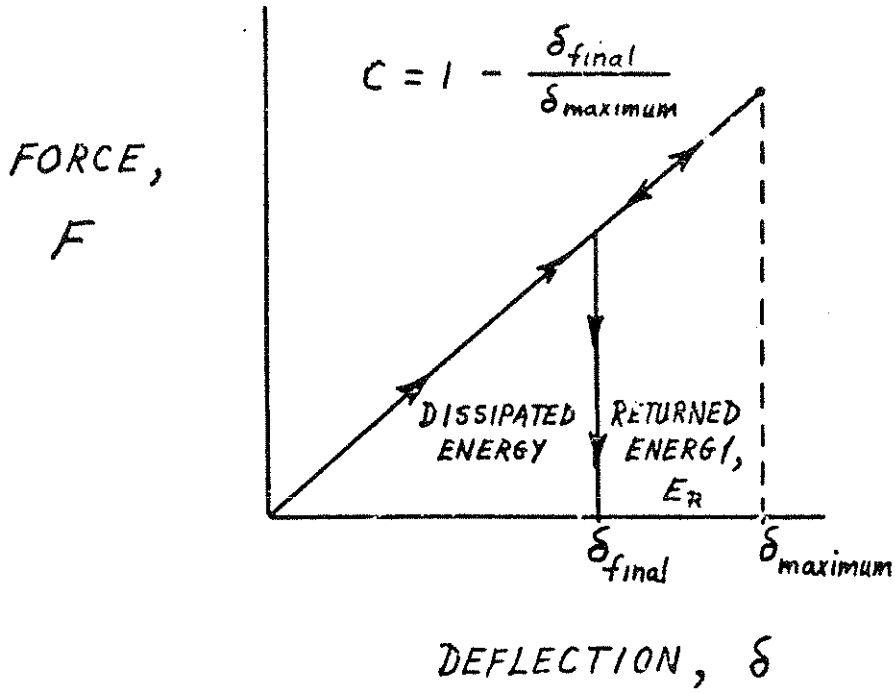


Figure A7.1 ASSUMED FORM OF LOAD-DEFLECTION CHARACTERISTIC FOR LOADING AND UNLOADING

If the slope of the loading-unloading line in Figure A7.1 is defined as the load-deflection rate, K, the returned energy, E_R, may be expressed

$$E_R = \frac{1}{2} K \left(\delta_{max}^2 - \delta_{final}^2 \right)$$
$$= \frac{1}{2} K \delta_{max}^2 \left(2C - C^2 \right) \tag{3}$$

Thus, the ratio of the returned to the total absorbed energy

$$\frac{E_R}{\frac{1}{2} K \delta_{max}^2} = 2C - C^2 \tag{4}$$

By definition, the coefficient of restitution

$$\epsilon = \frac{\dot{\delta}_f}{\dot{\delta}_o} = \sqrt{2C - C^2} \tag{5}$$

Relationship (5) may also be obtained from consideration of the sinusoidal nature of the response produced by the load-deflection characteristic in Figure A7.1.

Since $\delta = A \sin wt$,

$$\frac{\delta_f}{\delta_m} = \sin wt = 1 - C \tag{6}$$

The velocity of deflection

$\dot{\delta} = A\omega \cos wt$, therefore

$$\frac{\dot{\delta}_f}{\dot{\delta}_o} = \sqrt{2C - C^2} = \epsilon \tag{7}$$

Solving (7) for C, yields equation (1) of this Appendix:

$$C = 1.00 - \sqrt{1 - \epsilon^2}$$

The functional relationship defined by equation (1) is depicted in Figure A7.2. This relationship, or its inverse in equation (7), defines the effective coefficient of restitution corresponding to the program variable, C. Since C varies with the magnitude of deflection, as defined in equation (2), the achievement of a selected functional relationship between the effective coefficient of restitution and the deflection requires the following procedure.

In Figure A7.3, the assumed parabolic relationships between C and δ is depicted. Solution of equation (2) for the condition, $C = 0$, yields

$$\delta = \frac{C_1}{2C_2} \pm \frac{1}{2C_2}\sqrt{C_1^2 - 4C_0C_2} \tag{8}$$

For a single solution point,

$$C_1 = 2\sqrt{C_0C_2}\text{, and} \tag{9}$$

$$\delta = \frac{C_1}{2C_2} \tag{10}$$

Application of equations (9) and (10) in the selection of C_0, C_1, C_2 permits control of the effective coefficient of restitution at the end points of the parabolic curve:

$$C_0 = 1.00 - \sqrt{1 - (\epsilon_0)^2} \tag{11}$$

$$C_2 = \frac{C_0}{\delta_1^2} \tag{12}$$

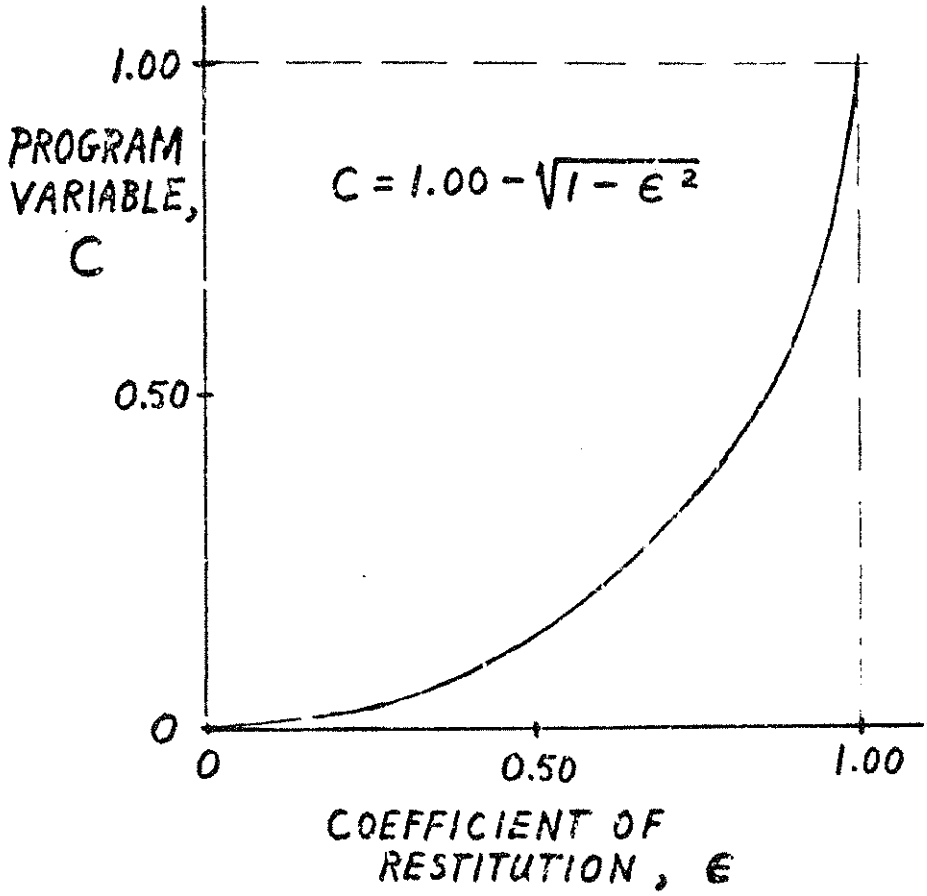


Figure A7.2 RELATIONSHIP BETWEEN PROGRAM VARIABLE C AND COEFFICIENT OF RESTITUTION

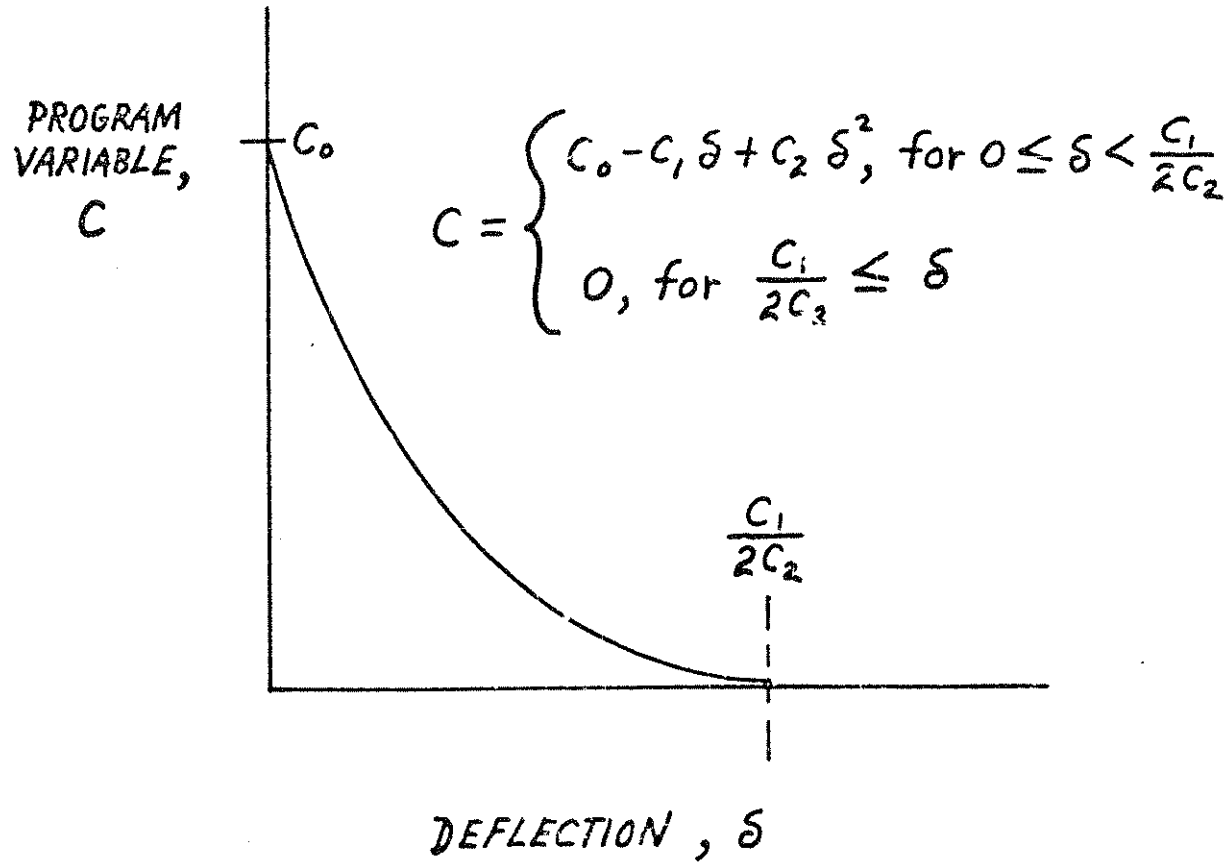


Figure A7.3 PROGRAM VARIABLE C VS DEFLECTION

$$C_1 = 2\,\delta_1 C_2 \tag{13}$$

where δ_1 = deflection at which $\epsilon = 0$.

Sample Applications

	Elastic	Plastic	"Typical" Automobile Frontal (see Figure A7.4)
ϵ_0	1.000	0.01	0.300
δ_1	10^5 inches	0.001 inches	52.5 inches
C_0	1.000	5×10^{-5}	0.04606
C_1	2×10^{-5}	0.100	1.7547×10^{-3}
C_2	1×10^{-10}	50.0	1.6711×10^{-5}

Results of an application to "typical" data for the coefficient of restitution in automobile frontal collisions are presented in Figure A7.4.

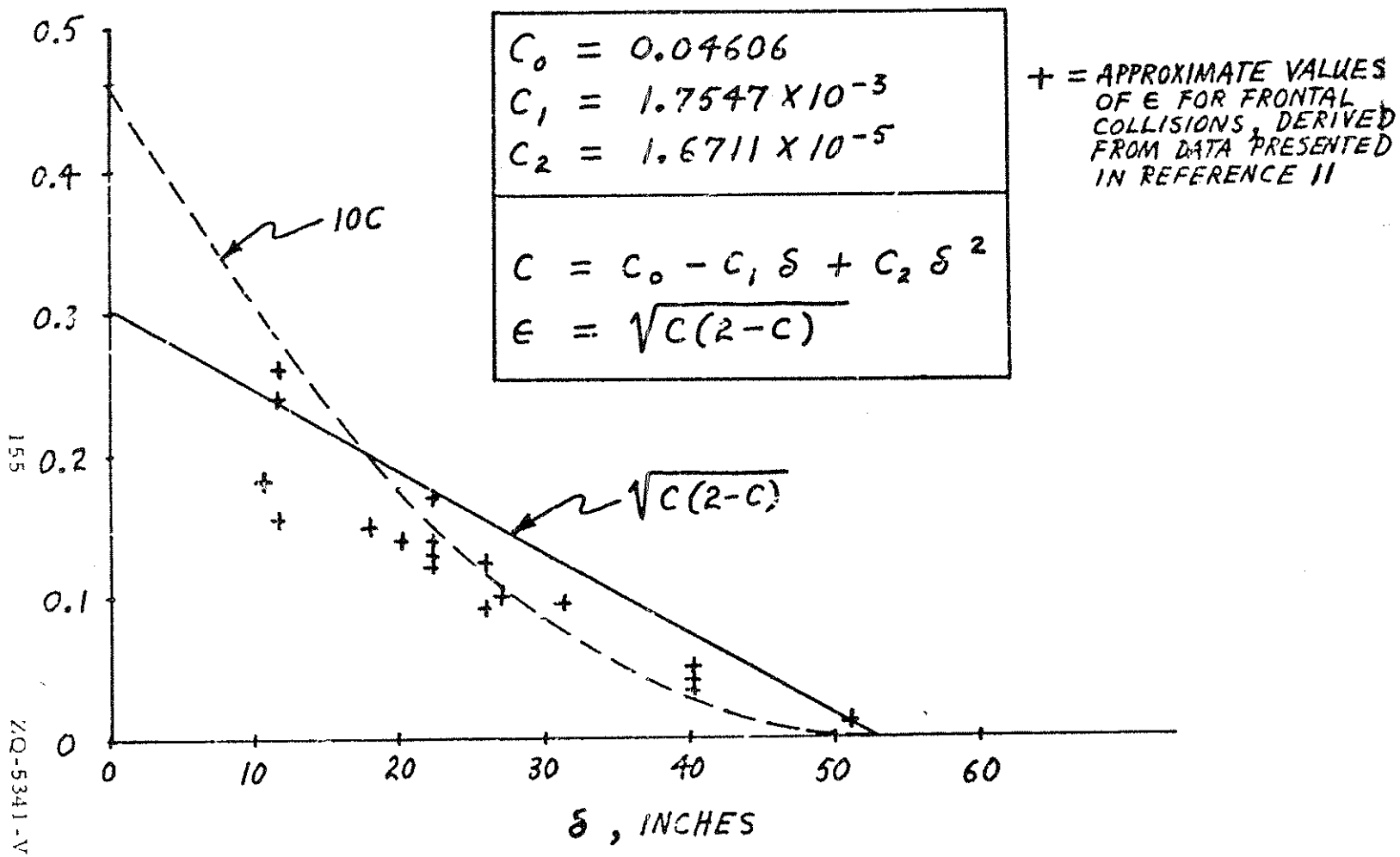


Figure A7.4 AUTOMOBILE FRONTAL COLLISIONS — C AND ϵ VS δ

APPENDIX 8

DECREMENT OF TIRE-GROUND FRICTION AS A FUNCTION OF SPEED

The SMAC computer program includes a capability of simulating a linear decrement of tire-ground friction as a function of the resultant speed of the tire in the ground plane. The existence of such a decrement on dry pavement is indicated in the literature on reconstruction (e.g., Reference 12) and an approximately linear dry-pavement decrement is indicated in some tire test data in the literature (e.g., Reference 13). The existence of a decrement on wet pavement is generally recognized (e.g., References 14 and 15). This simulation option can, of course, be suppressed by setting the coefficient of the decrement, C_μ, to zero on Card No. 12 of the input data.

When this option is used, and measured stopping distance data are available from the scene, it is necessary to insure that input values for the tire-terrain friction coefficient, the coefficient of linear decrement of friction with speed and the speed at the start of deceleration are compatible with the measured stopping distance data. For this purpose, the following relationship may be used:

$$\mu_s S_V = -\frac{6.6805}{C'_\mu}\left[V_o + \frac{100}{C'_\mu}\ln\left(1 - \frac{C'_\mu V_o}{100}\right)\right] \qquad (1)$$

where μ_s = tire-terrain friction coefficient at zero speed

S_V = stopping distance with varying friction coefficient, feet

V_o = initial speed, miles per hour

C_μ' = percentage decrement in friction coefficient per mile per hour increase in speed

(Note that the input quantity for the SMAC program, $C_\mu = \frac{C_\mu'}{1760}$)

With a constant friction coefficient, the corresponding product of friction coefficient and stopping distance,

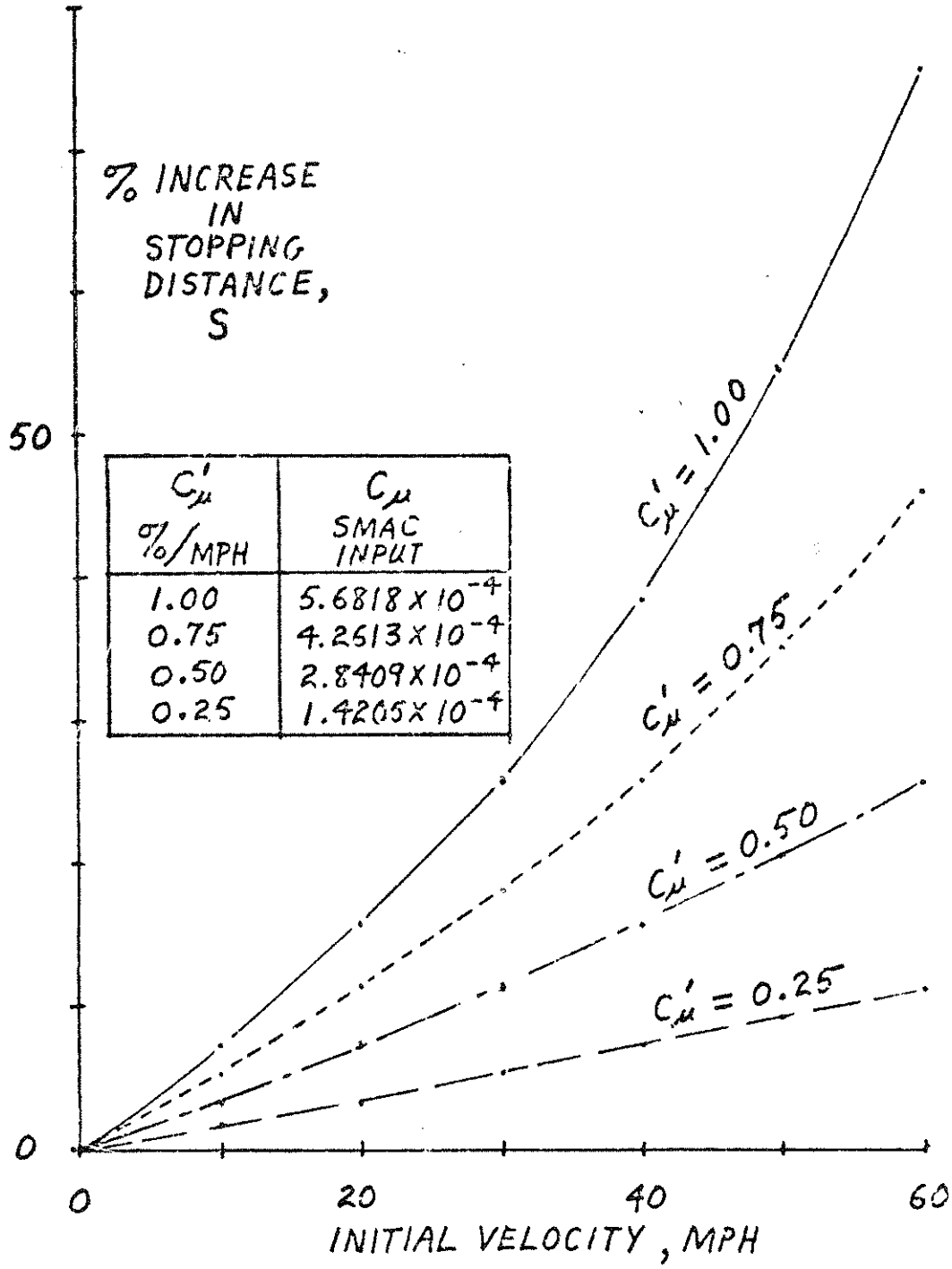
$$\mu_s S_c = \frac{V_o^2}{29.938} \tag{2}$$

where S_c = stopping distance with a constant friction coefficient, feet

From equations (1) and (2), the percentage increase in the stopping distance that is produced by a given value of C_μ' may be expressed,

$$\left(\frac{S_v}{S_c} - 1\right)(100\%) = \frac{-2 \times 10^4}{C_\mu' V_o}\left[1 + \frac{100}{C_\mu' V_o} \ln\left(1 - \frac{C_\mu' V_o}{100}\right)\right] - 100 \tag{3}$$

Representative solutions of equation (3) are displayed in Figure A8.1.



C'_μ %/MPH	C_μ SMAC INPUT
1.00	5.6818×10^{-4}
0.75	4.2613×10^{-4}
0.50	2.8409×10^{-4}
0.25	1.4205×10^{-4}

Figure A8.1 EFFECT OF LINEAR DECREMENT ON STOPPING DISTANCE