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REVISION OF THE CRASH2 COMPUTER PROGRAM

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16. Abstract

The Calspan Reconstruction of Accident Speeds on the Highway (CRASH) computer program was revised with the objectives of (1) improving the accuracy of reconstructions, (2) enhancing the convenience of applications, and (3) extending generality. This report documents the analytical bases for the program modifications.

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FOREWORD

This report summarizes part of the research results achieved within Tasks 5, 6 and 7 of Contract No. DOT-HS-6-01442 with the National Highway Traffic Safety Administration, U.S. Department of Transportation. A separate report, in the form of a revised User's Manual for the CRASH computer program, is also being sumbitted under the cited tasks of the research contract.

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:

John W. Garrett

John W. Garrett, Manager
Accident Research Division

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TABLE OF CONTENTS

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TABLE OF CONTENTS (Continued)

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LIST OF FIGURES

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LIST OF FIGURES (Continued)

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1. INTRODUCTION

The CRASH* computer program (Reference 1) is an accident investigation and reconstruction aid that has been developed with the objective of achieving accuracy and uniformity in the interpretation of physical evidence from automobile accidents. CRASH has recently been used extensively by field teams of the National Crash Severity Study and the National Accident Sampling System and that application experience has indicated the need for a number of relatively simple but important changes to achieve improvements both in the accuracy of results and in user convenience.

This report documents the analytical bases and the computer program aspects of a number of revisions of CRASH2. Conclusions and recommendations based on results of this research are presented in Section 2. The results of the research are summarized in Section 3. References are listed in Section 4.

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*Calspan Reconstruction of Accident Speeds on the Highway.

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2. CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

(1) The full development of an angular momentum form of impact-speed solution is an essential task for inclusion in future plans for the CRASH program.

(2) The empirical coefficients, α_i, that are applied in the SPIN2 routine are a likely source of at least part of the accuracy problems with the angular momentum solution mode.

(3) The simplifying assumption in CRASH of motion at separation that is directed along a straight line to the rest or end of skidding position contributes to accuracy problems with the angular momentum solution mode.

(4) The internal-check revisions that have been incorporated in the CRASH2 computer program within the present research effort constitute significant improvements in terms of insuring the compatibility of input data and of speed results for the two vehicles.

(5) User convenience has been enhanced by the addition of diagnostic messages, and by input and output modifications.

2.2 Recommendations

(1) The empirical tables in the SPIN2 routine should be overhauled using a large sample of representative spinout motions as the basis for revisions.

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(2) The advisability of a "piecemeal" incorporation of the program refinements that have been developed within this research effort into the McAuto system should be considered. The internal checks of compatibility could be immediately beneficial, whereas the angular momentum solution mode requires further development and evaluation.

(3) The test of compatibility of the direction of rotation with the effective moment arm of the principal force should be extended to test the compatibility of the magnitudes.

(4) Alternative solution forms for spinout motions should be investigated with a view toward the development of a technique simpler than the existing SPIN2 routine (e.g., an "average drag" approach based on linear and angular displacements).

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3. DISCUSSION OF RESULTS

3.1 Contract Task 5

This task consists of extensions of CRASH2 that have been found to be desirable on the basis of early application experience within the National Crash Severity Study.

Task 5.1 Solution of Cases with Initial Side-Slip Angles

One of the simplifying assumptions of CRASH2, whereby the pre-collision velocity vectors of the colliding vehicles are always treated as being aligned along their longitudinal axes, has been found to be inappropriate for a significant number of accident cases in which skidding of at least one vehicle occurs prior to the collision. In Reference 2, for example, more than 6% of the side-impact cases that were studied included skidding of at least one vehicle prior to the collision.

When pre-collision skidding occurs, the heading direction of the skidding vehicle is generally not aligned with its velocity vector at the point of impact. The angle between the heading direction and the velocity vector of the vehicle is referred to as the side-slip angle, β (e.g., see Figure 1).

The introduction of initial side slip angles makes a long-recognized application problem of the CRASH2 program more acute. In particular, the case of initial velocity vectors that are nearly parallel is approximated in CRASH2 by means of an "axial" form of solution that is based, in part, on damage information. The axial solution form is made necessary by the failure of linear momentum relationships to yield reliable results for nearly parallel initial velocity vectors. When the initial velocity vectors are actually parallel, the linear momentum relationships become indeterminate. The axial solution form is theoretically correct only for the case of central collisions (i.e., colinear velocity vectors) and, therefore, it yields reasonably accurate approximations only for nearly colinear velocity vectors (i.e., nearly central collisions).

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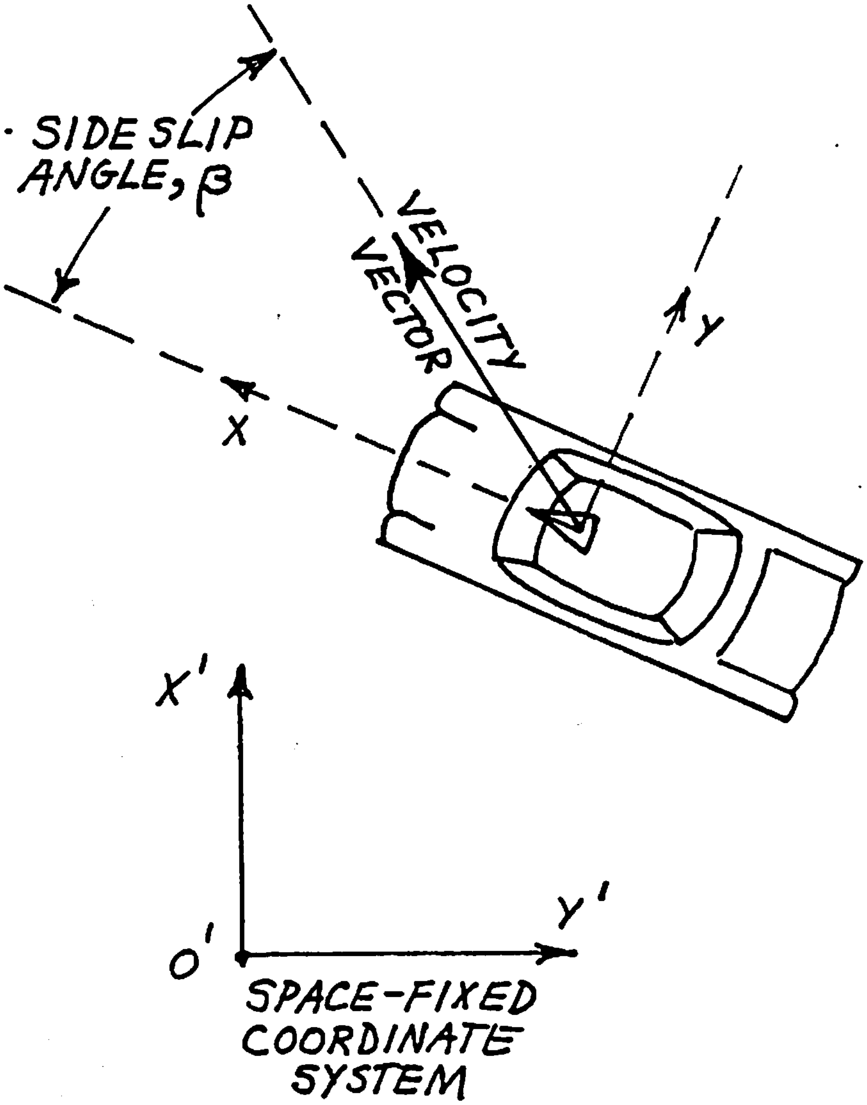
FIGURE 1 SIDE-SLIP ANGLE



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A transition from the oblique (i.e., conservation of linear momentum) to the axial solution form is made in CRASH2 when the initial velocity vectors are 10° from parallel. The transition has sometimes produced abrupt changes in speed results when the heading angles were changed by only one degree. Thus, it has long been recognized that related further development of CRASH2 would be required. Angular momentum relationships can, of course, provide a stable, alternative solution form for near-parallel velocity vectors that are not colinear.

The introduction of side slip angles creates an increased variety of impact configurations in which the initial velocity vectors may be nearly parallel and, also, may deviate substantially from the condition of being colinear (e.g., see Figure 2). Such impact configurations clearly require the use of angular momentum relationships to solve for the initial velocities.

The incorporation of angular momentum relationships entails some accuracy problems as a result of the use of analytical simplifications in CRASH2. For example, identical values are used for the positions and orientations of the vehicles at separation and at initial contact in the CRASH2 calculations. Also, the directions of motion at separation are approximated by straight lines to the rest positions for spinout trajectories in which curved paths are not specified. The suitability of all such simplifying approximations must, of course, be ultimately evaluated in applications to a variety of staged collisions. Only then can the need for revisions and/or further development be fully determined.

The derivation of analytical relationships for conservation of linear and angular momentum with initial side-slip angles is presented in Appendix 2 of this report. Those relationships and associated solution logic have been incorporated in subroutine OBLIQE of the CRASH2 program. Corresponding changes have also been made in the questions presented in subroutine QUIZ.

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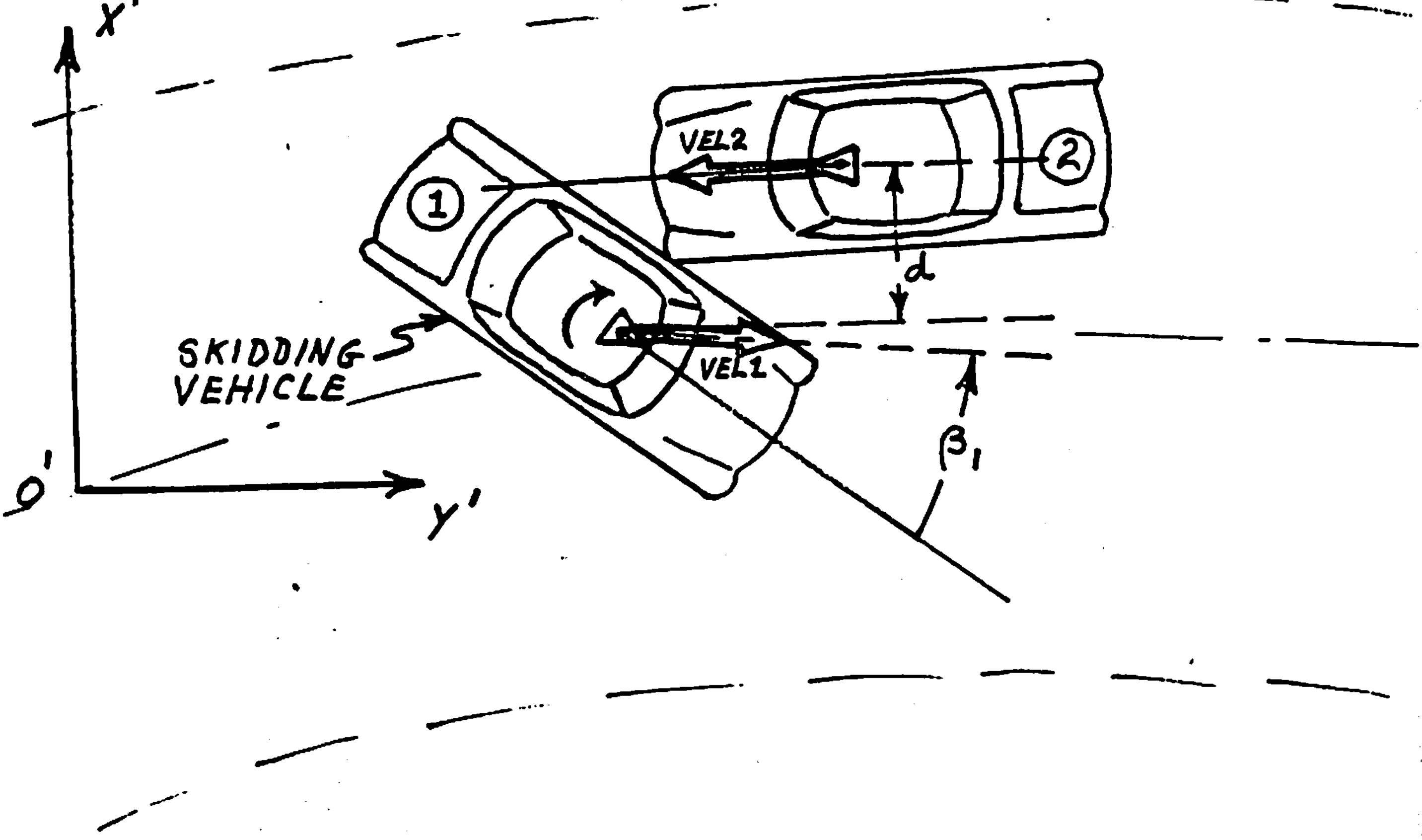
FIGURE 2 SAMPLE CASE REQUIRING ANGULAR MOMENTUM SOLUTION

$$350^\circ < |\Psi_{10} - \Psi_{20} + \beta_1 - \beta_2| < 10^\circ$$

OR

$$170^\circ < |\Psi_{10} - \Psi_{20} + \beta_1 - \beta_2| < 190^\circ$$

AND $d \neq 0$



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Results of Trial Applications

Problems with unacceptable error levels were encountered in some sample reconstruction calculations based on the developed conservation of angular momentum relationships. For this reason, an extensive amount of attention has been given to the tasks of (1) identifying sources of the related errors and (2) evaluating the prospects of achieving corresponding error reductions in general applications (i.e., without creating additional requirements for scene data measurement detail and accuracy). At the time of preparation of this report, the sources of error have not been fully resolved. However, the following findings are based on the results that have been obtained to date.

(1) The errors that occur in the angular momentum solutions can be reduced by means of:

(a) Revision of numerical values stored in the $\alpha = f(\rho)$ table, where $\rho = \dot{S}_s/\dot{\psi}_s$, in Subroutine SPIN2 (p. 48 of "User's Manual for CRASH Computer Program," Reference 3) to achieve improved approximations of angular and linear separation velocities in a larger and more representative sample of test cases.

Note that the original 18 single-vehicle SMAC runs that were used for this purpose involved relatively high linear and angular velocities for separation conditions (i.e., 25 to 40 MPH and 135 to 500 DEG/SEG at separation). The need for refinement of $\alpha = f(\rho)$ is not surprising in view of the limited prior efforts that have been applied to this fundamental aspect of the CRASH program. While the extent of related improvements that can be achieved in results by this means alone cannot be accurately predicted, the generally large magnitudes of $\dot{S}_s$ and $\dot{\psi}_s$ errors in sample applications suggest that a large potential exists for improvement.

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(b) Development and incorporation of a simple empirical relationship at the end of the SPIN2 calculations to adjust the initial directions of separation motion (γ_{si}) with respect to the present straight-lines to the rest or end-of-rotation positions, as a function of the magnitudes and algebraic signs of the angular and linear velocities at separation and of the rolling resistances at the individual wheels.

In the general case, where a curved trajectory is not specified by the CRASH user, the simplifying assumption is presently made that the centers of gravity of the vehicles move along straight line paths between their separation and rest, or end-of-rotation, positions. While this assumption yields acceptable accuracies of speed approximations based on conservation of linear momentum, it contributes to the large errors in calculations related to conservation of angular momentum. The actual directions of motion of the vehicles at the instant of separation must be accurately defined for the angular momentum calculations. When the separation motion of a vehicle includes significant yaw rotation, its path between separation and rest is generally curved. As a result, the initial velocity vector at separation does not point directly at the rest, or end-of-rotation position.

It appears that an empirical relationship can be developed to adjust the initial direction of motion at separation, away from the straight line to rest, as a function of the linear and angular velocities, the total linear and angular displacements, rolling resistances, etc. Such an adjustment will require no additional inputs by the user. Rather, it will make use of trajectory information that is already present within the SPIN2 subroutine. In Figure 3, the results of an exploratory related investigation of the original 18 SMAC runs, that were performed in 1975 to guide the initial development of the SPIN2 routine, are presented. As previously noted, those 18 SMAC runs involve relatively high linear and angular velocities for separation conditions. Also, the combinations of velocity directions and locked wheel conditions is limited (see Figure 4).

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FIGURE 3 ADJUSTMENT OF γ_s
(DEVIATION FROM STRAIGHT LINE
TO REST IN SMAC TRAJECTORIES)

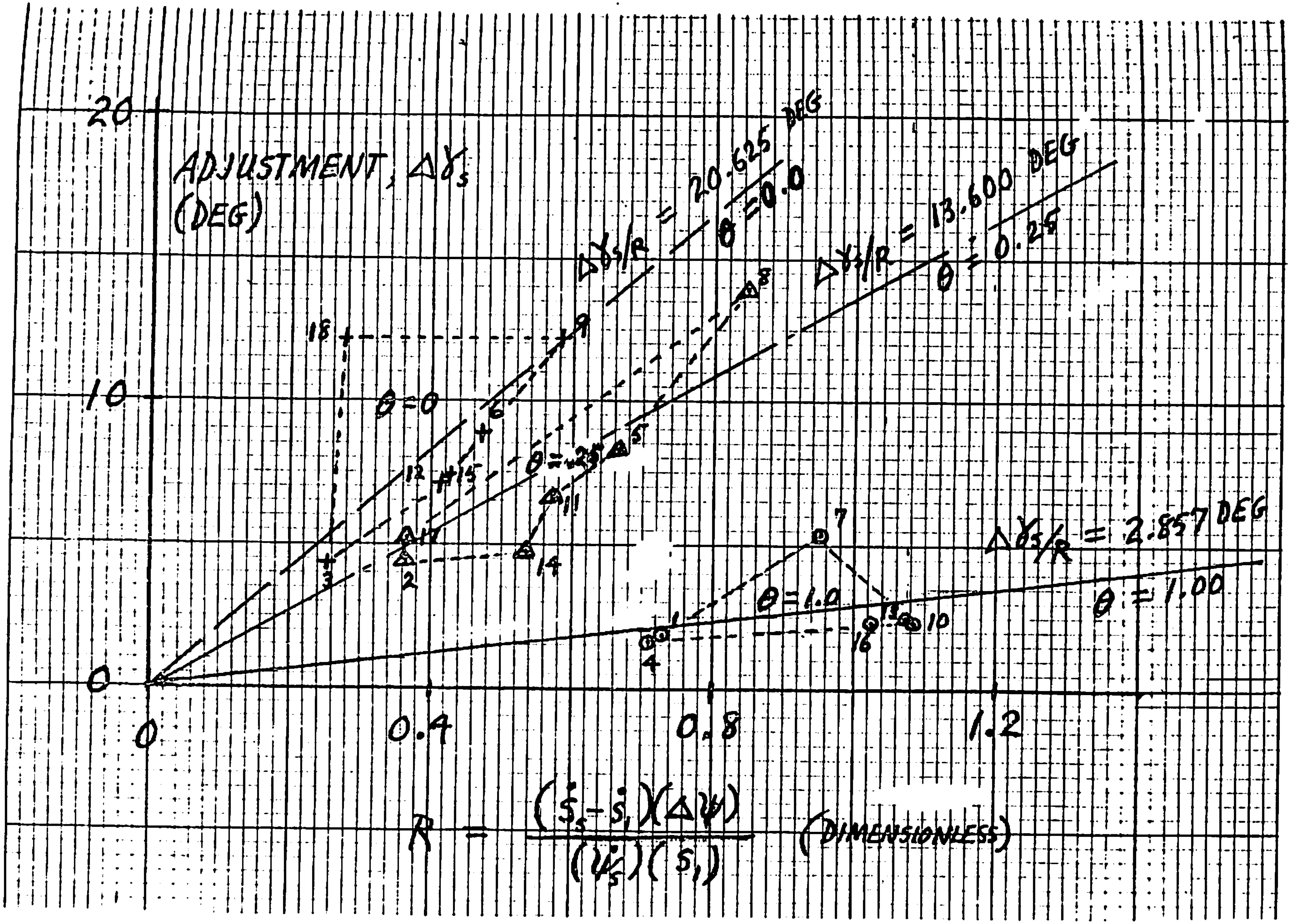

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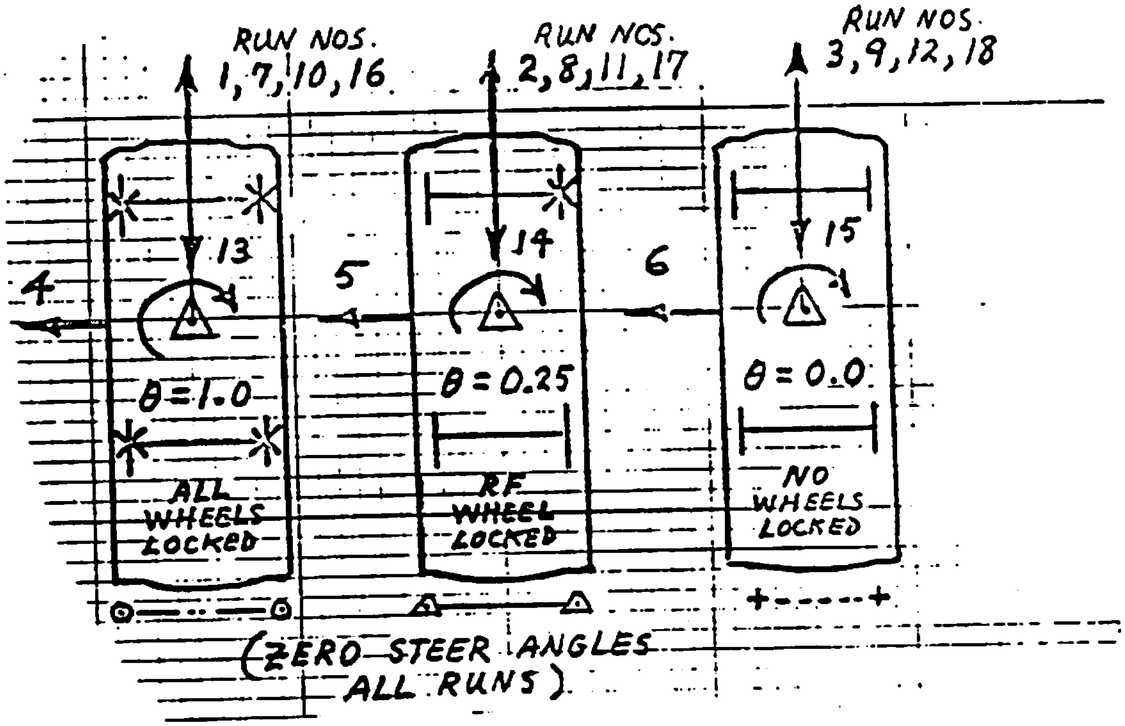
FIGURE 4 SMAC RUNS USED TO DEFINE $\alpha = f(\rho)$ $(\rho = \dot{S}_s / \dot{\psi}_s)$



$\dot{S}_s$ FT/SEC	RUN NOS.
36.7	1-9
58.7	10-18

$\dot{\psi}_s$ DEG/SEC	RUN NOS.
+500	1-6
+250	7-9
+200	10-15
+135	16-18

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In the data display of Figure 3, the required adjustment angle for the separation direction is plotted against a simple function of the linear speed-change during rotation, the angular speed change and the corresponding displacements. While a relatively large amount of scatter exists in the data points, the general clustering of points corresponding to different wheel-lock conditions is considered to show promise that an empirical function can be defined that will reduce the scatter.

On the basis of data displayed in Figure 3, a preliminary and exploratory form of adjustment of the direction of the velocity vector at separation for each vehicle was developed and incorporated in SPIN2:

```
                Subroutine SPIN2
105             PSISD  =  PSID(N)
                SSDOT  =  SSD(N)
                IF(JCV.EQ.1) GO TO 115
                TEMP1  =  (SSDOT-S1D)*DPSI
                TEMP2  =  PSISD*S1
                TEMP3  =  0.24044*THETA*THETA
                          -0.55055*THETA+0.35997
                TEMP4  =  SIGN(TEMP1/TEMP2,TEMP2)
                GAMS   =  GAMS-TEMP3*TEMP4
```

The above adjustment is not applied in the case where a curved path is specified by the CRASH user. The fitted relationship is graphically displayed in Figure 5. The defined preliminary form of program modification was found to produce improved results from the angular momentum solutions. However, the extent of improvement was not as great as expected. It is believed that this general approach can yield greater improvements if the basis of the empirical fits is extended to include a larger sample and more representative spinout conditions.

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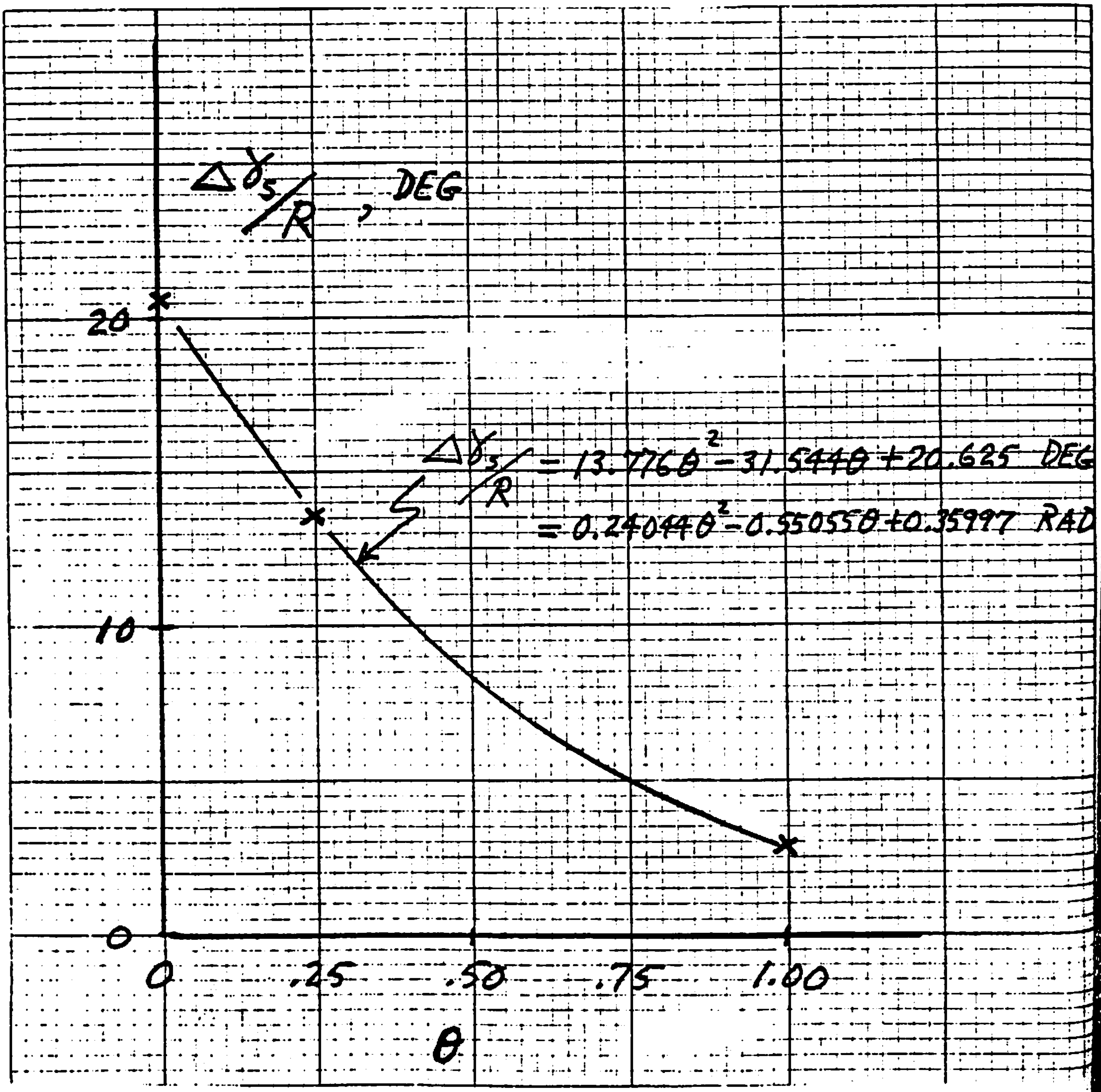
FIGURE 5 γ_s ADJUSTMENT VERSUS θ



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(c) Incorporation of an adjustment of the dimensions of the two-vehicle system, based on the extents of damage to the vehicle, to reflect the effects of vehicle crush on the moment of inertia of the system.

The existing CRASH2 calculation procedure does not include the effects of vehicle crush on the system configuration at separation. In some cases (e.g., a high-speed offset frontal collision) the moment of inertia of the system about the system center of gravity can undergo a significant change during the approach period of the collision.

(2) A realistic and meaningful evaluation of the remaining error levels, subsequent to completion of (1), must be based on results of applications to a large sample of actual staged collisions and SMAC runs. In other words, the accuracy of the resulting reconstruction technique must be evaluated for a variety of speed ranges and impact configurations.

(3) The potential benefits of the angular momentum solution mode to the CRASH reconstruction technique are sufficient to justify a major effort on the reduction of related errors. In particular, the following benefits can be achieved.

(a) A fully developed angular momentum solution mode can serve to substantially improve the accuracy of results obtained in cases where the initial velocity vectors are nearly parallel in non-central collisions (i.e., in cases where a damage plus trajectory solution constitutes a gross approximation and where linear momentum relationships cannot be applied). It has long been recognized that CRASH2 can produce abrupt changes in speed results at the existing transition between the linear momentum and the damage plus trajectory solution modes (i.e., initial velocity vectors 10° from parallel).

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(b) The angular momentum solution mode can produce a more complete utilization of the presently measured and reported trajectory evidence. The angular velocities at separation were previously approximated only as a necessary part of the approximation of linear velocities at separation (subroutine SPIN2). The angular velocities have not been utilized further. Neither have they been critically evaluated, other than for general ranges. If the angular velocity predictions can, through further refinement of the $\alpha = f(\rho)$ empirical coefficients (p. 48 of Reference 3), be made more accurate and reliable they can serve to provide further support for estimates of initial speed and of speed changes in oblique collisions without requiring the collection of any additional scene data.

DOPF Adjustment

With the incorporation of the side-slip option, CRASH2 now determines the initial lateral velocities as well as the initial longitudinal velocities. This fact has created a need, in the damage-based aspects of speed solutions, for a routine to make small adjustments, as required, in the user-entered directions of principal force. For example, an offset frontal collision could be run with a user-entered 12:00 direction of principal force (DOPF). Since lateral components of the separation velocities would occur, and a 12:00 DOPF cannot generate lateral speed changes, the results would indicate the existence of initial side-slip angles. Obviously, the actual DOPF is not exactly 12:00. The routine defined in Figure 6 was incorporated in START2 to "zero out" any indicated initial side-slip angles when the user has indicated that none existed.

A flow chart for the DOPF adjustment is presented in Figure 7.

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FIGURE 6 DOPF ADJUSTMENT FLOW CHART
(STEPS 8-13 AIMED AT MAINTAINING 180°
SPREAD BETWEEN DOPF'S FOR THE TWO VEHICLES)

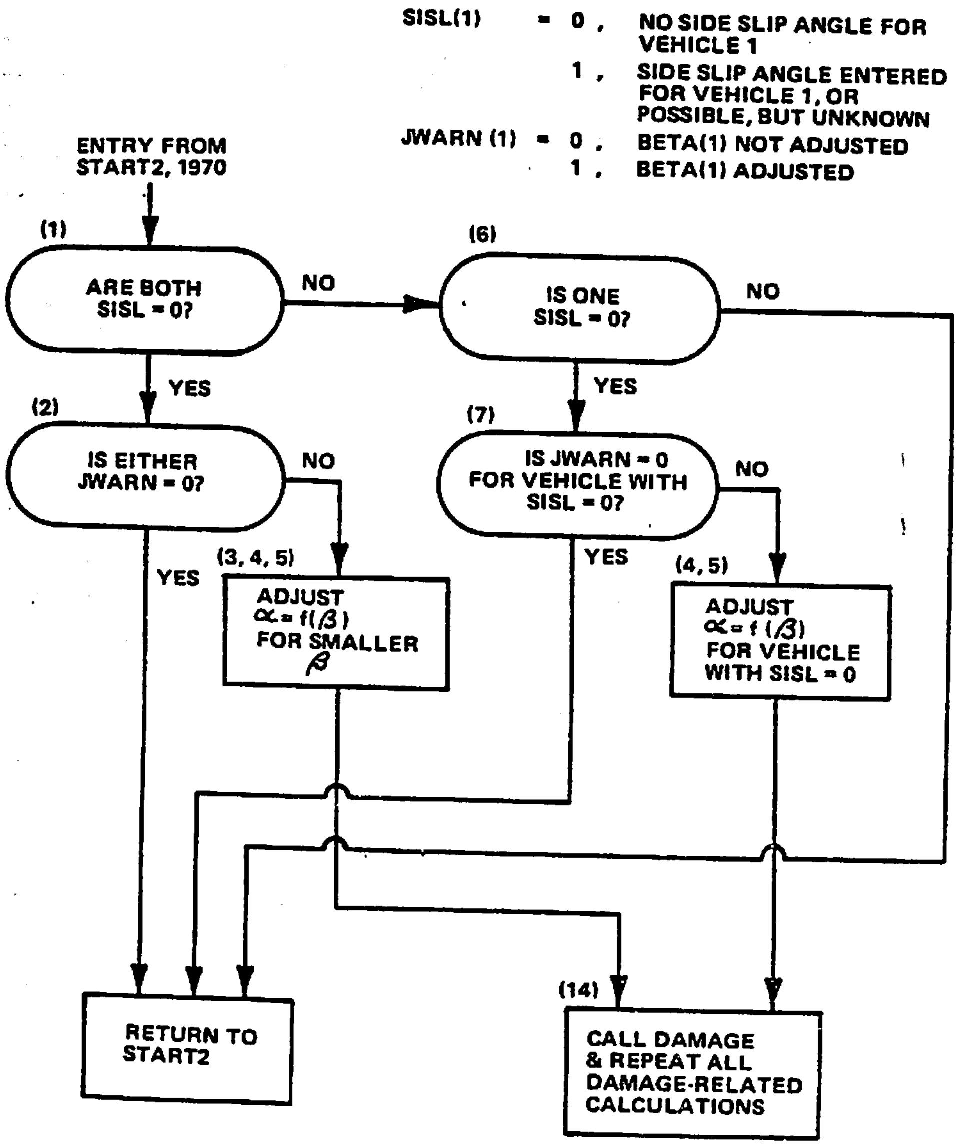

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FIGURE 7 DOPF ADJUSTMENT ROUTINE

(ANG (1), ANG(2), BETA1, BETA2, SISL(1), SISL(2), JWARN(1), JWARN(2), PSI10, PSI20, US1, US2, DELVX1, DELVX2)

```
SISL(1)    =    0   ,   NO SIDE SLIP ANGLE FOR VEHICLE 1
                1   ,   SIDE SLIP ANGLE ENTERED FOR VEHICLE 1,
                         OR POSSIBLE, BUT UNKNOWN
JWARN (1)  =    0   ,   BETA(1) NOT ADJUSTED
                1   ,   BETA(1) ADJUSTED
```

```
1        IF (SISL(1).GT.0.0) OR (SISL(2).GT.0.0) GO TO 6
2        IF (JWARN(1).GT.0.0) AND (JWARN(2).GT.0.0) GO TO 3
         RETURN
3        IF (ABS(BETA1).LT.ABS(BETA2)) GO TO 5
4*       ANG(2) = ARCTAN ((US2/DELVX2 - 1.0) * TAN (BETA2)) GO TO 8
5*       ANG(1) = ARCTAN ((US1/DELVX1 - 1.0) * TAN (BETA1)) GO TO 11
6        IF (SISL(1).EQ.0.0) OR (SISL(2).EQ.0.0) GO TO 7
         RETURN
7        IF ((SISL(1) + JWARN(1)).EQ.1.0) GO TO 5
         IF ((SISL(2) + JWARN(2)).EQ.1.0) GO TO 4
         RETURN
8        ANG(1) = PSI20-PSI10 + ANG(2) + 3.1416
9        IF (ABS(ANG(1).LT.3.665) GO TO 10
         ANG(1) = ANG(1) - SIGN(3.1416, ANG(1)) GO TO 9
10       ANG(1) = ANG(1) - SIGN(3.1416, ANG(1)) GO TO 14
11       ANG(2) = PSI10 - PSI20 + ANG(1) + 3.1416
12       IF (ABS (ANG(2)).LT.3.665) GO TO 13
         ANG(2) = ANG(2) - SIGN (3.1416, ANG(2)) GO TO 12
13       ANG(2) = ANG(2) - SIGN (3.1416, ANG(2))
14       CALL DAMAGE.
```

---

* Not reached if SISL ≠ 0.

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Task 5.2 Sustained Contact

A long-recognized shortcorming of the CRASH2 computer program is its inability to deal with those collisions in which vehicle-to-vehicle contact is maintained during the spinout motions. An example would be a case in which a parked vehicle is hit broadside (i.e., striking vehicle perpendicular to side of struck vehicle in a central side collision) and the struck vehicle is subsequently pushed laterally by the striking vehicle until they both come to rest. The difficulty with CRASH2 stems from an assumption that the individual vehicles go separately and independently to rest subsequent to a collision.

For oblique collisions in which the two involved vehicles separate rapidly and move in distinctly different directions, the stated assumption is a valid one. It is also valid for cases in which the two vehicles move in the same general direction so long as the trailing vehicle has a greater deceleration rate (i.e., rotational resistance at the wheels produced by braking and/or damage and tire side forces generated by large slip angles) than the leading vehicle. However, a greater deceleration rate in the leading vehicle can produce sustained intervehicle contact as the trailing vehicle pushes the leading vehicle.

The approach that has been taken in extending the CRASH2 program to accommodate cases of sustained contact is very simple and direct. The routine that has been developed and coded within SPIN2 tests the directions of motion, the extents of yaw rotations and the deceleration rates of the two vehicles. The selected test criteria are based on several actual near-central side impacts in which the struck vehicle was either parked or moving slowly. A schematic flow chart of the developed calculation procedure for sustained contacts is presented in Figure 8. The selected test values can, of course, be adjusted as experience is gained with collisions of this type.

The non-yawing drag factor that is discussed in the next section of this report is applied to the individual vehicles in some such cases.

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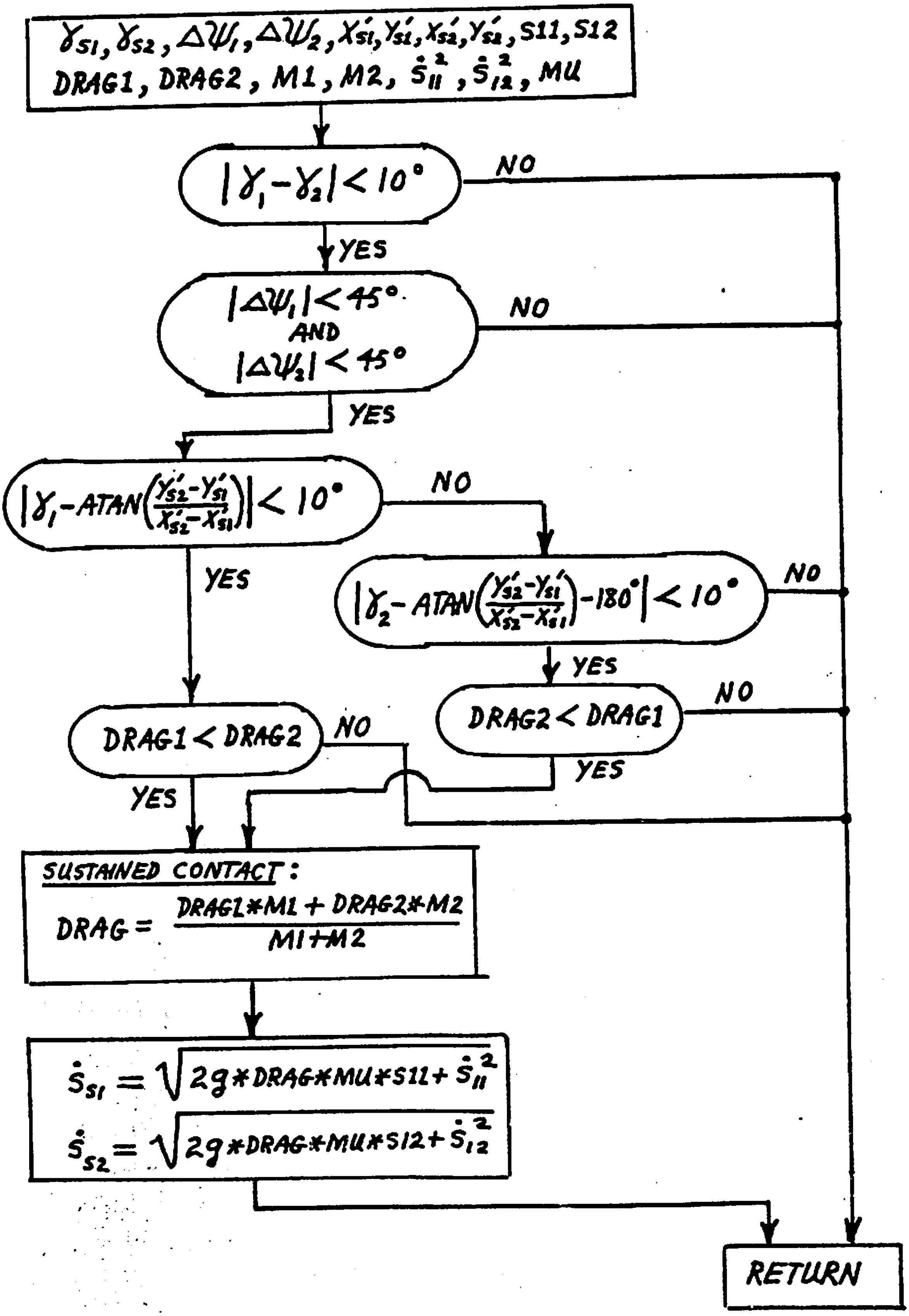
FIGURE 8 SUSTAINED CONTACT CALCULATION PROCEDURE



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Drag Factor in Non-Yawing Skids

For the purpose of approximating the resultant resistance force produced by the vehicles tires in non-yawing skids (i.e., translation of vehicle center of gravity without a significant change in heading), the following simplifying assumptions have been made. Note that vehicle motions of this type are frequently associated with sustained contacts.

(1) The maximum possible resistance force is independent of the direction of motion of the vehicle. In other words, the "friction circle" concept (e.g., References 4 and 5) has been adopted to approximate the combined effects of wheel rotational resistance (i.e., braking and/or damage) and tire side forces for the entire vehicle, as opposed to the more conventional application to a single tire (see Figure 9).

(2) Effects of steered angles at the front wheels are neglected. It should be noted that the existence of significant steered angles, in the case where rotational lockup of the wheels is not complete, would be expected to produce a changing heading direction and, thereby, a bypass of the presently described approximation procedure for non-yawing skids. With fully locked wheels, steered angles have no effect on the direction and magnitude of the resultant resistance force.

(3) Effects of deviations from the maximum possible values of tire side forces at small vehicle side slip angles are neglected. In the case of a vehicle side slip angle less than approximately 12° on a surface with an effective tire-terrain friction coefficient of 0.70, the contribution of the tire side forces to the resultant resistance force is overestimated by the adopted simplification. However, the magnitude of the corresponding error in the resultant resistance force is reduced by the presence of rotational resistance of the wheels (i.e., braking and/or damage) and also by a reduced friction coefficient for the tire-terrain interface (see Appendix 3).

The resulting "drag factor" that is applied to cases in which skidding without significant yaw rotation occurs is displayed in Figure 10.

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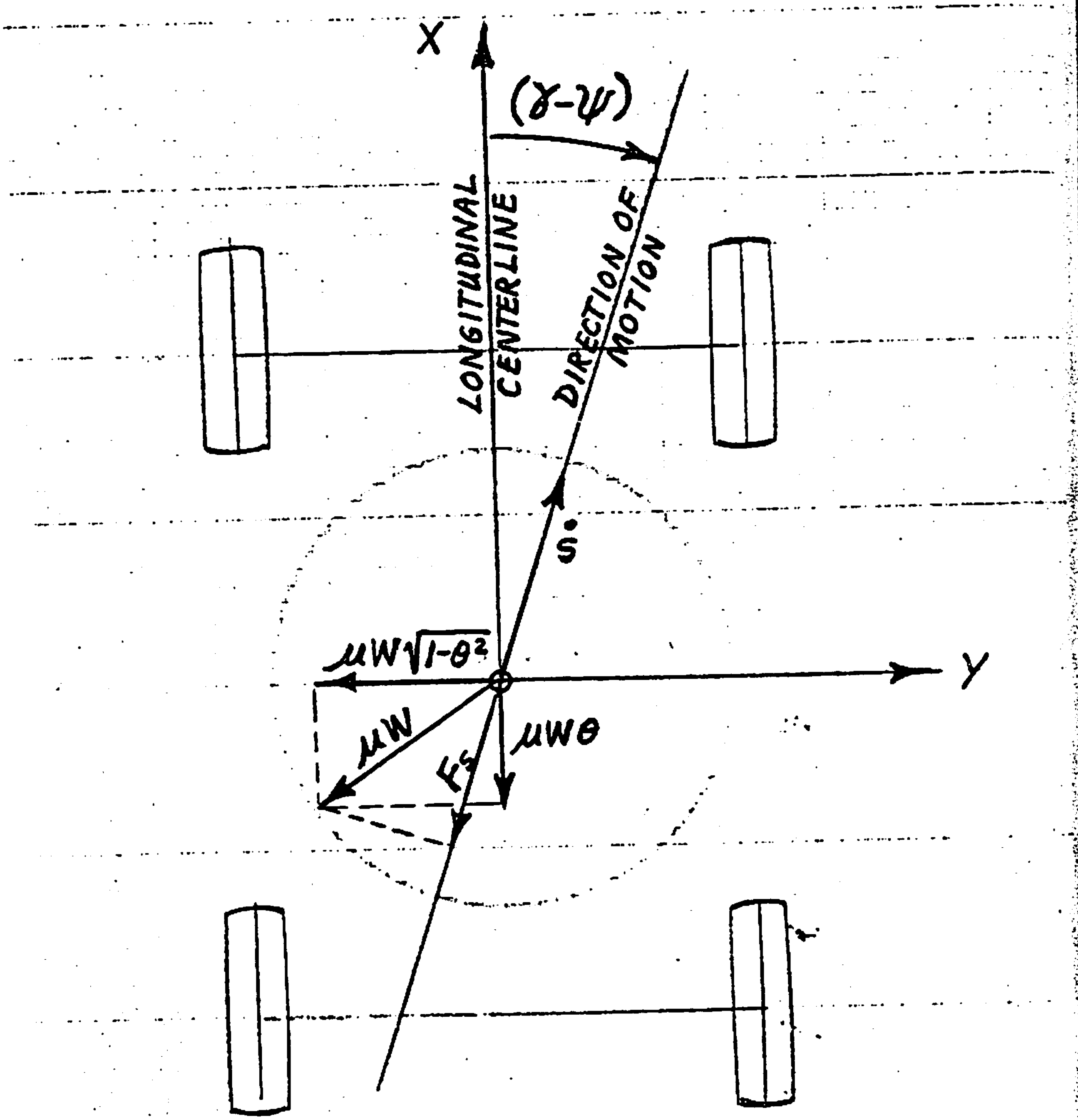
FIGURE 9 FRICTION CIRCLE FOR ROLLING RESISTANCE AND SIDE FORCES IN NON-YAWING SKID



$$F_s = \mu W\left[\theta \cos(\gamma-\psi) + \sqrt{1-\theta^2}\cdot \sin(\gamma-\psi)\right]$$

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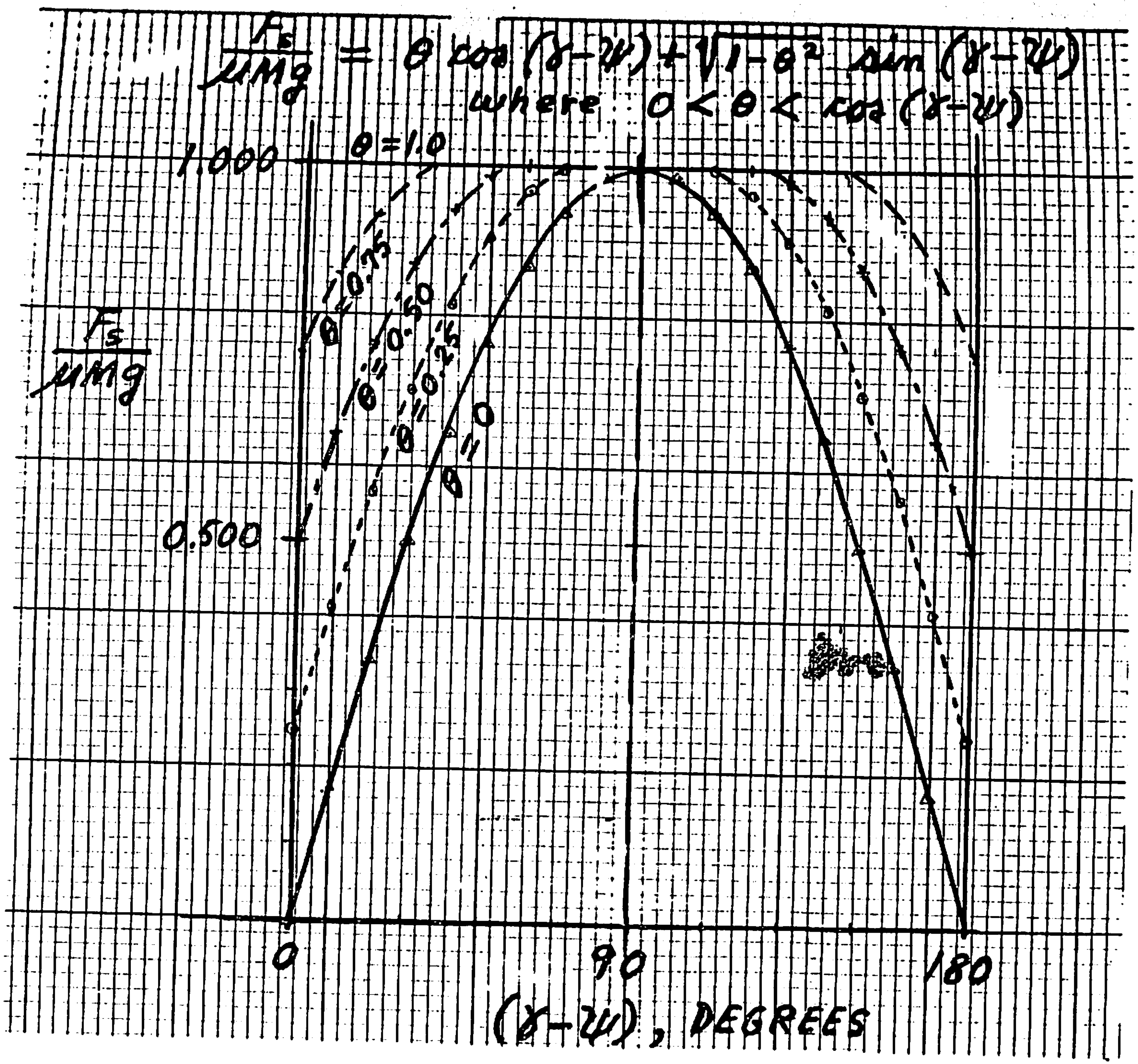
FIGURE 10   DRAG FACTOR IN NON-YAWING SKIDS



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Results of Trial Applications

The results of trial applications of the revised CRASH2 program to two cases from Reference 6, in which parked vehicles were struck broadside, are presented in Figures 11 and 12.

The correlation of reconstruction results with measured data in the two sample cases is considered to be excellent, with the exception of the damage-based results in the second case. As discussed in related footnotes on the sample results, the measured damage information was limited to a single dimension for the <u>maximum</u> deformation and the photographs (Figure 5.1 of Reference 6) indicate that the actual damage profile was non-uniform.

Displacement Ratio

In further checkout runs of the calculation procedure for sustained contacts, it was found that the SPIN2 routine, as originally coded, would sometimes overestimate the quantity DRAG* for the case of a near-longitudinal spinout direction and a small total yaw rotation. As a result, the sustained-contact solution form could be erroneously bypassed in some intersection collisions on the basis of the comparison of DRAG values for the struck and striking vehicles.

The problem was found to stem from two sources. First, the existing input questions (QUIZ) tend to invite a generally erroneous indication that rotational skidding was sustained throughout the trajectory to rest. Whenever the physical evidence does not clearly define the point at which rotation stopped, the CRASH user tends to enter a "NO" response for question 13 and/or 20[1]. (Did rotational and/or lateral skidding of vehicle i stop before rest position was reached?) Second, the SPIN2 routine does not presently distingui

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$$^{*}\ \text{DRAG} = \frac{\text{DECELERATION (G UNITS)}}{\text{TIRE-TERRAIN FRICTION COEFF.}}$$

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FIGURE 11 SUSTAINED CONTACT SAMPLE #1

SUMMARY OF CRASH RESULTS

SCHNEIDER CENTRAL COLLISION ABB.4

VEHICLE # 1

IMPACT SPEED MPH		SPEED CHANGE MPH			BASIS OF RESULTS
FWD	LAT	TOTAL	LONG.	LATERAL	
24.2 -0.1%	0.0	8.1 -1.2%	-8.1 -1.2%	0.0	SPINOUT TRAJECTORIES AND CONSERVATION OF LINEAR MOMENTUM
24.2	0.0	8.1	-8.1	0.0	SPINOUT TRAJECTORIES AND CONSERVATION OF ANGULAR MOMENTUM
0.0	0.0	~~-10.1~~	~~10.1~~	0.0	SPINOUT TRAJECTORIES AND DAMAGE
		8.1 -1.2%	-8.1 -1.2%	0.0	DAMAGE DATA ONLY

VEHICLE # 2

IMPACT SPEED MPH		SPEED CHANGE MPH			BASIS OF RESULTS
FWD	LAT	TOTAL	LONG.	LATERAL	
0.0	0.0	16.1 +0.4%	-0.0	-16.1 +0.4%	SPINOUT TRAJECTORIES AND CONSERVATION OF LINEAR MOMENTUM
-0.0	0.0	16.1	0.0	-16.1	SPINOUT TRAJECTORIES AND CONSERVATION OF ANGULAR MOMENTUM
0.0	0.0	~~16.1~~	0.0	~~-16.1~~	SPINOUT TRAJECTORIES AND DAMAGE
		16.2 +1.1%	-0.0	-16.2 +1.1%	DAMAGE DATA ONLY

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FIGURE 11 (Continued)

```
                                   SCENE INFORMATION
                                             VEHICLE # 1          VEHICLE # 2

IMPACT X-POSITION                              0.0    FT.          0.0    FT.
IMPACT Y-POSITION                            -10.77   FT.          0.0    FT.
IMPACT HEADING ANGLE                          89.99   DEG.       179.98   DEG.

REST X-POSITION                                0.0    FT.          0.0    FT.
REST Y-POSITION                               19.74   FT.         30.51   FT.
REST HEADING ANGLE                            89.99   DEG.       179.98   DEG.

END-OF-ROTATION X-POSITION                     0.0    FT.
END-OF-ROTATION Y-POSITION                   -10.77   FT.
END-OF-ROTATION HEADING ANGLE                 89.99   DEG.

DIRECTION OF ROTATION                         NONE                NONE
AMOUNT OF ROTATION                            <360                <360

                                  COLLISION CONDITIONS
        VEHICLE # 1                                    VEHICLE # 2

XC10'     =       0.0 FT.                   XC20'     =       0.0 FT.
YC10'     =     -10.8 FT.                   YC20'     =       0.0 FT.
PSI10     =      90.0 DEGREES               PSI20     =     180.0 DEGREES
PSI100    =       0.0 DEG/SEC               PSI200    =       0.0 DEG/SEC
       LINEAR    ANGULAR                           LINEAR    ANGULAR
     MOMENTUM  MOMENTUM DAMAGE                   MOMENTUM  MOMENTUM  DAMAGE
U10      24.2      24.2      0.0 MPH        U20       0.0      -0.0       0.0 MPH
V10       0.0       0.0      0.0 MPH        V20       0.0       0.0       0.0 MPH

                                 SEPARATION CONDITIONS

XCS1'     =       0.0 FT.                   XCS2'     =       0.0 FT.
YCS1'     =     -10.8 FT.                   YCS2'     =       0.0 FT.
PSIS1     =      90.0 DEG                   PSIS2     =     180.0 DEG
US1       =      16.1 MPH                   US2       =       0.0 MPH
VS1       =       0.0 MPH                   VS2       =     -16.1 MPH
PSISD1    =       0.0 DEG/SEC               PSISD2    =       0.0 DEG/SEC

                                 RELATIVE VELOCITY DATA

     SPEED CHANGE (DAMAGE)
          TOTAL      LONG.      LAT.       ANG.
VEH#1     16.1       16.1       0.0     -180.0
VEH#2     16.1        0.0     -16.1       90.0

     SPEED CHANGE (LINEAR MOMENTUM)
          TOTAL      LONG.      LAT.       ANG.
VEH#1      8.1       -8.1       0.0        0.0
VEH#1      8.1       -8.1       0.0        0.0
VEH#2     16.1       -0.0     -16.1       90.0

SPEED CHANGE (ANGULAR MOMENTUM)
          TOTAL      LONG.      LAT.       ANG.
VEH#1      8.1       -8.1       0.0        0.0
VEH#2     16.1        0.0     -16.1       90.0
ENERGY DISSIPATED BY DAMAGE                    9568.9 FT-LB   13287.6 FT-LB
SPEED ALONG LINE THRU CGS
              24.2       24.2       0.0
              -0.0        0.0       0.0

SPEED ORTHOG. TO CG LINE
              -0.0       -0.0       0.0
              -0.0        0.0       0.0

CLOSING VELOCITY
              24.2       24.2       0.0
```

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FIGURE 11 (Continued)

```
SUMMARY OF DAMAGE DATA                   (* INDICATES DEFAULT VALUE)

          VEHICLE # 1                             VEHICLE # 2

TYPE---------CATEGORY 4                   TYPE----------CATEGORY 1
WEIGHT-------  3461.0 LBS.                WEIGHT-------   1730.6 LBS.
VDI----------12FDEW1                      VDI-----------03RPEW2
L------------    75.0 IN.                 L-------------    75.0 IN.
C1-----------     3.1 IN.                 C1------------     8.7 IN.
C2-----------     3.1 IN.                 C2------------     8.7 IN.
C3-----------     0.0 IN.                 C3------------     0.0 IN.
C4-----------     0.0 IN.                 C4------------     0.0 IN.
C5-----------     0.0 IN.                 C5------------     0.0 IN.
C6-----------     0.0 IN.                 C6------------     0.0 IN.
D------------     0.0                     D-------------     0.0
RHO----------    1.00          *          RHO-----------    1.00          *
ANG----------    -0.1 DEG.     *          ANG-----------    90.0 DEG.     *
D*-----------     0.0 IN.                  D*------------     0.0 IN.

                      DIMENSIONS AND INERTIAL PROPERTIES

A1         =     54.7 INCHES              A2        =     45.1 INCHES
B1         =     59.2 INCHES              B2        =     48.1 INCHES
TR1        =     61.8 INCHES              TR2       =     51.1 INCHES
I1         =  33508.3 LB-SEC**2-IN        I2        =   8984.4 LB-SEC**2-IN
M1         =    6.957 LB-SEC**2/IN        M2        =    4.479 LB-SEC**2/IN
XF1        =     98.8 INCHES              XF2       =     76.0 INCHES
XR1        =   -114.0 INCHES              XR2       =    -83.6 INCHES
YS1        =     38.5 INCHES              YS2       =     30.4 INCHES

                   ROLLING RESISTANCE
   VEHICLE # 1
                                                 VEHICLE # 2
RF-----------     0.0
LF-----------     0.0                     RF------------     0.0
RR-----------     0.14                    LF------------     0.0
LR-----------     0.14                    RR------------     0.0
                                          LR------------     0.0


MU-----------     0.75
```

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FIGURE 12 SUSTAINED CONTACT SAMPLE #2

SUMMARY OF CRASH RESULTS

SCHNEIDER CENTRAL COLLISION ARR.5

VEHICLE # 1

IMPACT SPEED MPH		SPEED CHANGE MPH			BASIS OF RESULTS
FWD	LAT	TOTAL	LONG.	LATERAL	
17.4 -3.3%	0.0	11.6 -3.7%	-11.6 -3.7%	0.0	SPINOUT TRAJECTORIES AND CONSERVATION OF LINEAR MOMENTUM
17.4	0.0	11.6	-11.6	0.0	SPINOUT TRAJECTORIES AND CONSERVATION OF ANGULAR MOMENTUM
0.0	0.0	5.8	5.8	0.0	SPINOUT TRAJECTORIES AND DAMAGE
		*17.6 +46.1%	*-17.6 +46.1	0.0	*DAMAGE DATA ONLY

VEHICLE # 2

IMPACT SPEED MPH		SPEED CHANGE MPH			BASIS OF RESULTS
FWD	LAT	TOTAL	LONG.	LATERAL	
0.0	0.0	5.8 -2.8%	0.0	-5.8 -2.8%	SPINOUT TRAJECTORIES AND CONSERVATION OF LINEAR MOMENTUM
-0.0	0.0	5.8	0.0	-5.8	SPINOUT TRAJECTORIES AND CONSERVATION OF ANGULAR MOMENTUM
0.0	0.0	5.8	0.0	-5.8	SPINOUT TRAJECTORIES AND DAMAGE
		*8.8 +47.4%	-0.0	*-8.8 +47.4%	*DAMAGE DATA ONLY

*Ref. 6 provides only a single "maximum deformation" dimension. In the absence of other measured damage information, a uniform plan-view profile with the maximum crush dimension has been used herein. It may be seen in Figure 5.1 of Reference 6 that the actual damage profile was not uniform.

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FIGURE 12 (Continued)

```
                          SCENE INFORMATION
                                          VEHICLE # 1          VEHICLE # 2

 IMPACT X-POSITION                         0.0    FT.           0.0    FT.
 IMPACT Y-POSITION                        -9.54   FT.           0.0    FT.
 IMPACT HEADING ANGLE                     89.99   DEG.        179.98   DEG.

 REST X-POSITION                           0.0    FT.           0.0    FT.
 REST Y-POSITION                          -7.41   FT.           2.13   FT.
 REST HEADING ANGLE                       89.99   DEG.        179.98   DEG.

 END-OF-ROTATION X-POSITION                0.0    FT.
 END-OF-ROTATION Y-POSITION               -9.54   FT.
 END-OF-ROTATION HEADING ANGLE            89.99   DEG.

 DIRECTION OF ROTATION                    NONE                 NONE
 AMOUNT OF ROTATION                       <360                 <360

                          COLLISION CONDITIONS
        VEHICLE # 1
                                                 VEHICLE # 2
 XC10'     =      0.0 FT.
 YC10'     =     -9.5 FT.                 XC20'     =      0.0 FT.
 PSI10     =     90.0 DEGREES             YC20'     =      0.0 FT.
 PSI1D0    =      0.0 DEG/SEC             PSI20     =    180.0 DEGREES
         LINEAR      ANGULAR              PSI2D0    =      0.0 DEG/SEC
        MOMENTUM    MOMENTUM   DAMAGE              LINEAR     ANGULAR
 U10      17.4        17.4      0.0 MPH           MOMENTUM   MOMENTUM   DAMAGE
 V10       0.0         0.0      0.0 MPH   U20        0.0       -0.0       0.0 MPH
                                          V20        0.0        0.0       0.0 MPH

                          SEPARATION CONDITIONS

 XCS1'     =      0.0 FT.
 YCS1'     =     -9.5 FT.                 XCS2'     =      0.0 FT.
 PSIS1     =     90.0 DEG                 YCS2'     =      0.0 FT.
 US1       =      5.8 MPH                 PSIS2     =    180.0 DEG
 VS1       =      0.0 MPH                 US2       =      0.0 MPH
 PSISD1    =      0.0 DEG/SEC             VS2       =     -5.8 MPH
                                          PSISD2    =      0.0 DEG/SEC

                          RELATIVE VELOCITY DATA

     SPEED CHANGE (DAMAGE)
         TOTAL       LONG.       LAT.        ANG.
 VEH#1    5.8         5.8        0.0       -180.0
 VEH#2    5.8         0.0       -5.8         90.0

     SPEED CHANGE (LINEAR MOMENTUM)
         TOTAL       LONG.       LAT.        ANG.
 VEH#1   11.6       -11.6        0.0          0.0
 VEH#1   11.6       -11.6        0.0          0.0
 VEH#2    5.8         0.0       -5.8         90.0

 SPEED CHANGE (ANGULAR MOMENTUM)
         TOTAL       LONG.       LAT.        ANG.
 VEH#1   11.6       -11.6        0.0          0.0
 VEH#2    5.8         0.0       -5.8         90.1
 ENERGY DISSIPATED BY DAMAGE                      15715.7 FT-LB   11245.5 FT-LB
 SPEED ALONG LINE THRU CGS
                17.4        17.4       0.0
                -0.0         0.0       0.0
 SPEED ORTHOG. TO CG LINE
                -0.0        -0.0       0.0
                -0.0         0.0       0.0
 CLOSING VELOCITY
                17.4        17.4       0.0
```

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FIGURE 12 (Continued)

```
                       SCENE INFORMATION

SUMMARY OF DAMAGE DATA                  (* INDICATES DEFAULT VALUE)

           VEHICLE # 1                            VEHICLE # 2

TYPE--------CATEGORY 1                 TYPE---------CATEGORY 4
WEIGHT------  1730.6 LBS.              WEIGHT------   3461.2 LBS.
VDI---------12FDEW1                    VDI----------03RPEW1
L-----------    59.0 IN.               L-----------     59.0 IN.
C1----------     8.7 IN.    *          C1----------      6.7 IN.   *
C2----------     8.7 IN.               C2----------      6.7 IN.
C3----------     0.0 IN.               C3----------      0.0 IN.
C4----------     0.0 IN.               C4----------      0.0 IN.
C5----------     0.0 IN.               C5----------      0.0 IN.
C6----------     0.0 IN.               C6----------      0.0 IN.
D-----------     0.0                   D-----------      0.0
RHO---------     1.00       *          RHO---------      1.00      *
ANG---------    -0.1 DEG.   *          ANG---------     90.0 DEG.  *
D'----------     0.0 IN.                D'----------      0.0 IN.

                  DIMENSIONS AND INERTIAL PROPERTIES

A1      =     45.1 INCHES              A2       =      54.7 INCHES
B1      =     48.1 INCHES              B2       =      59.2 INCHES
TR1     =     51.1 INCHES              TR2      =      61.8 INCHES
I1      =   8984.4 LB-SEC**2-IN        I2       =   33510.2 LB-SEC**2-IN
M1      =    4.479 LB-SEC**2/IN        M2       =     6.959 LB-SEC**2/IN
XF1     =     76.0 INCHES              XF2      =      98.9 INCHES
XR1     =    -83.8 INCHES              XR2      =    -114.0 INCHES
YS1     =     30.4 INCHES              YS2      =      38.5 INCHES

                  ROLLING RESISTANCE

   VEHICLE # 1                              VEHICLE # 2

RF----------    0.0                    RF----------     0.0
LF----------    0.0                    LF----------     0.0
RR----------    0.22                   RR----------     0.0
LR----------    0.22                   LR----------     0.0


MU----------    0.75
```

*Ref. 6 provides only a single "maximum deformation" dimension. In the absence of other measured damage information, a uniform plan-view profile with the maximum crush dimension has been used herein. It may be seen in Figure 5.1 of Reference 6 that the actual damage profile was not uniform.

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the direction of the separation velocity vector with respect to the longitudinal axis of the vehicle (i.e., the same results are produced for longitudinal and broadside initial velocity vectors). For the case of partial braking and a small total yaw rotation, the actual deceleration rate in predominently longitudinal motions is determined primarily by the rolling resistances at the wheels.

The basis for the present form of SPIN2 is a set of 18 SMAC runs, which involved relatively large rotational velocities at separation, that were used to develop the empirical coefficients, $\alpha = f(\rho)$. Obviously, a larger sample of spinouts including small yawing velocities would be expected to display some sensitivity to the initial direction of the linear velocity. However, it should be noted that a relatively large angular (yaw) velocity is generally necessary to produce a sustained rotational skid in the case of partial braking. The rotational velocity tends to become transformed into linear velocity when a path of less resistance is offered to the skidding vehicle. Thus, a "YES" response is frequently appropriate for Question 13 and/or 20* in rotational skids.

To overcome the cited difficulties within the existing framework of SPIN2, a test of the ratio of linear to angular displacement has been incorporated to detect those cases in which the spinout motion is predominently a linear translation. Such cases are treated in the same manner as the case of skidding without rotation.

The initial selected test value for the displacement ratio is 500 inches per radian (i.e., approximately 8.7 inches/degree) which is based on several test cases that have constituted problems for the sustained-contact solution form. It is also based on the gross approximation that a displacement ratio below the range of 300 to 400 inches/radian is required to develop slip angles sufficiently large to produce maximum tire side forces (i.e., rotational skidding). Thus, the test may be viewed as a detector of gross deviations from a condition of rotational skidding. It should be noted that a related CRASH2 problem indicated in correspondence from the Transport and

---

*Questions No. 13 and 20 in CRASH3 were 12 and 19 in CRASH2.

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Road Research Laboratory (Reference 7) involved a linear to angular displacement ratio of 2,200 inch per radian.

A second test, of the total extent of heading change, has been incorporated to detect high-speed spinouts (i.e., long spinout distances) with significant total heading changes. The initially selected test value is 20°.

A larger sample of checkout application runs will be required to determine the possible need for adjustment of the indicated test values so that smooth transitions will be achieved between the different solution forms (i.e., rotational and lateral akidding, lateral skidding without significant rotation, and non-skidding motions). Ultimately, a larger sample of spinout motions can serve to guide further development and refinement of SPIN2. Such a sample may indicate a need and provide a basis for inclusion of the direction of the initial velocity vector with respect to the longitudinal vehicle axis $(\gamma-\psi)$ in the determination of the empirical coefficients, $\alpha_i = f(\rho)$ (p. 48 of Reference 3).

Task 5.3 Compatibility of Vehicle Heading Angles and DOPFs

With the CRASH2 program, it is possible for a careless user to enter vehicle heading angles and either directions of principal force or clock directions that are not compatible. In other words, the resulting directions of principal forces (DOPF) on the two vehicles may not be colinear. Such a set of inputs, of course, violates Newton's Third Law of Motion.

The present revision of CRASH2 consists of a simple test of inputs to insure that the principal forces are 180° apart. For discrepencies from 180° that are less that or equal to ±15°, the entered DOPFs are equally adjusted to achieve 180±0.10 degrees and a corresponding message is printed. For discrepencies from 180° greater than ±15°, a program stop is activated and a corresponding message is printed. The test procedure is outlined on the following pages. Symbols, other than those that are defined within the procedure (i.e., TEMP1, TEMP2, A, δ), are defined in Appendix 1.

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QUIZ Routine

```
Test Inputs:   $\psi_1, \psi_2, \alpha_1, \alpha_2$ (DEGREES)

(1)   TEMP1 = $\psi_1 + \alpha_1$

(2)   TEMP2 = $\psi_2 + \alpha_2$

(3)   A = TEMP1 - TEMP2

(4)   IF $|A| < 210°$, GO TO (6)

(5)   SET A = A - (180) (sgn A), GO TO (4)

(6)   $\delta$ = A - (180) (sgn A)

(7)   IF $15° < |\delta|$, STOP AND PRINT

      MESSAGE:

        "ENTERED VALUES FOR HEADING ANGLES AND DIRECTIONS OF PRINCIPAL
      FORCES ARE NOT COMPATIBLE (I.E., THE PRINCIPAL FORCES ARE NOT
      180° APART). CHECK INPUT DATA. ALSO, SEE USER'S MANUAL."

(8)   IF $|\delta| < 0.10$, RETURN

(9)   $\alpha_1 = \alpha_1 - \frac{\delta}{2}$  }
                                               }  PRINT MESSAGE: "ENTERED DOPF VALUES
(10)  $\alpha_2 = \alpha_2 + \frac{\delta}{2}$  }    ADJUSTED TO BE 180° APART"

(11)  RETURN TO (1)
```

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Check Cases:

	(1)	(2)	(3)	(4)	(5)	(6)
ψ_1	180	-90	270	-90	0	0
ψ_2	20	350	340	-20	225	225
α_1	0	-30	-30	-30	30	60
α_2	-30	60	90	90	0	0
1	180	-120	240	-120	30	60
2	-10	410	430	70	225	225
3	190	-530	-190	-190	-195	-165
4	-	-	-	-	-	-
5	-	-170	-	-	-	-
6	10	10	-10	-10	-15	15
7	-	-	-	-	-	-
8	-	-	-	-	-	-
9	-5	-35	-25	-25	37.5	52.5
10	-25	65	85	85	-7.5	7.5
1	175	-125	245	-115	37.5	52.5
2	-5	415	425	65	217.5	232.5
3	180	-540	-180	-180	-180.0	-180.0
4	-	-	-	-	-	-
5	-	-180	-	-	-	-
6	0	0	0	0	0	0
7	-	-	-	-	-	-
8	RETURN	RETURN	RETURN	RETURN	RETURN	RETURN
9						
10						

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Task 5.4 Rotation/Moment-Arm Compatibility Checks

With the CRASH2 program, it is possible for a careless user to enter damage data and directions of principal force (DOPF) that are not compatible with the entered directions of rotation for the spinout motions. In other words, the moment arms of the principal forces may not be in agreement with the angular accelerations indicated by the specified directions of rotation.

The present revision of CRASH2 consists of a simple test of the compatibility of the moment arms with the rotation directions. It was necessary to revise the CRASH2 procedure for calculation of the moment arm in order to retain its algebraic sign. The calculation and test procedure are presented on the following pages. Symbols are define in Appendix 1.

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The moment arm of the principal force on vehicle i may be calculated from:

$$h_i = -X_{Pi} \sin \alpha_i + Y_{Pi} \cos \alpha_i \text{ inches} \tag{1}$$

where α_i = 0° to ± 180°, as entered for the direction of the principal force, and

$\text{sgn } h_i$ = positive for clockwise angular (yaw) acceleration

The change in angular velocity of vehicle i is related to the resultant change in linear velocity of vehicle i in the following manner.

$$F_i h_i = M_i k_i^2 \ddot{\psi}_i \tag{2}$$

$$\frac{F_i}{M_i} = \frac{k_i^2}{h_i} \ddot{\psi}_i \tag{3}$$

Integration of both sides of equation (3) yields:

$$\int_0^t \frac{F_i}{M_i} dt = \frac{k_i^2}{h_i} \int \ddot{\psi}_i \, dt \tag{4}$$

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$$\Delta V_{Ri} = \frac{k_i^2}{h_i} \Delta\dot{\psi}_i \qquad (5)$$

From (5),

$$\Delta\dot{\psi}_i = \frac{h_i}{k_i^2} \Delta V_{Ri} \qquad (6)$$

Given $\dot{\psi}_{is}$ from SPIN2 and $\dot{\psi}_{io}$ from QUIZ,

$$\Delta\dot{\psi}_i = \dot{\psi}_{is} - \dot{\psi}_{io} \qquad (7)$$

$$\text{Let } K_i = \frac{(\dot{\psi}_{is} - \dot{\psi}_{io})}{(h_i/k_i^2)\Delta V_{Ri}} \qquad (8)$$

where ΔV_{Ri} is taken from DAMAGE.

Note that ΔV_{Ri} is always positive and that the test defined in the following constitutes a test only of the algebraic signs of h_i and $\Delta\dot{\psi}_i$. It would be relatively simple to extend the test to include an evaluation of the compatibility of the magnitudes of h_i and $\Delta\dot{\psi}_i$ through the use of ΔV_{Ri} from momentum calculations as well as from DAMAGE.

From equation (8), if $K_i < 0$, stop the program and print message:

"Direction of angular acceleration of vehicle i not consistent with moment arm of principal force."

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Task 5.5 Relative Velocity

The relative velocity and its components are determined by the following method; refer to Figure 13.

$\mathrm{ANGL1} = \mathrm{PSI10} - \mathrm{TAN}^{-1} (\mathrm{YC20}-\mathrm{YC10}/\mathrm{XC20}-\mathrm{XC10})$
$\mathrm{CG1} = \mathrm{U01L} * \mathrm{COS}\ (\mathrm{ANGL1})$
$\mathrm{CG1P} = \mathrm{U01L} * \mathrm{SIN}\ (\mathrm{ANGL1})$

where: ANGL1 = Slope of line through impact c.g.'s
PSI10 = V1 heading angle
(XC10,YC10) = Position of V1 at impact
(XC20,YC20) = Position of V2 at impact
U01L = Impact speed of V1
CG1 = Impact speed component resolved along c.g. line
CG1P = Impact speed component perpendicular to c.g. line

$\mathrm{ANGL2} = \mathrm{PSI20} - \mathrm{TAN}^{-1} (\mathrm{YC10}-\mathrm{YC20}/\mathrm{XC10}-\mathrm{XC20})$
$\mathrm{CG2} = \mathrm{U02L} * \mathrm{COS}\ (\mathrm{ANGL2})$
$\mathrm{CG2P} = \mathrm{U02L} * \mathrm{SIN}\ (\mathrm{ANGL2})$

where: ANGL2 = Slope of line through impact c.g.'s
PSI20 = V2 heading angle
(XC10,YC10) = Position of V1 at impact
(XC20,YC20) = Position of V2 at impact
U02L = Impact speed of V2
CG2 = Impact speed component resolved along c.g. line
CG2P = Impact speed component perpendicular to c.g. line

The closing velocity, CVEL, is determined by summing CG1 and CG2.

$\mathrm{CVEL} = \mathrm{CG1} + \mathrm{CG2}$

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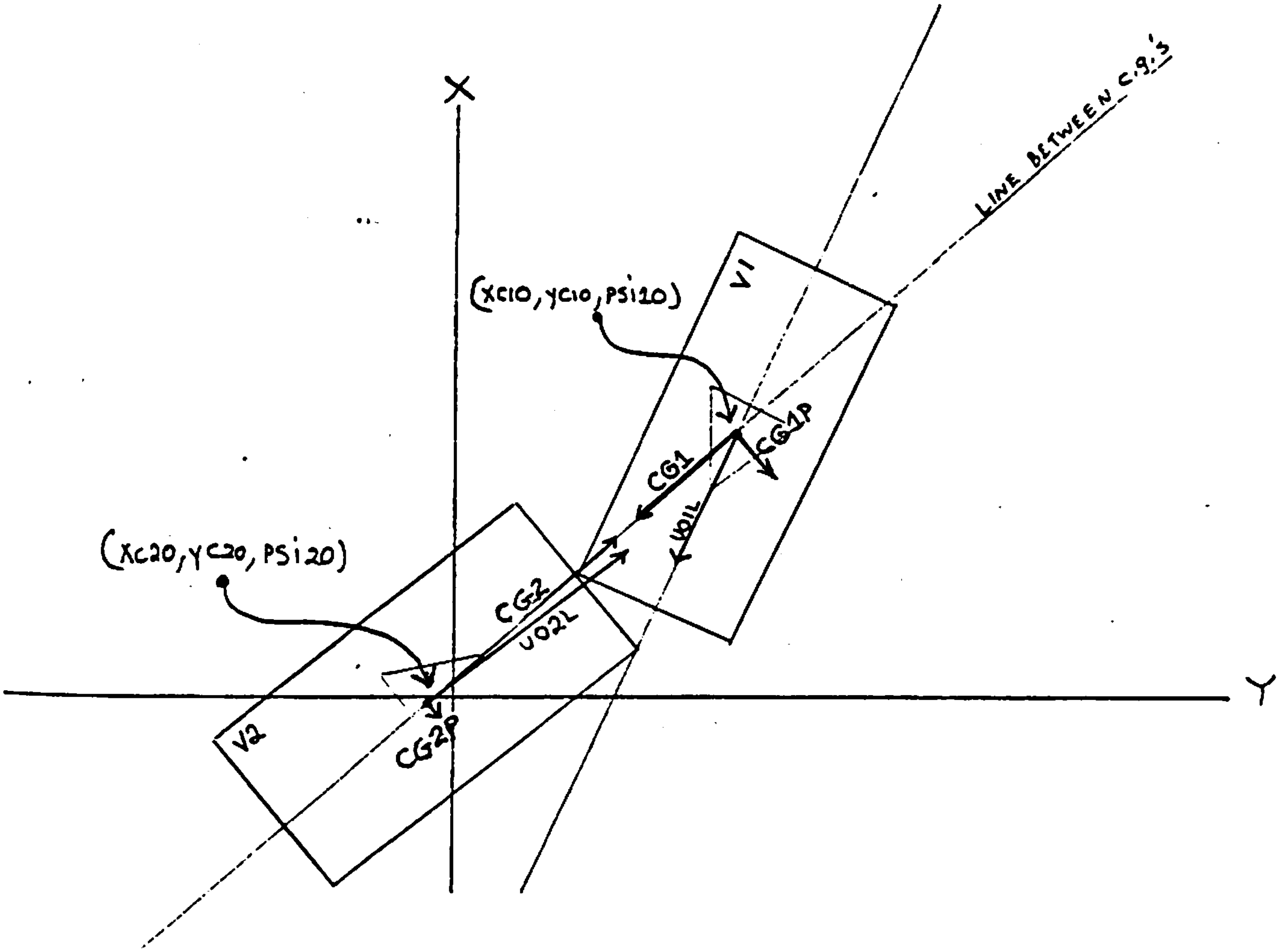
The relative velocity and associated components for impact speeds determined by angular momentum and axial methods are calculated by merely changing the V1 and V2 impact speeds in the above relationships. These changes are now incorporated in subroutine PRINT.

FIGURE 13 RELATIVE VELOCITY COMPUTATION



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Task 5.6 Spinout Error Diagnostic

In CRASH2, a test of the compatibility of user responses to questions related to the position and orientation at which rotational skidding stopped was introduced. The purpose of that test was to detect input data sets which would produce an incompatibility of the initial angular velocity and the time available for angular deceleration. In particular, the combination of rolling resistance, distance from the end of rotation to rest and tire-terrain friction coefficient establish the linear velocity at the end of rotation. Since the linear velocity at separation must be greater than or equal to that at the end of rotation, the cited user inputs determine the maximum elapsed time between separation and the end of rotation. The combination of maximum elapsed time and extent of total rotation establishes a minimum angular velocity at separation.

Within the present research task, diagnostic information has been added to the "Spinout Error" message so that the user will have a quantitative measure of extent of input incompatibility and also a summary of related system variables.

The input compatibility test (derivation presented in Reference 8) consists of the following relationship:

$$0 < \left\{ \frac{S_1}{|\Delta\psi| \left(1 + \frac{2S_{R1}}{S_1} + \frac{2\sqrt{S_{R1}(S_1 + S_{R1})}}{S_1} \right)} - \frac{4\alpha_1 k^2 \theta}{\alpha_5^2 \alpha_2 \, (a+b)} \right\}$$

Where S_1 = Linear distance between separation and end of rotation or rest, inches.

S_{R1} = Linear distance between end of rotation and rest, inches.

$|\Delta\psi|$ = Absolute value of angular displacement between separation and rest, or end of rotation, radians.

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

θ = Decimal portion of full deceleration, $0 \leq \theta \leq 1.00$

$a+b$ = Wheelbase, inches

α_i = Empirical coefficients used in the spinout trajectory portion of CRASH. Functions of the initial ratio of linear to angular velocity (Reference 3).

If the input compatibility test is failed (i.e., a negative or zero value), the numerical test value is printed out with the "Spinout Error" message. In this manner, the user has a numerical measure of the extent of input incompatibility. If estimated inputs are revised in a rerun, the numerical test value indicates the corresponding change in the extent of input incompatibility (i.e., a measure is provided of whether the input data set is better or worse than the proceding set).

To provide guidance for the program user in the case of spinout errors, the following four quantities are also printed out with the "Spinout Error" message:

$$\theta, S_1, |\Delta\psi|, S_{R1}$$

The four listed variables serve to provide a convenient input error check (e.g., an erroneous entry for the direction of rotation can produce a very large value for $|\Delta\psi|$ and a consequent failure of the compatibility test), and they also serve to summarize the results of pertinent inputs. The expanded and revised User's Manual (Part 2 of the final report on Tasks 5, 6 and 7) will include detailed instructions regarding interpretation of the diagnostic information provided with the "Spinout Error" message.

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Task 5.7 D'/D Printout

In the CRASH2 program the user-entered distance, D, for each vehicle is measured from the midpoint of the plan-view damaged region to the center of gravity along the vehicle axis that parallels the original plan-view profile of the involved side or end (i.e., along the longitudinal axis for side damage, the lateral axis for end damage). In the related CRASH2 calculations, D is adjusted by an amount equal to the distance between the midpoint and the centroid of the plan-view damaged area, taken along the same direction of measurement as D. The adjusted value of D is printed out in the "Summary of Damage Data" of CRASH2.

It has long been recognized that the printout of the adjusted D invites error in the repeat performance of a run, since an erroneous direct entry of the printout value of "D" as the midpoint dimension will result in a further adjustment equal to the midpoint to centroid distance. It also detracts from efficiency in the checking of inputs and/or the proper repeat performance of runs, since the original input value of D is not displayed in the outputs.

The present revision of CRASH2 includes the retention and printout of the user-entered values of D for the two vehicles as well as the adjusted dimensions which are designated as D' in the output summary.

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Task 5.8 Roadside Objects

Interaction with a roadside object can constitute either the primary or a secondary event in a highway accident. In CRASH applications involving roadside objects, it is necessary either (1) to represent the roadside object as a "vehicle" with appropriate mass and crush properties (primary event) or (2) to generate a virtual rest position and orientation corresponding to the vehicle velocities that existed at the point of contact with the roadside object (secondary event).

When a rigid and fixed roadside object is contacted, approximation of the corresponding speed change must be based entirely on the related damage to the vehicle. When the roadside object moves or is deformed by the collision, it is necessary to properly account for the corresponding energy absorption by the object.

In dealing with collisions with roadside objects, it is essential to recognize the fact that, while the extent of related damage to the vehicle provides a measure of the peak magnitude of the collision force, it is necessary to approximate the duration of the force in order to interpret the collision in terms of the speed change, ΔV. Thus the mass and crush resistance of a moveable obstacle must be taken into account.

It was originally planned to produce summary tables and/or graphs of representative properties of roadside objects within the present task. However, it became necessary to curtail effort on this task in view of unanticipated difficulties encountered with Task 5.1. As a result, the output of this research task will be limited to a brief appendix in the revised User's Manual (Part 2 of the Final Report) on the topic of roadside objects. A list of related references will be included.

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Task 5.9 Trajectory Analysis

The trajectory simulation option serves as a means of testing the match of rest positions and orientations and of other items of trajectory evidence that is achieved with the SPIN2 approximations of separation velocities. It includes an automatic procedure for adjusting the separation velocities, in up to five iterative steps, to achieve an acceptable overall evidence match.

User experience with the trajectory option has indicated several types of difficulties with convergence on an evidence match. The presently reported research has been aimed at (1) identifying sources of convergence problems and (2) modifying the coding to achieve a higher rate of success.

Algebraic Signs of Heading Angles

One source of difficulty that was recognized and discussed in Reference 9 was algebraic signs of the vehicle heading angles. Coding changes have been introduced to convert all user entries in the range of -360° to +360° into positive angles. Additional coding changes were incorporated to distinguish between clockwise and counterclockwise rotations in the calculation of orientation errors ε_3 and ε_4.

No Measured Rotation

In cases where the trajectory option has been activated in the absence of a heading change during the spinout, the calculation of orientation errors ε_3 and ε_4 as originally coded would involve division by zero. Coding changes were introduced to avoid the division by zero and to make a heading change of $\pm 2° = \pm 10\%$ error for the case of no measured rotation. An arbitrary error definition of this type is made necessary by the fact that the "correct" value of measured rotation is zero. A deviation from zero rotation in the trajectory simulation will yield an indeterminate "percentage" error.

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No Skidding

When the user indicates that no skidding occurred, the end of skidding (EOR) and the separation coordinates are set to be identical. As a result, the calculation of range error $\varepsilon_{2\ell}$ to the end of skidding involved division by zero. Coding changes were incorporated to avoid the division by zero and to make an EOR range error of ± 12 inches = $\pm 10\%$ for the case of no skidding. An arbitrary error definition of this type is made necessary by the fact that the "correct" value of the distance to the end of skidding is zero. A deviation from a zero value in the trajectory simulation will yield an indeterminate "percentage" error.

In the calculation of the azimuth error, $\varepsilon_{2\gamma}$, to the end of skidding, a no-skidding entry would produce an indeterminate arctan calculation. Coding changes were incorporated to avoid zero denominators in the arctan calculations and thereby, to produce a zero value for the azimuth error to the EOR, $\varepsilon_{2\gamma}$ for the case of no skidding.

End of Rotational and/or Lateral Skidding

The trajectory simulation can generate a position and heading for an end of rotational and/or lateral skidding (EOR) prior to rest whether or not the user has entered such data (i.e., the physical evidence may not have clearly indicated an EOR before rest). When no EOR data are entered, the rest position and heading are used as the EOR in CRASH2 for any related program calculations. Thus, an "evidence" data set can be created such that a match by the trajectory simulation can be achieved only if the positions and heading at EOR and rest are identical. In other words, the calculation of errors and the adjustment of separation conditions have made use of comparisons between the trajectory simulation values for the EOR and the entered position and heading at rest for the case of no EOR entries (IFLAG(JVEH)=0).

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The described situation could prevent convergence as a result of the corresponding need to achieve EOR and rest nearly simultaneously. Coding changes have been incorporated so that the calculation and application of errors related to the EOR are bypassed in the absence of a user-entered EOR.

Results of Trial Applications

The above program changes have been found to eliminate a number of convergence problems. However, the extent of effort applied to this task was curtailed as a result of unanticipated problems encountered in Task 5.1. Therefore, it is believed that additional development effort on the iterative adjustment procedure may be desirable to achieve the maximum degree of success (i.e., convergent solutions) that is possible within the existing framework of the trajectory routine.

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Task 5.10 Common Velocity Check

It has long been recognized that additional internal checks of the compatibility of the different items of user inputs would be required to achieve improved reliability of reconstruction results obtained with the CRASH2 computer program. In particular, a need for checking the independently calculated (SPIN2) values of separation velocities for the two involved vehicles for compatibility with a "common" velocity at the regions of collision contact was discussed in Reference 9. Without such a check, it is possible for a user to specify spinout distances, heading changes and wheel-rotational resistances for the individual vehicles corresponding to separation velocities that are not compatible with a common velocity at the plan-view centroids of the damaged regions.

In applications of the SPIN2 subroutine within CRASH2, the spinout motions of the two colliding vehicles are separately analyzed. In subsequent conservation of momentum relationships, it is assumed without verification that the plan-view centroids of the damaged areas of the two vehicles reached a common velocity along the direction of the principal forces (i.e., along the line-of-action of the principal forces acting on the two vehicles, Figure 14). Since the extents of drag (i.e., wheel-rotational resistances and/or side slip of tires) on the two vehicles are independently specified, it is possible to calculate and apply separation velocities that are not compatible with a common velocity at the plan-view centroids of the damaged regions.

The individual spinout calculations (SPIN2) for Vehicles 1 and 2 may be viewed as two independent approximations of the common velocity achieved by the two vehicles. Thus, the average of the two values for the common velocity should be more reliable than either individual value. In the calculation sequence depicted in Figure 15, the average of the two independently determined values for the common velocity (TEM6) along the direction of principal force (DOPF) is taken to be the most reliable value and individual errors [ERR(1), ERR(2)] are calculated in relation to TEM6.

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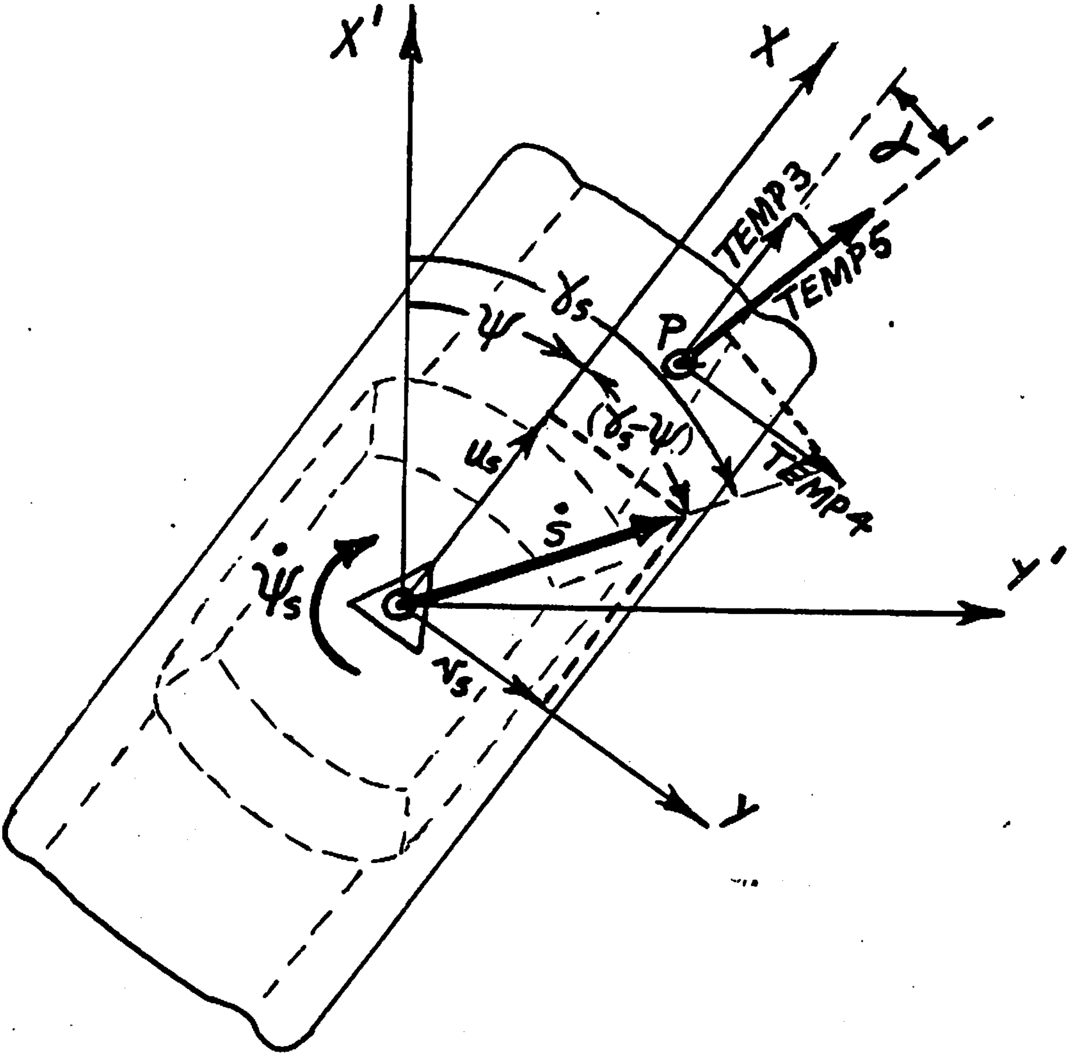
FIGURE 14 COMPONENT OF SEPARATION VELOCITY ALONG DIRECTION OF PRINCIPAL FORCE IN VEHICLE COORDINATE SYSTEM



$$u_s = \dot{S} \cos(\gamma_s - \psi)$$

$$v_s = \dot{S} \sin(\gamma_s - \psi)$$

$$TEMP3 = u_s - y_p \dot{\psi}_s$$

$$TEMP4 = v_s + x_p \dot{\psi}_s$$

$$\begin{aligned} TEMP5 &= (TEMP3)\cos\alpha + (TEMP4)\sin\alpha \\ &= \dot{S}\cos(\gamma_s - \psi - \alpha) + \dot{\psi}_s (x_p \sin\alpha - y_p \cos\alpha) \end{aligned}$$

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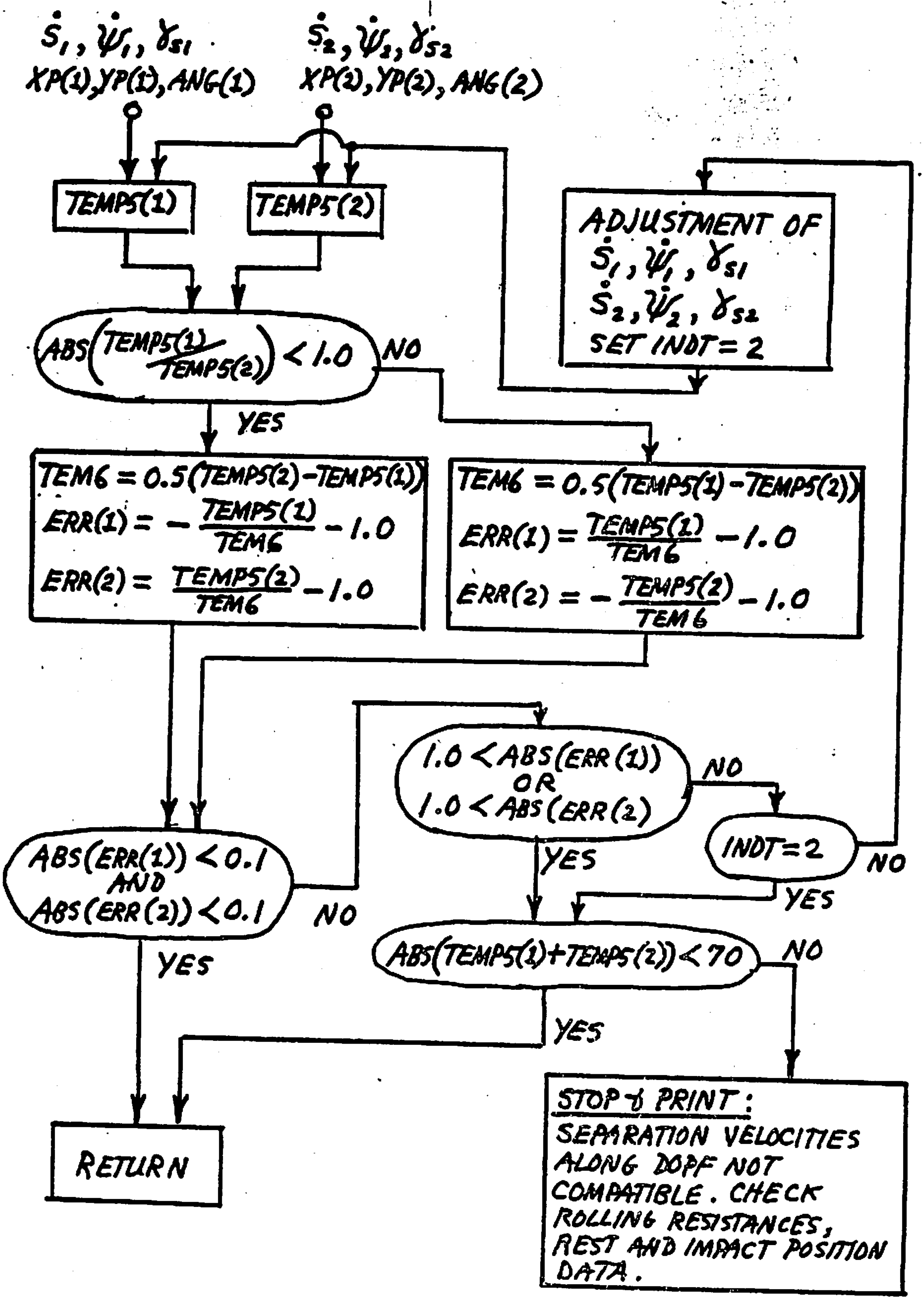
FIGURE 15 SCHEMATIC FLOW CHART OF COMMON-VELOCITY CHECK



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For errors less than ± 10% about the mean value, TEM6, or for an absolute value of the difference in velocities along the DOPF less than 4 MPH, no adjustments are made. For errors greater than ± 100% and for an absolute value of the difference in velocities along the DOPF greater than 4 MPH, the program is stopped and an error message is printed.

When the errors, ERR(1) and ERR(2) are within the range of ± 10% to ± 100%, an adjustment procedure based on the partial derivatives of TEMP5 is applied:

$$\text{TEMP5} = \dot{S}\cos(\gamma_s - \psi - \alpha) + \dot{\psi}_s (X_p \sin\alpha - y_p \cos\alpha) \tag{1}$$

$$\frac{\partial(\text{TEMP5})}{\partial\dot{S}} = \cos(\gamma_s - \psi - \alpha) \tag{2}$$

$$\frac{\partial(\text{TEMP5})}{\partial\dot{\psi}_s} = X_\rho \sin\alpha - y_\rho \cos\alpha \tag{3}$$

$$\frac{\partial(\text{TEMP5})}{\partial\gamma_s} = -\dot{S}\sin(\gamma_s - \psi - \alpha) \tag{4}$$

$$\Delta(\text{TEMP5}) = \Delta\dot{S}\,[\cos(\gamma_s-\psi-\alpha)] + \Delta\dot{\psi}_s(X_\rho \sin\alpha - y_\rho \cos\alpha) - \Delta\gamma_s\,[\dot{S}\sin(\gamma_s - \psi - \alpha)] \tag{5}$$

Adjustments of $\dot{S}$, $\dot{\psi}_s$ and γ_s are made in the indicated sequence and with limits of ± 7.5%, ± 15%, and ± 15°, respectively. Subsequent to each individual adjustment, the variable TEMP5 is compared with a target value which will achieve the ± 10% error range about TEM6. If the objective is achieved at any point within the adjustment procedure, further adjustments are bypassed.

The common-velocity check has been coded in Subroutine VELCHK. Checkout runs have been performed and the described calculation procedure is fully operational.

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3.2 Contract Task 6

This task consists of coding changes in CRASH2 that are aimed at enhancing the convenience of applications.

Task 6.1 ΔV Components

In accordance with the Work Statement, the ΔV components as well as the direction and magnitude of the resultant ΔV have been added to the "Relative Velocity Data" portion of the CRASH summary.

Task 6.2 Size and Weight Question

In accordance with the Work Statement, the entry of size categories and weights for both vehicles has been modified to involve only a single line. This change required elimination of the original vehicle size question and the three questions pertaining to vehicle weight. The replacement question is printed in its final complete form below:

```
2. ENTER CLASSIFICATIONS AND WEIGHTS FOR BOTH VEHICLES.
   SUGGESTED CLASSIFICATIONS ARE:
   1 -  80.0 TO  94.8 INCH WHEELBASE
   2 -  94.8 TO 101.6 INCH WHEELBASE
   3 - 101.6 TO 110.4 INCH WHEELBASE
   4 - 110.4 TO 117.5 INCH WHEELBASE
   5 - 117.5 TO 123.2 INCH WHEELBASE
   6 - 123.2 TO 150.0 INCH WHEELBASE
   7 - SAE MOVING BARRIER
   8 - SAE FIXED BARRIER
   9 - SPECIAL
   LEGAL WEIGHTS ARE 1500 TO 10000 LBS.
   FORMAT:  CLASS(V1)  WEIGHT (V1)  CLASS (V2)  WEIGHT (V2)
   EXAMPLE:  2  1850.  4  3750.
4    4247.0          4     4247.0
```

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The previous vehicle categories of minicar, subcompact compact et. al. have been eliminated in favor of a wheelbase identification. Classification 9 (special) is left undefined at this release to facilitate inclusion of roadside objects at a future date. To implement the combined classification/weight question, a subroutine called SIZWGT has been added to CRASH3.

Task 6.3 VDI and PDOF Question

The Work Statement also called for combining the vehicle damage index (VDI) and the principal direction of force (PDOF) for each vehicle into a single line entry. This required elimination of the two VDI questions and the two PDOF questions. They were replaced by the two questions illustrated below. Processing of these questions required inclusion of a new subroutine VDIPDF in the CRASH3 program.

```
    3.  ENTER THE VEHICLE DAMAGE INDEX AND THE DIRECTION OF PRINCIPAL FORCE
        VEHICLE #1.
        NOTE: THE VDI IS A 7 CHARACTER CODE, SEE APPENDIX 2 IN THE CRASH2
              USERS GUIDE FOR DETAILS.
              THE PDOF ENTRY ALLOWS THE USER TO SPECIFY THE DIRECTION OF
              PRINCIPAL IMPACT FORCE MORE ACCURATELY THAN THE VDI CLOCK
              DIRECTION ALLOWS. THE PDOF ENTRY IS OPTIONAL.
        FORMAT:  VDI(7 CHARACTER CODE)    PDOF(+ OR - 180 DEGREES MAX.)
        EXAMPLE:  12RFEW2   17.
01FDEW2      32.0
```

```
    4.  ENTER THE VEHICLE DAMAGE INDEX AND THE DIRECTION OF PRINCIPAL FORCE
        VEHICLE #2.
        NOTE: THE VDI IS A 7 CHARACTER CODE, SEE APPENDIX 2 IN THE CRASH2
              USERS GUIDE FOR DETAILS.
              THE PDOF ENTRY ALLOWS THE USER TO SPECIFY THE DIRECTION OF
              PRINCIPAL IMPACT FORCE MORE ACCURATELY THAN THE VDI CLOCK
              DIRECTION ALLOWS. THE PDOF ENTRY IS OPTIONAL.
        FORMAT:  VDI(7 CHARACTER CODE)    PDOF(+ OR - 180 DEGREES MAX.)
        EXAMPLE:  12AFEW3   17.
10LZEW3      -62.0
```

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Task 6.4 Rerun Modification

A modification to the rerun feature has been incorporated which provides for "topical" reruns to be made; that is, a request for a rerun with a single question to be reanswered will in effect present to the user all related questions. For example, if the user indicates a desire to change the answer to Question 10 (any pre-impact yaw velocity?) from no to yes, then Question 11 must be answered also (the actual entry of the pre-impact yaw velocity). This "topical" rerun feature has been implemented in the form of a simple table lookup procedure whereby each question number has a table of related question numbers assigned to it. The rerun processor not only presents the desired question but also all of the related questions stored in the table.

3.3 Contract Task 7

The results of this task will be presented in the revised User's Manual which will constitute Part 2 of the Final Report on Tasks 5, 6 and 7 of Contract No. DOT-HS-6-01442.

3.4 Software Modification Effort

The software development effort within this research contract involved the specifics of providing new algorithms, modification of certain aspects of the operational procedures and a general cleanup of the CRASH2 program that was long overdue. The following paragraphs document the software development effort.

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3.4.1 Technical Enhancements

Figure 16 shows a conceptual flow diagram of the CRASH3 computer program. The basic flow of the program has not changed. Subroutine OPTION presents a menu of options to the user. Assuming that the user has requested an interactive run, subroutine QUIZ presents a sequence of questions about the accident. The accident speed-changes based upon an energy calculation pertaining to the type of vehicle and extent of deformity are calculated in subroutine DAMAGE. If the user has entered trajectory measurements, then subroutine START2 determines the separation conditions and impact velocities. The completed results are displayed in a coherent format by subroutine PRINT.

Subroutine DAMAGE, flowcharted in Figure 17, has undergone some minor modifications. These changes include simplified calculation of the moment arm of the principal force, calculation of the center-of-gravity location of the two vehicle system for use in angular momentum computations and retention of the centroid-modified and unmodified versions of the damage midpoint offset.

The separation velocity and impact velocity computations are performed in subroutine START2, flowcharted in Figure 18, and within associated routines. There have been major coding modifications to subroutine START2. These changes include addition of an angular momentum computation of impact speeds (modification to subroutine OBLIQE) and an automatic adjustment of the side slip angles and the principal directions of force (PDOF) as described earlier in this report. Several new error messages have been installed in START2 for later display in the printout. Subroutine OBLIQE, which originally determined only the linear momentum solution, has now been completely reworked to provide both a linear and an angular momentum solution.

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FIGURE 16 CONCEPTUAL FLOW CHART FOR TYPICAL CRASH3 RUN

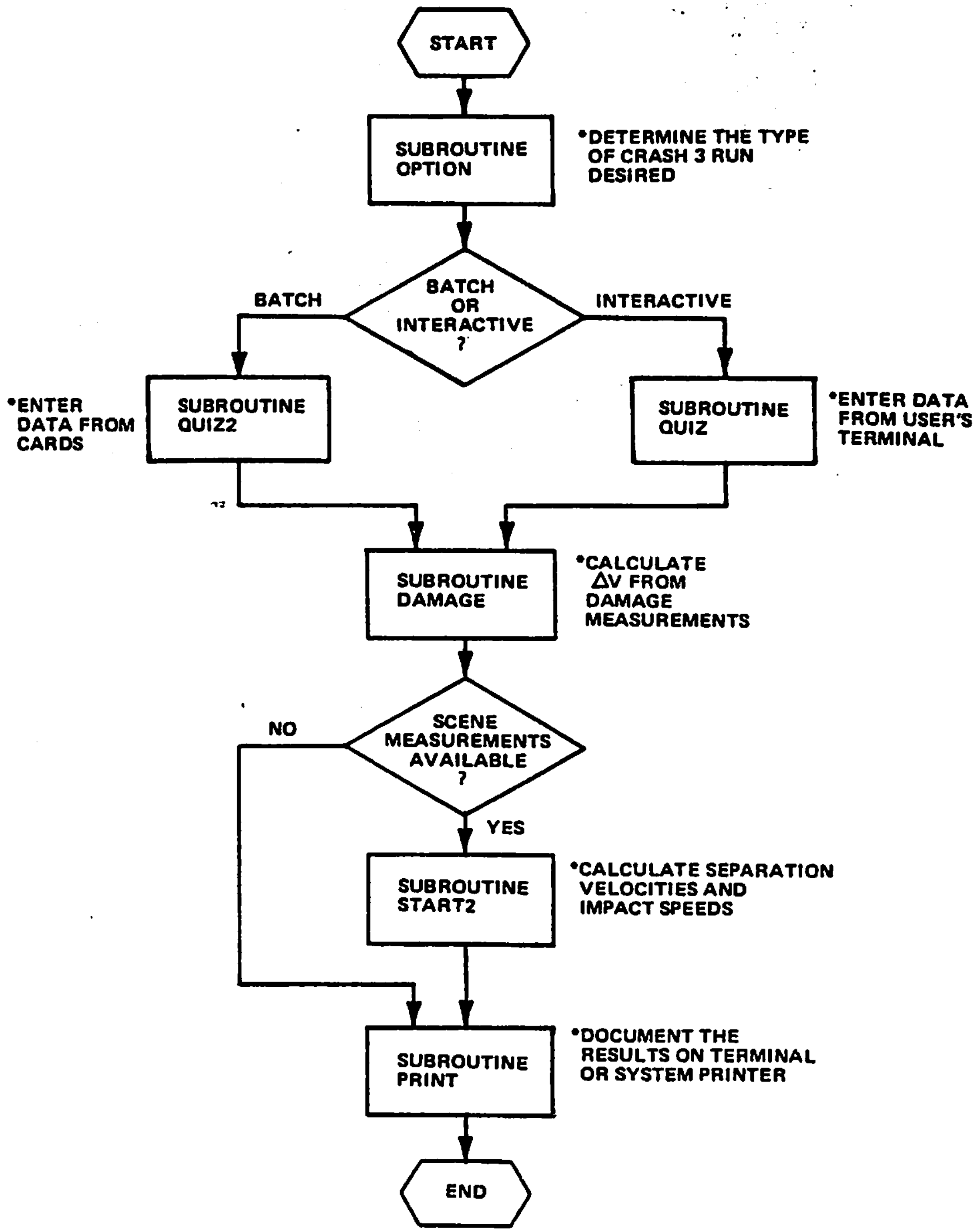

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FIGURE 17 FLOW CHART FOR SUBROUTINE DAMAGE

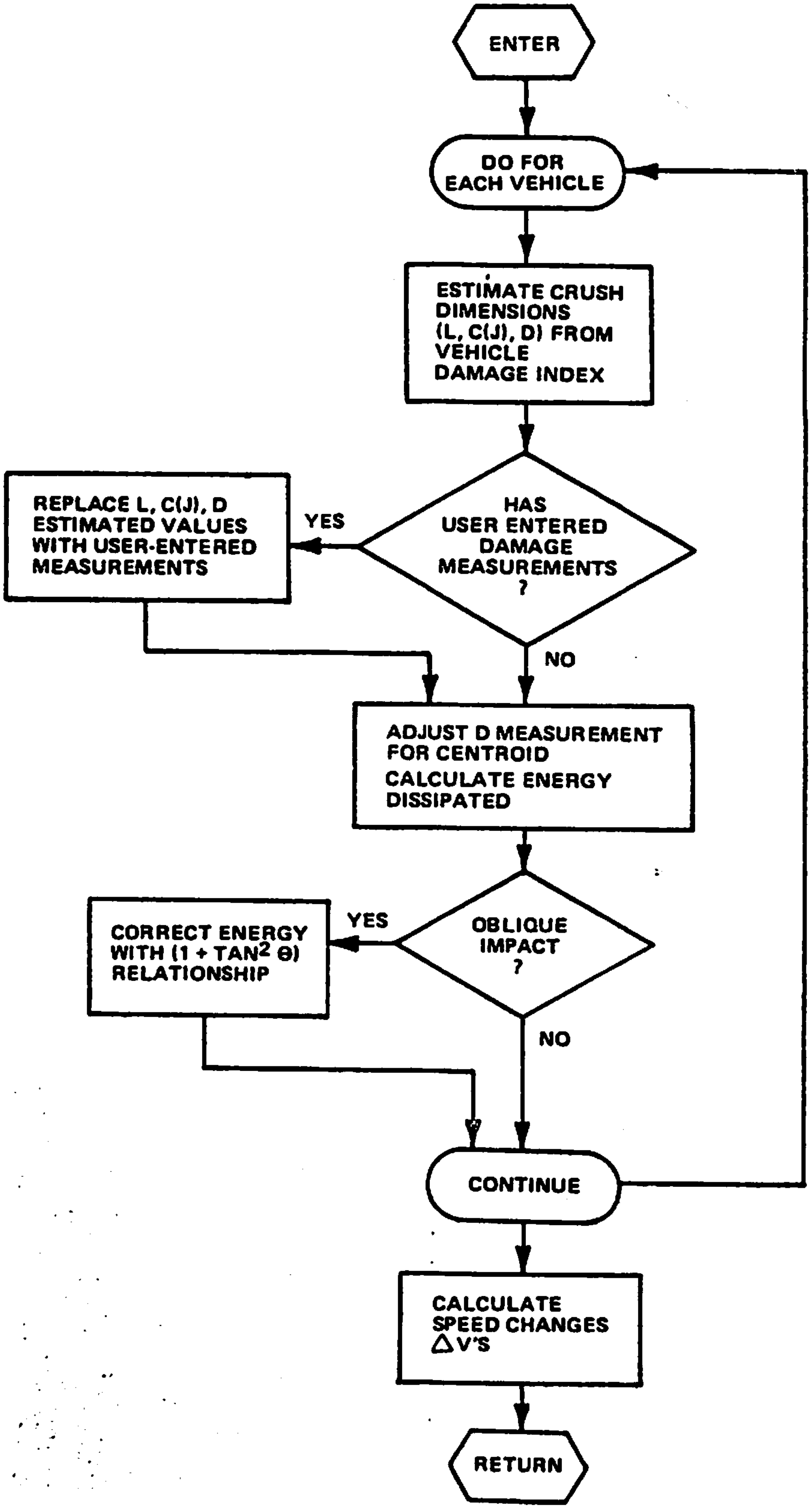

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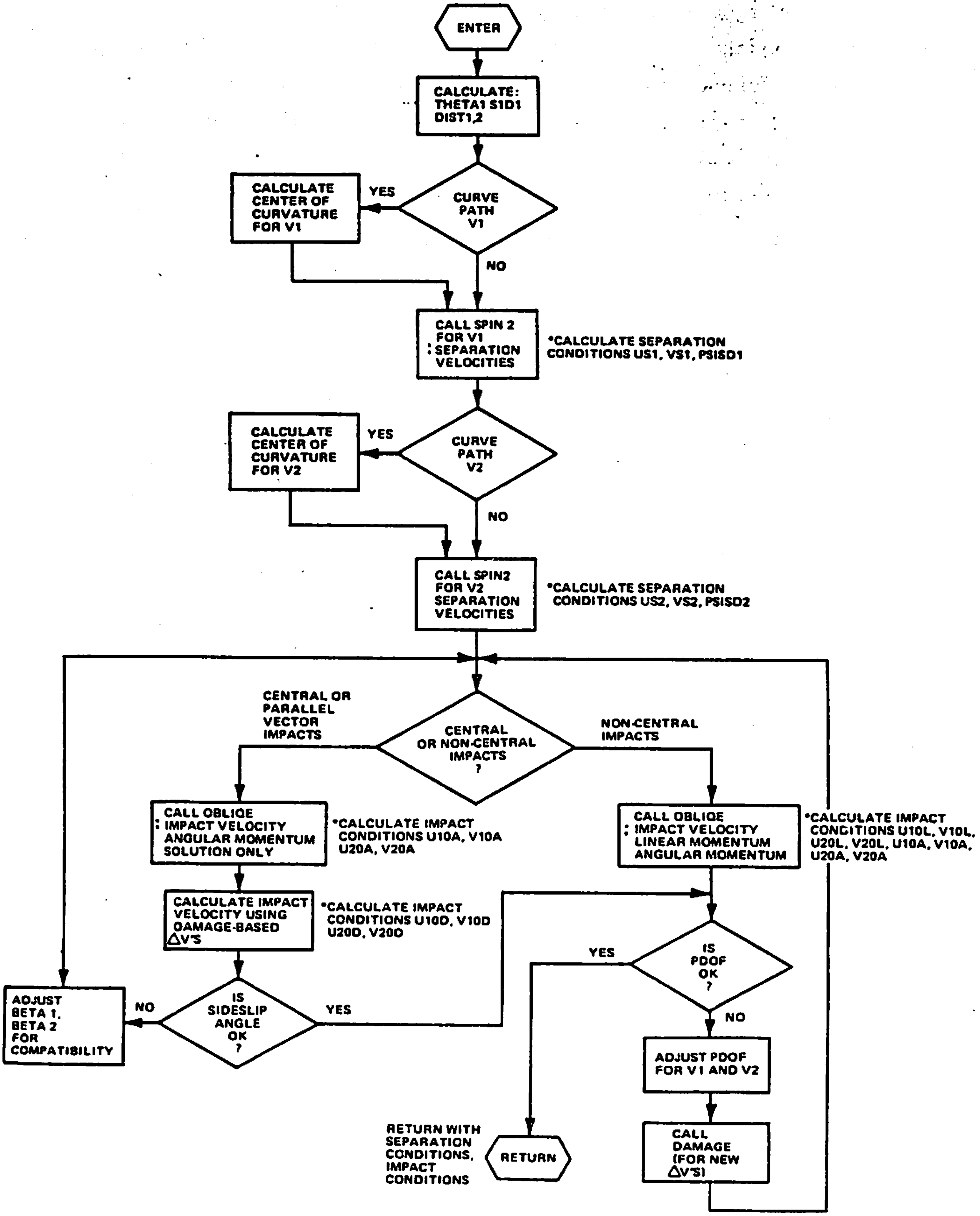
FIGURE 18 FLOW CHART FOR SUBROUTINE START2



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The routine that calculates the separation velocities, subroutine SPIN2, has undergone extensive modification as outlined in Figure 19. While the SPIN2 algorithm is essentially unchanged, a new subroutine VELCHK has been added to insure that a common velocity has been achieved at the regions of collision contact on the two vehicles. Also, a set of tests and calculations have been included to handle the sustained contact case. These changes should greatly extend the applicatibility of the CRASH3 program to real-world cases.

The trajectory simulation package has been improved to remove some known bugs in the original implementation. Several of the error tests have been modified to make convergence more likely. The main control subroutine in the trajectory simulation package, subroutine USMAC, is flowcharted in Figure 20.

3.4.2 Changes in Interactive Questions

In addition to the changes described under Tasks 6.2, 6.3 and 6.4, two additional questions have been added; they are the side slip angle entry and the pre-impact yaw velocity entry. The purpose of these questions is to extend the useful applications of CRASH3 to include collisions where the impacting vehicles are rotating or sliding obliquely just prior to collision. The added questions are shown below; adding these new input data items had a rippling effect throughout the program as all collision statements had to be amended in CRASH3.

```
     8. DID EITHER OR BOTH VEHICLES HAVE A SIDE SLIP ANGLE PRIOR TO IMPACT?
        NOTE: SIDE SLIP IS A DIRECTION OF MOTION THAT IS NOT STRAIGHT AHEAD
              (ANSWER YES OR NO)

     9. ENTER THE SIDE SLIP ANGLE FOR VEHICLE 1 AND VEHICLE 2.
        NOTE: ENTRY IN + OR - DEGREES FROM STRAIGHT AHEAD
        FORMAT:  BETA1     BETA2   (DEG.)
    0.0    0.0

    10. DID EITHER OR BOTH VEHICLES HAVE A YAWING VELOCITY PRIOR
        COLLISION?     (ANSWER YES OR NO)
    YES
```

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FIGURE 19 FLOW CHART FOR SUBROUTINE SPIN2

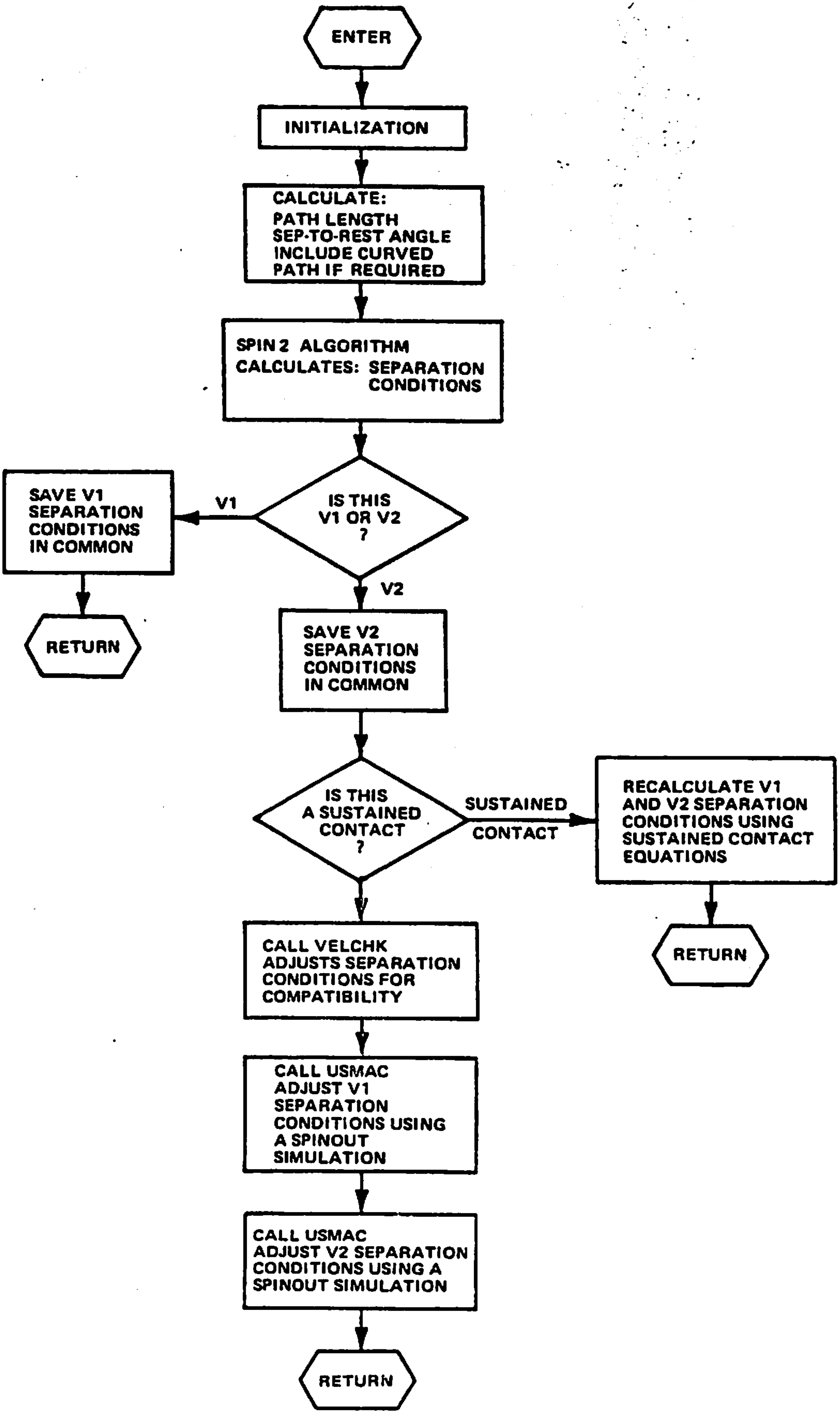

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FIGURE 20a FLOW CHART OF SUBROUTINE USMAC

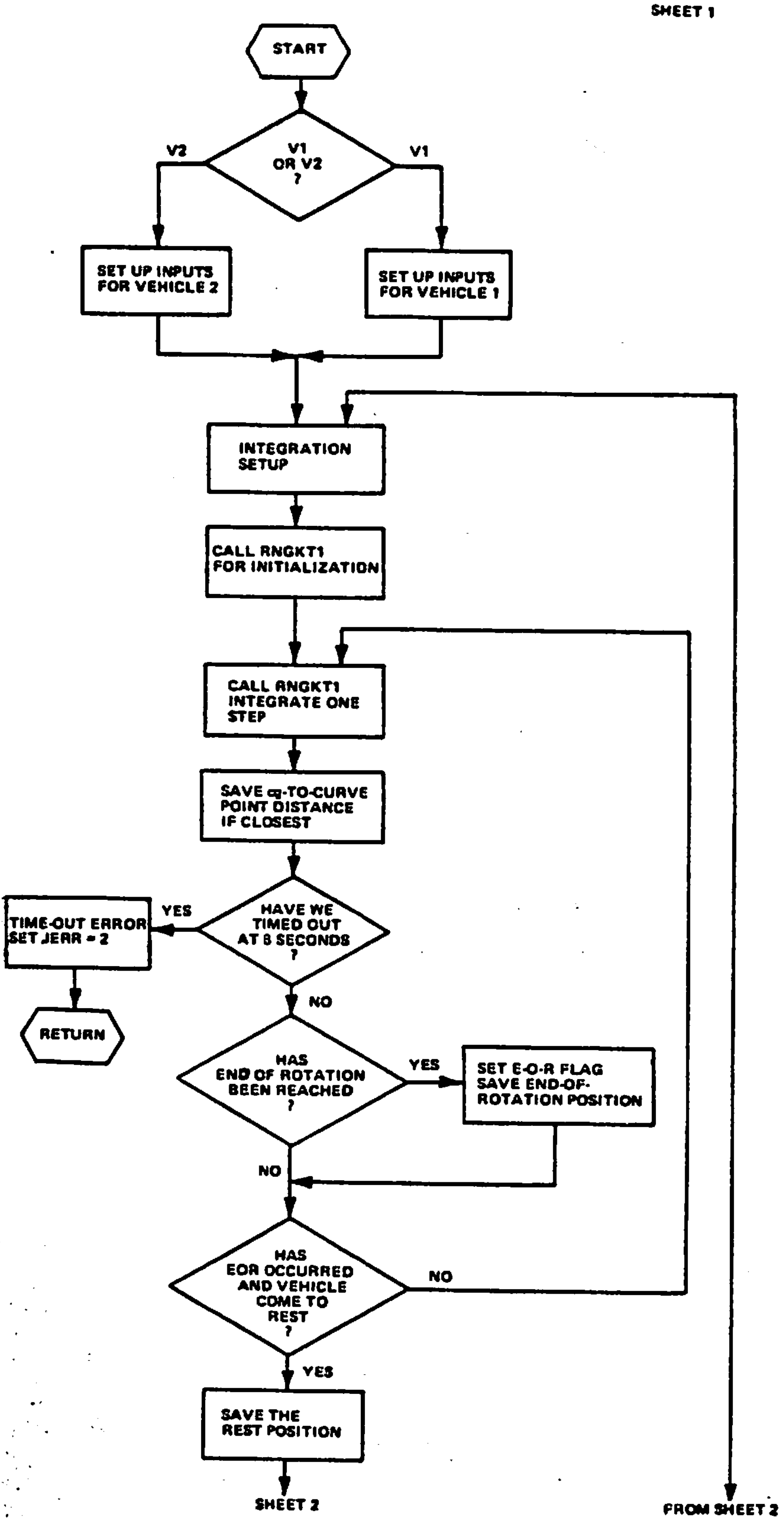

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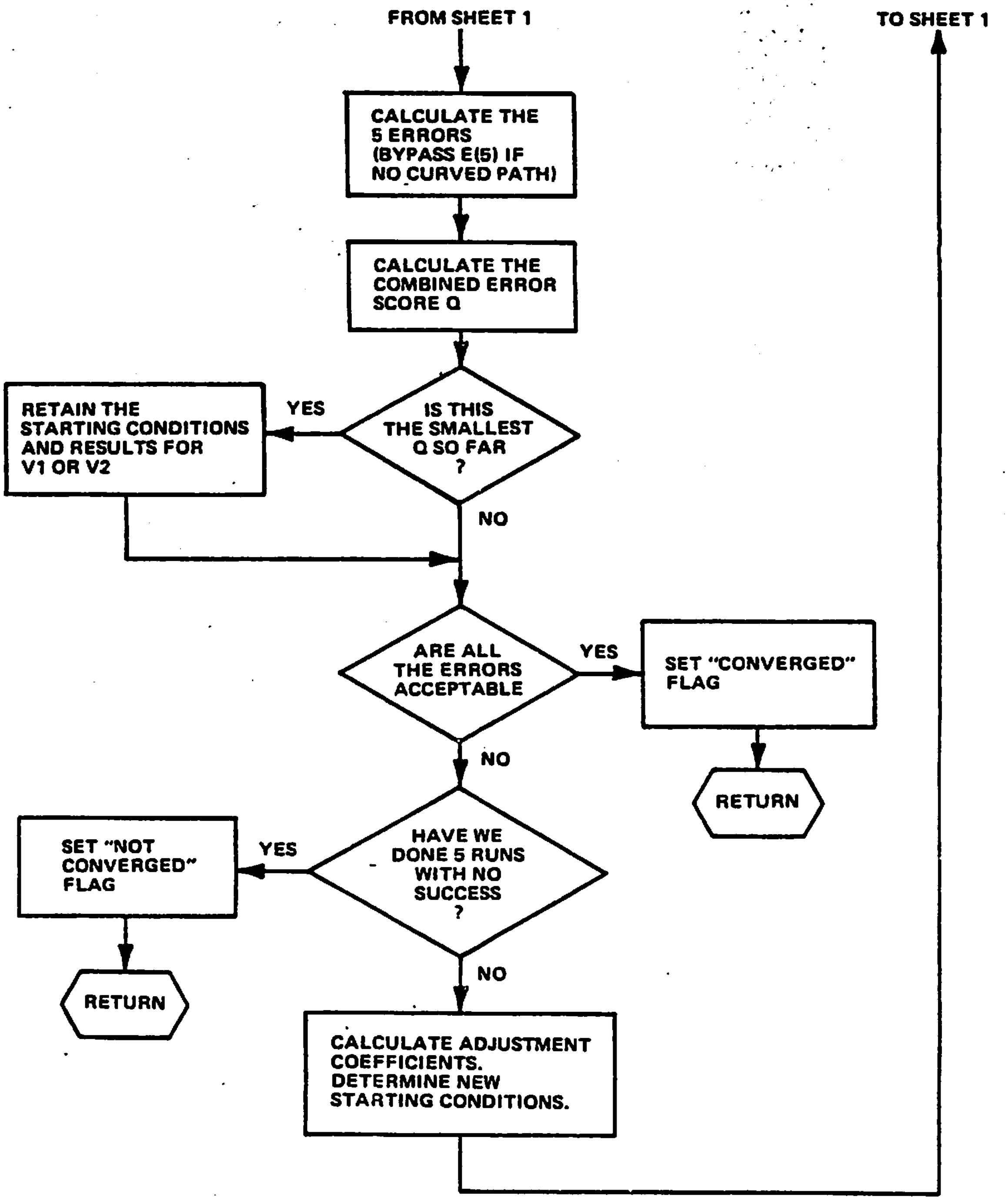
FIGURE 20b FLOW CHART OF SUBROUTINE USMAC

SHEET 2



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```
11,  ENTER THE PRE-IMPACT YAW VELOCITIES IN DEG/SEC FOR VEHICLES 1 AND 2
     EXAMPLE:    0.     125. (DEG/SEC)
0.0      0.0
```

A section of code has been added to the interactive QUIZ routine which which determines if the user-entered principal direction of force is compatible with the entered impact heading angles. If the angles are not compatible, a disgnostic message is displayed and the VDI/PDF question is resubmitted. Questions 10 and 11 will be bypassed in the QUIZ routine until completion of the development and checkout of the angular momentum algorithm.

3.4.3 General Coding Improvements

The CRASH program has been developed over the last three years as a series of small developmental efforts. As a result of this situation, the condition of the coding reflected the iterative process of development. The FORTRAN statement numbers were not in a coherent sequence (this only affects the readability however), variable names were not consistent and many subroutines manipulated data in various units, hence the appearance of many feet-to-inches conversions. To clean up the program, several efforts that were not part of the contract were done. This cleanup included passing the source programs through a Calspan-developed "Renumber" program that made the FORTRAN statement numbers sequential with an increment of ten. This makes a dramatic improvement in the readability of the program. To make conversions consistent, all calculations are done in inches/radians and this standard has been applied to every subroutine and every COMMON statement. The amount of comments has been increased which also improves readability. Most of the subroutines have an extensive heading which includes a table and definition of all variable names used in that routine.

An additional user option, DOCUMENT, has been provided which allows the user employing a cathode ray tube (CRT) terminal to route a copy of the CRASH3 printout to a system printer or master report file. The described changes are considered to be sensible and appropriate for a program of this size and number of users.

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4. REFERENCES

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APPENDIX 1

DEFINITIONS OF SYMBOLS

The subnumbers 1 and 2 are used herein to designate variables corresponding to vehicles 1 and 2, respectively. The subletters 0 and S are used to indicate the values of the variables that exist at initial contact (0) and at separation (S). Note that changes in the positions and orientations of the two vehicles between the times of initial contact and separation are presently neglected in the CRASH calculations.

A = Linear momentum of the two-vehicle system in the X' direction at time of vehicle separation, lb sec.

B = Linear momentum of the two-vehicle system in the Y' direction at time of vehicle separation, lb sec.

C = Angular momentum of the two-vehicle system about the space-fixed reference point, P'_M, at time of vehicle separation, lb in sec.

C' = Angular momentum of the two-vehicle system about the space-fixed reference point, P'_M, less that portion corresponding to the initial yawing velocities ($\dot{\psi}_{10}$, $\dot{\psi}_{20}$), lb in sec.

C_T = Cornering stiffness of vehicle tires (all four combined) for small slip angles, lbs/radian.

DRAG1, DRAG2 = Ratio of resultant motion-resisting force in skids to product of vehicle weight and tire-terrain friction coefficient.

D = Distance from the center of the damaged region to the vehicle center of gravity, measured along the vehicle-fixed X axis for side impacts on the vehicle-fixed Y axis for end impacts, inches.

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D' = Distance from the plan-view centroid of the damaged region to the vehicle center of gravity, measured along the vehicle-fixed X axis for side impacts or the vehicle-fixed Y axis for end impacts, inches.

F_s = Resultant drag force opposing vehicle motion in non-rotating separation trajectories, lbs.

F_i = Principal force that acts on vehicle i, lbs.

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

h_i = Moment arm of the principal force that acts on vehicle i, positive for clockwise angular (yawing) acceleration of vehicle i, inches.

k_i^2 = Radius of gyration squared for complete vehicle i in yaw, in^2.

K_i = Test ratio for evaluation of the compatibility of vehicle rotational acceleration and the moment arm of the principal force.

M_1, M_2 = Complete-vehicle masses of vehicles 1 and 2, respectively, lb-sec^2/in.

MU = Nominal tire-terrain friction coefficient.

P'_M = Space-fixed point corresponding to location of two-vehicle system center of gravity at instant of collision contact, defined by coordinates X'_M, Y'_M, inches.

Q_A, Q_B = Terms in denominators of angular momentum relationships defining vehicle velocities, lb^{2}sec^4/in.

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QUIZ = Input subroutine of CRASH computer program.

S11, S12 = Distance between vehicle center of gravity position at separation and at end of skidding (i.e., lateral and/or rotational [yaw]), inches

$\dot{S}_{11}$, $\dot{S}_{12}$ = Residual linear velocity of vehicle at end of skidding (i.e., lateral and/or rotational [yaw]), inches/second.

SPIN2 = Trajectory analysis subroutine of the CRASH computer program.

U_i = Longitudinal component of linear velocity of vehicle i, taken along vehicle-fixed X axis, inches/sec.

V_i = Lateral component of linear velocity of vehicle i, taken along vehicle-fixed Y axis, inches/sec.

ΔV_{Ri} = Magnitude of resultant velocity change of vehicle i, inches/sec.

$(VEL)_i$ = Magnitude of resultant velocity vector of vehicle i at time of initial contact between vehicles, inches/sec.

W = Total vehicle weight, lbs.

X', Y' = Space-fixed coordinates of the center of gravity of vehicle, inches.

X'_M, Y'_M = Space-fixed coordinates of point P'_M corresponding to location of two-vehicle system center of gravity at instant of collision contact, inches.

X_{Pi}, Y_{Pi} = Vehicle-fixed coordinates of the centroid of the plan-view damaged region of vehicle i, inches.

X'_{Pi}, Y'_{Pi} = Space-fixed coordinates of the centroid of the plan-view damaged region of vehicle i, inches.

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X'_{Ci}, Y'_{Ci} = Spaced-fixed coordinates of the center of gravity of vehicle i, inches.

X_i, Y_i = Vehicle-fixed coordinates of points on vehicle i, inches.

X'_i, Y'_i = Space-fixed coordinates of points on vehicle i, inches.

X_F, X_R = 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 is entered as a negative quantity).

Y_S = 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.

α_i = Direction from which the principal force acts on vehicle i, measured in the range of ± 3.142 from the straight-ahead direction, radians.

β_i = Initial side slip angle of vehicle i, radians.

γ_i = Direction of resultant velocity vector of vehicle i at separation, measured clockwise (+) from the space-fixed X' axis, radians.

θ = Decimal portion of full longitudinal deceleration produced by rotational resistance (i.e., braking and/or damage at wheels, $0 \leq \theta \leq 1.00$.

μ = Nominal tire-terrain friction coefficient.

ψ_i = Heading angle of vehicle i, measured clockwise (+) from the space-fixed X' axis, radians.

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$\Delta\psi_i$ = Change in heading angle of vehicle i between the times of separation and of the end of rotational skidding, measured clockwise (+), radians.

$\dot{\psi}_i$ = Angular velocity of vehicle i about a vertical axis through the center of gravity (i.e., yaw velocity), radians/second.

$\Delta\dot{\psi}_i$ = Change in angular velocity (yaw) of vehicle i, radians/sec.

$\ddot{\psi}_i$ = Angular acceleration (yaw) of vehicle i, radians/sec^2.

The following seven variable definitions apply only to Section 5.10 of this report (Subroutine VELCHK).

TEMP1 = Distance from vehicle center of gravity to the centroid of the plan-view damage area, measured along the vehicle-fixed Y axis for side impacts or the vehicle-fixed X axis for end impacts, inches.

TEMP2 = Distance from the center to the centroid of the plan-view damage region, measured along the vehicle-fixed X axis for side impacts or the vehicle-fixed Y axis for end impacts, inches.

TEMP3 = Longitudinal components (vehicle coordinate system) of separation velocity at centroid of plan-view damaged region, inches/sec.

TEMP4 = Lateral component (vehicle coordinate system) of separation velocity at centroid of plan-view damaged region, inches/sec.

TEMP5 = Component of separation velocity along direction of principal force in vehicle coordinate system, inches/sec.

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TEM6 = Average of the independently determined values for the common velocity along the directions of principal force for vehicles 1 and 2, inches/sec.

ERR(1), ERR(2) = Errors in velocity components along directions of principal force with respect to average value, TEMP6, expressed as decimal fractions.

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APPENDIX 2

CONSERVATION OF LINEAR AND ANGULAR MOMENTUM WITH INITIAL SIDE SLIP ANGLES

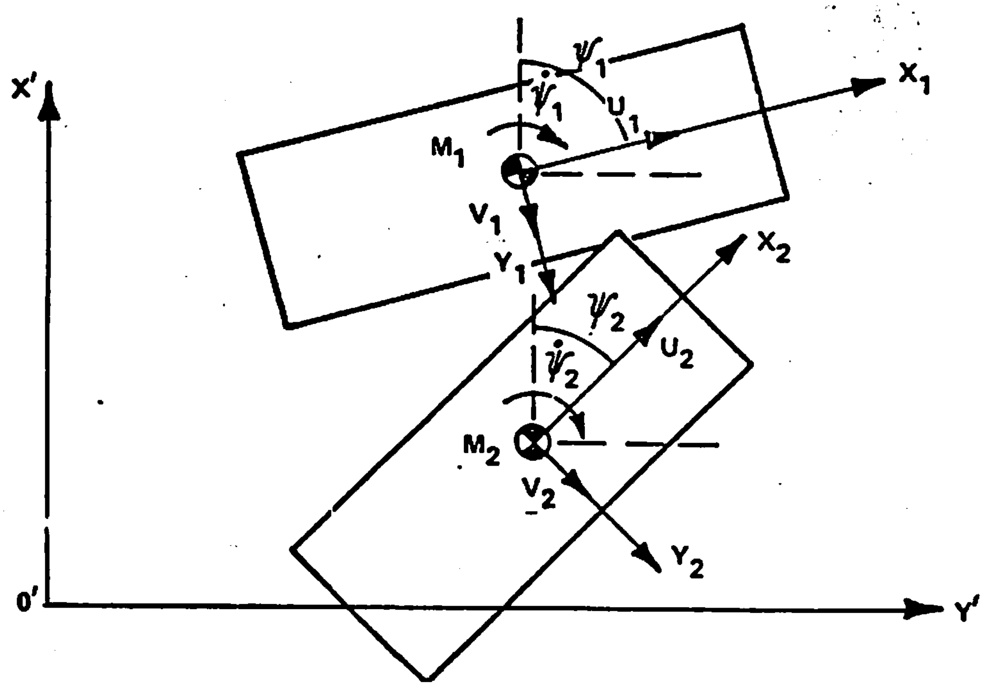

FIGURE A1 TWO-BODY SYSTEM REPRESENTING PLANE-MOTION VEHICLE COLLISION

(1) Momentum Relationships

From conservation of linear momentum, the following equations may be written for the system depicted in Figure A1. The subletters 0 and S are used herein to denote the values of the variables that exist at initial contact (0) and at separation (S). Symbols are defined in Appendix 1.

$$M_1 (U_{10} \cos \psi_{10} - V_{10} \sin \psi_{10}) + M_2 (U_{20} \cos \psi_{20} - V_{20} \sin \psi_{20})$$
$$= M_1 (U_{1S} \cos \psi_{1S} - V_{1S} \sin \psi_{1S}) + M_2 (U_{2S} \cos \psi_{2S} - V_{2S} \sin \psi_{2S}) \qquad (1)$$

$$M_1 (U_{10} \sin \psi_{10} + V_{10} \cos \psi_{10}) + M_2 (U_{20} \sin \psi_{20} + V_{20} \cos \psi_{20})$$
$$= M_1 (U_{1S} \sin \psi_{1S} + V_{1S} \cos \psi_{1S}) + M_2 (U_{2S} \sin \psi_{2S} + V_{2S} \cos \psi_{2S}) \qquad (2)$$

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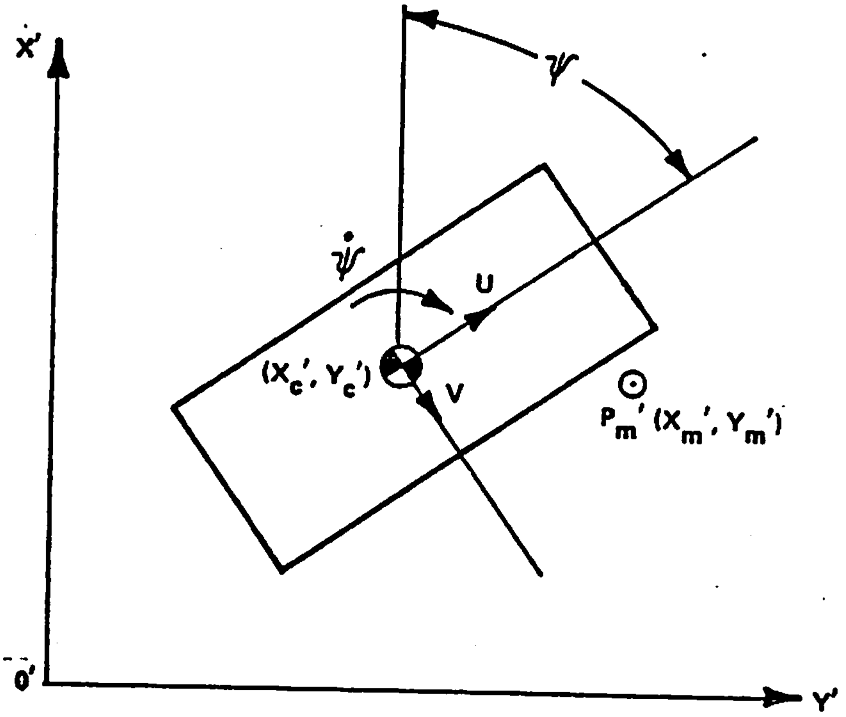
FIGURE A2 SCHEMATIC SKETCH OF REFERENCE POINTS USED IN ANGULAR MOMENTUM CALCULATIONS



Angular momentum about the space-fixed point, P'_M (X'_M, Y'_M) shown in Figure A2 may be expressed:

$$M\,[(U \cos \psi - V \sin \psi)(Y'_M - Y'_C) - (V \cos \psi + U \sin \psi)(X'_M - X'_C) + k^2 \dot{\psi}] \quad (3)$$

In the CRASH program, the separation velocities, U_{1S}, V_{1S}, $\dot{\psi}_{1S}$, U_{2S}, V_{2S}, $\dot{\psi}_{2S}$, are obtained from SPIN2.

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$$\text{Let } A = M_1 \left(U_{1S} \cos \psi_1 - V_{1S} \sin \psi_1\right) + M_2 \left(U_{2S} \cos \psi_2 - V_{2S} \sin \psi_2\right) \tag{4}$$

$$B = M_1 \left(U_{1S} \sin \psi_1 + V_{1S} \cos \psi_1\right) + M_2 \left(U_{2S} \sin \psi_2 + V_{2S} \cos \psi_2\right) \tag{5}$$

$$\begin{aligned} C = M_1 \Big[&(U_{1S} \cos \psi_1 - V_{1S} \sin \psi_1)(Y'_M - Y'_{C1}) - (V_{1S} \cos \psi_1 + U_{1S} \sin \psi_1) \\ &(X'_M - X'_{C1}) + k_1^2 \dot{\psi}_{1S}\Big] + M_2 \Big[(U_{2S} \cos \psi_2 - V_{2S} \sin \psi_2)(Y'_M - Y'_{C2}) \\ &- (V_{2S} \cos \psi_2 + U_{2S} \sin \psi_2)(X'_M - X'_{C2}) + k_2^2 \dot{\psi}_{2S}\Big] \end{aligned} \tag{6}$$

$$(\text{VEL})_1 = \sqrt{U_{10}^2 + V_{10}^2} \tag{7}$$

$$(\text{VEL})_2 = \sqrt{U_{20}^2 + V_{20}^2} \tag{8}$$

From (7) and (8),

$$U_{10} = (\text{VEL})_1 \cos \beta_1 \tag{9}$$

$$V_{10} = (\text{VEL})_1 \sin \beta_1 \tag{10}$$

$$U_{20} = (\text{VEL})_2 \cos \beta_2 \tag{11}$$

$$V_{20} = (\text{VEL})_2 \sin \beta_2 \tag{12}$$

where β_1 = initial side slip angle of vehicle 1,

β_2 = initial side slip angle of vehicle 2.

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Application of the relationships defined by equations (1) through (12) yields the following:

$$M_1(VEL)_1\cos(\psi_1+\beta_1) + M_2(VEL)_2\cos(\psi_2+\beta_2) = A \qquad (13)$$

$$M_1(VEL)_1\sin(\psi_1+\beta_1) + M_2(VEL)_2\sin(\psi_2+\beta_2) = B \qquad (14)$$

$$\begin{aligned} &M_1(VEL)_1\ [(Y'_M-Y'_{C1})\cos(\psi_1+\beta_1) - (X'_M-X'_{C1})\sin(\psi_1+\beta_1)] \\ &\quad + M_2(VEL)_2[(Y'_M-Y'_{C2})\cos(\psi_2+\beta_2) - (X'_M-X'_{C2})\sin(\psi_2+\beta_2)] \\ &\quad + M_1k_1^2\ \dot{\psi}_{10} + M_2\ k_2^2\ \dot{\psi}_{20} = C \end{aligned} \qquad (15)$$

$$\text{Let } C' = C - M_1\ k_1^2\ \dot{\psi}_{10} - M_2\ k_2^2\ \dot{\psi}_{20} \qquad (16)$$

Simultaneous solution of equations (13) and (14) yields:

$$(VEL)_1 = \frac{A\sin(\psi_2+\beta_2) - B\cdot\cos(\psi_2+\beta_2)}{M_1\sin(\psi_2+\beta_2-\psi_1-\beta_1)} \qquad (17)$$

$$(VEL)_2 = \frac{B\cos(\psi_1+\beta_1) - A\sin(\psi_1+\beta_1)}{M_2\sin(\psi_2+\beta_2-\psi_1-\beta_1)} \qquad (18)$$

Simultaneous solution of equations (13) and (15) yields:

$$(VEL)_1 = \frac{A[(Y'_M-Y'_{C2})\cos(\psi_2+\beta_2)-(X'_M-X'_{C2})\sin(\psi_2+\beta_2)]-C'\cos(\psi_2+\beta_2)}{Q_A/M_2} \qquad (19)$$

$$(VEL)_2 = \frac{-A[(Y'_M-Y'_{C1})\cos(\psi_1+\beta_1)-(X'_M-X'_{C1})\sin(\psi_1+\beta_1)]+C'\cos(\psi_1+\beta_1)}{Q_A/M_1} \qquad (20)$$

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where

$$Q_A = M_1M_2\Big\{(Y'_{C1}-Y'_{C2})\cos(\psi_1+\beta_1)\cos(\psi_2+\beta_2) + X'_M\sin(\psi_1+\beta_1-\psi_2-\beta_2)$$
$$+ X'_{C2}\cos(\psi_1+\beta_1)\sin(\psi_2+\beta_2) - X'_{C1}\cos(\psi_2+\beta_2)\sin(\psi_1+\beta_1)\Big\} \quad (21)$$

Simultaneous solution of (14) and (15) yields:

$$(VEL)_1 = \frac{B[(Y'_M-Y'_{C2})\cos(\Psi_2+\beta_2)-(X'_M-X'_{C2})\sin(\psi_2+\beta_2)]-C'\sin(\Psi_2+\beta_2)}{Q_B/M_2} \quad (22)$$

$$(VEL)_2 = \frac{-B[(Y'_M-Y'_{C1})\cos(\Psi_1+\beta_1)-(X'_M-X'_{C1})\sin(\Psi_1+\beta_1)]+C'\sin(\Psi_1+\beta_1)}{Q_B/M_1} \quad (23)$$

where

$$Q_B = M_1M_2\Big\{(X'_{C2}-X'_{C1})\sin(\Psi_1+\beta_1)\sin(\Psi_2+\beta_2)+Y'_M\sin(\Psi_1+\beta_1-\Psi_2-\beta_2)$$
$$-Y'_{C2}\sin(\Psi_1+\beta_1)\cos(\Psi_2+\beta_2)+Y'_{C1}\cos(\Psi_1+\beta_1)\sin(\Psi_2+\beta_2)\Big\} \quad (24)$$

The velocity components are obtained from equations (9) through (12).

Obviously, equations (19) and (20) cannot be applied when the value of the denominator term, Q_A, approaches zero. Neither can equations (22) and (23) be applied when Q_B approaches zero. The Q values for several impact configurations are displayed in Figure A3. It may be seen in Figure A3 that angular momentum relationships cannot be applied to central impact configurations. Also, in cases with parallel initial velocity vectors, the selection of appropriate equations from (19), (20), (22) and (23) must be based on the initial directions of motion with respect to the space-fixed coordinate system.

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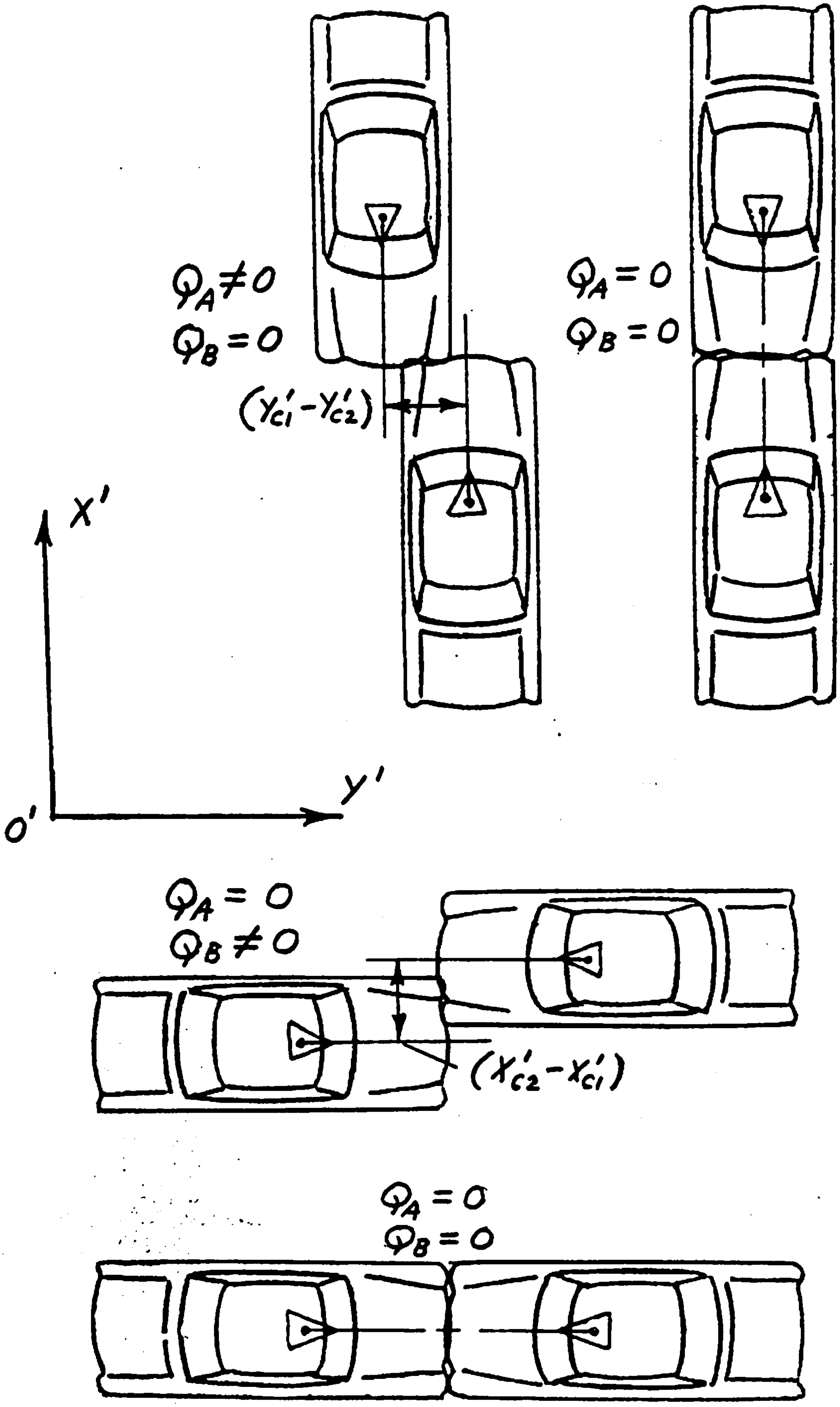
FIGURE A3 Q VALUES FOR SEVERAL IMPACT CONFIGURATIONS



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Another consideration with regard to the selection of appropriate equations for $(VEL)_1$ and $(VEL)_2$, in the general case, is the coefficient of C' in the numerator. A zero coefficient for C' eliminates the angular momentum term from the analytical relationship. In effect, a zero coefficient for C' reduces the resulting equation to a relationship involving only linear momentum. In Figure A4, a sample application is displayed to illustrate the described effect.

The physical sense of the momentum equation selections should be recognized. First, the linear momentum equations, (17) and (18), cannot be applied to cases in which the initial velocity vectors are near parallel (i.e., denominators approaching zero). Clearly, the contributions of the individual vehicles to the total linear momentum of a two-vehicle system cannot be distinguished in such cases.

For the case of nearly parallel initial velocity vectors that are not colinear, angular momentum relationships may be applied. However, the appropriate analytical relationships must be selected from (19), (20), (22) and (23). In such cases, the total angular momentum of the system is defined in terms of the resultant linear momentum. The component of system linear momentum that is perpendicular to the initial (near parallel) velocity vectors is close to zero. Therefore, a solution form involving that component of the system linear momentum tends to be indeterminate.

In the case of the perpendicular impact shown in Figure A4, the total linear momentum of the system in the X' direction is equal to the initial linear momentum of Vehicle #1. Therefore, these two quantities cannot serve to provide an angular momentum solution for the initial velocity of Vehicle #1

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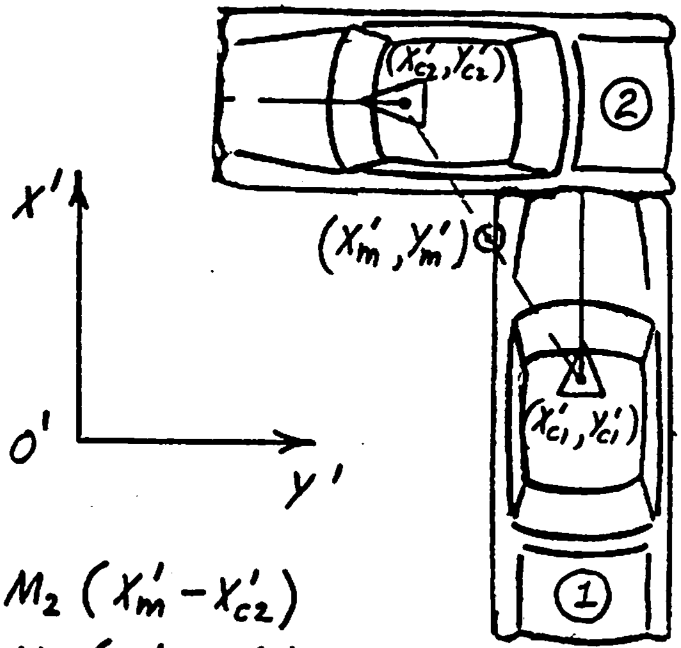
FIGURE A4 SAMPLE APPLICATION



$$\Psi_1 = 0$$
$$\Psi_2 = -90^\circ$$

$$Q_A = M_1 M_2 (X'_m - X'_{c2})$$
$$Q_B = M_1 M_2 (y'_m - y'_{c1})$$

$$(VEL)_1 = \frac{A}{M_1} \tag{19}$$

$$(VEL)_2 = \frac{-A(y'_m - y'_{c1}) + C'}{M_2 (X'_m - X'_{c2})} \tag{20}$$

$$(VEL)_1 = \frac{B(X'_m - X'_{c2}) + C'}{M_1 (y'_m - y'_{c1})} \tag{22}$$

$$(VEL)_2 = -\frac{B}{M_2} \tag{23}$$

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Logic has been coded into subroutine OBLIQE to test the coefficients of C' and to then test the values of denominators prior to application of equations (19), (20), (22) and (23).

In the case of colinear initial velocity vectors, the momentum relationships cannot be applied.

(2) Space-Fixed Reference Point

One of the difficulties involved in the application of analytical relationships for conservation of angular momentum is that of defining a space-fixed reference point that will yield acceptable accuracy in a variety of impact configurations. At the present time, the CRASH calculations make use of a single set of vehicle positions and orientations to define both initial contact and separation. In other words, the changes in positions and headings that occur during the time period of the collision contact are presently neglected. For that reason, the reference point used for angular momentum calculations must be selected with care to minimize corresponding errors in the analytical results.

A point fixed in space and corresponding to the location of the center of gravity of the two-vehicle system at the instant of collision contact is used in angular momentum calculations. This selection, which was suggested by the CTM, has inherent advantages.

The use of the system center of gravity as the reference point for angular momentum calculations combined with the common assumption that external forces on the system can be neglected during the collision contact eliminates any need for consideration of movement of the selected reference point through space during the collision contact. As a result of conservation of linear momentum, the linear velocity vector of the system center of gravity passes through the space-fixed point corresponding to the initial position of the system center of gravity (see Figure A5).

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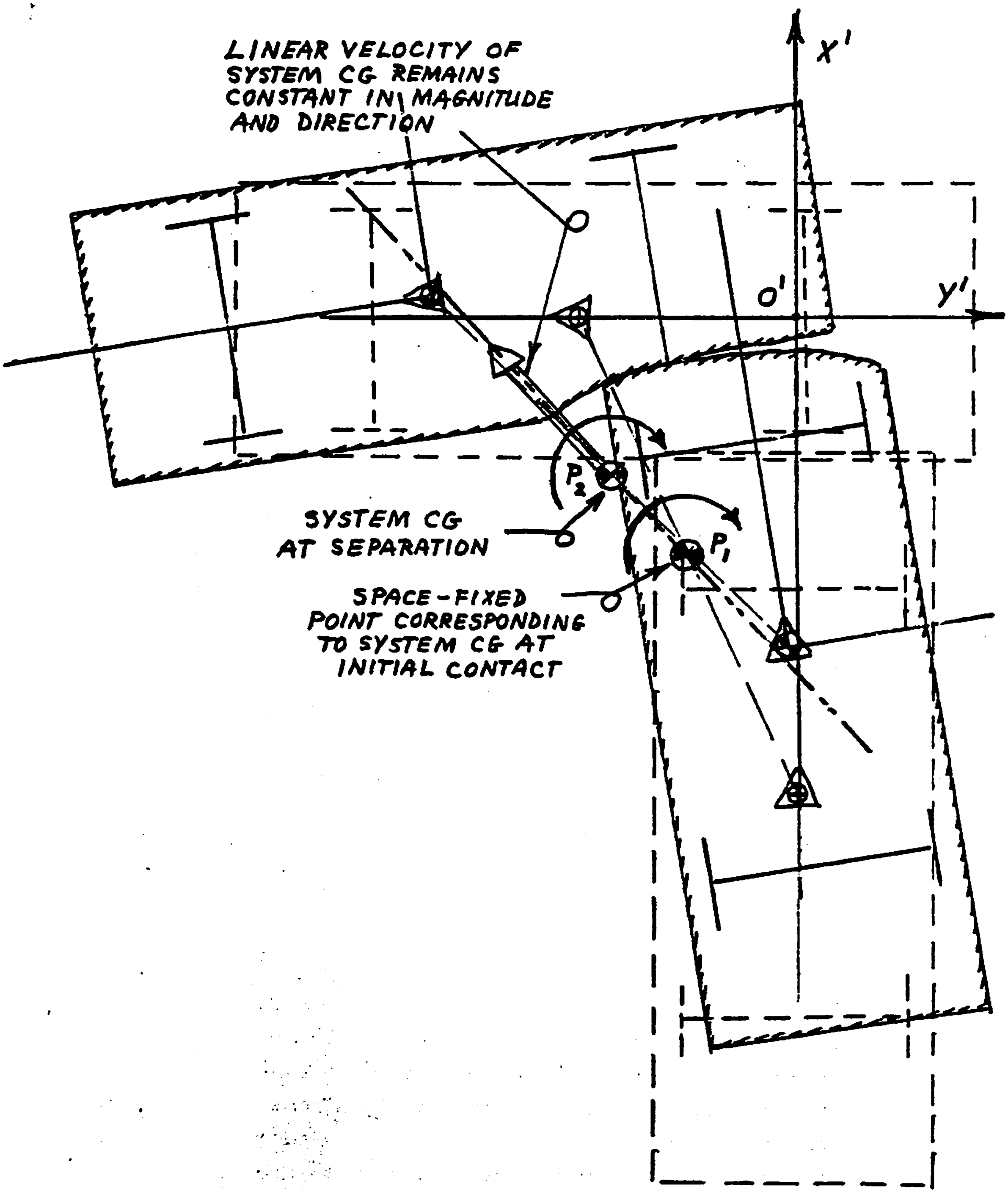
FIGURE A5   ANGULAR MOMENTUM ABOUT SYSTEM CG



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In Figure A5, the angular momentum of the system about point P_1 is equal to the angular momentum about the system CG (point P_2) plus the product of the system linear momentum and its moment arm about point P_1. As a result of conservation of linear momentum, the linear velocity vector of the system CG passes through point P_1. Thus, the moment arm is equal to zero.

The only angular momentum errors introduced by neglect of vehicle motions during the collision consist of those errors that are introduced by small changes in the system geometry with respect to the system center of gravity (Figure A5).

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APPENDIX 3

TIRE SIDE FORCES

A tire develops a side force (i.e., a force parallel to its axis of rotation) as the result of a deviation of its path of travel from the direction of rolling. In simple linear analyses of vehicle dynamics, the side force is assumed to be proportional to the angle of deviation, or slip angle (e.g., see Reference 10). However, in skidding motions, the side force "saturates" at large slip angles. The effect of saturation of the side force has been approximated by means of a nondimensional tire side force curve (Figure A6) which was developed in Reference 4 and adopted in Reference 5.

The "drag factor" for non-yawing skids that is presented elsewhere in this report makes use of fully saturated tire side forces. The magnitude of the corrrsponding error that is introduced in the resultant resistance force is investigated in the following paragraphs.

In Figure A7, the case of unsaturated tire side forces is depicted. In the depicted operating range of the tire slip angles, the following relationship may be used to approximate the drag force (based on Reference 4):

$$F_S = C_T\,(\gamma-\psi)\left\{1 - \frac{1}{3}\,\frac{C_T\,|\gamma-\psi|}{\mu W\sqrt{1-\theta^2}} + \frac{1}{27}\,\frac{C_T^2\,(\gamma-\psi)^2}{\mu^2 W^2\,(1-\theta^2)}\right\}\sin\,(\gamma-\psi)$$

$$+\ \theta\mu W\cos\,(\gamma-\psi) \qquad (1)$$

for $$\frac{C_T\,(\gamma-\psi)}{\mu W\sqrt{1-\theta^2}} < 3.0 \qquad (2)$$

and $$0 < \theta < \cos\,(\gamma-\psi) \qquad (3)$$

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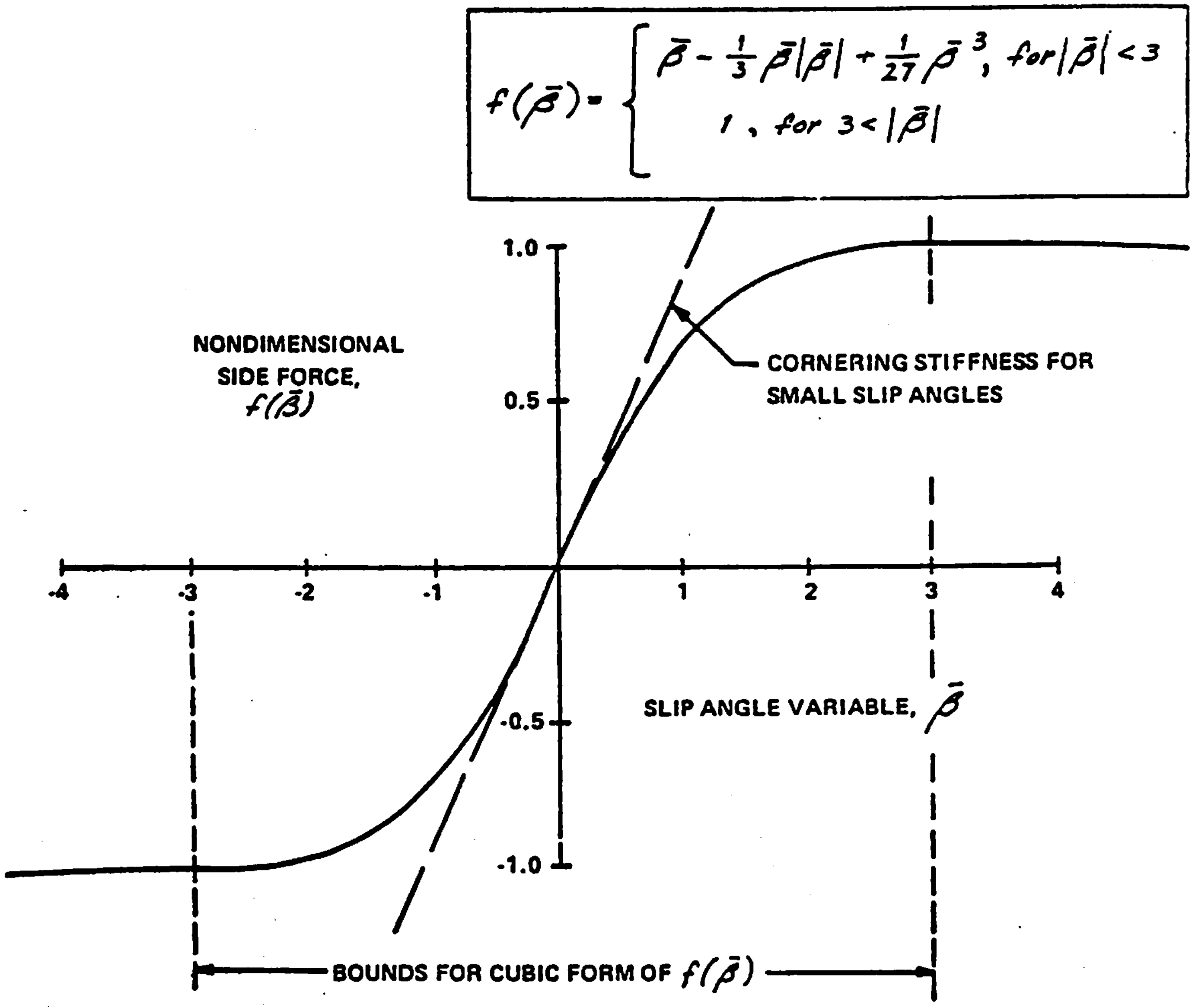
FIGURE A6 NONDIMENSIONAL TIRE SIDE-FORCE CURVE



$$f(\bar{\beta}) = \begin{cases} \bar{\beta} - \frac{1}{3}\bar{\beta}|\bar{\beta}| + \frac{1}{27}\bar{\beta}^3, & \text{for } |\bar{\beta}| < 3 \\ 1, & \text{for } 3 < |\bar{\beta}| \end{cases}$$

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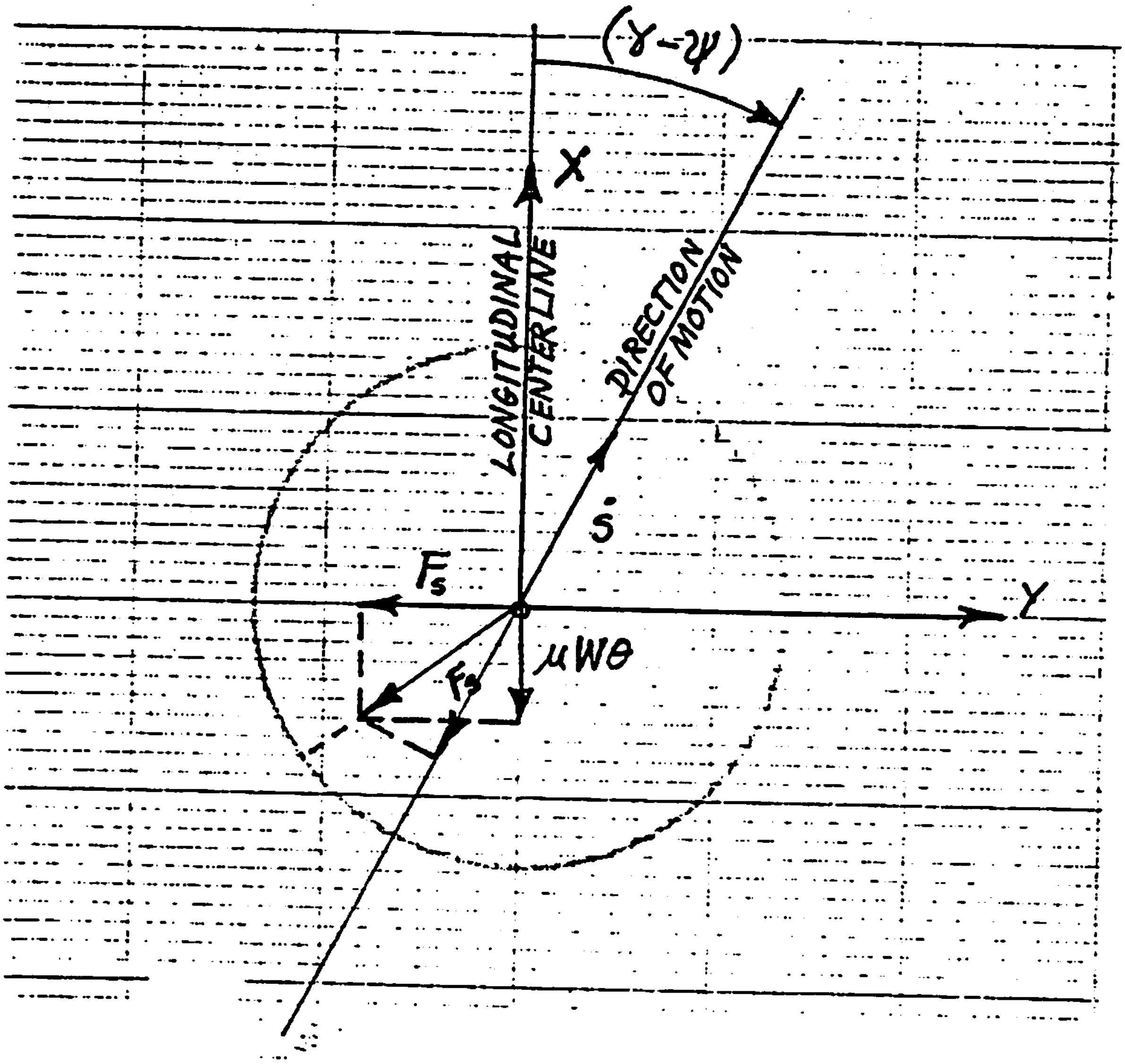
FIGURE A7 DRAG FORCE WITH UNSATURATED TIRE SIDE FORCES



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When $\frac{C_T(\gamma-\psi)}{\mu W\sqrt{1-\theta^2}} = 3.0$, the side force is fully saturated. When $\theta = \cos(\gamma-\psi)$, the wheel is fully locked.

In Reference 11, 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,

$$C_T \simeq (0.165)(57.3)(W) \simeq 9.455 \text{ W lb/radian} \qquad (4)$$

Application of (4) to the relationship defining the saturation point (2) yields:

$$(\gamma-\psi) = 0.3173\,\mu\sqrt{1-\theta^2} \qquad (5)$$

In Figure A8, it may be seen that full saturation of the tire side forces occurs at relatively small vehicle side slip angles and, further, that the required side slip angles are reduced by the presence of rotational resistance at the wheels and by reduction of the tire terrain friction coefficient.

In Figure A9, a comparison is made of the resultant drag forces corresponding to saturated and unsaturated side forces for the indicated worst combination of conditions (i.e., $\theta = 0$, $\mu = 1.0$). It should be noted that θ is generally not zero in a shallow slip angle skid to rest. Rather, θ generally predominates in the dissipation of energy in such a skid. Otherwise, an extremely long distance must be traveled to come to rest.

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FIGURE A8 SLIP ANGLES FOR SATURATION OF TIRE SIDE FORCES

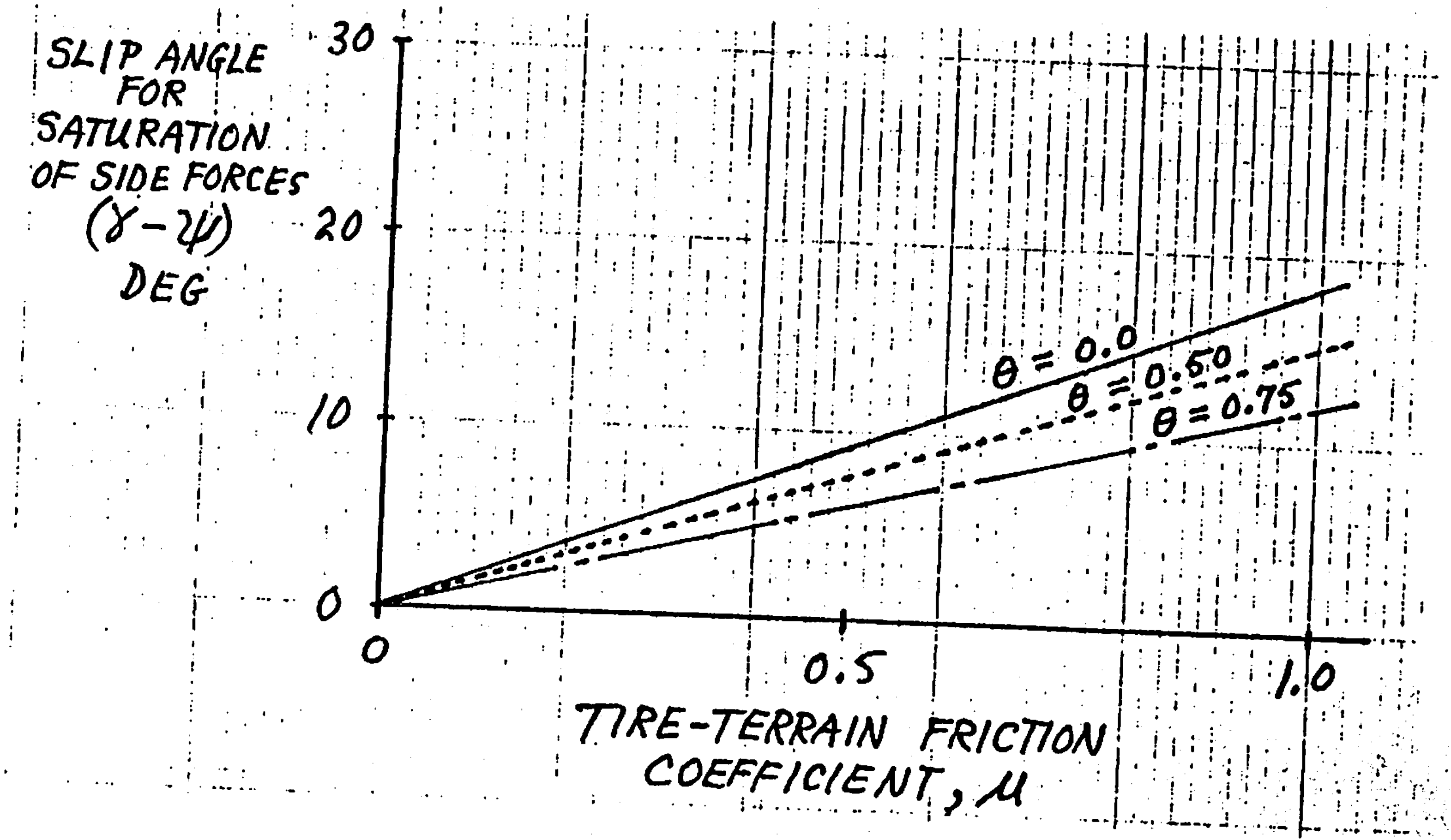

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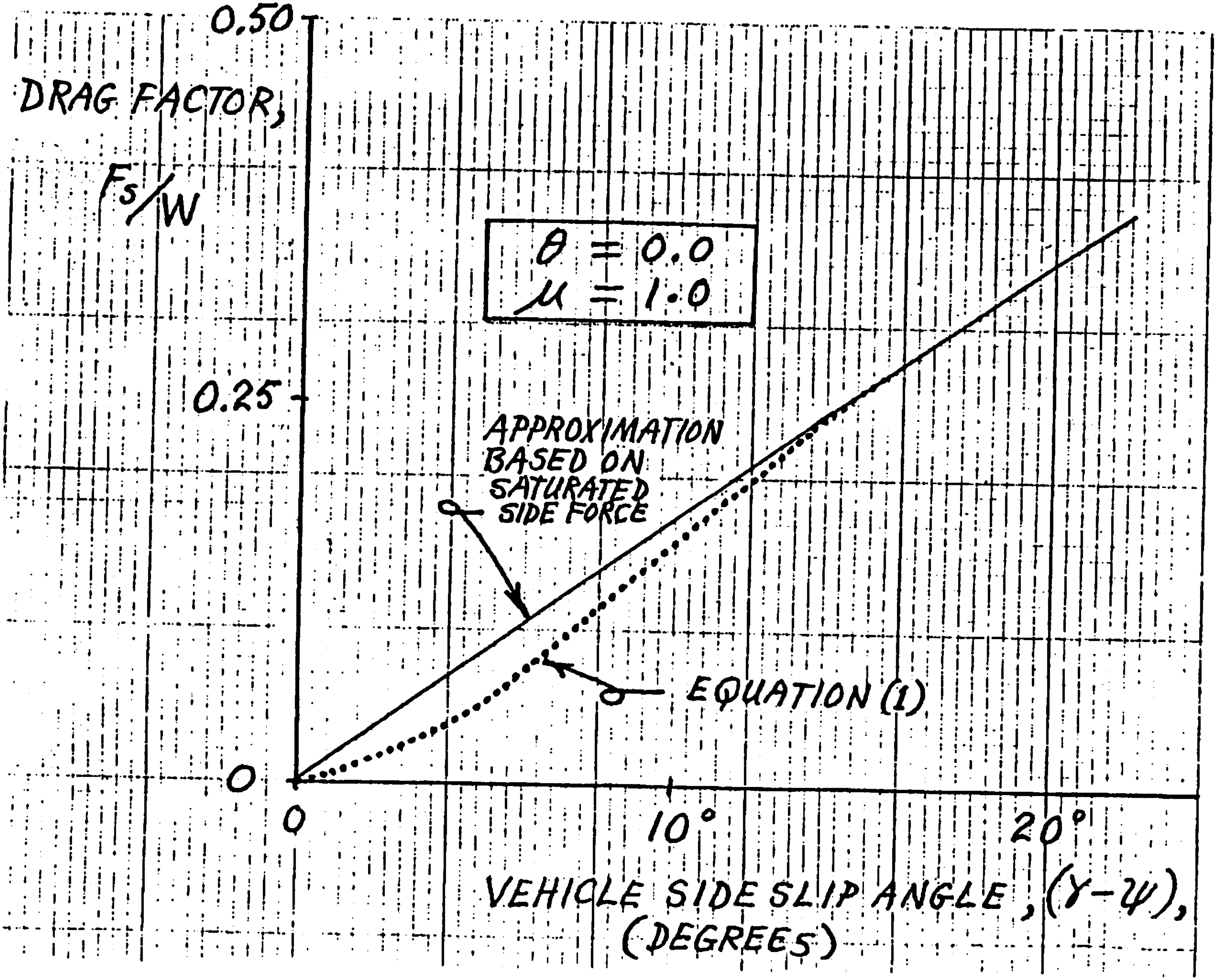
FIGURE A9 "WORST CASE" ERROR IN DRAG FORCE PRODUCED BY USE OF SATURATED SIDE FORCE



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