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A Simplified, Interactive Simulation for Predicting the Braking and Steering Response of Commercial Vehicles

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August 1975

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16. Abstract

An interactive computer program which predicts the response of trucks and tractor-trailers to braking and steering inputs is documented. The mathematical model simulating the vehicle and the input/output of the computer program have been designed to elicit simplicity of operation rather than extreme accuracy. Thus, quasi-static load transfer is used, and wheel spin degrees of freedom are neglected. Special features of the simulation include provisions for tandem axles with inter-axle load transfers, dual tires, brake imbalance, and the effectiveness of antilock braking systems.

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Project 360932

Truck and Tractor-Trailer Braking
and Handling Project

August 1975

Sponsored by

The Motor Vehicle Manufacturers Association

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NOMENCLATURE

AA	Distance between tractor tandem axles (in)
AAT	Distance between trailer tandem axles (in)
ALFA	Tire slip angle (degrees)
ANTEFF	Antilock effectiveness—lateral and longitudinal components
A1	Distance from tractor c.g. to front axle (in)
A2	Distance from tractor c.g. to center of rear suspension (in)
A3	Distance from trailer c.g. to fifth wheel (in)
A4	Distance from trailer c.g. to center of trailer suspension (in)
BB	Distance from center of tractor rear suspension to fifth wheel (in). (Fifth wheel located aft of suspension is negative.)
CALF	Cornering stiffness of a tire (lb/deg)
DDØT	Suffix representing differentiation twice with respect to time (i.e., GAM-DDOT)
DELTA	Average steer angle of front wheels (deg)
DFX	Longitudinal load transfer onto one side of an axle (lb)
DFY	Lateral load transfer onto one side of an axle (lb)
DØT	Suffix representing differentiation with respect to time (i.e., GAMMADØT, PSIDØT, U-DØT, V-DØT)
F(S)	Weighting factor dependent on the value of slip, which multiplies the tire side force due to slip angle. F(S) vs. S is referred to as the "slip roll-off table."
FBZ	Static load on an axle (lb)

FSX	Attempted brake force on one side of an axle (lb) (brake torque divided by tire rolling radius)
FX	Longitudinal force generated by the tire or tires on one side of an axle (lb)
FY	Lateral force generated by the tire or tires on one side of an axle (lb)
FYF	Lateral force generated by a tire, computed using Fiala's tire model which assumes zero slip (lb) (see Reference 7)
FZ	Dynamic load on one side of an axle (lb)
GAMMA	Articulation angle of trailer with respect to tractor (deg). If trailer swings clockwise with respect to tractor looking down on the vehicle, GAMMA is positive. (Note: GAM-DDØT is the second derivative of GAMMA.)
GAM1	Fraction of lateral load transfer of tractor which occurs at front axle of tractor
GAM2	Fraction of rear lateral load transfer of tractor. Equal to 1.0-GAM1
GAM3	Tractor tandem axle load transfer coefficient
GAM4	Trailer tandem axle load transfer coefficient
GVW1	Gross vehicle weight of tractor (lb)
GVW2	Gross vehicle weight of trailer (lb)
IQUIT	Maximum articulation angle allowed before execution of program is stopped (deg)
IR	Input device number for computer terminal. It is set equal to 5 in main routine.
ITZZ	Trailer yaw moment of inertia (in-lb-sec^2)
IW	Output device number for computer terminal. It is set equal to 6 in main routine.
IZZ	Tractor yaw moment of inertia (in-lb-sec^2)
KEYANT	Antilock key
KEYTD	Tandem axle/dual tire key

LAT ACC (AX)	Acceleration of tractor along y-axis (ft/sec^2)
LONG ACC (AY)	Acceleration of tractor along x-axis (ft/sec^2)
MUP	Peak tire-road friction coefficient
MUS	Locked-wheel tire-road friction coefficient
MU5	Fifth wheel friction coefficient
PSI	Clockwise rotation of tractor (looking down on vehicle) from its initial position (deg)
RAD5	Equivalent radius of fifth wheel (in)
SIDESLIP (β)	Sideslip angle of c.g. of tractor (deg) [Equal to $\tan^{-1}$ (V-VEL/U-VEL)]
SP	Assuming a three-point MU-slip curve, SP is the slip at which the peak friction coefficient, MUP, is obtained
TIMF	User-entered simulation time after which program's execution is terminated (sec)
TRA1	Half lateral distance between centers of tire contact on tractor front axle (in)
TRA2	Half lateral distance between centers of tire contact on tractor rear axles (in)
TRA3	Half lateral distance between centers of tire contact on trailer axles (in)
TURN RAD	Radius of curvature of c.g. of tractor (ft)
U-VEL	Velocity of c.g. of tractor along x-axis (ft/sec)
VEL	User-entered initial velocity of tractor along x-axis (mph)
V-VEL	Velocity of c.g. of tractor along y-axis (ft/sec)
x-axis	Body-fixed axis in tractor which intersects c.g. and is positive forward
XH	Reaction force on trailer at fifth wheel directed along the negative x-axis (lb)
y-axis	Body-fixed axis in tractor which intersects c.g. and is positive to the right, looking forward

YH	Reaction force on trailer at fifth wheel directed along the negative y-axis (lb)
Z0	Height of fifth wheel above the ground (in)
Z1	Height of tractor c.g. above the ground (in)
Z2	Height of trailer c.g. above the ground (in)

1. INTRODUCTION

Comprehensive computer programs for simulating the response of commercial vehicles to steering and/or braking inputs have been developed at HSRI under MVMA sponsorship [1, 2].* These programs were developed with the intent of producing results that would be as accurate as is technically and economically feasible. To this end, careful analyses have been performed of (a) unsprung mass dynamics with or without tandem axles, and (b) brake and antilock systems. Furthermore, extensive provisions for representing measured tire data were included in these simulations.

The developed computer programs require a large number of input parameters to characterize the properties of the simulated vehicle (e.g., geometry, mechanical characteristics of components, inertias, tires, brakes, and brake actuating systems). The outputs of these programs are lengthy, and require careful analysis to yield meaningful conclusions. Since the input/output (I/O) is so lengthy, these simulations have been designed exclusively for batch operation.

During the course of development of these programs, it has become apparent that there is a need for less complex simulations which can be run interactively using minimal I/O. Hence, the BRAKES2 simulation was developed to simulate the straight line response of commercial vehicles to a step brake input. This simulation is documented in an earlier report [3]. The present document presents the TBS simulation. This simulation contains a simplified vehicle model for predicting the directional response of commercial vehicles to braking and/or steering inputs. The simulation consists of two interactive computer programs—one for a straight truck and the other for a tractor-trailer.

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*Numbers in square brackets designate references listed in Section 6.

The mathematical model for TBS was constructed using the model developed by Leucht [4] as a starting point. Additions and changes, particularly with respect to the tire model, were made to produce the present simulation.

The next section (2.) discusses the assumptions and features of the simplified model. Following in Section 3., the steps involved in running the computer program are described. Section 4. contains sample results. A brief discussion in Section 5. concerning the utility of this simulation concludes the main body of this report. Finally, a flow chart outlining the options available to the user in running the computer program is included as an Appendix.*

*The listing and source code for the TBS computer program may be obtained by contacting the authors of this report at the Highway Safety Research Institute.

2. FEATURES OF THE SIMULATION

In developing the TBS simulation, a mathematical model was formulated and programmed to describe the directional dynamics of a tractor-trailer. A similar model was then developed for a straight truck by simplifying the tractor-trailer model. Hence, the following discussion treats the tractor-trailer model only, since the truck model is a simple derivative of the tractor-trailer model.

A schematic diagram for the tractor-trailer is shown in Figure 1. The vehicle model consists of two rigid bodies—one for the tractor and the other for the trailer. The model has four degrees of freedom, namely, the longitudinal velocity and the lateral velocity of the tractor, the yaw rate of the tractor, and the articulation angle of the trailer relative to the tractor. There are no roll or pitch degrees of freedom. Load transfers, both longitudinal and lateral, are computed quasi-statically.

In the computer program developed, the equations of motion are integrated numerically using the HPCG numerical integration subroutine, based on Hamming's Predictor-Corrector method [5].

2.1 THE HITCH ("FIFTH WHEEL")

In this simulation the hitch is assumed to transmit a yaw moment (but not a roll or pitch moment) through the hitch due to friction in it. The hitch is modeled as a circular plate of radius RAD5 with a constant pressure distribution equal to the static load divided by the area of the plate. The friction coefficient of the hitch is designated as MU5. (For a fifth wheel employing "steel on steel" MU5 is approximately .05 [4].) To ignore the frictional coupling of the hitch, MU5 should be entered as 0, and nothing need be entered for RAD5.

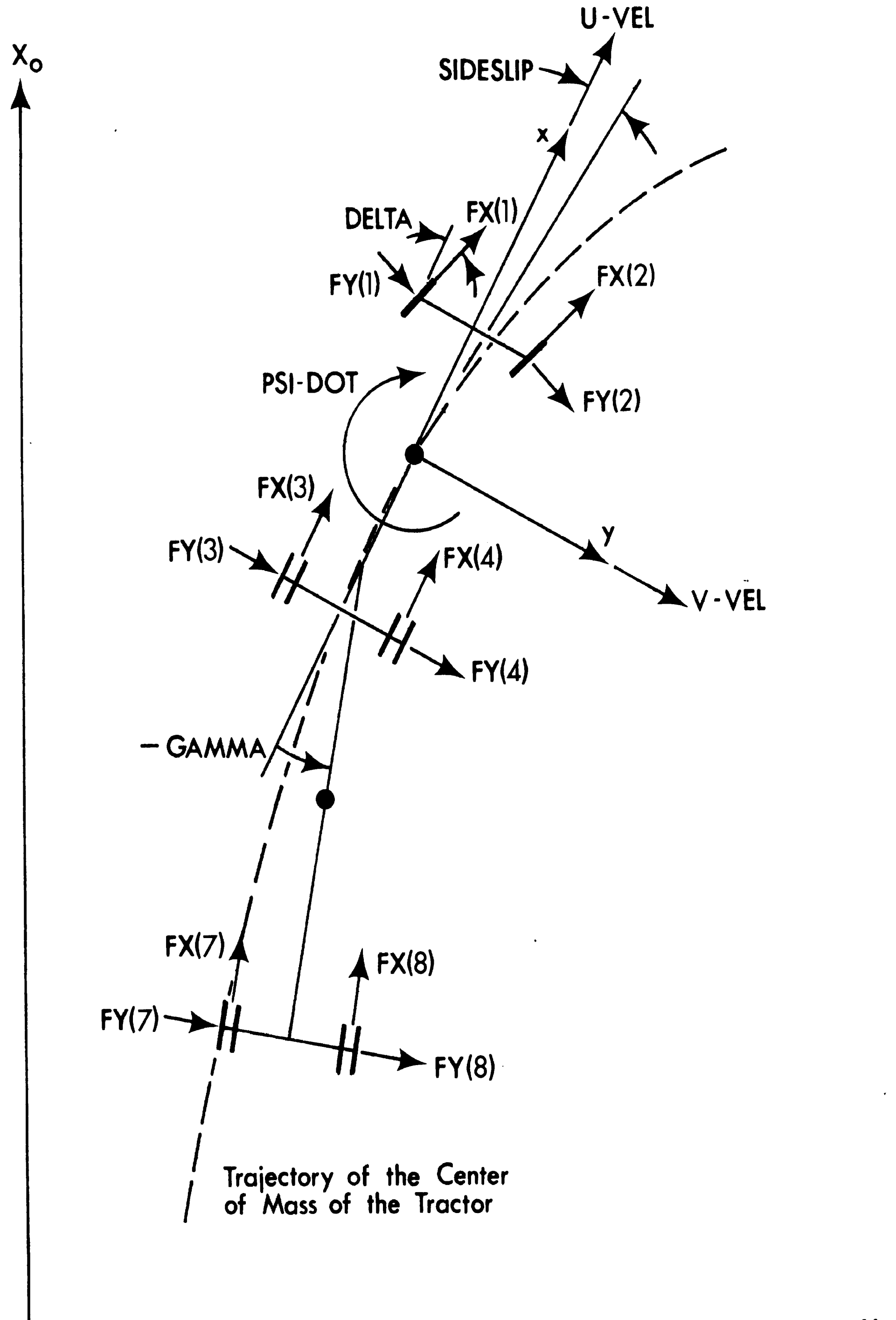


Figure 1. Tractor-semitrailer vehicle model.

2.2 NORMAL LOADS

The normal load on each wheel of the vehicle is equal to the sum of the static load on that wheel and the load transfer (both longitudinal and lateral) taking place at any instant of time. Since it is assumed that no pitch or roll moments are transmitted through the hitch, the load transfer at the trailer wheels may be determined in a straightforward manner based on the trailer c.g. height, the hitch height, the forces on the trailer at the hitch and the road, the track of the trailer, and the distance between the fifth wheel and the trailer axle.

The computation of the load transfer on the tractor wheels is not quite so straightforward. The total longitudinal and lateral load transfers can be computed in the same manner as for the trailer. However, the apportionment of the lateral load transfer between the front and rear axles of the tractor depends on properties of the suspension system which are not included in the simple TBS simulation. Hence, the user must input the parameter, GAM1, which is the fraction of the total lateral load transfer that takes place at the front axle of the tractor. An estimate of this distribution can be obtained by dividing the front roll moment per unit of roll angle for a steady turn (i.e., roll rate is zero, and hence shock absorbers are ignored) by the sum of the front and rear roll moments. The fraction of the lateral load transfer taking place on the rear axle or axles of the tractor, GAM2, is equal to 1.-GAM1.

2.3 TANDEM AXLES

A simplified model for tandem axles is included. The distance between the tandem axles (AA) is entered by the user. The properties of all the tires at both axles in the tandem pair (including cornering stiffness and MU-slip curves) are assumed equivalent and are specified for one tire. A quasi-static inter-axle load transfer is specified by entering the load transfer coefficient—GAM3 for the tractor tandem axles and GAM4 for the trailer tandem axles. The product of this coefficient and the brake force on one side of the tandem axles gives the inter-axle load transfer for that side. By proper choice of GAM3 (or GAM4), the inter-axle load transfer may be approximated for the four spring or walking beam suspensions. Based on a simplified analysis of the four spring suspension [6], GAM (GAM3 or GAM4) can be approximated by -0.5. However, vehicle tests have shown that the load transfer is over-predicted using this simple model. Based on validation studies at HSRI, it is recommended that a value of -0.38 be used for GAM for a four spring suspension. The negative sign indicates that the load transfer in braking is rearward (from the leading to the trailing tandem axle).

For a walking beam suspension, GAM may be approximated by $(AA/R)(100.0 - T_E)/100.0$ [1], where R is the radius of the tire and T_E is the percent of torque rod effectiveness. For "perfect" torque rods, T_E will be 100.0, and there will be no inter-axle load transfer. The coefficient, GAM, for the walking beam suspension is positive since the load transfer produced by braking is forward onto the leading tandem axle.

It should be noted that the inter-axle load transfer may be ignored entirely by entering "zeros" for GAM3 and GAM4.

2.4 TIRE MODEL

It is convenient to think of the simulation of the shear forces at the tire-road interface in three distinct categories, namely, lateral forces of a free rolling tire operated at a slip angle, longitudinal forces of a straight running tire, and finally, the tire shear forces due to combined braking and steering. Each of these categories will be considered below.

2.4.1 LATERAL FORCES OF A FREE ROLLING TIRE. Lateral forces generated by a free rolling tire are computed based on a formulation first offered by Fiala [7]. The lateral force, FYF, is given by

$$FYF = - MUP*FZ(\bar{\alpha} - \frac{\bar{\alpha}|\bar{\alpha}|}{3} + \frac{\bar{\alpha}^3}{27}) \qquad \text{for } \bar{\alpha} < 3 \tag{1a}$$

$$FYF = - MUP*FZ \frac{\bar{\alpha}}{|\bar{\alpha}|} \qquad \text{for } \bar{\alpha} > 3 \tag{1b}$$

where

$$\bar{\alpha} = \frac{CALF*ALPHA}{MUP*FZ} \tag{1c}$$

This model has been used with some success in the Calspan simulations [8], and in the APL Hybrid Simulation [9]. The user input parameters are the cornering stiffness, CALF, and MUP, the ratio of peak side force to normal load, FZ.

Given appropriate CALF and MUP as input, the tire model should produce a reasonably good fit to measured tire data across a wide range of slip angles. It should be noted, however, that CALF and MUP may be load sensitive (and perhaps speed sensitive). Thus caution must be exercised in the analysis of results involving extreme load transfer.

2.4.2 LONGITUDINAL FORCES OF A TIRE IN BRAKING. The TBS tire model does not include a wheel spin degree of freedom for the wheels. Thus quasi-static calculations replace wheel spin dynamics. The user input parameters are MUP, the ratio of peak longitudinal force to normal load; SP, the value of longitudinal slip at which MUP occurs; and MUS, the friction coefficient of the sliding or locked wheel. It should be noted that the value of MUP for each of the longitudinal and lateral force calculations is assumed identical. It is most convenient to determine MUP from μ-slip curves of FX/FZ vs. S. A three-point representation of a typical μ-slip curve is shown in Figure 2.

Straight-line braking calculations take place in the following way: An attempted brake force is determined based on the input brake force table. (This tabular input is explained in Section 2.8.) If the magnitude of the attempted brake force is less than MUP*FZ, then the simulated brake force will be set equal to the attempted brake force. Otherwise, the simulated brake force will be set equal to -MUS*FZ.

Note that, although spin dynamics are neglected, longitudinal slip can be estimated. If

$$|FX| \leq MUP*FZ, \quad \text{then}$$

$$S = -SP \frac{FX/FZ}{MUP} \tag{2a}$$

Otherwise, the wheel is assumed to lock and

$$S = 1 \tag{2b}$$

As in the case of the free rolling tire model, reasonable input data should lead to reasonable results. However, it should be noted that the peak and slide friction coefficients, MUP and MUS, are likely to be speed and load sensitive. Thus caution should be exercised in the interpretation of the absolute values of the calculated results.

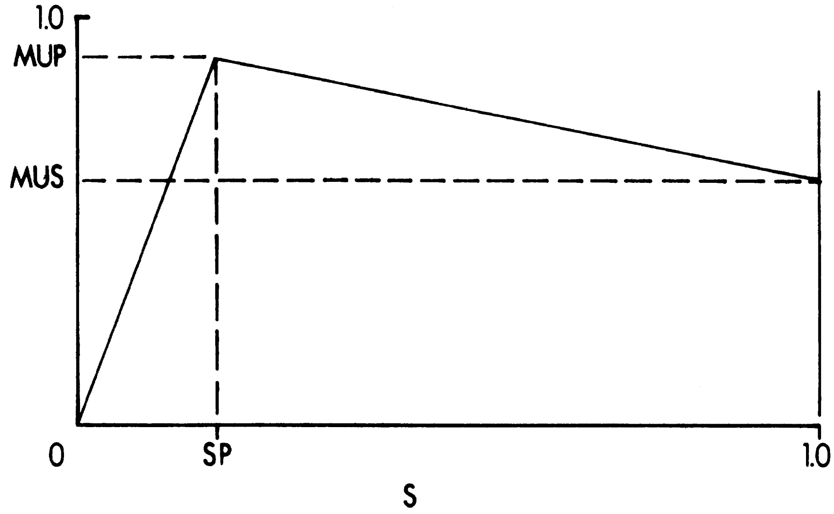


Figure 2. MU-slip curve.

2.4.3 TIRE SHEAR FORCES DUE TO COMBINED BRAKING AND STEERING INPUTS. Maneuvers in which simultaneous steering and braking take place result in the generation of both lateral and longitudinal forces at the tire-road interface. The calculation of these forces proceeds as follows.

The peak longitudinal friction coefficient is assumed to decrease as a function of slip angle, ALPHA. The modified peak friction coefficient is given by

MUMOD = MUP(1. - 1.7*ALPHA) (3)

Simulated wheel lockup will occur if the magnitude of the attempted brake force is greater than MUMOD*FZ.

The locked wheel brake force is given by

FX = - MUS*FZ*COS(ALPHA) (4)

The simulated lateral forces, in turn, are modified by the brake forces. If the wheel is not locked, the lateral force generated is

FY = FYF*F(S) (5)

where FY is the lateral force due to combined braking and steering, FYF is the lateral force of the free rolling tire due to slip angle, ALPHA and F(S). The "slip rolloff function" accounts for the effect of slip on the lateral force generated. The function F(S) is empirical and is compiled in the computer program as a table of weighting factor, F, versus the slip, S. The user has the option of entering his own table of F(S) versus S if he so desires. However, the table provided in the computer program is based on data taken from two types of truck tires (sizes 8.00-16.5(E) and 10.00-20(F)) tested at the Calspan TIRF facility [10]. Though the tires varied greatly in load ratings, and the tires were tested at different velocities, the tables of F(S) versus S were found to be similar for speeds of 40 and 55 mph, as shown in Figure 3. Hence, a table of F(S) versus S was constructed from Figure 3 by using the average value of F(S) at each value of longitudinal slip.

For the locked wheel condition, it is assumed that the resultant force at the tire-road interface opposes the direction of the sliding wheel. Since the locked wheel longitudinal force is

FX = -MUP*COS(ALPHA) ,

the locked wheel lateral force must be

FY = - MUP*SIN(ALPHA) (6)

To briefly summarize, provisions have been made in the TBS tire model to determine the tire shear forces due to steering only, or due to braking only, or due to combined steering and braking. The input data required for the tire model are CALF, MUP, SP, and MUS.

2.5 ANTILOCK MODEL

In theory, an antilock system can improve the average traction output of a tire (both laterally and longitudinally) over that produced by a locked wheel. To include antilock in the model, lateral and longitudinal antilock effectiveness coefficients (AFY, AFX) are defined. These coefficients are used to modify the locked wheel traction as follows:

First, for both longitudinal and lateral traction, a "best case" and a "locked-wheel case" are defined. These cases are:

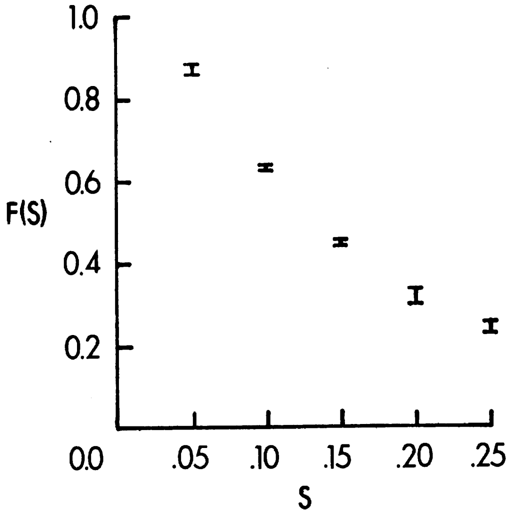


Figure 3. F(s) vs. slip s for light [8.00-16.5(E)] and heavy [10.00-20(F)] truck tires.

Note: horizontal bars bracket extent of variation in F(s).

Longitudinal Traction

a. Best Case --- MUP*FZ symbolized by FX_{PEAK}

b. Locked-Wheel Case --- MUS*FZ*CØS(ALPHA) symbolized by FX_{LOCKED}

Lateral Traction

a. Best Case --- FY computed from Fiala's model with slip equal 0 , symbolized by FY_{PEAK}

b. Locked-Wheel Case --- MUS*FZ*SIN(ALPHA) symbolized by FY_{LOCKED}

Then the antilock effectiveness coefficients are employed as shown by the following equations.

$$FX = FX_{LOCKED} + AFX(FX_{PEAK} - FX_{LOCKED})$$

$$FY = FY_{LOCKED} + AFY(FY_{PEAK} - FY_{LOCKED})$$

As is evident, AFX = AFY = 0 for no antilock system. It should be noted that a negative value for either AFX or AFY would simulate an antilock system which gives a performance poorer than the locked-wheel case.

2.6 DUAL TIRES

Dual tires are treated as two single tires, each sharing the vertical load on them equally and each yielding the same longitudinal and lateral forces, FX and FY. Thus, FX and FY, for dual tires, will be twice the respective values of FX and FY for a single tire.

2.7 END OF COMPUTATIONS

The model cannot handle the case when a wheel lifts off the ground (i.e., FZ less than 0). Hence, computations are stopped if this happens, and the wheel which lifted off is indicated on the computer output. (The wheels are numbered as shown in Figure 4.) Further, if the articulation angle, GAMMA, grows to become larger than the user-specified value of IQUIT, computations are stopped. By studying the time history of GAMMA (the trailer articulation angle) and other output variables, it is possible to determine whether the tractor jackknifed, or if the less violent instability of trailer-swing occurred. If none of the above occurrences takes place, computations will end when the vehicle stops or when the user-entered termination time, TIMF, is exceeded.

2.8 BRAKING AND STEERING INPUTS

Braking is handled in the model by specifying (in tabular form) the time history of attempted brake force for the brakes on each side of each axle. Since each side is considered separately, brake imbalance may be simulated. For a tandem axle pair, the two sets of brakes on one side of the tandem axles are assumed equivalent. Hence the brake force time history is entered for the brakes on each side of the leading tandem axle only. The brakes on the trailing tandem axle are then assumed to have the same time histories as the brakes directly ahead of them on the leading tandem axle. It should be noted that if the peak friction coefficient, MUP, for the tire-road interface considered won't support the attempted brake force at a wheel, that wheel is assumed to lock (or cycle if the axle has an antilock system), and the brake force is computed as shown in Sections 2.4 and 2.5. Since this model assumes quasi-static load transfer, the effect

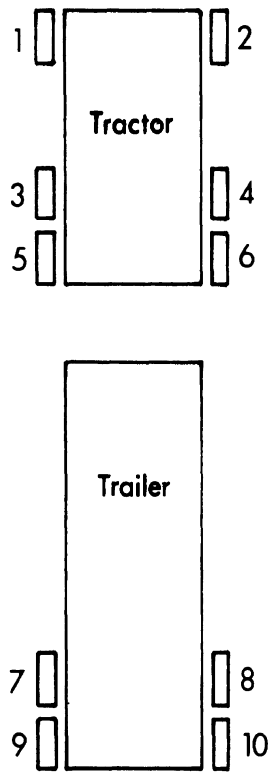


Figure 4.

The wheels on the tractor-trailer are identified by the numbers shown in the figure above. Numbers 1, 2, 3, 4, 7, and 8 are always used whether or not tandem axles are simulated. If the tractor has a single rear axle, numbers 3 and 4 identify the wheels on that axle. The numbers 5 and 6 are then omitted. If the tractor has tandem axles, then 3 and 4 identify the wheels on the front tandem, and 5 and 6 identify the wheels on the rear tandem. The same applies for the trailer. Numbers 7 and 8 identify the wheels on the trailer axle if it is single, or they identify the wheels on the front tandem if the trailer has tandem axles. In this latter case, 9 and 10 identify the wheels on the rear tandem.

of "brakes-on" is immediate rather than suffering a delay time during which the load is transferred and the tires build up their new forces.

Each line of the brake force table entered must contain the time, followed by the attempted brake force, FSX, on each side of each axle (or tandem pair of axles). Up to fifteen lines may be entered. If the time, t, at which the attempted brake forces must be determined, is larger than the last time given in the table, the attempted brake forces are set equal to the last line of brake forces given. If t is between two successive times given in the table, then the attempted brake forces are linearly interpolated between those two times.

Figure 5a shows three attempted brake force time histories—one for a tractor front brake, the second for a brake on the tractor leading tandem axle, and the third for a brake on the trailer leading tandem axle. Brake imbalance is assumed to be zero. The brake force table entered to simulate the brakes represented by these time histories is shown in Figure 5b.

Steering inputs are also entered in tabular form. Each line of the table consists of the time followed by the average steer angle for the front wheels. Up to twenty-five lines may be entered. As with the brake force table, at time t less than the last time entered, the steer angle is determined by linear interpolation between the times (with their associated steer angles) bracketing time t. If t is larger than the last time entered, then the steer angle is set equal to the last steer angle entered. The first entry in both the brake force table and the steer table must be at time equal to zero. However, the initial brake forces and steer angle may be nonzero.

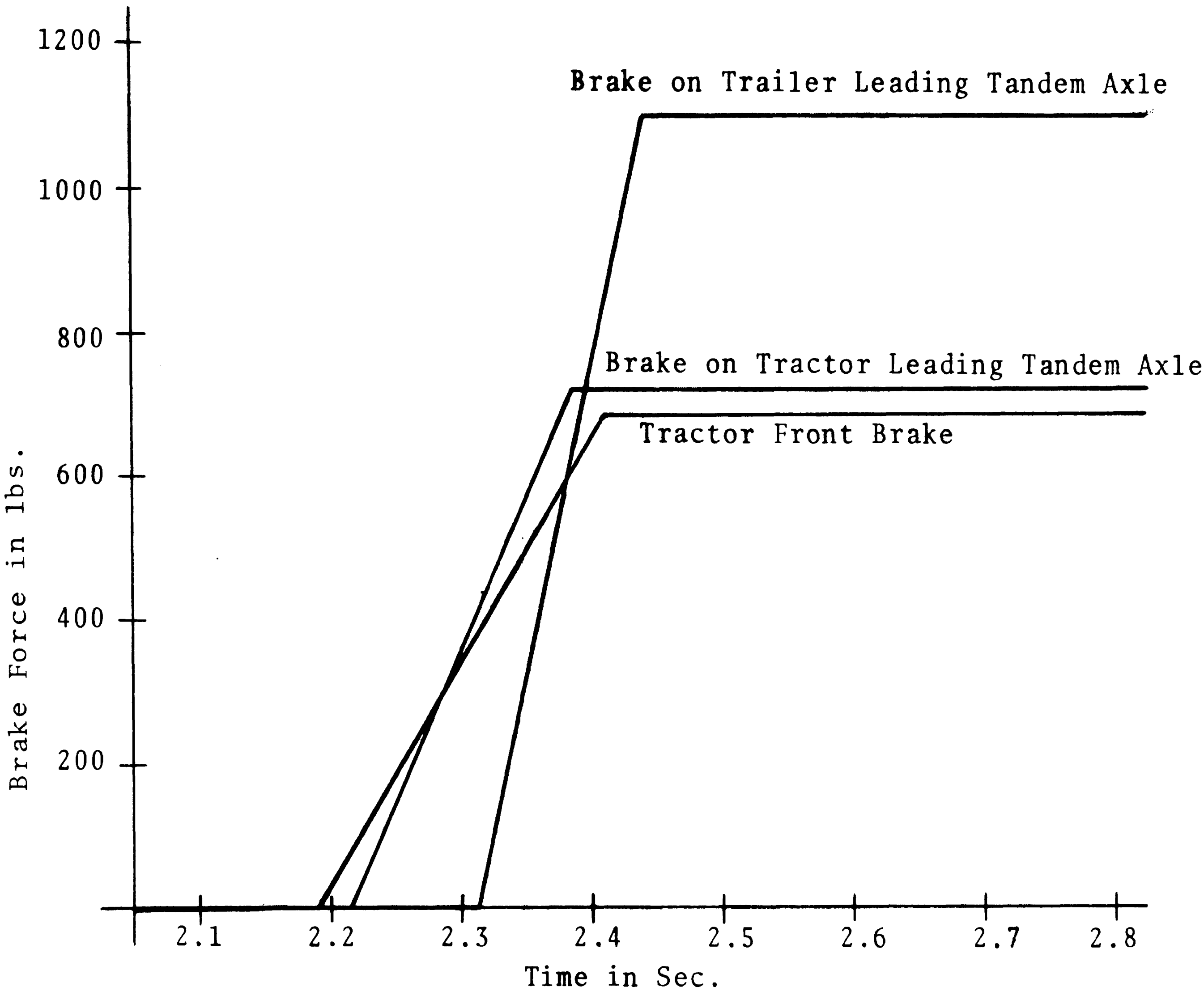


Figure 5a

TIME (SEC)	FSX(1)	FSX(2)	FSX(3)	FSX(4)	FSX(7)	FSX(8)
	DESIRED FORCES:					
0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.1900	0.0	0.0	0.0	0.0	0.0	0.0
2.2150	77.40	77.40	0.0	0.0	0.0	0.0
2.3150	387.00	387.00	420.00	420.00	0.0	0.0
2.3850	604.00	604.00	713.00	713.00	598.00	598.00
2.4100	682.00	682.00	713.00	713.00	812.00	812.00
2.4430	682.00	682.00	713.00	713.00	1094.00	1094.00

Figure 5b. Attempted brake force time histories for a tractor-trailer

3. RUNNING THE PROGRAM

In the previous section the connection between the vehicle model and the computer program was described. This section presents the mechanics of operating the computer program.

3.1 PREPARATION

The program calls for two subroutines that are included in the IBM scientific subroutine package. These subroutines are HPCG, a numerical integration subroutine, and SIMQ, which is used to invert a 4×4 matrix in subroutine FCT (in the tractor-trailer program only).

Data for the program may be input from a file, though an input file is optional. Additionally, an output file may be specified to record the computed time histories for later examination or for plotting purposes. (In the computer program as written, 5 and 6 were used for the input and output device numbers, respectively, of the computer terminal. These may be changed by the user by changing the cards IR=5 and IW=6 which appear in the main routine.)

3.2 INPUT

The program is designed so that the user answers questions or enters data in response to questions or commands from the computer.* The options available to the user in entering his data are outlined in the flow chart shown in the appendix.

---

*In answering yes/no questions, a yes answer will be interpreted by the computer program if the first letter of the user's response is a "y." Any other response will be interpreted as no.

The first input to be entered is the antilock key (KEYANT), which specifies whether or not each set of axles—tractor front, tractor rear, and trailer—has an antilock system. Next to be entered is the tandem axle/dual tire key (KEYTD) which indicates whether or not the tractor rear and/or trailer have tandem axles and/or dual tires.

If the user has asked for a list of input parameters and has indicated that he will input the data from the terminal, he is primed by the symbol and verbal description for each parameter that must be entered. After each parameter is described, the user enters the value he wishes it to have. The input data entered up through this point are shown in Figure 6. The underlined quantities in the figure indicate the responses of the user. Note that the number which precedes each symbol is the identifying datum number for that parameter. This number is used when changing a parameter, as explained in the next section.

Depending on what the user entered for the keys KEYANT and KEYTD, certain input parameters will not be necessary, and are thus not called for by the computer. For instance, if the user indicated that the trailer has a single axle, then the parameter AAT (the distance between the trailer tandem axles) will not be called for. Figure 7 shows the input data for a tractor with tandem axles and dual tires and a trailer with a single rear axle. As shown, data not necessary are not entered. It should be noted that in entering data from a file, the same rule applies—data not necessary is not entered. Figures 8 and 9 show examples of two data files, corresponding to the data shown in Figures 6 and 7, respectively. These data files also include the brake and steer tables which will be discussed shortly.

The last parameters to be entered are the antilock effectiveness coefficients (ANTEFF) and the tire properties—cornering stiffness (CALF), the peak and slide friction coefficients (MUP and MUS), and the slip (SP) at which the

Figure 6. Input data for White tractor and Fruehauf Trailer. (Underlined quantities are responses of user.)

```
YOU ARE ABOUT TO RUN THE HSRI SIMULATION PROGRAM FOR
A TRACTOR-TRAILER IN THE HORIZONTAL PLANE
PRINT PROGRAM EXPLANATIONS? (Y OR N): N
LIST INPUT PARAMETERS? Y
READ DATA FROM FILE? N

*** BEGIN INPUT ***
41 ENTER ANTILOCK CODE FOR TRACTOR FRONT, TRACTOR REAR,
   AND TRAILER AXLES.
    0=NO ANTILOCK,  1=INDEPENDENT ANTILOCK,  FORMAT=3I1.
000
42 ENTER CODE FOR TANDEM AXLE: TRACTOR REAR, DUAL TIRES
    TRACTOR REAR, TANDEM AXLE: TRAILER, DUAL TIRES TRAILER
    0=NO,  1=YES,  FORMAT=4I1.
1111

INPUT PARAMETER TABLE

NO. SYMBOL      DESCRIPTION                                      INITIAL VALUE


01  GVW1        WT. OF TRACTOR (LBS)                            14970.
02  GVW2        WT. OF TRAILER (LBS)                            11160.
03  IZZ         TRACTOR MOM. OF INERTIA (IN-LB-SEC**2)          241636.
04  ITZZ        TRAILER MOM. OF INERTIA (IN-LB-SEC**2)          736963.
05  AA          DIST. BETWEEN TRACTOR TANDEM AXLES (IN)         54.4
06  AAT         DIST. BETWEEN TRAILER TANDEM AXLES (IN)         49.3
07  A1          DIST. FROM TRACTOR CG TO FRONT AXLE(IN)         63.9
08  A2          DIST. FROM TRACTOR CG TO REAR AXLE(IN)          78.1
09  A3          DIST. FROM TRAILER CG TO FIFTH WHL (IN)         261.2
10  A4          DIST. FROM TRAILER CG TO AXLE (IN)              104.8
11  BB          DIST. FROM TRACTOR REAR SUSPENSION TO
                  FIFTH WHL (IN).  FIFTH WHL LOCATED
                  AFT OF SUSPENSION IS NEGATIVE.                0.0
12  TRA1        HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                  CONTACT ON TRACTOR FRONT AXLE (IN)            40.0
13  TRA2        HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                  CONTACT ON TRACTOR REAR AXLE/S (IN)           36.5
14  TRA3        HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                  CONTACT ON TRAILER AXLE/S (IN)                36.0
15  Z0          HEIGHT OF FIFTH WHL ABOVE GROUND (IN)           48.0
16  Z1          HEIGHT OF TRACTOR CG ABOVE GROUND(IN)           39.9
17  Z2          HEIGHT OF TRAILER CG ABOVE GROUND (IN)          55.5
18  MU5         FIFTH WHEEL FRICTION COEFFICIENT                .05
19  RAD5        EQUIVALENT RADIUS OF FIFTH WHEEL (IN)           19.0
20  GAM1        PORTION OF TOTAL LAT. LOAD TRANSFER
                  ON FRONT AXLE OF TRACTOR                      .16
21  GAM3        TRACTOR TANDEM AXLE LOAD X-FER COEF.            -.38
22  GAM4        TRAILER TANDEM AXLE LOAD X-FER COEF.            -.38
23  VEL         INITIAL VELOCITY: U-DIRECTION (MPH)             26.8
                                            (FPS)                         39.31
24  TIMF        MAX. SIMULATION TIME FOR THIS RUN (SEC)         6.0
25  IQUIT       MAX. ARTICULATION ANGLE ALLOWED    (DEG)        30.0
  CALF          CORNERING STIFFNESS OF TIRES (LBS/DEG)
29                                                  CALF(1)=    467.
30                                                  CALF(3)=    208.
31                                                  CALF(7)=    200.
DO ALL TIRES HAVE THE SAME MU-SLIP CURVE? N
   MUP          PEAK TIRE-ROAD FRICTION COEFFICIENT
32                                                   MUP(1)=    .942
33                                                   MUP(3)=    .939
34                                                   MUP(7)=    .960
   MUS          SLIDING TIRE-ROAD FRICTION COEF.
35                                                   MUS(1)=    .895
36                                                   MUS(3)=    .895
37                                                   MUS(7)=    .895
    SP          SLIP CORRESPONDING TO PEAK MU
38                                                    SP(1)=    .11
39                                                    SP(3)=    .11
40                                                    SP(7)=    .11
```

Figure 7. Tractor with tandem axles and trailer with single axle. Tractor has antilock systems on front and rear axles. (Underlined quantities are responses of user.)

```
*** BEGIN INPUT ***
41 ENTER ANTILOCK CODE FOR TRACTOR FRONT, TRACTOR REAR,
    AND TRAILER AXLES.
    0=NO ANTILOCK,   1=INDEPENDENT ANTILOCK,   FORMAT=3I1.
110
42 ENTER CODE FOR TANDEM AXLES TRACTOR REAR, DUAL TIRES
    TRACTOR REAR, TANDEM AXLES TRAILER, DUAL TIRES TRAILER
    0=NO,   1=YES,   FORMAT=4I1.
1100

INPUT PARAMETER TABLE

NO. SYMBOL        DESCRIPTION                                     INITIAL VALUE

01  GVW1          WT. OF TRACTOR (LBS)                            14970.
02  GVW2          WT. OF TRAILER (LBS)                            11160.
03  IZZ           TRACTOR MOM. OF INERTIA (IN-LB-SEC**2)          241636.
04  ITZZ          TRAILER MOM. OF INERTIA (IN-LB-SEC**2)          736963.
05  AA            DIST. BETWEEN TRACTOR TANDEM AXLES (IN)         54.4
07  A1            DIST. FROM TRACTOR CG TO FRONT AXLE(IN)         63.9
08  A2            DIST. FROM TRACTOR CG TO REAR AXLE(IN)          78.1
09  A3            DIST. FROM TRAILER CG TO FIFTH WHL (IN)         261.2
10  A4            DIST. FROM TRAILER CG TO AXLE (IN)              104.8
11  BB            DIST. FROM TRACTOR REAR SUSPENSION TO
                    FIFTH WHL (IN).  FIFTH WHL LOCATED
                    AFT OF SUSPENSION IS NEGATIVE.                0.0
12  TRA1          HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                    CONTACT ON TRACTOR FRONT AXLE (IN)            40.0
13  TRA2          HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                    CONTACT ON TRACTOR REAR AXLES (IN)            36.0
14  TRA3          HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                    CONTACT ON TRAILER AXLES (IN)                 36.0
15  Z0            HEIGHT OF FIFTH WHL ABOVE GROUND (IN)           48.0
16  Z1            HEIGHT OF TRACTOR CG ABOVE GROUND(IN)           39.9
17  Z2            HEIGHT OF TRAILER CG ABOVE GROUND (IN)          55.5
18  MU5           FIFTH WHEEL FRICTION COEFFICIENT                .05
19  RAD5          EQUIVALENT RADIUS OF FIFTH WHEEL (IN)           19.0
20  GAM1          PORTION OF TOTAL LAT. LOAD TRANSFER
                    ON FRONT AXLE OF TRACTOR                      .16
21  GAM3          TRACTOR TANDEM AXLE LOAD X-FER COEF.            -.38
23  VEL           INITIAL VELOCITY: U-DIRECTION (MPH)             45.
                                                (FPS)                     66.00
24  TIME          MAX. SIMULATION TIME FOR THIS RUN (SEC)         2.0
25  IQUIT         MAX. ARTICULATION ANGLE ALLOWED    (DEG)        30.0

ANTEFF            ANTILOCK EFFECTIVENESS COEFFICIENT (LAT.,LONG.)
26                                    FRONT AXLE: ANTEFF=         .5,0.
27          TRACTOR REAR AXLE (OR TANDEM AXLES): ANTEFF=          .3,.2
  CALF            CORNERING STIFFNESS OF TIRES (LBS/DEG)
29                                               CALF(1)=         467.
30                                               CALF(3)=         208.
31                                               CALF(7)=         400.
DO ALL TIRES HAVE THE SAME MU-SLIP CURVE? Y
   MUP            PEAK TIRE-ROAD FRICTION COEFFICIENT
32                                                MUP(1)=         .95
   MUS            SLIDING TIRE-ROAD FRICTION COEF.
35                                                MUS(1)=         .90
    SP            SLIP CORRESPONDING TO PEAK MU
38                                                 SP(1)=         .15
```

Figure 8. Sample data file for data shown in Figures 6 and 10.

```
000                          WHITE TRACTOR-FRUEHAUF TRAILER
1111                         TANDEM/DUAL KEY
14970.                       GVW1
11160.                       GVW2
241636.                      IZZ
736983.                      ITZZ
54.4                         AA
49.3                         AAT
63.9                         A1
78.1                         A2
261.2                        A3
104.8                        A4
0.0                          BB
40.0                         TRA1
36.0                         TRA2
36.0                         TRA3
48.0                         Z0
39.9                         Z1
55.5                         Z2
.05                          MU5
19.0                         RAD5
.16                          GAM1
-.375                        GAM3
-.375                        GAM4
26.8                         VEL
6.0                          TIMF
30.0                         IQUIT
467.                         CALF(1)
208.                         CALF(3)
200.                         CALF(7)
NO
.942                         MUP(1)
.939                         MUP(3)
.96                          MUP(7)
.895                         MUS(1)
.895                         MUS(3)
.894                         MUS(7)
.11                          MUSLOP(1)
.11                          MUSLOP(3)
.11                          MUSLOP(7)
07                           BRAKE TABLE
0.,0.,0.,0.,0.,0.,0.
2.19,0.,0.,0.,0.,0.,0.
2.215,77.4,77.4,0.,0.,0.,0.
2.315,387.,387.,420.,420.,0.,0.
2.385,604.,604.,713.,713.,598.,598.
2.41,682.,682.,713.,713.,812.,812.
2.443,682.,682.,713.,713.,1094.,1094.
02                           STEER TABLE
0.,0.
1.0,4.62
```

```
110           ANTILOCK KEY
1100          TANDEM/DUAL KEY
14970.        GVW1
11160.        GVW2
241636.       IZZ
736383.       ITZZ
54.4          AA
63.9          A1
78.1          A2
261.2         A3
104.8         A4
0.0           BB
40.0          TRA1
36.0          TRA2
36.0          TRA3
48.0          Z0
39.9          Z1
55.5          Z2
.05           MU5
19.0          RAD5
.16           GAM1
-.38          GAM3
45.           VEL
2.0           TIME
30.0          IQUIT
.5,0.         ANTEFF(1)
.3,.2         ANTEFF(2)
467.          CALF(1)
208.          CALF(3)
400.          CALF(7)
YES
.95           MUP(1)
.90           MUS(1)
.15           SP(1)
```

Figure 9. Sample data file for data shown in Figure 7.

peak friction coefficient is obtained. The antilock effectiveness coefficients are entered in pairs—the lateral coefficient and the longitudinal coefficient separated by commas (AFY, AFX). The coefficients MUP, MUS, and SP define a MU-slip curve. Separate MU-slip curves may be entered for each set of axles. However, the user may enter one MU-slip curve for all the tires on the vehicle by answering "YES" to the question, "DO ALL TIRES HAVE THE SAME MU-SLIP CURVE?"

Finally, the brake table and steer table are entered (Figure 10). In entering data for these tables the user first enters the number of lines the table has in I2 format. The table is then entered line by line. For the brake table, each line contains the time, followed by the brake force on each side of the tractor front, tractor rear, and trailer axles. Each line of the steer table contains the time, followed by the average steer angle of the front wheels.

3.3 CHANGES

After all data has been entered, or after a run has been completed—yielding the time histories for a particular data set as output—any parameter in the data set may be changed. A parameter is changed by keying its identifying datum number, and then entering its new value. Subsequent changes are primed by a "?" after which the datum number to be changed should be entered. After all changes to be made have been completed, a "0" is entered in response to the "?".

It should be noted that the antilock key (KEYANT) need not be changed to engage the antilock option. If ANTEFF is changed so that it has a non-zero component, the antilock key is automatically adjusted. The same is not true for the tandem axle/dual tire key (KEYTD). For example, if AAT (the distance between the trailer tandem axles) is changed from its assumed value of zero for a single axle to a finite length, the tandem axle/dual tire key must also be adjusted by the user.

```
BRAKE FORCE TABLE
NUMBER OF LINES:   07

TIME                                    DESIRED FORCES:
(SEC)      FSX(1)     FSX(2)     FSX(3)     FSX(4)     FSX(7)     FSX(8)

0.,0.,0.,0.,0.,0.,0.
2.19,0.,0.,0.,0.,0.,0.
2.215,77.4,77.4,0.,0.,0.,0.
2.315,387.,387.,420.,420.,0.,0.
2.385,604.,604.,713.,713.,598.,598.
2.41,682.,682.,713.,713.,812.,812.
2.443,682.,682.,713.,713.,1094.,1094.
ECHO TABLE? Y
```

TIME (SEC)	FSX(1)	FSX(2)	FSX(3)	FSX(4)	FSX(7)	FSX(8)
0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.1900	0.0	0.0	0.0	0.0	0.0	0.0
2.2150	77.40	77.40	0.0	0.0	0.0	0.0
2.3150	387.00	387.00	420.00	420.00	0.0	0.0
2.3850	604.00	604.00	713.00	713.00	598.00	598.
2.4100	682.00	682.00	713.00	713.00	812.00	812.
2.4430	682.00	682.00	713.00	713.00	1094.00	1094.

```
STEER TABLE
NUMBER OF LINES:   02

TIME      STEER ANGLE
(SEC)        (DEG)

0.,0.
1.,4.62
ECHO TABLE? Y
```

TIME (SEC)	STEER ANGLE (DEG)
0.0	0.0
1.0000	4.62

```
CHANGE PARAMETERS? N
CHANGE BRAKE FORCE TABLE? N
CHANGE STEER TABLE? N
ECHO STATIC LOADS? Y
   STATIC LOADS (LB.)
 TRACTOR FRONT AXLE:            8233.49
 TRACTOR LEADING TANDEM:        4966.02
         TRAILING TANDEM:       4966.02
 TRAILER LEADING TANDEM:        3982.23
         TRAILING TANDEM:       3982.23

ENTER INITIAL ARTIC. ANGLE:  0.
WILL ARTIC. ANGLE BE VARIED?  N
ANY DATA CHANGES NOW?  N


       *** END OF INPUT ***
```

Figure 10. Input data for brake and steer tables. (Continuation of input data shown in Figure 6.)

The option set by the user as to whether or not he wants to enter one MU-slip curve for all tires on the vehicle remains as specified in the input data until the program is reloaded. Hence, if the user specified one MU-slip curve for all tires, he need only change MUP(1), MUS(1), and SP(1) to effect a new MU-slip curve for all the tires. (It should be noted that with the single MU-slip curve option in effect, the user may change <u>only</u> MUP(1), MUS(1), or SP(1) and not any other elements of MUP, MUS, or SP.) If the single MU-slip curve option wasn't in effect, the user must change the MU-slip curves for the tractor front, tractor rear, and trailer tires separately.

The brake and steer tables may also be changed. Lines may be added after the last entry as long as the table capacity isn't exceeded. Fifteen lines are permitted for the brake table; twenty-five are permitted for the steer table. Any lines already contained in either table may be changed by reentering those lines with the new values.

After the brake and steer tables have been changed and the static axle loads displayed (upon command), the user must enter the initial articulation angle. If he enters zero for this angle, and it is the first time through the program's execution, the user is asked, "WILL ARTIC. ANGLE BE VARIED?" If he answers "NO," the initial articulation angle will thereafter be assumed zero until the program is reloaded. If the user answers "YES," or if, initially, he entered a non-zero value for the articulation angle, he will have to enter the initial articulation angle each time he goes through the change procedure.

Before the input is ended, the user is asked one last time whether or not the data set, including the brake and steer tables, is correct. If it is not, the entire change procedure is repeated.

An example of the "change procedure" is shown in Figure 11. The number of changes shown is large in order that the change procedure be clearly understood. (A flow diagram of the change procedure is shown on page 52 .)

3.4 OUTPUT

There are 83 output variables for the articulated vehicle and 52 for the straight truck. Each of these may be displayed as a function of time. These variables are shown in Figures 12 and 13. They may be listed at the terminal on command the first time through the program's execution. It should be noted that the output variables FX, FSX, FY, and FZ are given for each side of each axle.

As shown in Figure 14, the user specifies the number of output variables (to a maximum of 6), their identifying numbers, and the time step upon which the output will be printed.* After this output has been echoed, the user may demand more output in the same manner. When the user has seen (or has put on file) all the output variables he wishes, he answers "NO" to the question, "DO YOU WANT ANY MORE OUTPUT?" The run is then completed. The user may then change the input data or else input a whole new data set.

*It should be noted that the times actually printed on output may be as much as .02 sec off the desired values, due to the method of integration of HPCG and the manner in which the next time step to be displayed is triggered.

Figure 11. Change procedure. (Underlined quantities are responses of user.)

```
STOP? N
CHANGE PARAMETERS? Y

ENTER PARAMETER NUMBER TO BE CHANGED (01-42)
23
23   VEL            INITIAL VELOCITY: U-DIRECTION (MPH)      40.
                                                  (FPS)                58.67
? 24
24   TIME           MAX. SIMULATION TIME FOR THIS RUN (SEC) 5.0
? 26

ANTEFF              ANTILOCK EFFECTIVENESS COEFFICIENT (LAT.,LONG.)
26                                   FRONT AXLE: ANTEFF= .5,0.
? 42
42 TANDEM AXLE/DUAL TIRE CODE (4I1): 1011
05   AA             DIST. BETWEEN TRACTOR TANDEM AXLES (IN) 50.
21   GAM3           TRACTOR TANDEM AXLE LOAD X-FER COEF.     -.3
06   AAT            DIST. BETWEEN TRAILER TANDEM AXLES (IN) 50.
22   GAM4           TRAILER TANDEM AXLE LOAD X-FER COEF.     .2
? 21
21   GAM            TRACTOR TANDEM AXLE LOAD X-FER COEF.     .3
? 0
CHANGE BRAKE FORCE TABLE? Y
ADD NEW LINES? N
HOW MANY LINES ARE TO BE CHANGED? 02
ENTER LINE NUMBERS TO BE CHANGED:  02,07

ENTER CORRECTIONS:
2.1,0.,0.,0.,0.,0.,0.
2.5,682.,682.,713.,713.,1094.,1094.
```

TIME (SEC)	DESIRED FORCES: FSX(1)	FSX(2)	FSX(3)	FSX(4)	FSX(7)	FSX(8)
0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.1000	0.0	0.0	0.0	0.0	0.0	0.0
2.2150	77.40	77.40	0.0	0.0	0.0	0.0
2.3150	387.00	387.00	420.00	420.00	0.0	0.0
2.3850	604.00	604.00	713.00	713.00	598.00	598.00
2.4100	682.00	682.00	713.00	713.00	812.00	812.00
2.5000	682.00	682.00	713.00	713.00	1094.00	1094.00

```
IS TABLE CORRECT NOW? Y
```

Figure 11. (cont.)

```
CHANGE STEER TABLE? Y
ADD NEW LINES? Y
HOW MANY LINES ARE TO BE ADDED? 01

ENTER NEW LINES:
5.,0.

  TIME      STEER ANGLE
  (SEC)        (DEG)

    0.0          0.0
    1.0000       4.62
    5.0000       0.0
IS TABLE CORRECT NOW? N
ADD NEW LINES? N
HOW MANY LINES ARE TO BE CHANGED? 01
ENTER LINE NUMBERS TO BE CHANGED:  02

ENTER CORRECTIONS:
2.,2.

  TIME      STEER ANGLE
  (SEC)        (DEG)

    0.0          0.0
    2.0000       2.00
    5.0000       0.0
IS TABLE CORRECT NOW? Y
ECHO STATIC LOADS? Y
    STATIC LOADS (LBS)
 TRACTOR FRONT AXLE:           8233.49
 TRACTOR LEADING TANDEM:       4966.02
         TRAILING TANDEM:      4966.02
 TRAILER LEADING TANDEM:       3982.23
         TRAILING TANDEM:      3982.23
ANY DATA CHANGES NOW? Y
CHANGE PARAMETERS? Y

ENTER PARAMETER NUMBER TO BE CHANGED (01-42)
29
  CALF          CORNERING STIFFNESS OF TIRES (LBS/DEG)
29                                                 CALF(1)= 400.
? 0
CHANGE BRAKE FORCE TABLE? N
CHANGE STEER TABLE? N
ECHO STATIC LOADS? N
ANY DATA CHANGES NOW? N


    *** END OF INPUT ***
```

Figure 12. List of tractor-trailer output variables.

```
DO YOU WANT A LIST OF OUTPUT VARIABLES? Y

*** POSITION VARIABLES ***

 1          X0-COORD
 2          Y0-COORD
 3               PSI
 4             GAMMA

*** VELOCITY VARIABLES ***

 5             U-VEL
 6             V-VEL
 7            PSIDOT
 8          GAMMADOT

***

 9          TURN RAD
10          SIDESLIP

*** TIRE SLIP ANGLES ***

11          ALFA 1+2
12          ALFA 3+4
13          ALFA 5+6
14          ALFA 7+8
15          ALFA9+10

*** ACCELERATION VARIABLES ***

16             U-DOT
17             V-DOT
18          PSI-DDOT
19          GAM-DDOT
20          LONG ACC
21          LAT. ACC

*** TIRE-ROAD INTERFACE FORCES ***
*** BRAKE FORCES: FX(I), SIDE FORCES FY(I) ***

22             FX(1)
23             FX(2)
24             FX(3)
25             FX(4)
26             FX(5)
27             FX(6)
28             FX(7)
29             FX(8)
30             FX(9)
31            FX(10)
32             FY(1)
33             FY(2)
34             FY(3)
35             FY(4)
36             FY(5)
```

37	FY(6)
38	FY(7)
39	FY(8)
40	FY(9)
41	FY(10)

*** LOAD TRANSFERS, LONG. DFX(I),LAT. DFY(I) ***

42	DFX(1)
43	DFX(2)
44	DFX(3)
45	DFX(4)
46	DFX(5)
47	DFX(6)
48	DFX(7)
49	DFX(8)
50	DFX(9)
51	DFX(10)
52	DFY(1)
53	DFY(2)
54	DFY(3)
55	DFY(4)
56	DFY(5)
57	DFY(6)
58	DFY(7)
59	DFY(8)
60	DFY(9)
61	DFY(10)

*** IN TANTANEOUS LOAD FORCES ***

62	FZ(1)
63	FZ(2)
64	FZ(3)
65	FZ(4)
66	FZ(5)
67	FZ(6)
68	FZ(7)
69	FZ(8)
70	FZ(9)
71	FZ(10)

*** PROGRAMMED BRAKE FORCES ***

72	FSX(1)
73	FSX(2)
74	FSX(3)
75	FSX(4)
76	FSX(5)
77	FSX(6)
78	FSX(7)
79	FSX(8)
80	FSX(9)
81	FSX(10)

*** HITCH FORCES ***

82	XH
83	YH

```
DO YOU WANT A LIST OF OUTPUT VARIABLES? Y

*** POSITION VARIABLES ***

 1          X0-COORD
 2          Y0-COORD
 3               PSI

*** VELOCITY VARIABLES ***

 4             U-VEL
 5             V-VEL
 6           PSI-DOT

***

 7          TURN RAD
 8          SIDESLIP

*** TIRE SLIP ANGLES ***

 9          ALFA 1+2
10          ALFA 3+4
11          ALFA 5+6

*** ACCELERATION VARIABLES ***

12             U-DOT
13             V-DOT
14          PSI-DDOT
15          LONG ACC
16          LAT. ACC
```

Figure 13. List of truck output variables.

◆◆◆ TIRE-ROAD INTERFACE FORCES ◆◆◆
◆◆◆ BRAKE FORCES: FX(I), SIDE FORCES FY(I) ◆◆◆

17	FX(1)
18	FX(2)
19	FX(3)
20	FX(4)
21	FX(5)
22	FX(6)
23	FY(1)
24	FY(2)
25	FY(3)
26	FY(4)
27	FY(5)
28	FY(6)

◆◆◆ LOAD TRANSFERS, LONG. DFX(I),LAT. DFY(I) ◆◆◆

29	DFX(1)
30	DFX(2)
31	DFX(3)
32	DFX(4)
33	DFX(5)
34	DFX(6)
35	DFY(1)
36	DFY(2)
37	DFY(3)
38	DFY(4)
39	DFY(5)
40	DFY(6)

◆◆◆ INSTANTANEOUS LOAD FORCES ◆◆◆

41	FZ(1)
42	FZ(2)
43	FZ(3)
44	FZ(4)
45	FZ(5)
46	FZ(6)

◆◆◆ PROGRAMMED BRAKE FORCES ◆◆◆

47	FSX(1)
48	FSX(2)
49	FSX(3)
50	FSX(4)
51	FSX(5)
52	FSX(6)

Figure 13. (cont.)

```
PRINT OUTPUT ON FILE? N
ENTER TOTAL NUMBER OF OUTPUT VARIABLES (01-06): 05

ENTER NUMBERS OF VARIABLES YOU WANT
SEPARATE NUMBERS BY COMMAS-(01,83)
05,20,21,07,04

ENTER TIME INCREMENT TO BE PRINTED OUT
.25
```

TIME	U-VEL	LONG ACC	LAT. ACC	PSIDOT	GAMMA
0.0	39.31	-0.0	0.0	0.0	0.0
0.26	39.30	-0.02	1.65	1.48	-0.13
0.52	39.30	-0.07	3.32	4.17	-0.77
0.76	39.28	-0.14	5.03	6.87	-1.81
1.02	39.24	-0.23	6.80	9.80	-3.32
1.26	39.21	-0.22	7.30	11.23	-4.86
1.52	39.17	-0.22	7.74	11.63	-6.26
1.76	39.12	-0.24	7.91	11.72	-7.22
2.02	39.07	-0.26	7.98	11.74	-7.95
2.26	38.98	-1.76	7.74	11.74	-8.42
2.52	37.11	-10.22	7.34	11.39	-8.81
2.76	34.68	-10.18	7.11	10.75	-9.02
3.02	32.04	-10.20	6.14	10.04	-9.15
3.26	29.61	-10.23	5.24	9.40	-9.24
3.52	26.97	-10.26	4.32	8.70	-9.34
3.76	24.53	-10.30	3.54	8.03	-9.44
4.02	21.87	-10.33	2.76	7.27	-9.55
4.26	19.41	-10.35	2.11	6.52	-9.65
4.52	16.73	-10.32	1.62	5.64	-9.75
4.76	14.26	-10.32	0.77	4.88	-9.85
5.02	11.60	-10.28	0.47	3.99	-9.93
5.26	9.14	-10.27	0.12	3.16	-10.00
5.52	6.48	-10.26	-0.18	2.25	-10.06
5.76	4.02	-10.25	-0.29	1.40	-10.09
6.02	1.35	-10.25	-0.29	0.48	-10.11

```
DO YOU WANT ANY MORE OUTPUT? Y
```

Figure 14. Output of tractor-trailer program. (Continuation of Figures 6 and 10.)

```
ENTER TOTAL NUMBER OF OUTPUT VARIABLES (01-06): 02

ENTER NUMBERS OF VARIABLES YOU WANT
SEPARATE NUMBERS BY COMMAS-(01,83)
01,02
```

TIME	X0-COORD	Y0-COORD
0.0	0.0	0.0
0.26	10.22	0.02
0.52	20.44	0.15
0.76	29.86	0.47
1.02	40.04	1.15
1.26	49.40	2.17
1.52	59.47	3.74
1.76	68.67	5.65
2.02	78.50	8.21
2.26	87.44	11.03
2.52	96.76	14.49
2.76	104.67	17.90
3.02	112.45	21.73
3.26	118.92	25.32
3.52	125.18	29.19
3.76	130.30	32.65
4.02	135.16	36.22
4.26	139.05	39.30
4.52	142.64	42.33
4.76	145.42	44.80
5.02	147.87	47.10
5.26	149.66	48.83
5.52	151.09	50.27
5.76	151.97	51.17
6.02	152.45	51.68

```
DO YOU WANT ANY MORE OUTPUT? N
```

Figure 14. (cont.)

4. SAMPLE RESULTS

Figure 15 shows the input data used to simulate a Diamond Reo straight truck. This truck is described in detail in Reference 2. The brake and steer tables were set up to simulate braking in a turn. The results were compared to measurements and Phase II simulation results (Ref. 2, p. 98) obtained previously for the same maneuver (Fig. 16).* Since the TBS simulation is quasi-static, the brake force at the tires occurs instantaneously with the actuation of the brakes. Hence the longitudinal force, AX, due to the brakes is generated about two-tenths of a second before it occurs on the actual vehicle as shown by the measured results in Figure 16. Because the brake force is actuated early, the TBS simulation predicts that the vehicle stops early, as can be inferred from the yaw rate time history. The magnitude of the yaw rate reaches a higher value in the TBS simulation than for the measured results, since aligning torque and front roll steer were ignored in the TBS simulation. These effects were included in the Phase II simulation, and hence the agreement between the Phase II simulation results and measured results is much better than that yielded by TBS.

Figure 6, previously referred to in Section 3.2, shows the input data used to simulate a White tractor and a Freuhauf trailer. The brake and steer tables entered (Fig. 10) were used to simulate the same maneuver as was run and simulated in the Phase II work (Ref. 2). Figure 18 shows a comparison of the TBS results and the measured and Phase II simulation results.** Again, the differences in the longitudinal and yaw rate time histories is attributed to the fact that the quasi-static simulation predicts premature braking. Further,

---

*The computer output of TBS used to plot the results shown in Figure 16 is shown in Figure 17.

**Figure 14 shows the computer output.

Figure 15. Input data for Diamond Reo truck. (Data read from file.)

```
*** BEGIN INPUT ***
23 ENTER ANTILOCK CODE FOR TRACTOR FRONT, TRACTOR REAR
    0=NO ANTILOCK,  1=INDEPENDENT ANTILOCK,  FORMAT=2I1
00
24 ENTER CODE FOR TANDEM AXLES TRACTOR REAR, DUAL TIRES
    TRACTOR REAR
    0=NO,  1=YES,  FORMAT=2I1
11

INPUT PARAMETER TABLE

NO. SYMBOL      DESCRIPTION                                        INITIAL VALUE

01  GVW1        WT. OF TRACTOR (LBS)                                  21375.00
02  IZZ         TRACTOR MOM. OF INERTIA (IN-LB-SEC**2)               605500.00
03  AA          DIST. BETWEEN TRACTOR TANDEM AXLES (IN)                  50.00
04  A1          DIST. FROM TRACTOR CG TO FRONT AXLE(IN)                 113.00
05  A2          DIST. FROM TRACTOR CG TO REAR AXLE(IN)                   77.00
06  TRA1        HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                  CONTACT ON TRACTOR FRONT AXLE (IN)                     40.00
07  TRA2        HALF LAT. DIST. BETWEEN CENTERS OF TIRE
                  CONTACT ON TRACTOR REAR AXLE(S) (IN)                   36.00
08  Z1          HEIGHT OF TRACTOR CG ABOVE GROUND(IN)                    46.40
09  GAM1        PORTION OF TOTAL LAT. LOAD TRANSFER
                  ON FRONT AXLE OF TRACTOR                                0.20
10  GAM2        TRACTOR TANDEM AXLE LOAD X-FER COEF.                      0.0
11  VEL         INITIAL VELOCITY: U-DIRECTION (MPH)                      25.20
                                              (FPS)                      36.96
12  TIMF        MAX. SIMULATION TIME FOR THIS RUN (SEC)                   6.00
  CALF        CORNERING STIFFNESS OF A TIRE (LB/DEG)
15                                                CALF(1)=              623.00
16                                                CALF(3)=              215.00
  MUP         PEAK TIRE-ROAD FRICTION COEFFICIENT
17                                                 MUP(1)=                0.87
18                                                 MUP(3)=                0.96
  MUS         SLIDING TIRE-ROAD FRICTION COEF.
19                                                 MUS(1)=                0.74
20                                                 MUS(3)=                0.74
  SP          SLIP CORRESPONDING TO PEAK MU
21                                                  SP(1)=                0.11
22                                                  SP(3)=                0.11

    BRAKE FORCE TABLE
    NUMBER OF LINES:   4

    TIME                             DESIRED FORCES:
    (SEC)      FSX(1)      FSX(2)      FSX(3)      FSX(4)

    0.0         0.0         0.0         0.0         0.0
    2.0320      0.0         0.0         0.0         0.0
    2.0700    109.00      109.00        0.0         0.0
    2.3140    849.00      849.00     1510.00     1510.00


       STEER TABLE
    NUMBER OF LINES:   2

  TIME      STEER ANGLE
  (SEC)        (DEG)

    0.0          0.0
    1.0000       7.70
CHANGE PARAMETERS? N
CHANGE BRAKE FORCE TABLE? N
CHANGE STEER TABLE? N
ECHO STATIC LOADS? Y
    STATIC LOADS (LBS)
 FRONT AXLE:            8662.49
 LEADING TANDEM:        6356.25
 TRAILING TANDEM:       6356.25
ANY DATA CHANGES NOW? N


    *** END OF INPUT ***
```

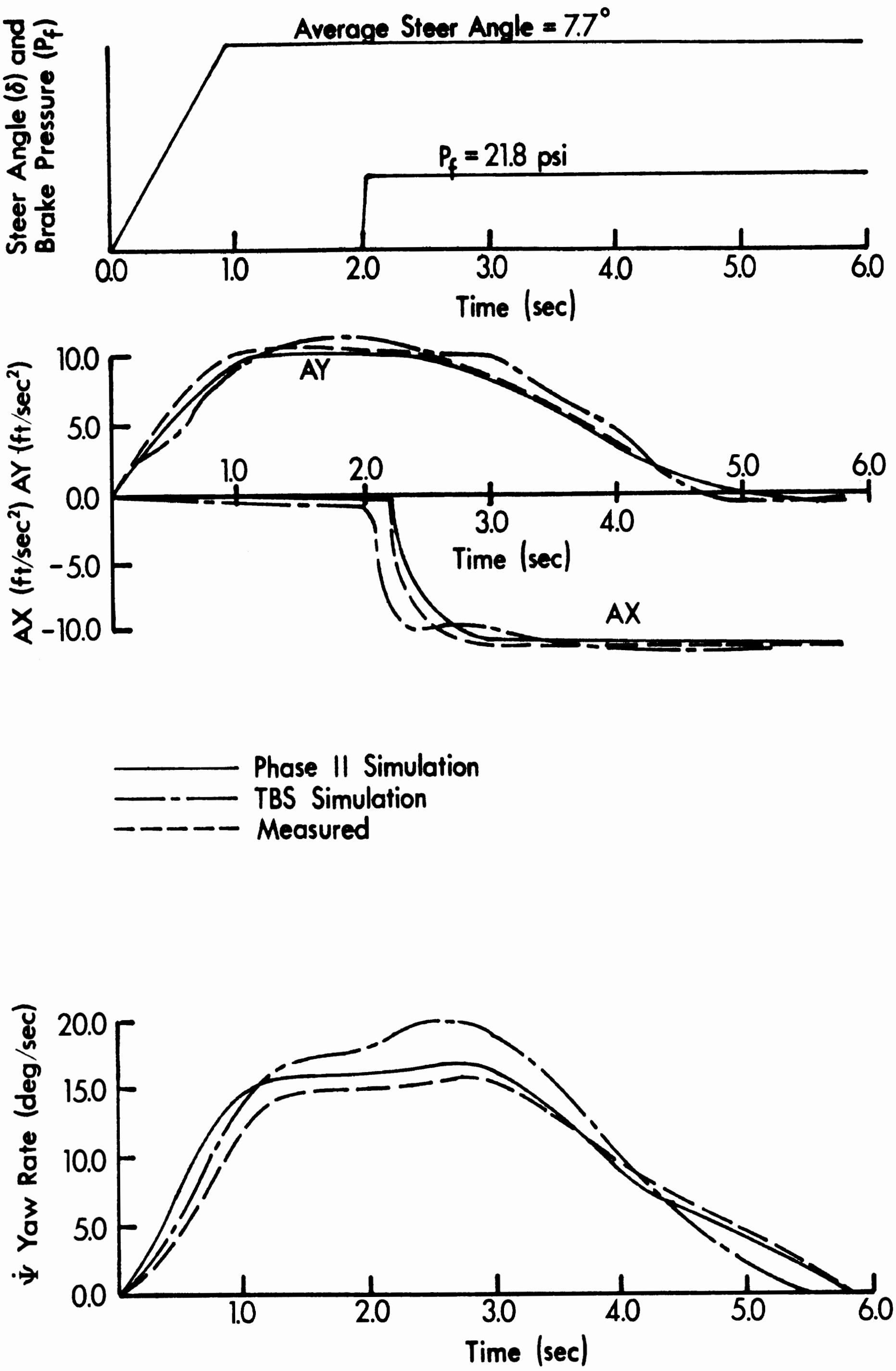


Figure 16. Time history of a braking-in-a-turn maneuver.

```
ENTER THE TOTAL NUMBER OF OUTPUT VARIABLES (01-06): 03

ENTER NUMBERS OF VARIABLES YOU WANT
SEPARATE NUMBERS BY COMMAS-(01,52)
15,16,06

ENTER TIME INCREMENT TO BE PRINTED OUT
.25



       TIME   LONG ACC   LAT. ACC    PSI-DOT
      0.0       -0.0       0.0        0.0
      0.26      -0.07      2.24       2.14
      0.52      -0.22      4.37       5.98
      0.76      -0.43      6.60       9.85
      1.02      -0.69      8.88      14.11
      1.26      -0.63      9.64      16.45
      1.52      -0.63     10.46      17.46
      1.76      -0.64     10.93      17.92
      2.02      -0.65     11.22      18.16
      2.25      -8.97      8.73      18.80
      2.50     -10.14     10.05      19.95
      2.76      -9.95     10.49      19.86
      3.00     -10.04     10.02      18.93
      3.26     -10.36      8.79      17.17
      3.50     -10.80      7.21      15.06
      3.76     -11.36      5.26      12.55
      4.00     -11.76      4.39       9.74
      4.26     -11.70      1.56       6.88
      4.50     -11.67      0.57       5.28
      4.76     -11.64     -0.04       3.74
      5.00     -11.62     -0.38       2.35
      5.26     -11.62     -0.38       0.87
      5.42     -11.62     -0.38      -0.04
DO YOU WANT ANY MORE OUTPUT? N

*** TRUCK HAS STOPPED IN  5.42 SECONDS ***
```

Figure 17. Output of truck program.

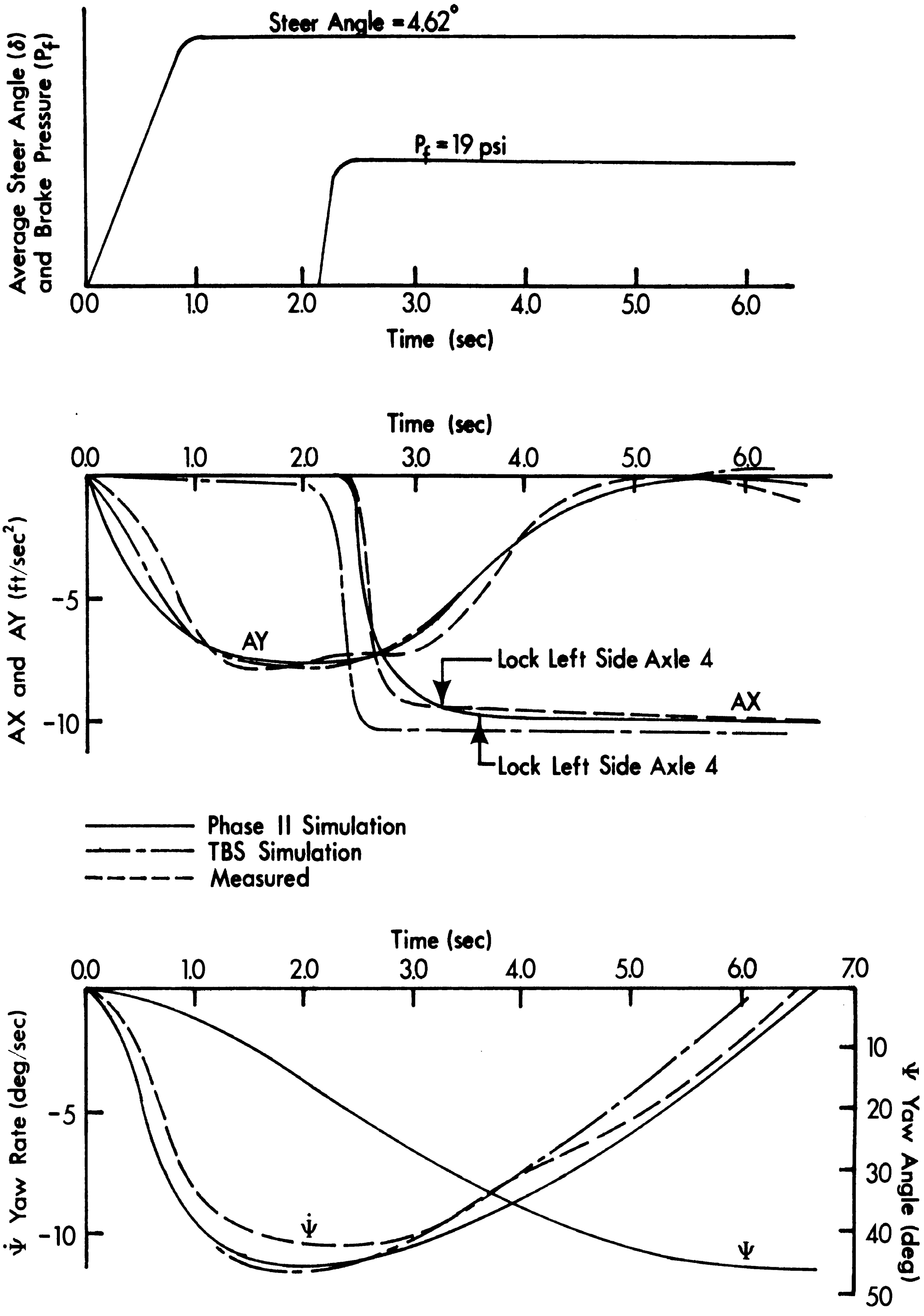


Figure 18. Time history of a braking-in-a-turn maneuver.

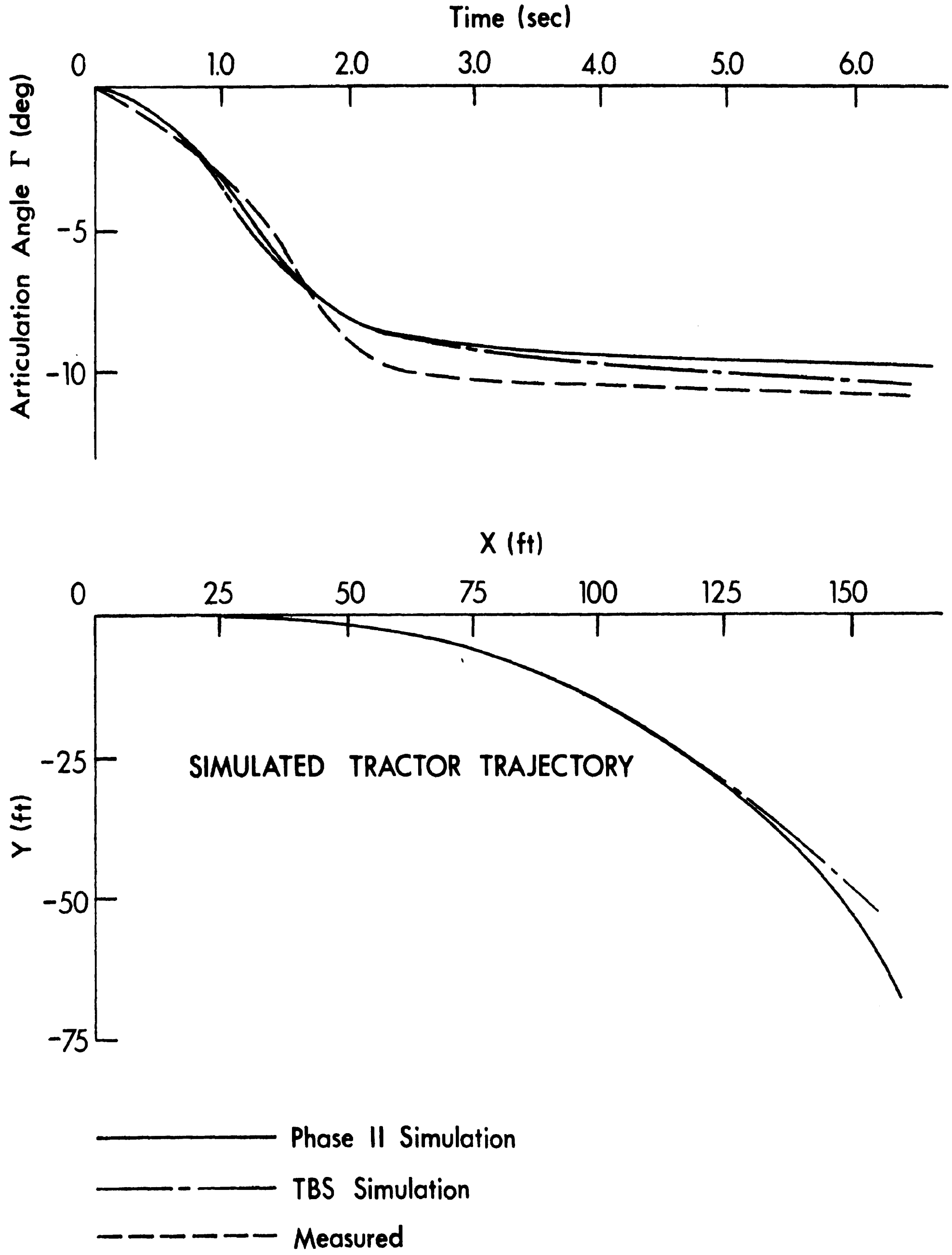


Figure 18. (Cont.)

the quasi-static load transfer of the TBS simulation causes the left side of axle 4 (the trailer front tandem axle) to lock immediately upon actuation of the brakes. This illustrates the fact that entering the inter-axle load transfer coefficients, GAM3 and GAM4*, results in the correct prediction of which wheel locks,** though the time of the occurrence is miscalculated. It should be noted that if GAM3 and GAM4 were ignored (setting them equal to 0), lockup would not have been predicted.

---

*These coefficients were estimated very crudely using engineering judgment, based on the considerations outlined on page 6.

**Lockup is determined by comparing the outputs of attempted brake force, FSX, and achieved brake force, FX. If FX is less than FSX, lockup has occurred.

5. CONCLUDING REMARKS

A computer program for predicting the braking and steering response of trucks and tractor-semitrailers has been presented in this report.

This program uses a vehicle model which is much less complex than the comprehensive model developed by HSRI in Reference 1. Nevertheless, the model has features which provide means for representing brake imbalance, tandem axles, dual tires, longitudinal and lateral load transfer, the interaction of longitudinal slip and slip angle in determining the longitudinal and lateral components of tire shear force, and the effectiveness of antilock braking systems.

This program is designed for user convenience. The model employs a relatively small number of input parameters in order to simplify the parameter-gathering demands placed on the user. The program is written in an interactive form for use at a computer terminal. The user is guided by cues printed out at the terminal. Thus, the user can load the input data, operate the simulation, and tabulate vehicle response variables with only a limited familiarity with the computer program.

It is intended that this computer program be useful for (1) making preliminary studies of new or proposed vehicle designs, (2) addressing engineering questions concerning combined braking and steering maneuvers, (3) planning large-scale vehicle test programs, or (4) planning detailed simulation analyses using more complex vehicle models.

6. REFERENCES

1. Bernard, J.E., "A Computer Based Mathematical Method for the Prediction of Braking Performance of Trucks and Tractor-Trailers," SAE Paper No. 730181, 1973.

2. Bernard, J.E., Winkler, C.B., and Fancher, P.S., A Computer Based Mathematical Method for Predicting the Directional Response of Trucks and Tractor-Trailers, Phase II Technical Report, Motor Truck Braking and Handling Performance Study, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-PF-73-1, June 1, 1973.

3. Moncarz, H.T. and Bernard, J.E., An Interactive Computer Program for the Prediction of Commercial Vehicle Braking Performance, Highway Safety Research Institute, Univ. of Michigan, Ann Arbor, Report No. UM-HSRI-PF-75-4, April 1975.

4. Leucht, P.M., "Directional Dynamics of the Tractor-Semitrailer Vehicle," Ph.D. Thesis, Mechanical Engineering Dept., Univ. of Michigan, 1970.

5. System/360 Scientific Subroutine Package, Version III, Programmer's Manual.

6. Winkler, C.B., "Analysis and Computer Simulation of the Four Elliptical Leaf Spring Tandem Suspension," SAE Paper No. 740136, 1974.

7. Fiala, E., "Seitenkrafte am rollenden Luftreifen," (Lateral Forces on Rolling Pneumatic Tires), Zeitschrift V.D.I., 96, No. 29, October 1954.

8. McHenry, R.R., et al., Vehicle Dynamics in Single-Vehicle Accidents, National Technical Information Service, PB 182 663, December 1968.

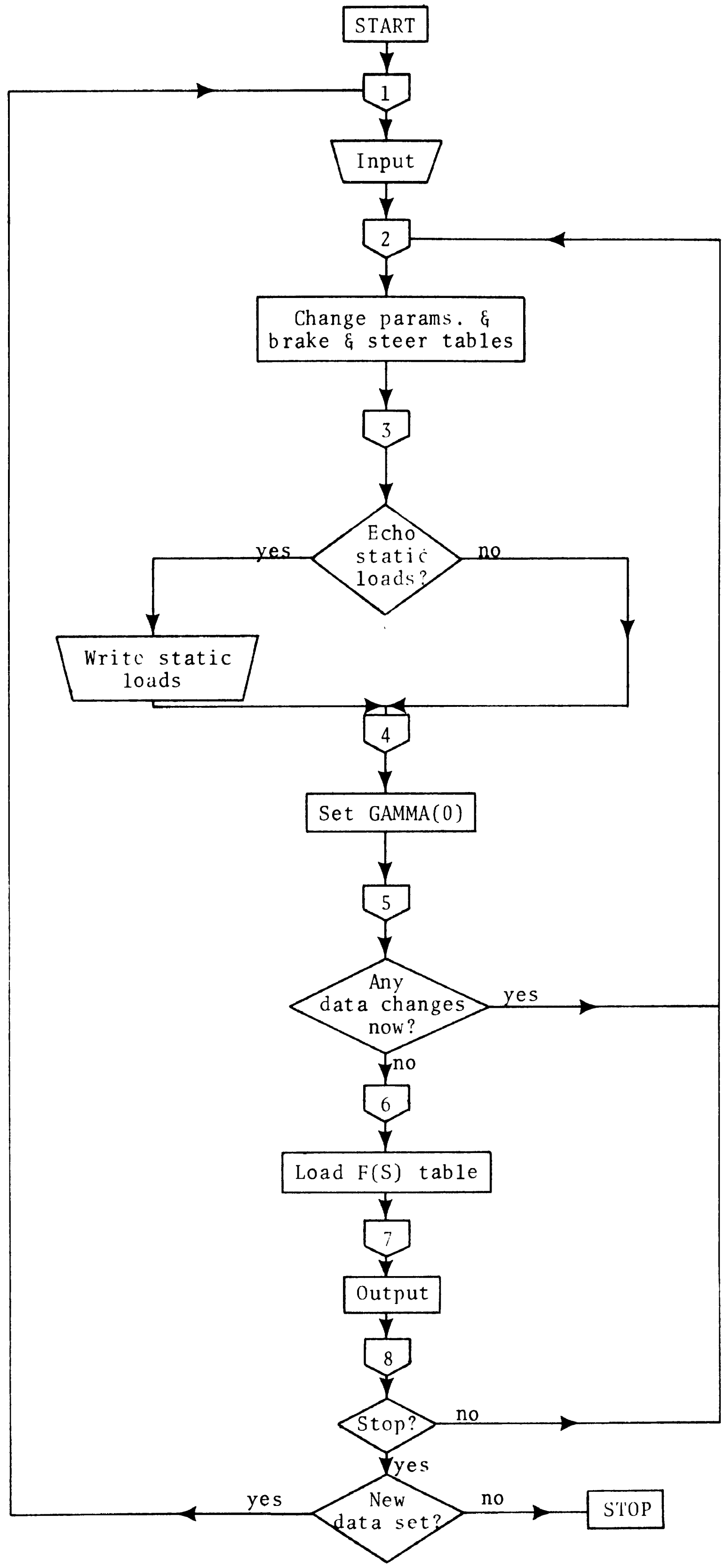
9. Bohn, P.F. and Keenan, R.J., Hybrid Computer Vehicle Handling Program, The Johns Hopkins University, Applied Physics Laboratory, Report No. DOT-HS-801-290, November 1974.

10. Dry Braking and Cornering Tests of 8.00-16.5E and 10.00-20F Truck Tires, Calspan Report No. ZM-5656-T, January 27, 1975.

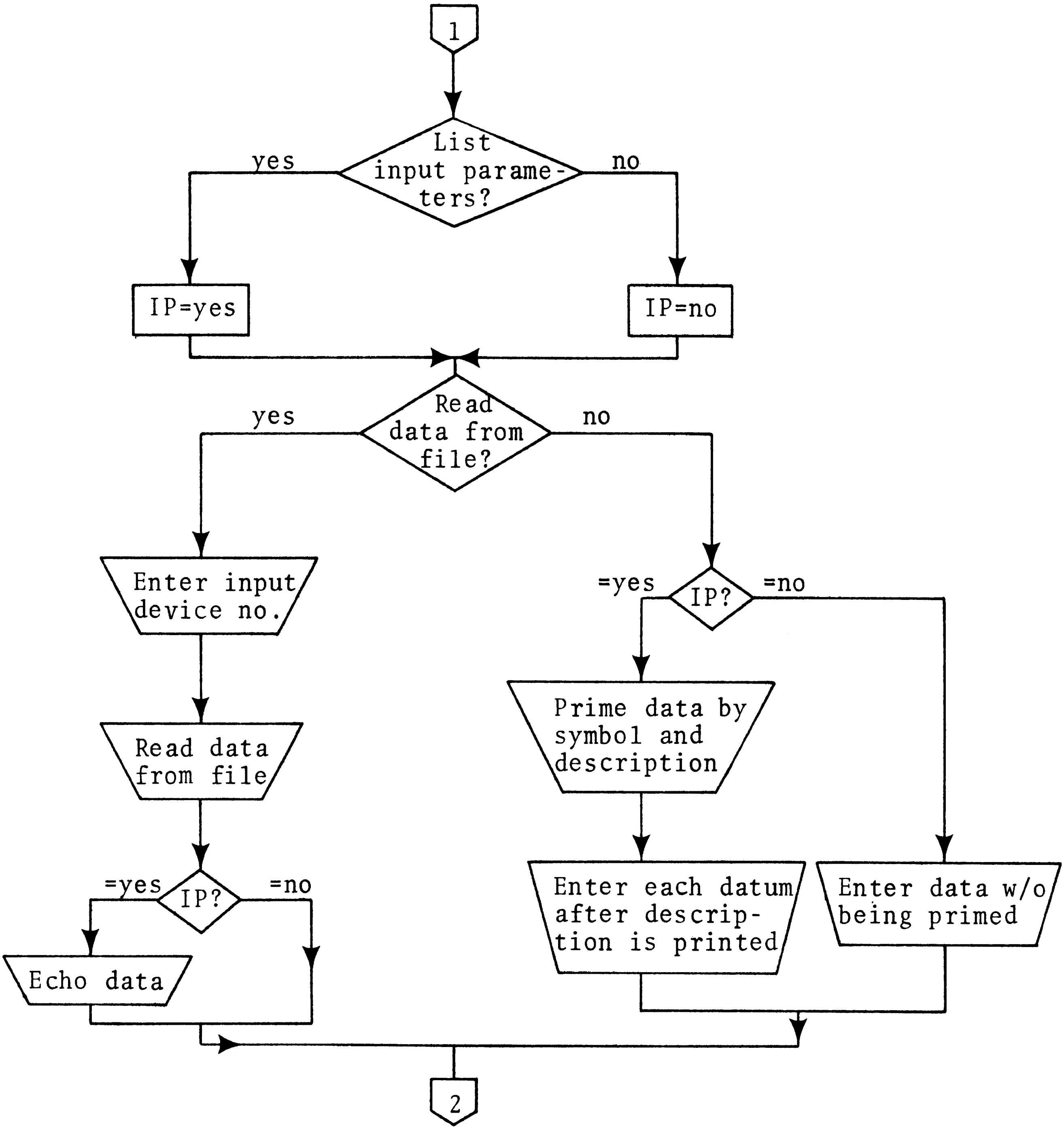
APPENDIX

This appendix contains a flow chart which indicates the options available to the user in running the TBS computer program.

Users Flow Chart

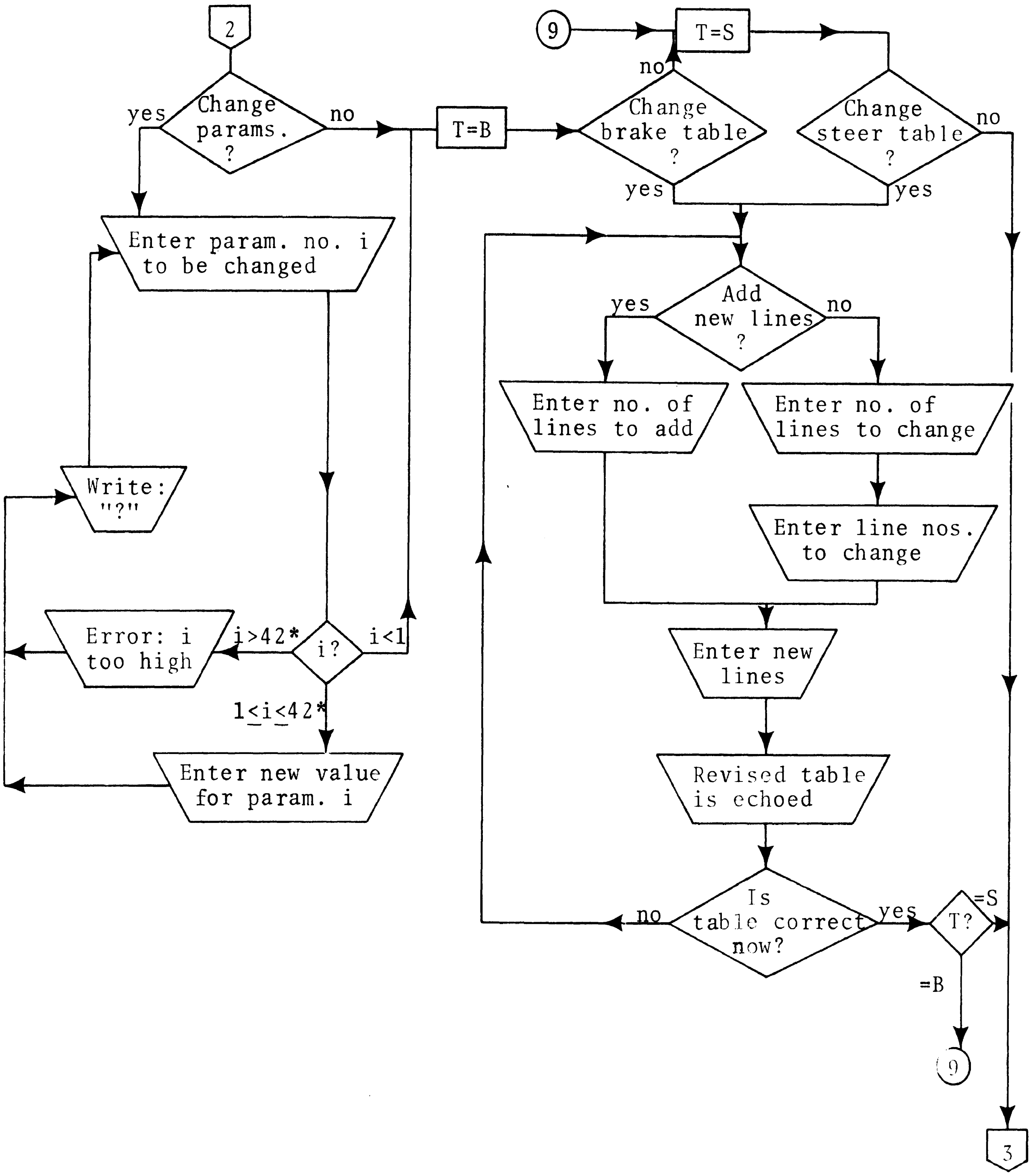


Input



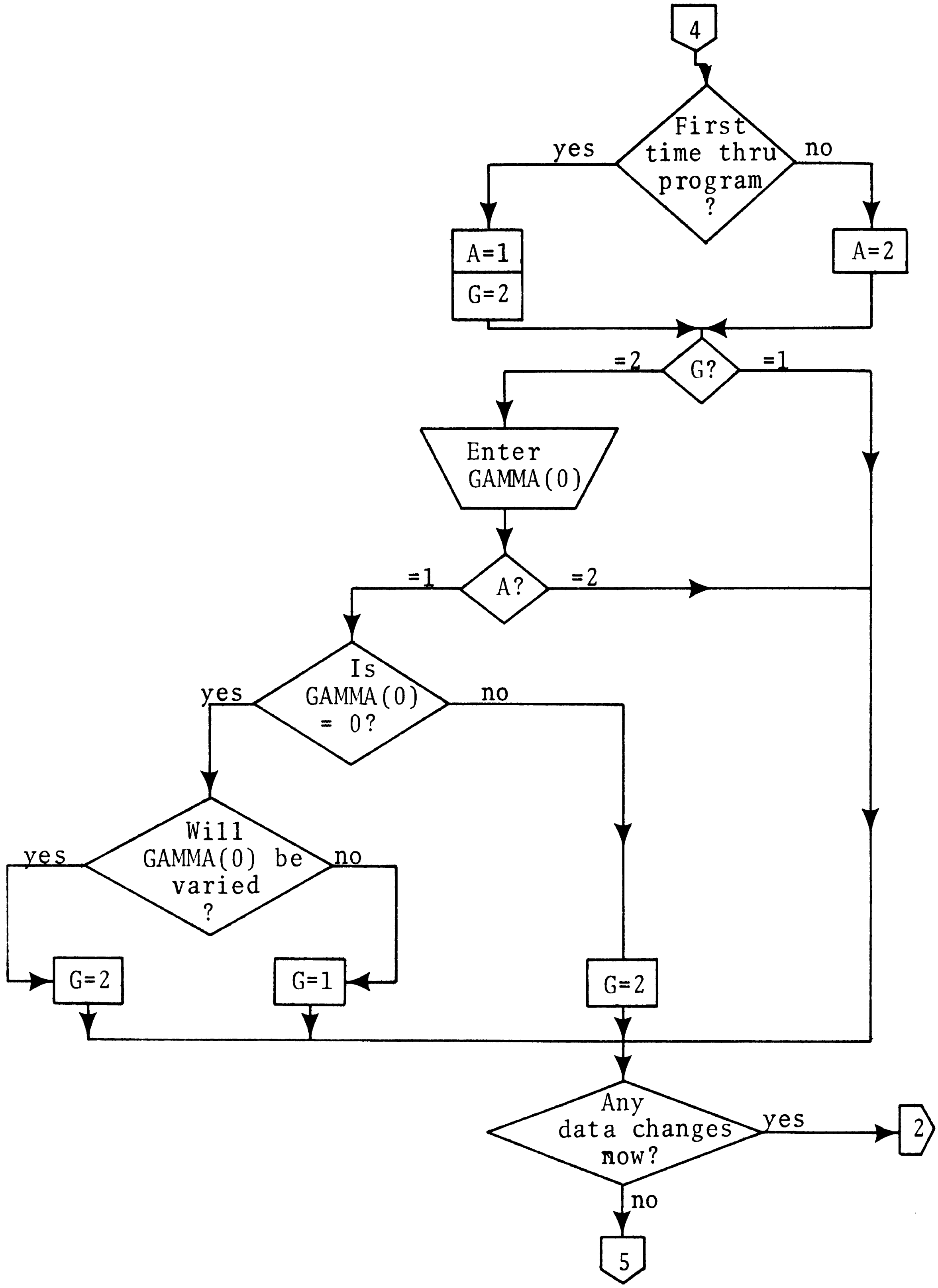
1
List input parameters?
yes
no
IP=yes
IP=no
Read data from file?
yes
no
Enter input device no.
Read data from file
=yes
IP?
=no
Echo data
=yes
IP?
=no
Prime data by symbol and description
Enter each datum after description is printed
Enter data w/o being primed
2

Change Procedure

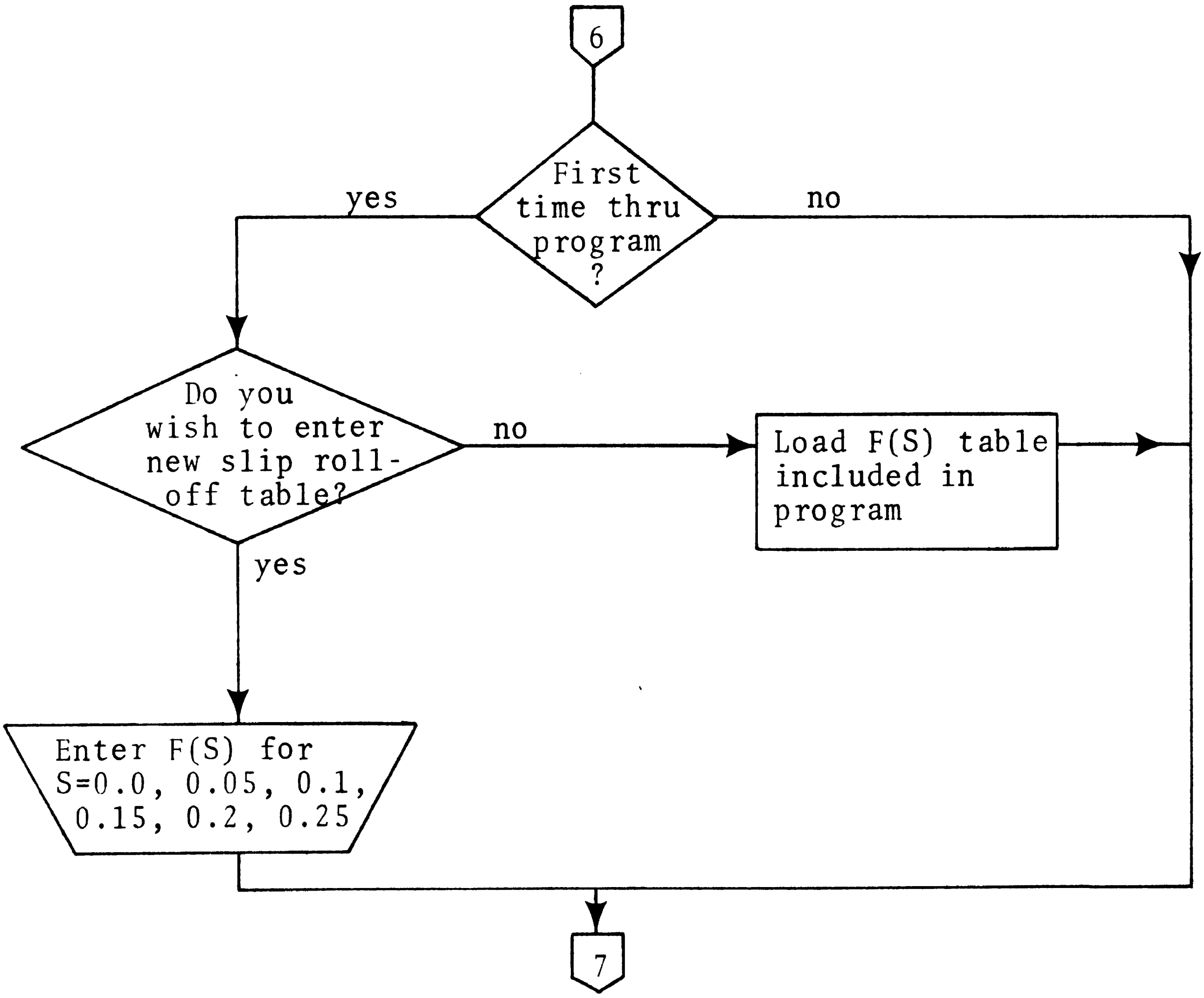


*24 for straight truck program

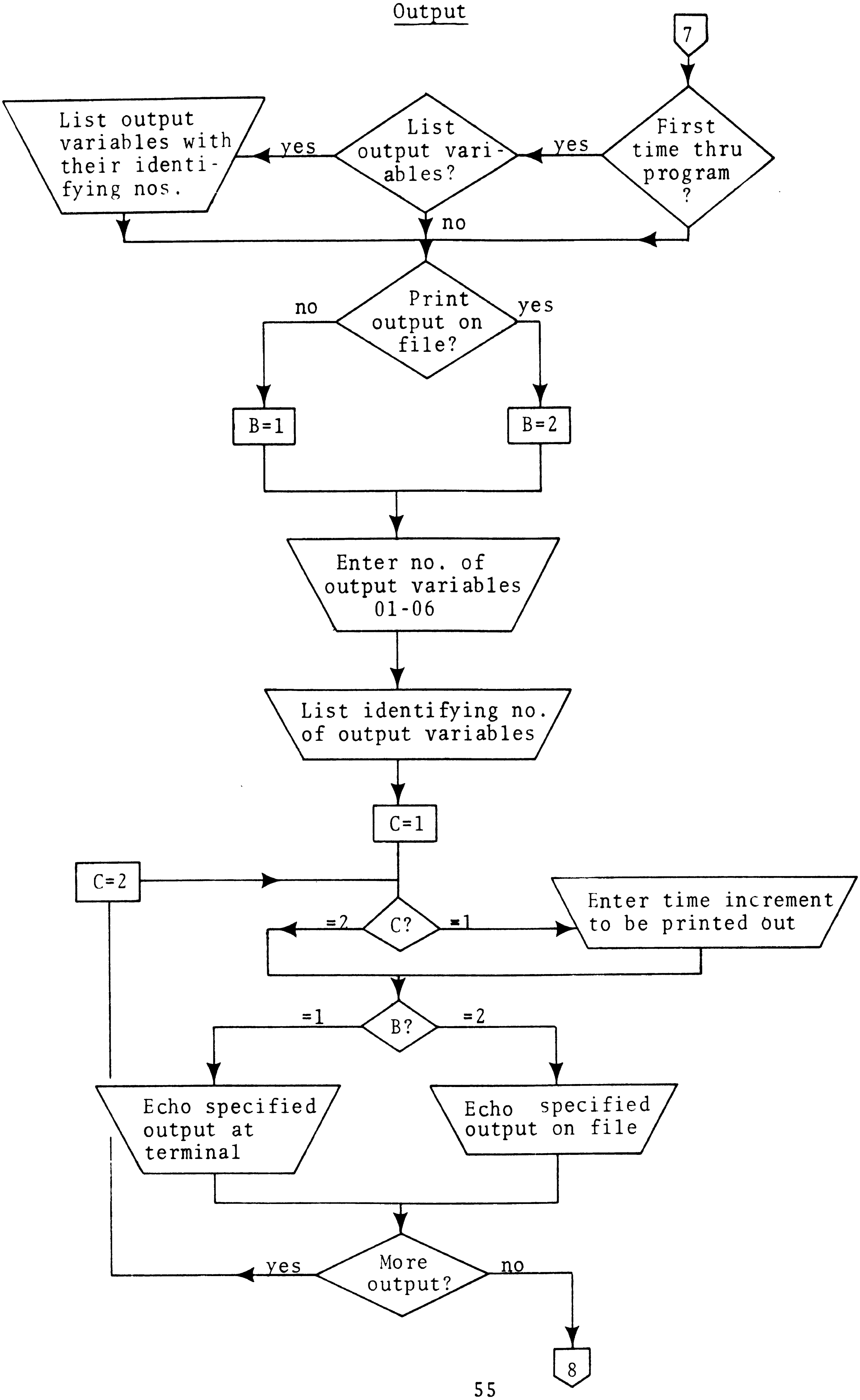
Set Initial Artic. Angle—GAMMA(0)



Load F(S) Table



Output



7
First time thru program ?
yes
List output variables?
yes
List output variables with their identifying nos.
no
Print output on file?
no
yes
B=1
B=2
Enter no. of output variables 01-06
List identifying no. of output variables
C=1
C=2
C?
=2
=1
Enter time increment to be printed out
B?
=1
=2
Echo specified output at terminal
Echo specified output on file
More output?
yes
no
8