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An Interactive Computer Program for the Prediction of Commercial Vehicle Braking Performance

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16. Abstracts

An interactive computer program which predicts the steady-state deceleration and stopping distance of commercial vehicles is documented. The user of this program has the option of entering as input data either brake torques or the brake proportioning. The principal utility of the program lies in its simplicity of input/output and its economy of operation.

17. Key Words and Document Analysis. 17a. Descriptors

braking, proportioning, stopping distance, average deceleration, commercial vehicle

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UM-HSRI-PF-75-4

AN INTERACTIVE COMPUTER PROGRAM FOR THE PREDICTION OF COMMERCIAL VEHICLE BRAKING PERFORMANCE

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Project 360932

Truck and Tractor-Trailer Braking
and Handling Project

April 1975

Sponsored by

The Motor Vehicle Manufacturers Association

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1.0 INTRODUCTION

A variety of computer programs simulating the straight-line braking of commercial vehicles have been developed at HSRI under MVMA sponsorship. These simulations have been developed with the goal of producing results (in terms of vehicle motion time histories) having as much accuracy as technically and economically feasible. In this regard, careful analyses have been performed of (a) unsprung mass dynamics with or without tandem axles and (b) brake and antilock systems.

The resulting computer programs require a large number of input parameters to characterize the geometry and inertial properties, as well as the brake and antilock systems, of the simulated vehicle. The output of the program is also lengthy, and it requires 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 a less complex simulation, having minimal I/O, and which can be run interactively. Two computer programs, which are herein documented, have been developed to meet this need—one for a straight truck and the other for a tractor-trailer. Since both of these computer programs are based on the same assumptions and have similar I/O, it is expedient to have a single name to refer to them. Hence, these two computer programs will be referred to as the BRAKES2 simulation in this documentation.

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*The development of these programs is an ongoing process. Currently, the antilock algorithm is being refined and the tire model is being altered to allow more versatile "μ-slip" relationships.

The next section presents the various capabilities of the BRAKES2 simulation, followed by an assessment of its strengths and weaknesses. Sample runs are presented and compared with results from the previously developed simulations. The last section of the document is devoted to mathematical details and a "user-oriented" flow chart of BRAKES2.

2.0 THE USE OF THE SIMULATION

The BRAKES2 simulation can be run in either of two modes: (1) the brake torque at each axle may be input* and the steady-state deceleration and resulting stopping distance calculated, or (2) the brake proportioning (distribution) may be input and the maximum possible steady-state deceleration and the resulting stopping distance calculated. In either case, the user must input the weight of the straight truck or the weights of the tractor and trailer, the c.g. location(s), and the peak and slide coefficients of friction at each wheel. These input data will be considered in detail in the next section.

2.1 INPUT DATA

For the straight truck program, the total weight of the vehicle and the location of the c.g. are the first parametric values asked for by the interactive program. This is shown by the first four entries in Table 1. For example, the horizontal distance between the location of the center of gravity and the center of the front suspension is represented by datum number, 01, symbol, A1, and parametric value 113 inches. (The data entered in the table describe the Diamond Reo straight truck, which has been extensively tested and simulated [1], [2].) It is not necessary to input the weights or locations of the unsprung masses—the dimensions A1, H, and L locate the c.g. of the total vehicle, which includes both sprung and unsprung masses. Note that for vehicles with tandem axles the wheelbase is measured from the front wheels to a point midway between the tandem axles.

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*That is, the user may select brake torques corresponding to a desired brake line pressure for a given vehicle.

Table 1. A Sample Run of the Straight Truck Program. Note: Underlined quantities are entered by the user.

```
**ENTER DATA**

01 A1   HORIZONTAL DISTANCE BETWEEN TOTAL C.G. AND
          CENTER OF FRONT SUSPENSION (IN)              113.
02 H    HEIGHT OF C.G. ABOVE GROUND (IN)                46.4
03 L    WHEELBASE (IN)                                 190.
04 GVW  WEIGHT OF VEHICLE (LB)                       21375.
13 DO YOU WISH TO INPUT BRAKE DISTRIBUTION? NO


  BRAKE AND TIRE PARAMETERS
PEAK BRAKE TORQUE (IN-LB),ROLLING RADIUS OF TIRE (IN),PEAK FRICTION
COEFFICIENT,EFFECTIVE (OR SLIDING) FRICTION COEFFICIENT: TM,R,MUP,MUE

AXLE 1 (05,07,09,11)          40960.,13.95,.867,.735
AXLE 2 (06,08,10,12)          144000.,20.,.862,.735


**END DATA INPUT**


 THE STEADY-STATE DECEL IS APPROXIMATELY 13.9 FPSPS.


                               AXLE 1        AXLE 2
          TORQUES (IN-LB):   40960.00     144000.00

        STATIC LOADING (LB):    8662.50      12712.50
       DYNAMIC LOADING (LB):   10922.21      10452.79

           BRAKE FORCE (LB):    2053.13       7200.00
 EFFECTIVE FRICTION (FX/FZ):    0.19          0.69

    NEITHER AXLE LOCKED (CYCLED)

INITIAL VELOCITY (MPH): 30.
BRAKE DELAY TIME (SEC): .25
THE ESTIMATED STOPPING DISTANCE IS   81. FEET.

INITIAL VELOCITY (MPH): 60.
BRAKE DELAY TIME (SEC): .25
THE ESTIMATED STOPPING DISTANCE IS  300. FEET.

INITIAL VELOCITY (MPH): 0
```

Similar data are obtained for the tractor-trailer program, as shown in the first ten entries in Table 2. Again, the measurements are taken from the mid-points of tandem axle suspensions. (The data entered in Table 2 describe the White tractor and Fruehauf trailer which has been extensively tested and simulated [1], [2].)

Still to be discussed is the entry of the brake torques, the effective rolling radii of the wheels, and "μ-slip" information. The brake torques may be entered in either of two ways: (a) by specifying the brake torques in inch pounds at each axle, or (b) by specifying the brake proportioning (distribution). The first of these options is illustrated in Tables 1 and 2. The "proportioning" option will be considered in the next section. Note that the brake torque, rolling radius, and peak and slide friction coefficients are entered separately for each axle. The rolling radius entered is assumed to be constant, even though in practice the radius varies slightly due to dynamic changes in the axle loads.

The peak and sliding coefficients of friction define a "μ-slip" curve as shown in Figure 1. (Figure 1 displays the "μ-slip" curve given in Table 1.)

If the axle is equipped with an antilock system, the "effective" coefficient of friction, reflecting "average" antilock performance, should be entered in place of the sliding coefficient.* The peak and sliding coefficients entered are assumed to remain constant, even though in practice these quantities may show some sensitivity to speed and load.

Based on the input data, the quasi-static deceleration may be calculated, as shown in Tables 1 and 2. After the computed axle loads and deceleration data are printed, the program asks for an "initial speed," and a "brake delay time." The brake delay time approximates the average of the lag time between the brake line pressure and the step treadle valve pressure over all the brakes, as illustrated in Figure 2.

*Note that the symbol "MUE" (see Table 1) is used to represent either the effective or the slide coefficient of friction.

Table 2. A Sample Run of the Tractor-Trailer Program. Note: Underlined quantities are entered by the user.

```
01 A1   DISTANCE BETWEEN TRACTOR C.G. AND TRACTOR
          FRONT SUSPENSION (IN)                              63.9
02 A3   DISTANCE BETWEEN TRAILER C.G. AND FIFTH
          WHEEL (IN)                                         261.2
03 A4   DISTANCE BETWEEN TRAILER SUSPENSION AND
          TRAILER C.G. (IN)                                  104.8
04 BB   DISTANCE BETWEEN FIFTH WHEEL AND TRACTOR
         REAR SUSPENSION (IN).  (FIFTH WHEEL LO-
          CATED AFT OF SUSPENSION IS POSITIVE)               0.0
05 L    WHEELBASE OF TRACTOR (IN)                           142.
06 H    HEIGHT OF TRACTOR C.G. ABOVE GROUND (IN)            39.9
07 HH   HEIGHT OF FIFTH WHEEL ABOVE GROUND (IN)             48.0
08 HT   HEIGHT OF TRAILER C.G. ABOVE GROUND (IN)            55.5
09 GVW1 WEIGHT OF TRACTOR (LB)                              14970.
10 GVW2 WEIGHT OF TRAILER (LB)                              11160.
DO YOU WISH TO INPUT BRAKE DISTRIBUTION (23)? NO

  BRAKE AND TIRE PARAMETERS
TOTAL ATTEMPTED BRAKE TORQUE AT AN AXLE (IN-LB), ROLLING RADIUS
OF TIRE (IN), PEAK FRICTION COEFFICIENT, EFFECTIVE (OR SLIDING)
FRICTION COEFFICIENT: TP,R,MUP,MUE

AXLE 1 (11,14,17,20)        38869.,19.2,.942,.895
AXLE 2 (12,15,18,21)        83234.,19.5,.939,.895
AXLE 3 (13,16,19,22)        112796,19.5,.96,.894

***END DATA INPUT


 THE STEADY-STATE DECEL IS APPROXIMATELY 14.9 FPSPS.


                                  AXLE 1        AXLE 2        AXLE 3
    TOTAL ATTEMPTED
    TORQUE PER AXLE (IN-LB):   38869.00      83234.00     112796.00

        STATIC LOADING (LB):    8233.50       9932.04       7964.46
       DYNAMIC LOADING (LB):    9965.97       9063.88       7100.15

           BRAKE FORCE (LB):    2024.43       4268.41       5784.41
 EFFECTIVE FRICTION (FX/FZ):    0.20          0.47          0.81

 HITCH FORCES (LB)   STATIC:  FX =      0.00    FZ =   3195.54
(COMPRESSION POS.)  DYNAMIC:  FX =   -626.28    FZ =   4059.85


    NO AXLES LOCKED (CYCLED)

INITIAL VELOCITY (MPH): 30.
BRAKE DELAY TIME (SEC): .35
THE ESTIMATED STOPPING DISTANCE IS   81. FEET.

INITIAL VELOCITY (MPH): 60.
BRAKE DELAY TIME (SEC): .35
THE ESTIMATED STOPPING DISTANCE IS  291. FEET.

INITIAL VELOCITY (MPH): 0
```

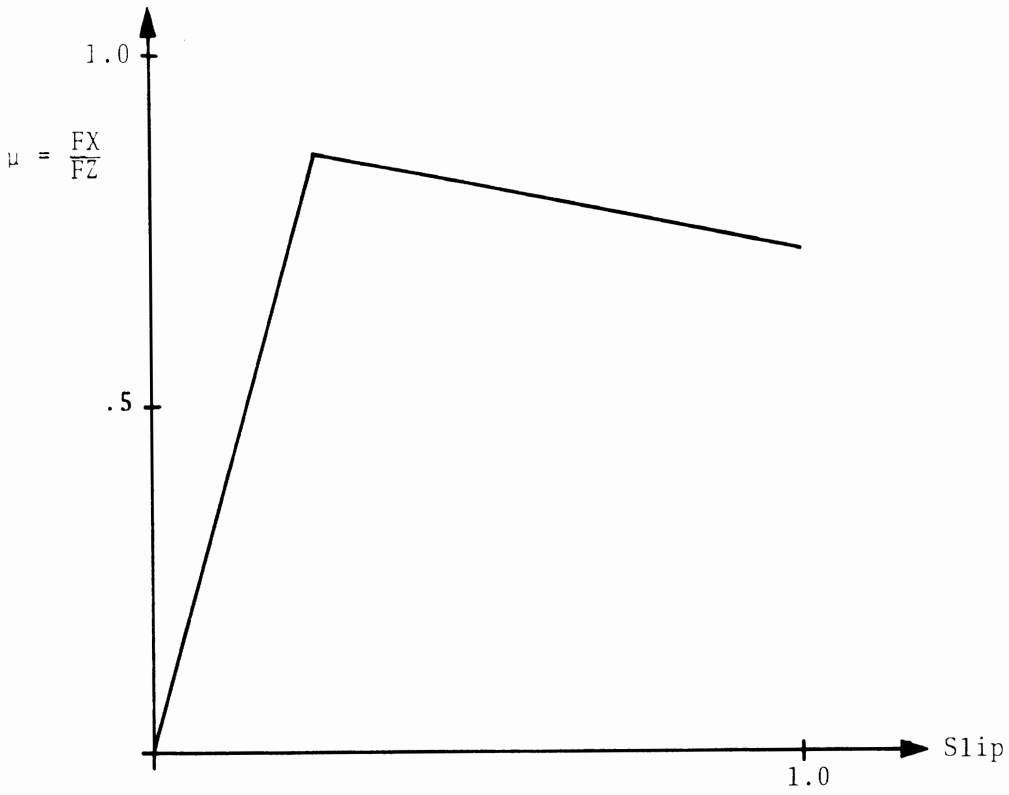

Figure 1. A μ-slip curve.

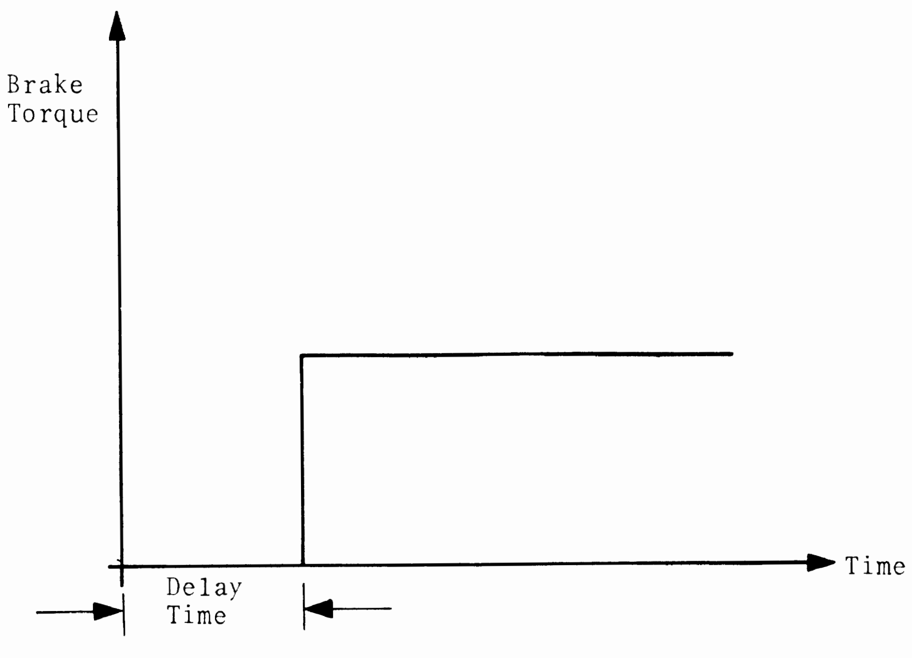

Figure 2. Brake delay time.

Based on these data, the stopping distance is estimated. This latter calculation may be repeated for different initial velocities and/or brake delay times. The user stops this procedure by entering a zero velocity.

At this point, the "run" is complete and the user is asked the question, "CHANGES?" If he answers "yes" he may change one or more pieces of input data by first entering the identifying datum number, as specified on the input, and then its new value. This is shown in Table 3. (Table 3 is a continuation of the run illustrated in Table 2.) Note from the table that the first change is called for explicitly, while subsequent changes are called for by a question mark. Once all changes have been made, a zero should be entered in response to the question mark, and program execution begins using the revised data.

Thus far, sufficient information has been given to enable the user to find the quasi-static deceleration and the estimated stopping distance as a function of the user-entered brake torques. In the next section, a different use of the program is discussed, namely, the calculation of peak wheels-unlocked deceleration or peak deceleration.

2.1.1 BRAKE PROPORTIONING OPTION. The purpose of this option is to provide the user with a computer tool for rapidly determining the influence of different levels of brake proportioning on the maximum deceleration attainable under a variety of conditions.

This brake proportioning option has within itself two options. In the first option, the program determines the maximum deceleration (and/or minimum stopping distance) which can be attained without locking any wheels for a chosen or trial value of brake proportioning. If the truck under study is equipped with antilock systems on each axle, the program determines the maximum attainable deceleration without antilock system cycling.

Table 3. Tractor-Trailer Sample Run Continued.
Note: Underlined quantities are entered by the user.

```
CHANGES? YES
ENTER TWO-DIGIT DATUM NUMBER TO BE CHANGED: 19
ENTER MUP(3)     : .75
? 22
ENTER MUE(3)     : .5
? 0


 THE STEADY-STATE DECEL IS APPROXIMATELY 12.3 FPSPS.


                                       AXLE 1       AXLE 2       AXLE 3
    TOTAL ATTEMPTED
    TORQUE PER AXLE (IN-LB):          38869.00     83234.00    112796.00

         STATIC LOADING (LB):          8233.50      9932.04      7964.46
        DYNAMIC LOADING (LB):         10034.17      8703.72      7392.10

             BRAKE FORCE (LB):         2024.43      4268.41      3696.05
 EFFECTIVE FRICTION (FX/FZ):            0.20         0.49         0.50

 HITCH FORCES (LB)     STATIC:    FX =        0.00     FZ =    3195.54
(COMPRESSION POS.)   DYNAMIC:    FX =      570.79     FZ =    3767.90


    AXLE 3 LOCKED (CYCLED)

INITIAL VELOCITY (MPH): 30.
BRAKE DELAY TIME (SEC): .33
THE ESTIMATED STOPPING DISTANCE IS    93. FEET.

INITIAL VELOCITY (MPH): 0


CHANGES? NO
NEW DATA SET? NO

 STOP       0
*EXECUTION TERMINATED
```

In the second option, the program determines the maximum attainable deceleration allowing lockup of one or more sets of wheels. If the vehicle has antilock systems on each axle, then the program determines the maximum deceleration attainable with antilock system cycling.

It should be noted that whether an axle has an antilock system or not shows up in the value of "MUE" entered into the program. Thus the user knows whether or not the vehicle under study has an antilock system, but the program computes results based on the value of "MUE" regardless of what "MUE" means to the user.

Since the program employs different friction parameters for each axle, it is possible to study vehicles with antilock systems on some axles and no antilock systems on other axles. However, the user must keep track of the meaning of "MUE" for each axle for himself.

The exact details of the brake proportioning option are described in the material which follows.

Consider Table 4. Note that this table is identical to Table 1 with the exception that the "brake proportioning" question is answered in the affirmative, and subsequently the proportioning is entered. At this point the user is asked to respond to "PEAK DECEL OR FIRST AXLE TO LOCK OR CYCLE (P OR F)?" The response "F" indicates the user wishes to determine the maximum deceleration obtainable for the given proportioning prior to wheel lockup or cycling on <u>any</u> axle. The entry of "P" here, rather than "F", indicates the user wishes to determine the maximum deceleration obtainable allowing lockup or cycling of one or more sets of wheels. Depending on the μ-slip data at each axle, the peak deceleration may occur at the incipient lockup (or cycling) of one, two, or all three of the axles (in the case of the tractor-trailer).

Table 4. Straight Truck Run Using Brake Proportioning
Note: Underlined quantities are entered by the user.

```
01 A1   HORIZONTAL DISTANCE BETWEEN TOTAL C.G. AND
          CENTER OF FRONT SUSPENSION (IN)                113.
02 H    HEIGHT OF C.G. ABOVE GROUND (IN)                 46.4
03 L    WHEELBASE (IN)                                  190.
04 GVW  WEIGHT OF VEHICLE (LB)                        21375.
13 DO YOU WISH TO INPUT BRAKE DISTRIBUTION? YES


  TIRE PARAMETERS
ROLLING RADIUS OF TIRE (IN),PEAK FRICTION COEFFICIENT,
EFFECTIVE (OR SLIDING) FRICTION COEFFICIENT: R,MUP,MUE

AXLE 1 (07,09,11)          19.95,.867,.735
AXLE 2 (08,10,12)          20.,.862,.735
13 ENTER BRAKE RATIO,FRONT TO REAR: 1.0,2.0
PEAK DECEL OR FIRST AXLE TO LOCK OR CYCLE (P OR F)? F


 THE DECEL OBTAINED WITH BRAKE TORQUE RATIO OF  1.00 : 2.00
 JUST PRIOR TO LOCKUP (CYCLING) IS APPROXIMATELY 18.8 FPSPS.
                                 AXLE 1        AXLE 2
              TORQUES (IN-LB):   83074.69     166149.56

          STATIC LOADING (LB):    9662.50      12712.50
         DYNAMIC LOADING (LB):   11708.20       9666.79

             BRAKE FORCE (LB):    4164.14       8307.49
  EFFECTIVE FRICTION (FX/FZ):     0.36          0.86

AXLE 2 JUST PRIOR TO LOCKING (CYCLING).

INITIAL VELOCITY (MPH): 30.
BRAKE DELAY TIME (SEC): .25
THE ESTIMATED STOPPING DISTANCE IS   63. FEET.

INITIAL VELOCITY (MPH): 0


CHANGES? YES
ENTER TWO-DIGIT DATUM NUMBER TO BE CHANGED: 13
ENTER BRAKE RATIO:  1.0,2.0
PEAK DECEL OR FIRST AXLE TO LOCK OR CYCLE (P OR F)? P
? 0
 THE PEAK DECEL OBTAINABLE WITH BRAKE TORQUE RATIO OF
1.00 : 2.00 IS APPROXIMATELY 26.2 FPSPS.


                                 AXLE 1        AXLE 2
              TORQUES (IN-LB):  223352.37     446705.37

          STATIC LOADING (LB):    8662.50      12712.50
         DYNAMIC LOADING (LB):   12910.68       8464.32

             BRAKE FORCE (LB):   11195.61       6221.27
  EFFECTIVE FRICTION (FX/FZ):     0.87          0.73

AXLE 2 LOCKED (CYCLED).  AXLE 1 JUST PRIOR TO LOCKING (CYCLING).
```

In the example presented in Table 4, the brake proportioning for the straight truck has been entered as 1.0 to 2.0. The user has then opted to determine the deceleration prior to lockup or cycling of either axle. Table 4 indicates that the deceleration obtained is 18.8 ft/sec^2 at the incipient lockup of the rear wheels.

When a run is completed, the user may change the brake proportioning (or use this option for the first time) by entering 23 (13 for the truck) for the datum number to be changed. The user then enters the numbers, separated by commas, for the new brake proportioning. If the user enters a number less than 0 for the first number in the ratio, the program will switch to its other mode of computing the deceleration for a particular set of brake torques. If this option is engaged, the user must remember to input the appropriate brake torques.

In the previous example (Table 4), the user continued by opting to determine the peak deceleration obtainable with the same data and proportioning. Table 4 indicates that the peak deceleration is 26.6 ft/sec^2, which occurs with the rear wheels locked and the front wheels at incipient lockup.

3.0 AN ASSESSMENT OF THE STRENGTHS AND WEAKNESSES OF THE SIMULATION

It has been demonstrated in the previous section that BRAKES2 requires few input parameters and is easy to use. In addition, it should be noted that the computation costs are minimal—on the order of a few cents per run. The question remains as to the accuracy of the calculations. Before addressing this issue, certain simplifying assumptions made in developing BRAKES2 should be noted:

1) The brake torque is assumed constant throughout the run. Thus fade cannot be simulated.

2) The quasi-static nature of the normal load calculations neglects the time lag required to attain the quasi-static loads. In practice, however, the brakes are applied while the axle is still loaded to approximately its static load—i.e., before the load transfer takes place, as illustrated in Figure 3. This may lead to inaccurate predictions of wheel lockup using quasi-static methods.

3) Tandem axle dynamics are neglected. Thus the calculations tend to predict initial lockup at higher line pressures than one would expect to find if the simulated suspension leads to appreciable inter-axle load transfer during braking.

4) Brake time lags and rise time are accounted for in a very simplified manner. This may lead to errors in the "estimated stopping distance."

5) The operation of an antilock system can only be simulated on a time average basis. Thus detailed studies of antilock systems are impossible.

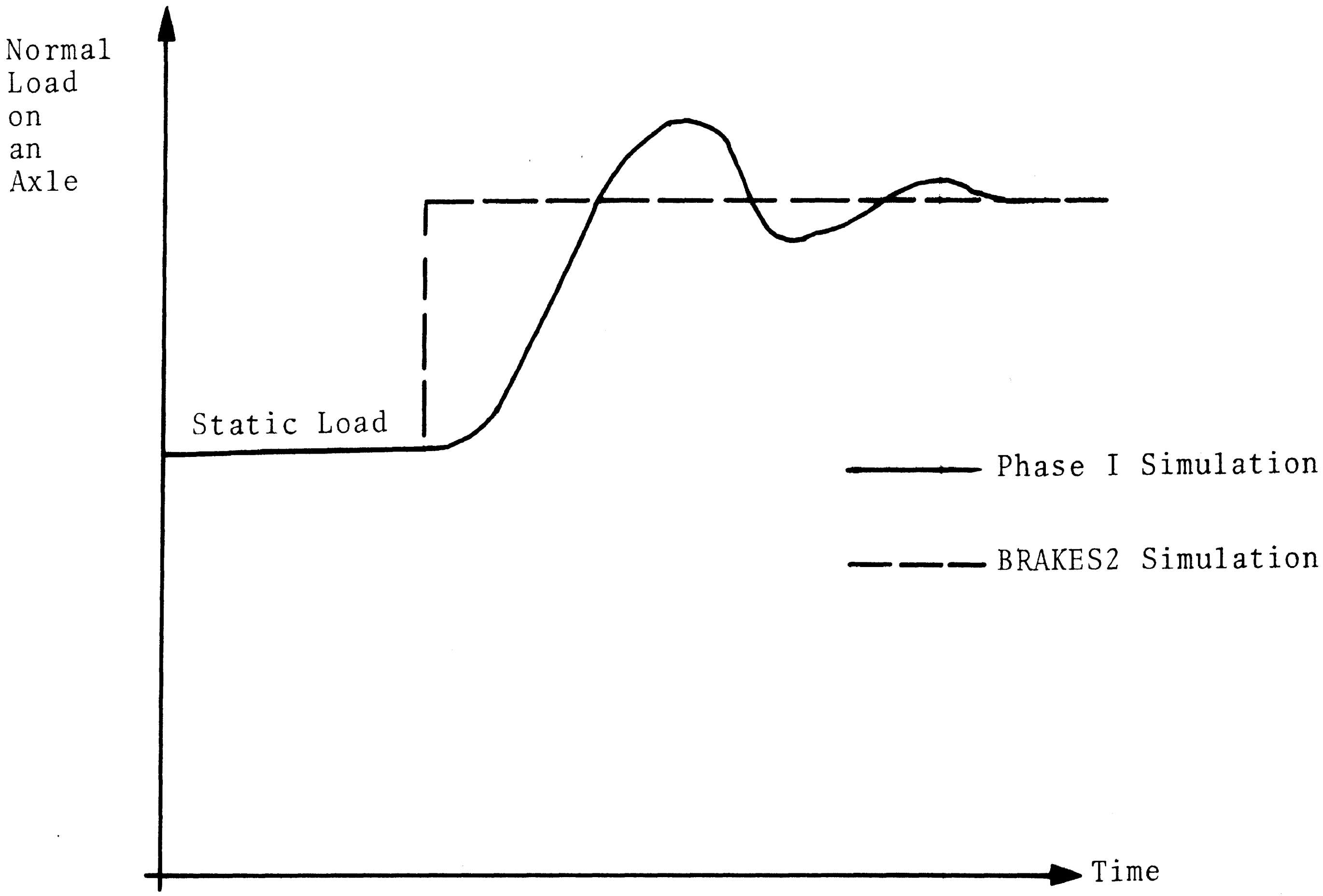

Figure 3. Simulated load transfer during braking.

6) Changes in the properties of the tire-road interface with load and speed are neglected.

Results illustrating the strengths and weaknesses of BRAKES2 are indicated in Figures 4 and 5. In Figure 4, the stopping distances of the Diamond Reo as a function of line pressure are plotted. The solid line indicates the results using the Phase I computer program (as presented in Reference 1), with lockup noted by L2 and L3 for the lead tandem axle and trailing tandem axle, respectively. The dashed line indicates results using the BRAKES2 program, with lockup noted by $\ell 2$ for the rear tandem axle pair.

The Phase I computer program predicted no appreciable inter-tandem-axle load transfer for the Diamond Reo in braking. Thus the agreement in predicted wheel lockup between the Phase I and BRAKES2 programs is very good. Additionally, the BRAKES2 stopping distances, which were computed based on a .25-second brake lag time (see Figure 2), also compare well with the Phase I results.

The stopping distances of the White tractor with Fruehauf trailer are plotted versus line pressure in Figure 5. The solid line indicates the results of the Phase I computer program as presented in Reference 1, with lockup noted by L2, L3, L4, L5 for the lead tractor tandem axle, trailing tractor tandem axle, lead trailer tandem axle, and trailing trailer tandem axle, respectively. The dashed line indicates the results using the BRAKES2 program, with lockup noted by $\ell 2$ and $\ell 3$ for the tractor rear tandem axle pair and the trailer tandem axle pair, respectively.

In this case, the Phase I program predicted significant inter-axle load transfer as indicated by the early lockup of axles 2 and 4 (and confirmed by experiment [1]). This information, of course, is lost in the BRAKES2 results, which neglect tandem axles altogether. Nevertheless, the BRAKES2 stopping distances, which were calculated using a .35-second brake delay time, appear quite reasonable.

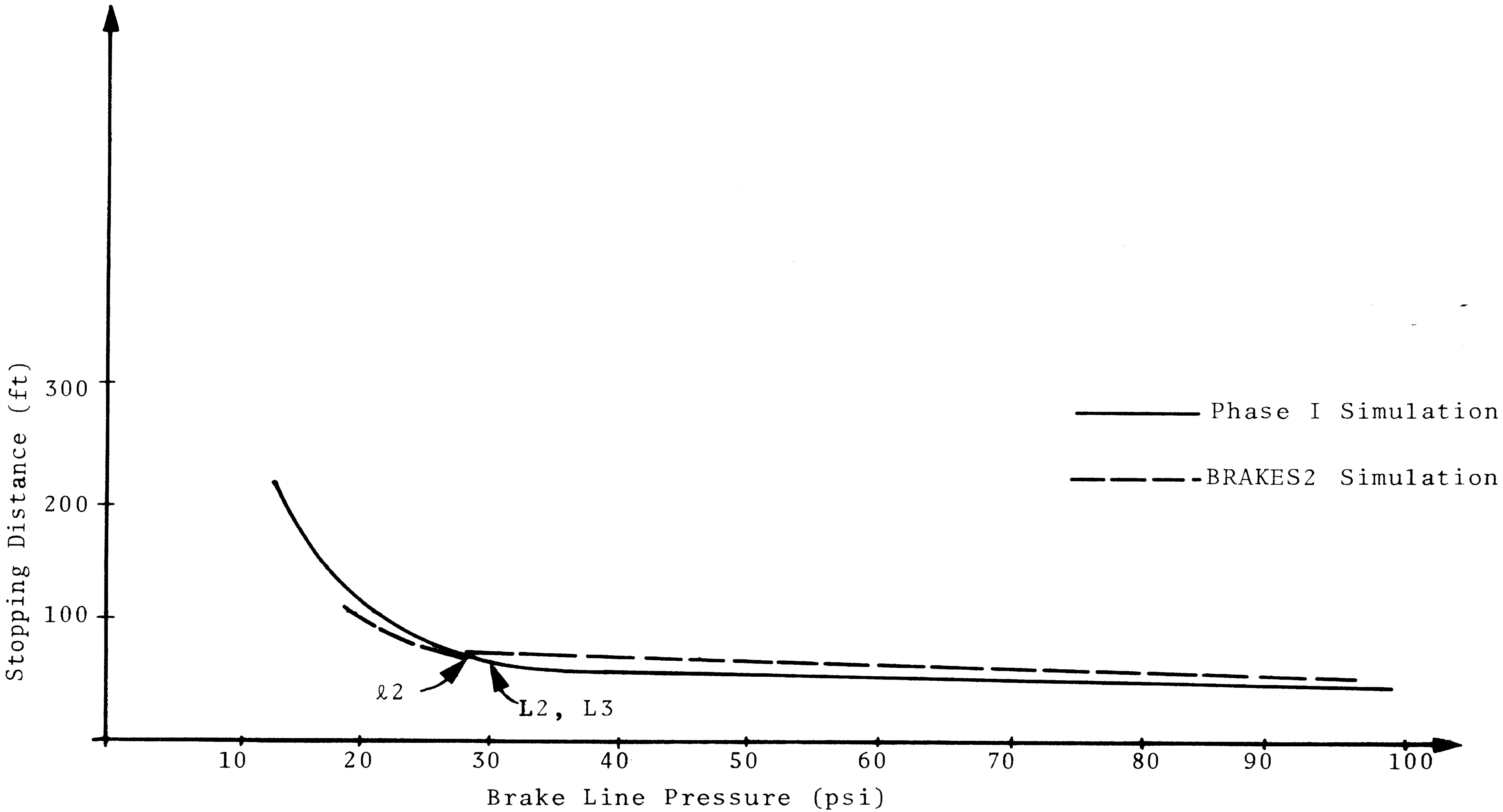

Figure 4. A comparison of lockup and stopping distance calculations for the straight truck.

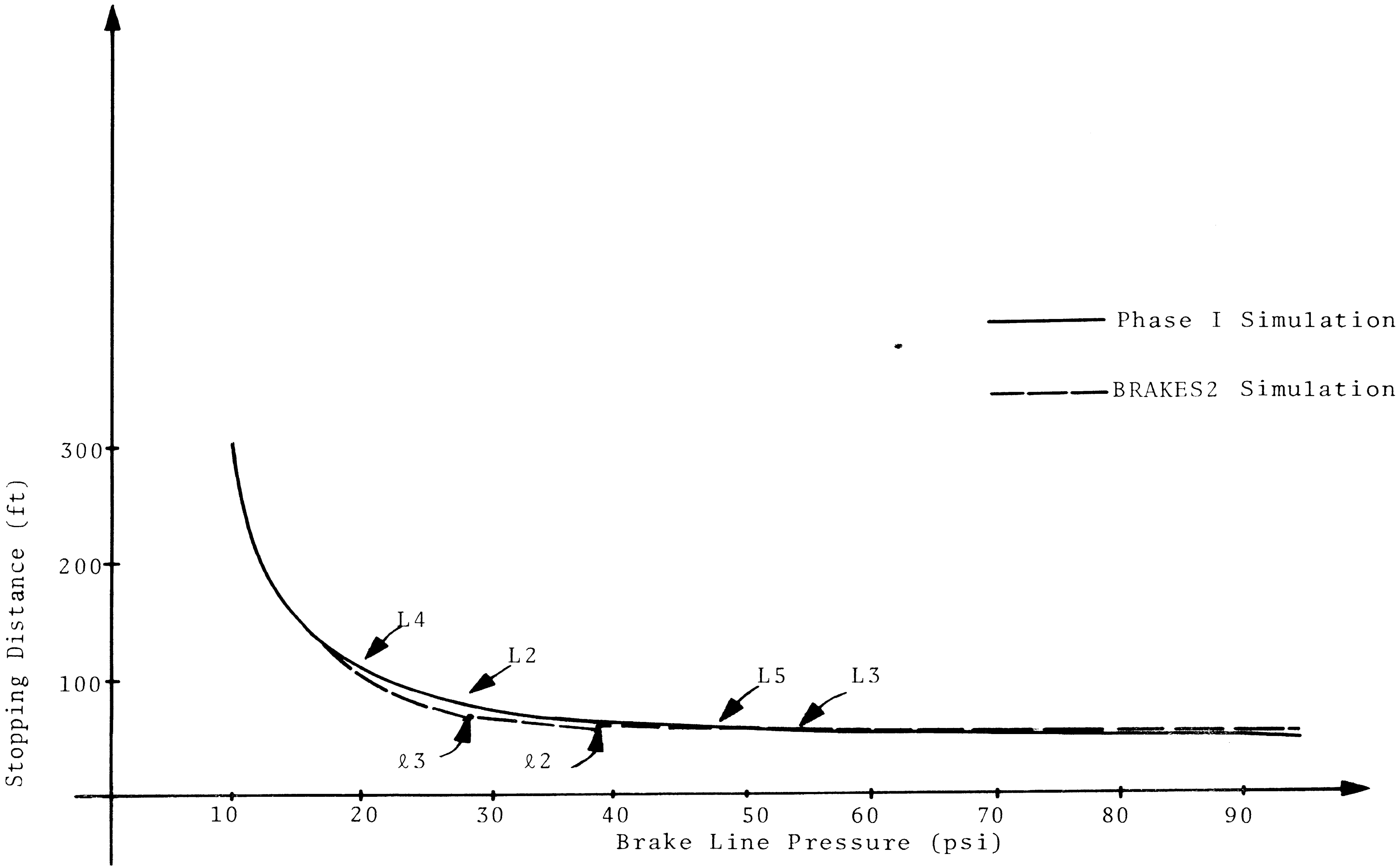

Figure 5. A comparison of lockup and stopping distance calculations for the tractor-trailer.

4.0 EQUATIONS OF MOTION

This section presents the mathematical details of the BRAKES2 simulation. Initially, the pertinent assumptions are discussed, followed by the appropriate free-body diagrams, and finally the equations of motion.

4.1 ASSUMPTIONS

4.1.1 QUASI-STATIC LOAD TRANSFER. Perhaps the most important assumption used in the BRAKES2 simulation concerns the fore-aft load transfer resulting from the brake forces. This transfer is assumed to occur instantaneously, independent of spring rates and pitch inertia. Thus the simulated vehicle has only one degree of freedom, namely, the longitudinal position of the mass center.

4.1.2 THE FORCES AT THE TIRE-ROAD INTERFACE. The user-entered brake torque, TP, determines the brake force at each axle. If the brake torque is less than the product of the dynamic load, FZ, and the peak friction coefficient, MUP, the brake force will be equal to the brake torque divided by the rolling radius of the tire. If the entered brake torque is greater than or equal to the product MUP*FZ, either the anti-lock system will be assumed to cycle or the wheels will be assumed to lock (if there is no antilock system at that axle). In this case, the brake force will be equal to MUE*FZ where MUE represents either an effective coefficient of friction characterizing the time average of the operation of the anti-lock system or else the locked wheel friction coefficient.

In developing the BRAKES2 simulation the assumption was made that once the torque levels are high enough to lock an axle, that axle will remain locked if higher torque levels are applied. Thus the output may show that the torque level at an axle is not high enough to lock that axle given the dynamic load indicated and the peak friction coefficient specified. Nevertheless, the output may indicate that the axle has locked. For example, suppose torques T(1) and T(2) are applied to the front and rear axles, respectively, of the straight truck. This causes axle 2 to lock. Now suppose torques KT(1) and KT(2) are applied where K is greater than 1. Assuming axle 2 remains locked and yields the brake force of MUE(2)*FZ(2), the torque KT(1) may be found to lock axle 1, yielding a brake force at axle 1 of MUE(1)*FZ(1). However, the dynamic load on axle 2 may now indicate that

$$KT(2)/R(2) < MUP(2)*FZ(2)$$

However, since axle 2 locked previously at a lower torque level than KT(2), it is assumed to remain locked.

4.1.3 BRAKE TIMING. The quasi-static deceleration is assumed constant during the course of the stop. Thus, given the initial velocity, it is a straightforward matter to compute the stopping distance.

Any such calculations, however, must take into account the significant lags between the time the treadle valve has been depressed and the time the brakes are actuated. Thus after the quasi-static deceleration is computed, the user is asked to enter both an initial speed and a brake delay time. The stopping distance is then computed assuming that the brakes are not applied until the end of the brake delay time, when the total brake torque is applied. Thus, for brake delay time Δt, initial velocity V_o, and deceleration a_x, the calculated stopping distance D is

$$D = V_o \Delta t + \frac{V^2}{2a_x} \qquad (1)$$

where the first term on the right-hand side results from travel for Δt seconds at velocity V_0, and the second term is the stopping distance given instantaneous actuation of the brake forces.

4.1.4 TANDEM AXLES. Tandem axles are assumed to be replaced by one equivalent axle located at the center of the tandem axle assembly. Thus the user must enter the sum of all brake torques at a tandem axle assembly. If the brake proportioning option is used, the user must enter a brake ratio accounting for all four brakes on the tandem axle.

4.2 THE EQUATIONS OF MOTION

The simulation first establishes which axles lock (or cycle) for the specified torque and friction levels, then calculates the deceleration.

A free-body diagram for the straight truck is presented in Figure 6. (A complete nomenclature list is given at the end of this section.) The equations of motion are:

$$\mathrm{DECEL} = -\frac{\mathrm{FX}(1) + \mathrm{FX}(2)}{\mathrm{GVW1}/\mathrm{G}} \tag{2}$$

$$\mathrm{FZ}(1) = \frac{\mathrm{GVW1} \times \mathrm{A2}}{\mathrm{L}} + \frac{\mathrm{GVW1}}{\mathrm{G}} \times \frac{\mathrm{H}}{\mathrm{L}} \times \mathrm{DECEL} \tag{3a}$$

$$\mathrm{FZ}(2) = \frac{\mathrm{GVW1} \times \mathrm{A1}}{\mathrm{L}} - \frac{\mathrm{GVW1}}{\mathrm{G}} \times \frac{\mathrm{H}}{\mathrm{L}} \times \mathrm{DECEL} \tag{3b}$$

$$\mathrm{FX}(1) = -\frac{\mathrm{TP}(1)}{\mathrm{R}(1)} \quad \text{if } |\mathrm{FX}(1)| < \mathrm{MUP}(1) \times \mathrm{FZ}(1) \tag{4a}$$

$$\mathrm{FX}(2) = -\frac{\mathrm{TP}(2)}{\mathrm{R}(2)} \quad \text{if } |\mathrm{FX}(2)| < \mathrm{MUP}(2) \times \mathrm{FZ}(2) \tag{4b}$$

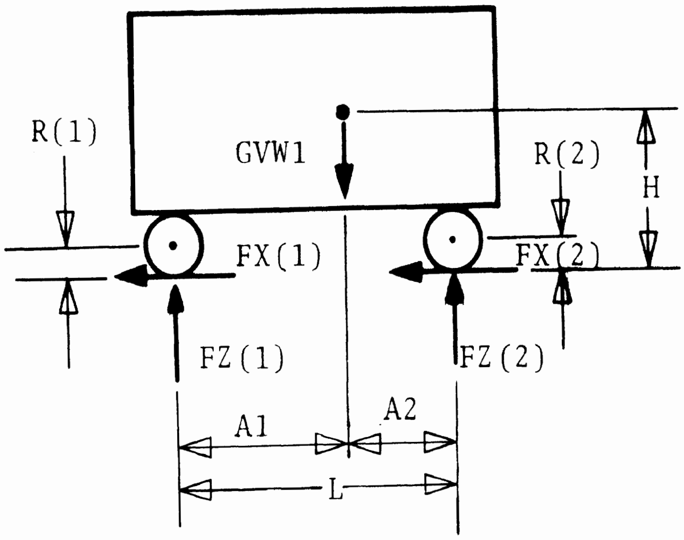

Figure 6. Free-body diagram of straight truck.

$$FX(1) = -\ MUE(1) \times FZ(1) \quad \text{if } |FX(1)| \geq MUP(1) \times FZ(1) \tag{5a}$$

$$FX(2) = -\ MUE(2) \times FZ(2) \quad \text{if } |FX(2)| \geq MUP(2) \times FZ(2) \tag{5b}$$

A free-body diagram of the tractor-trailer is presented in Figure 7. The equations of motion are:

$$DECEL = -\ \frac{FX(1) + FX(2) + FX(3)}{(GVW1+GVW2)/G} \tag{6}$$

$$FZ(1) = \left\{ A2 \times GVW1 + \frac{DECEL}{G} \left[(H \times GVW1 + HH \times GVW2) + \frac{BB \times GVW2}{A3 + A4}(HH-HT) \right] + HH \times FX(3) \left(1 + \frac{BB}{A3 + A4}\right) - \frac{BB \times A4 \times GVW2}{A3 + A4} \right\} / L \tag{7a}$$

where $A2 = L - A1$

$$FZ(2) = GVW1 + \left[\frac{GVW2 \times DECEL(HT-HH) + A4 \times GVW2 - HH \times FX(3)}{A3 + A4} \right] - FZ(1) \tag{7b}$$

$$FZ(3) = GVW2 - \left[\frac{\frac{GVW2}{G} \times DECEL(HT-HH) + A4 \times GVW2 - HH \times FX(3)}{A3 + A4} \right] \tag{7c}$$

$$FX(1) = -\ \frac{TP(1)}{R(1)} \quad \text{if } |FX(1)| < MUP(1) \times FZ(1) \tag{8a}$$

$$FX(2) = -\ \frac{TP(2)}{R(2)} \quad \text{if } |FX(2)| < MUP(2) \times FZ(2) \tag{8b}$$

$$FX(3) = -\ \frac{TP(3)}{R(3)} \quad \text{if } |FX(3)| < MUP(3) \times FZ(3) \tag{8c}$$

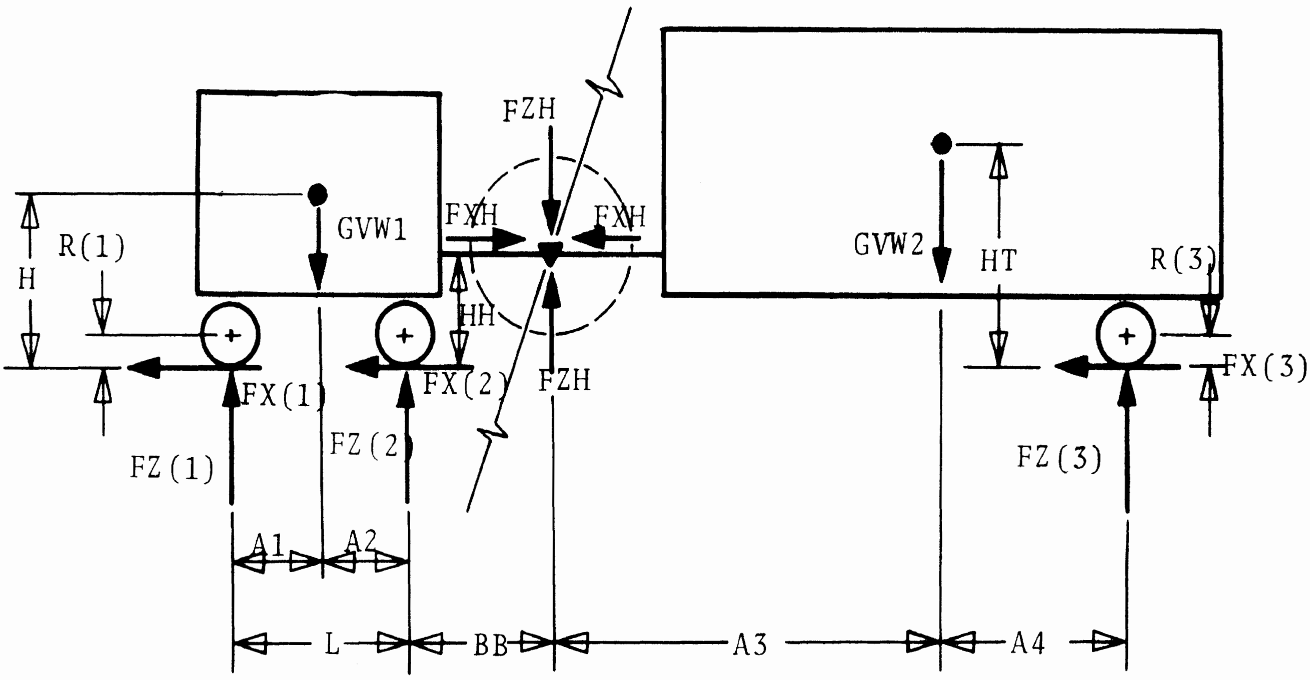

Figure 7. Free-body diagram of tractor-trailer

$$FX(1) = -\,MUE(1) \times FZ(1) \quad \text{if } |FX(1)| \geq MUP(1) \times FZ(1) \tag{9a}$$

$$FX(2) = -\,MUE(2) \times FZ(2) \quad \text{if } |FX(2)| \geq MUP(2) \times FZ(2) \tag{9b}$$

$$FX(3) = -\,MUE(3) \times FZ(3) \quad \text{if } |FX(3)| \geq MUP(3) \times FZ(3) \tag{9c}$$

4.3 NOMENCLATURE LIST

A1	Horizontal distance between the tractor* c.g. and the center of the tractor front suspension (in)
A2	Horizontal distance between the center of the tractor rear suspension and the tractor c.g. (in)
A3	Horizontal distance between the trailer c.g. and the fifth wheel (in)
A4	Horizontal distance between the center of the trailer suspension and the trailer c.g. (in)
BB	Horizontal distance between the fifth wheel and the center of the tractor rear suspension (in). (Fifth wheel located aft of suspension gives positive BB.)
DECEL	Steady-state deceleration of the tractor c.g. (ft/sec^2)
FX	Longitudinal force at the tire-road interface (lb). A negative value indicates a braking force.
FZ	Dynamic axle loading (lb)
FXH	Longitudinal force at hitch (lb). A positive value indicates compression.
FZH	Vertical load at hitch (lb)

*Tractor refers to truck in the case of the unit vehicle.

G	Gravity constant equal to 32.17 ft/sec^2
GVW1	Weight of tractor (lb)
GVW2	Weight of trailer (lb)
H	Height of tractor c.g. above ground (in)
HH	Height of fifth wheel above ground (in)
HT	Height of trailer c.g. above ground (in)
L	Wheelbase of the tractor (in)
MUE	Effective longitudinal friction coefficient for the tire-road interface when the antilock system is cycled
MUP	Peak longitudinal friction coefficient of the tire-road interface
R	Rolling radius of a tire (in)
TP	Sum of attempted brake torques applied at an axle or tandem pair of axles (in-lb)

The subscripts 1, 2, and 3 refer to the tractor front axle, tractor rear axle, and trailer axle, respectively.

5.0 USERS FLOW CHART

The flow chart shown on page 27 indicates the options available to the user in running BRAKES2. This flow chart is diagrammed for the tractor-trailer program. The flow chart for the truck program is the same, except that the datum number, i, for the brake proportioning is 13 rather than 23, and additionally, there is no B(3). (Note: B(1), B(2), and B(3) give the brake proportioning.)

When the program is begun, the user is asked if the data is to be read in from a file.* If the user answers "no" to this question, 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.

If data is to be read from a file, the user should enter the device input number in I1 format when the program calls for it. The data file should be set up in the same format as if it were primed, with the answer to the question, "DO YOU WISH TO ENTER BRAKE DISTRIBUTION?", assumed to be "no." A sample data file is shown in Table 5.

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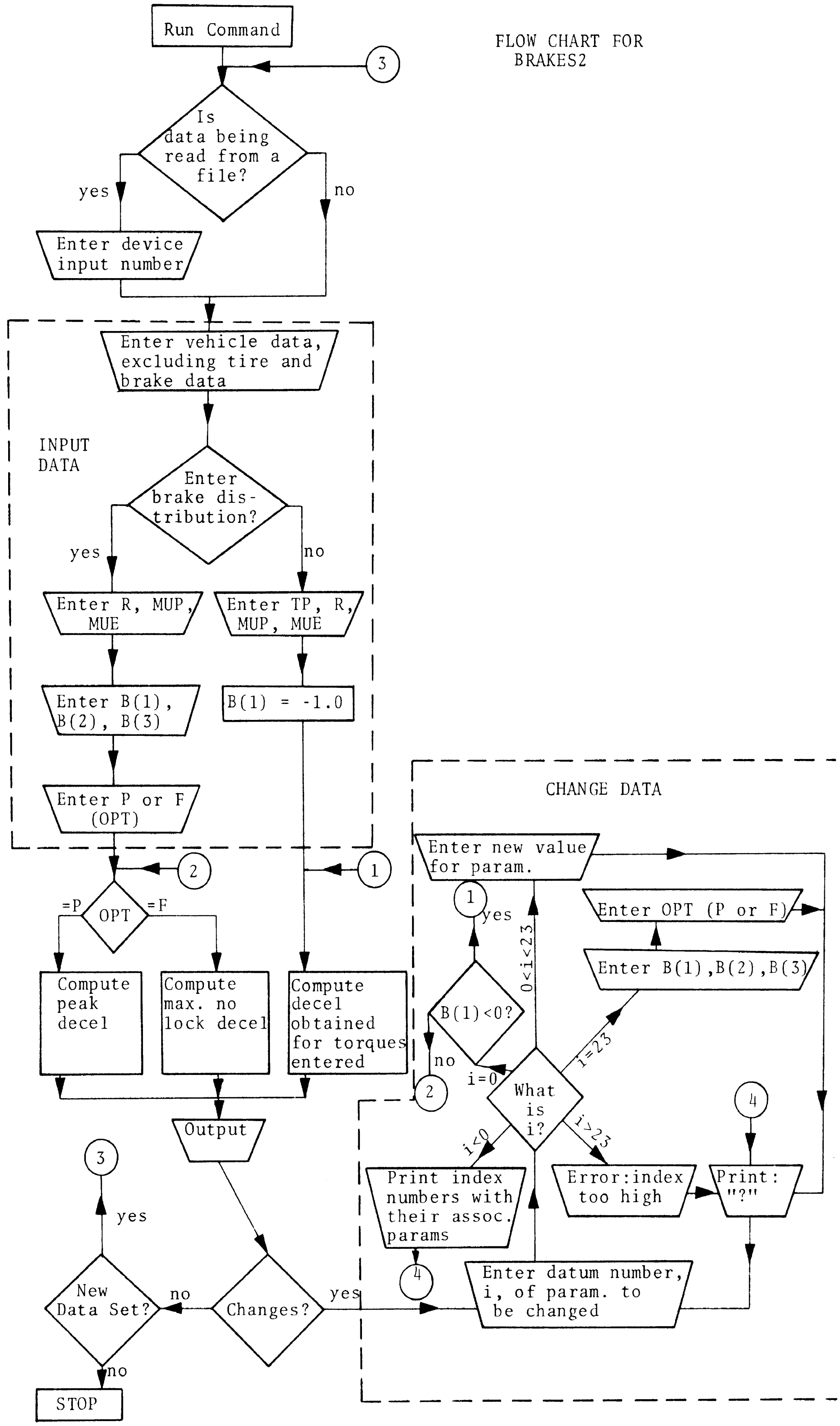
*In answer to a yes/no question, "y" for the first letter of the answer signifies yes. Any other response is assumed to be no.



FLOW CHART FOR BRAKES2

Table 5. Sample Data File for the White Tractor and Fruehauf Trailer.

```
63.9                                WHITE TRACTOR-FRUEHAUF TRAILER
261.2
104.8
0.0
142.
39.9
48.0
55.5
14970.
11160.
38869.,19.2,.942,.895
83234.,19.5,.939,.895
112796.,19.5,.96,.894
```

6.0 REFERENCES

1. Murphy, R.W., Bernard, J.E., and Winkler, C.B., A Computer Based Mathematical Method for Predicting the Braking Performance of Trucks and Tractor-Trailers, Phase I Report, Motor Truck Braking and Handling Performance Study, HSRI, Univ. of Michigan, September 15, 1972.

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, HSRI, Univ. of Michigan, June 1, 1973.