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# CONSTANT VELOCITY YAW/ROLL PROGRAM
# USER'S MANUAL

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16. Abstract


This document is a User's Manual for the computer-based mathematical simulation program entitled "Constant Velocity Yaw/Roll Model" developed in 1980 at The University of Michigan Transportation Research Institute. This manual provides an introduction to the simulation program with a description of its external characteristics sufficient for a user to submit a run and interpret the output obtained. Additional documentation describing the modeling of the vehicles inside the program is given in Appendix C. As the name suggests, the Constant Velocity Yaw/Roll Model simulates the turning and rolling behavior of motor vehicles in constant-speed maneuvers. Turning behavior may be controlled either by defined steering inputs or by a driver model following a prescribed trajectory. The model's particular features are tailored to simulation of trucks and tractor-trailers, accommodating up to four vehicle units. The simulation is particularly versatile in representation of multiple-axle configurations and different types of hitching mechanisms between the vehicle units.

The simulation generates time-based output indicating motions of each vehicle and the controlling forces internal to the vehicles.


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# 1.0 GENERAL INFORMATION

## 1.1 Purpose of the Manual

This document is a preliminary version of a User's Manual for the Constant Velocity Yaw/Roll Model, a computer-based mathematical simulation program developed in 1980 by Dr. C. Mallikarjunarao [9][1] at The University of Michigan Transportation Research Institute (UMTRI). The manual provides an introduction to the simulation program with a description of its external characteristics sufficient for a user to submit a run and interpret the output obtained. The program was developed for personal use, and as yet, the input/output has not been reworked to bring it up to the usual standards for public use of the program. Nevertheless, this manual has been prepared for current users to document the program in its current state.

## 1.2 Background

Since 1971, the UMTRI has been conducting research under the sponsorship of the Motor Vehicle Manufacturers Association (MVMA) to develop computer-based methods for analyzing and predicting the directional and braking response of commercial vehicles. The initial phase of this research dealt with modeling the braking performance of commercial vehicles and was reported in Reference [1] (Phase I). The second phase extended vehicle modeling to allow for directional response and was reported in Reference [2] (Phase II). The continuation of research into braking performance led to additional refinements in the braking simulation which were reported in Reference [3] (Phase III). Subsequently, additional simulation programs have been developed for the government [4] and industry [5], in which the detail of the modeling has been tailored to specific needs. Though all programs evolved from the same approach to vehicle modeling, the separate programs offer a somewhat different menu of features to simplify their use in different applications.

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[1]Cited References are listed in Section 5.0 of this Manual.

In 1980, the need developed for a combination vehicle simulation program allowing more general representation of the number of axles and articulation points. Inasmuch as braking performance was not an issue, the program (and its use) could be greatly simplified by the assumption of a constant forward speed, while being expanded to allow for a broader range of axle and articulation arrangements. Because the application of the program was to be the prediction of the stability and turning behavior of generalized articulated vehicles, state-of-the-art modeling of the vehicle as it determines yaw and roll response was included.

## 1.3 Engineering Units

Throughout the Yaw/Roll Model, the English system of units is used. With the exceptions listed below, all input data are given in units of pounds, inches, degrees, and seconds. Masses and weights are in units of pounds, with a gravitational constant of 386 in/sec/sec assumed. The units for input data parameters are defined in the input data echo.

Exceptions:

1) Input for the initial velocity is given in units of ft/sec.
2) Input describing trajectory points for the path-follower steering mode are defined in terms of feet lateral versus feet longitudinal.
3) The tire aligning torque information is entered in units of ft-lbs/deg, but echoed in units of in-lbs/deg.

Output data units are defined on the printed output pages. In general, the same units are used throughout.

## 1.4 Computer Requirements

The Yaw/Roll Model is written for use on any large-scale computer system, and requires only one input and one output device. The source code is in level-G Fortran IV language, with 300,000 bytes of memory required for loading. Support software must include the following subroutines from the IBM Scientific Subroutine Package: HPCG, SMPY, LOC, GMPRD, and GMADDS. Two additional subroutines from the National Argonne Laboratory software package, DBS and DLUD, are also required.

Copies of the program and support software are available to the public by contacting the Engineering Research Division, The University of Michigan Transportation Research Institute, 2901 Baxter Road, Ann Arbor, Michigan 48109.

# 2.0 APPLICATION

## 2.1 Description of the Program

The Yaw/Roll Model is a time-domain mathematical simulation capable of simulating the yaw/roll response of multiple-articulated vehicles. The model was formulated for the purpose of analyzing the combined directional and roll behavior of trucks, tractor-semitrailers, and doubles combinations during dynamic maneuvers which approach the rollover limit. The model is limited to a maximum of four vehicle units and eleven axles, and the axles can be distributed as desired among the vehicle units. Vehicles equipped with a variety of hitching mechanisms can also be studied by making simple modifications to the computer code.

A detailed description of the differential equations of motion is given in Appendix C. In this section, the description of the model is therefore restricted only to essential features and to the important assumptions made in the process of developing the equations of motion.

2.1.1 Degrees of Freedom. The equations of motion of the vehicle are formulated by treating each of the sprung masses as a rigid body with five degrees of freedom, namely: lateral, vertical, yaw, roll, and pitch. The longitudinal degree of freedom is not included, since the forward velocity of the lead unit (or tractor) is assumed to remain constant during the maneuver. The axles are treated as beam axles which can roll and bounce with respect to the sprung masses to which they are attached. The total number of degrees of freedom, Nd, of a multiple-articulated vehicle with Ns sprung masses and Na axles is therefore given by the expression: $Nd = 5Ns + 2Na$.

2.1.2 Features of the Model. The simplifying assumptions made in the process of deriving the equations and the essential features of the model are given below.

1. The vehicle is assumed to travel on a horizontal surface with uniform friction characteristics.

2. The pitch motion of the sprung masses are assumed to be small such that the approximations $\sin x = x$, and $\cos x = 1$ hold true.

3. The relative roll angle between the sprung masses and the axles are assumed to be small so that the same approximations may be applied to the roll deflections between the sprung and unsprung masses.

4. The relative roll motion between the sprung and unsprung masses is assumed to take place about a roll center, R, which is at a fixed height beneath the sprung mass, as illustrated in Figure 1. In order to simplify the equations, the suspension springs are assumed to remain parallel to the ku axis and transmit only compressive or tensile forces. Since the roll center is permitted to slide freely along the ku axis, all axle forces which act in a direction parallel to the ku axis are taken up by the suspension springs, while all axle forces along the ju axis are assumed to act through the roll center, Ri. When a relative roll motion takes place between the sprung mass and the axles of a leaf-spring-type suspension, the leaf springs tend to be twisted in the roll plane and hence produce an additional roll-resisting moment. This effect is represented in the model by an auxiliary roll stiffness parameter, KRS.

5. Suspension nonlinearities such as backlash are represented by using a tabular load-deflection input format, shown in Figure 2.

6. The model permits the simulation of vehicles equipped with a wide variety of hitching mechanisms. The equations are formulated such that the equations of motion are independent of the constraint equations. Hence, the vehicles equipped with any given hitching mechanism can be analyzed by simply altering the constraint equations (see Appendix C).

7. The nonlinear cornering force and aligning torque characteristics of the tires are represented as tabular functions. The tire forces and moments are computed by a double table look-up for the given vertical load and sideslip angle.

8. The forces acting on each axle are treated independently, i.e., no interaxle load transfer effects are incorporated in the model.

9. Simulations can be performed in the closed-loop or open-loop modes. In the open-loop mode, the time history of the steering input is provided as input to the model. In the closed-loop mode, the trajectory

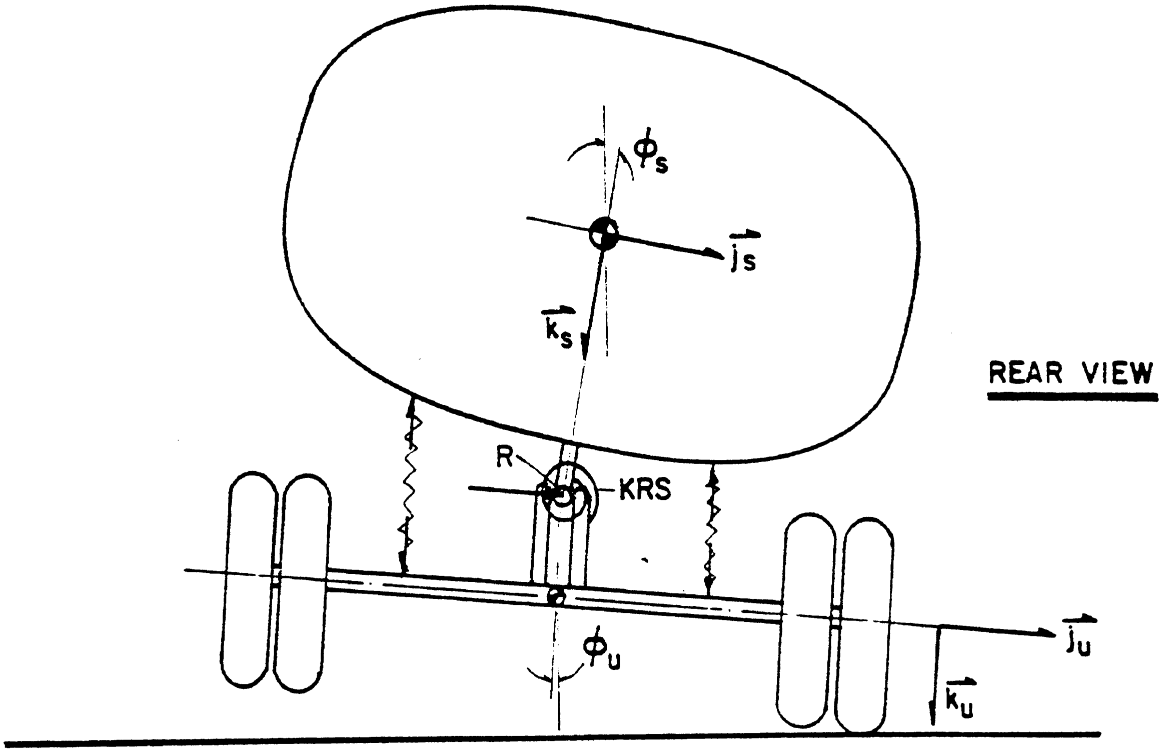



Figure 1. Representation of axles and suspension springs in the yaw/roll model.

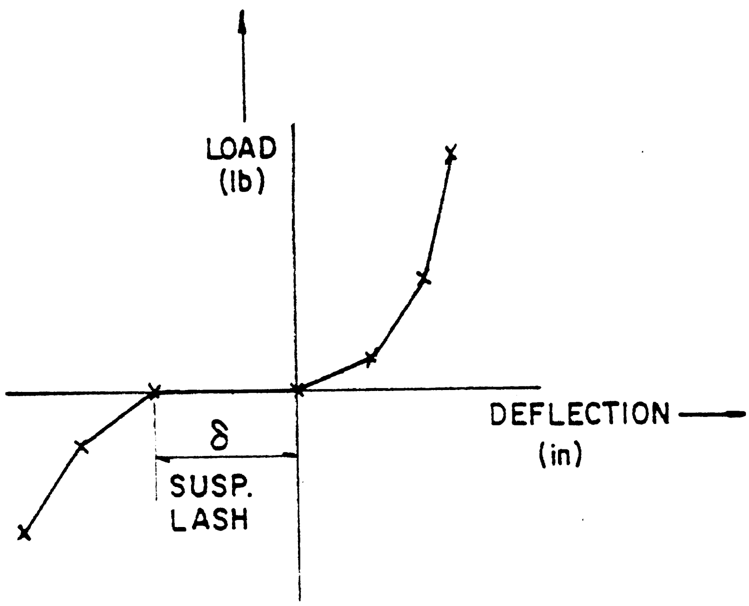



Figure 2. Representation of suspension nonlinearities in the yaw/roll model.

to be followed by the vehicle is specified and the "driver model" [6] computes the steering input that is necessary to accomplish the maneuver.

## 2.2 Operation

Operation of the Yaw/Roll program is accomplished by submission of the necessary job control instructions followed by a list of input parameters. The specific job control instructions required are dependent on the user's computer system and whether batch or remote job entry is being used. However, the input parameter list is common to all and is described in Section 3.0 of this Manual.

The program commences by reading the input list containing parametric data describing the vehicle configuration, initial conditions, and steering inputs. As input data is read, the data is normally "echoed" as the first pages of output. The program then "runs," solving the differential equations of motion for the vehicle until the vehicle reaches a default stop (such as rollover), or until the designated maximum simulation time is reached. At various points during the run, simulation output is printed, which includes time-based values for the vehicle motion variables, tire forces at each axle, and the suspension motions and forces.

## 2.3 Validity

The validity of the Yaw/Roll program, like any computer program, is dependent on the accuracy and execution of program statements, the capabilities of the simulation models, and the quality of the vehicle and maneuver descriptions defined by the input data.

Every effort, of course, is made to ensure that the program statements are correct and result in solution of the problem to a reasonable level of precision. The time steps have been selected so that round-off and truncation errors do not substantially influence the precision of the calculated results. Nevertheless, if programming errors are discovered, the user should contact the Engineering Research Division, The University of Michigan Transportation Research Institute, Ann Arbor, Michigan 48109.

The modeling used in the simulation is effectively state-of-the-art, reflecting the most practical approaches to mathematical representation of commercial vehicles for handling studies. With nearly every component model used in the simulation, there are instances where more modeling details would be appropriate for the study at hand; yet, provision for every instance would result in a simulation for which the input data requirements would be untenable. To some extent, these needs are provided for in the Yaw/Roll Model by allowing optional use of lookup tables, in lieu of a single numerical parameter, as means to describe component characteristics in more detail when needed.

Finally, the ultimate determinant of validity is the user-supplied input data and the interpretation applied to the results. Properly used, the program is capable of validly predicting most aspects of directional response in maneuvers up to the limits of wheel liftoff. In the special case where a direct comparison between a vehicle and simulation (i.e., validation) is intended, an iterative process is often involved as the first comparisons of simulation and test reveal unexpected differences, which, when examined, are traced to inaccuracies or errors in the experimental measurements or program input. Fortunately, the usefulness of these simulation programs are not dependent on every user going through the same process. In most applications, the user can assume, for example, a given tire characteristic and investigate vehicle performance with that tire, knowing that it is typical, but yet, not precisely equivalent to any specific tire on hand. Much of the utility of computer simulation programs derives not from absolute prediction of a certain vehicle/test maneuver situation (as required for validation), but as a tool for studying generalized performance and sensitivity of performance to the vehicle parameters.

The Yaw/Roll Model was found to be capable of accurately predicting the directional and roll response of tractor-semitrailers and double-trailer-type vehicles in its use to date. Directional response data collected during the double-tanker study [7] conducted in 1978 was used for the purpose of validating the Yaw/Roll Model. The match between test data and simulated response was found to be good even for severe maneuvers which result in wheel lift-off. Since tractor front-wheel measurements had not been made during the double-tanker experiments, steering-wheel time histories were used to estimate the front-wheel angles.

Shown in Figure 3 is a comparison of test data and simulation results for a two-second lane-change maneuver conducted on a 55-foot conventional double tanker at a speed of 50 mph. A schematic diagram of the tanker is shown in Figure 4. This relatively mild maneuver resulted in a peak tractor lateral acceleration of about 0.1 g and a peak lateral acceleration of the full trailer which is in the vicinity of 0.2 g. The roll angles are seen to be small and the maneuver is well within the linear regime. The agreement between test data and simulated response can be seen to be excellent for all of the measured variables. The simulation makes an accurate prediction of the amplification and the timing of the full trailer's response.

A more severe lane-change maneuver performed on the same 55-foot double tanker is shown in Figure 5. The peak lateral acceleration response of the full trailer is in the vicinity of 0.3 g and exhibits a highly nonlinear response. The combination of large slip angles (which reach 6 degrees in the simulation) and a complete lift-off of the left-hand side tires on the full trailer cause the lateral tire forces to saturate and hence produce the dwell in the lateral acceleration response at the point marked "x" in Figure 5. Except for some minor discrepancies, the simulation is found to predict the nonlinear lateral acceleration response of the full trailer rather well. The peak full trailer roll angle predicted by the simulation is higher than the measured roll angle by about 0.7 degree. The absence of accurate data on suspension backlash (the backlash was assumed to be 1.5 inches for the simulation) and spring stiffness could have resulted in this discrepancy.

Another example of the capability of the Yaw/Roll Model in predicting limit behavior is portrayed in Figure 6. The test data shown in Figure 6 is for the tractor-semitrailer portion of the double tanker. In this experiment, the backlash on the semitrailer suspension springs was reduced to 0.5 inch by the installation of spring lash reduction

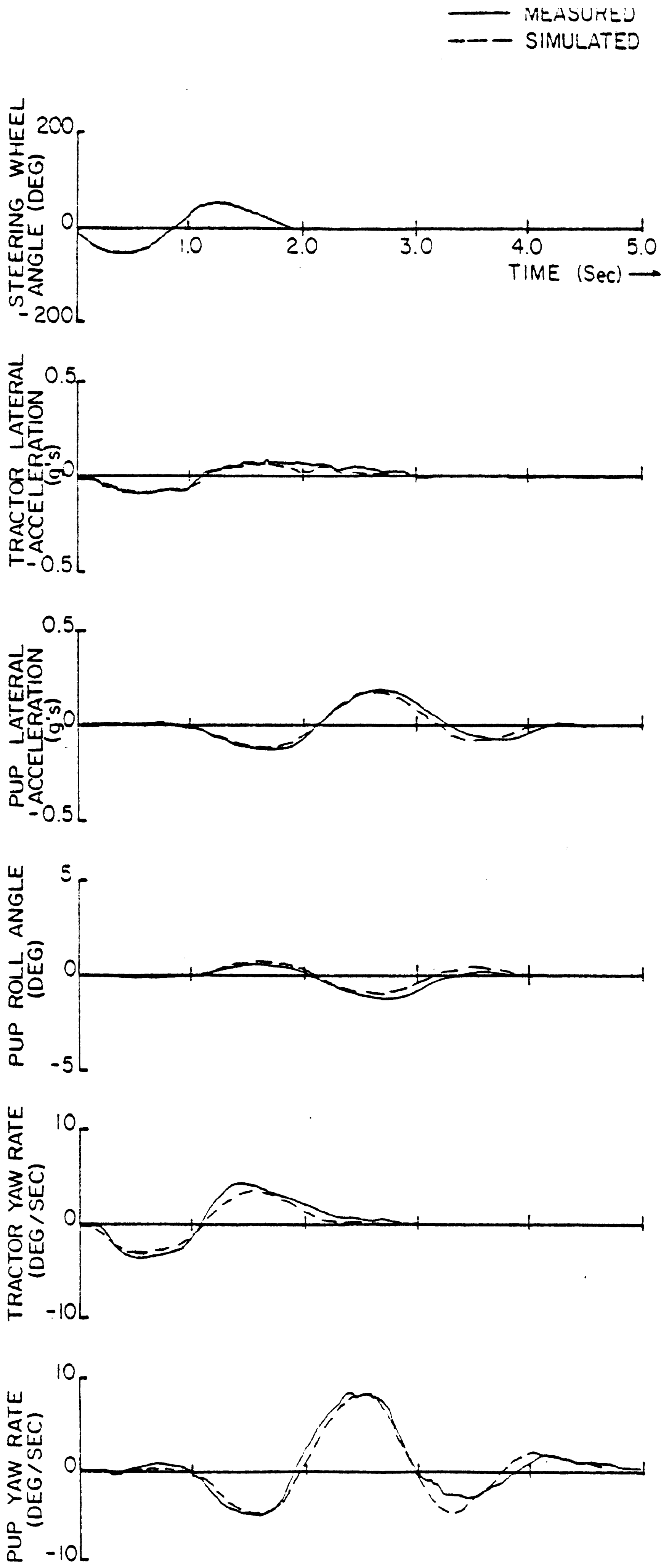
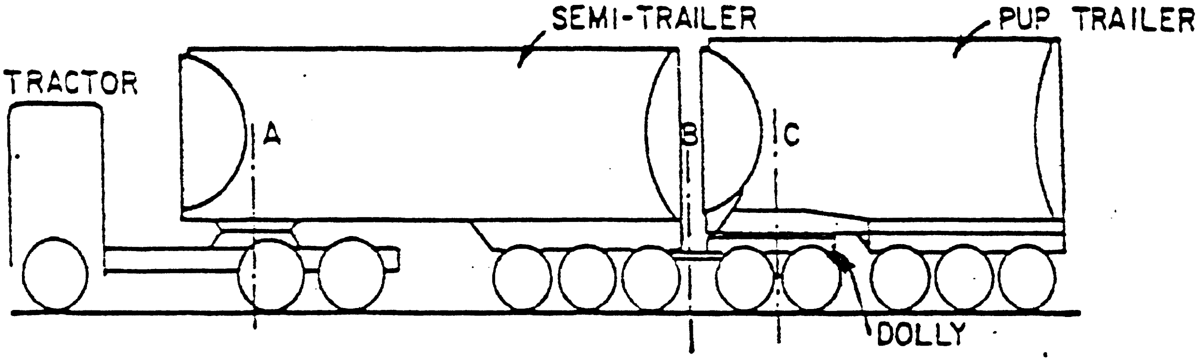



Figure 3. Fully loaded conventional 55-foot double tanker - forward speed 50 mph.




55 FT, 11 AXLE DOUBLE BOTTOM TANKER

Figure 4.

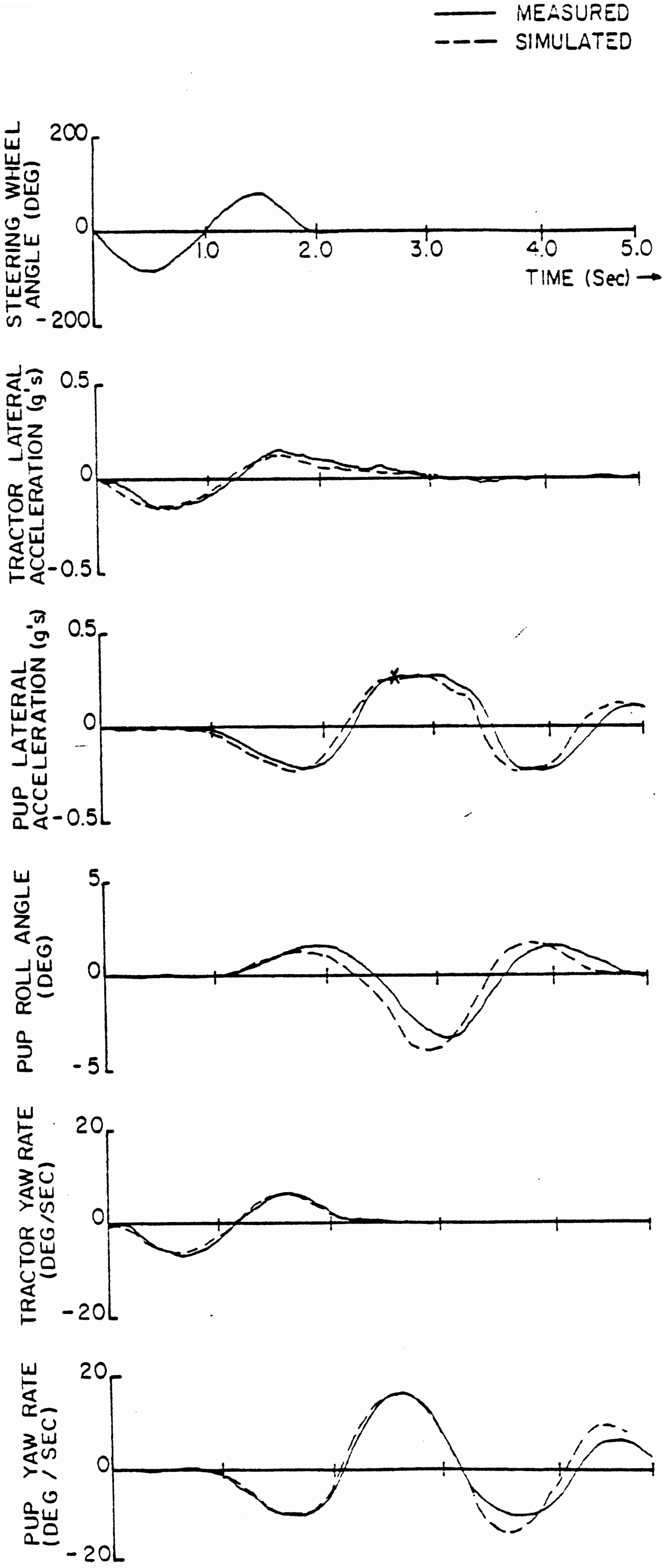



Figure 5. Severe lane change, performed on a fully loaded 55-foot double tanker - forward speed 39 mph.

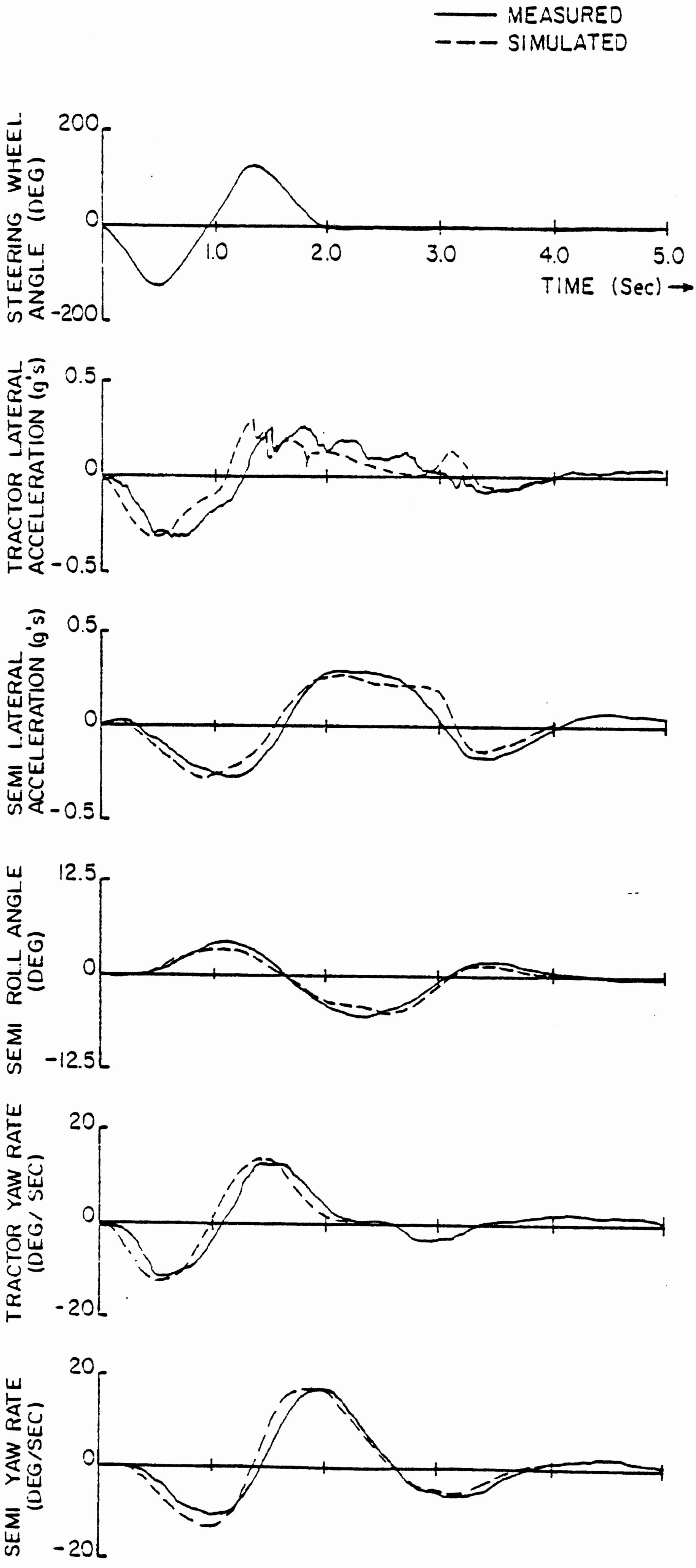



Figure 6. Tractor-semitrailer portion of 55-foot double tanker - forward speed 44 mph.

devices. Several interesting observations can be made with regard to this maneuver. Both the tractor and the semitrailer lateral accelerations reach relatively high peak levels which are in the vicinity of 0.3 g. The simulation results indicated that the tires on the left-hand side of the semitrailer lifted off the ground at 1.8 seconds and remained off the ground until about 2.9 seconds. This wheel lift-off once again produces the long dwell in the semitrailer lateral acceleration response. The lift-off of the semitrailer tires during the second half of the maneuver produces roll-induced oscillations in the lateral acceleration response of the tractor. The model is seen to only qualitatively match the measured oscillation in the tractor lateral acceleration response.

In summary, it can therefore be stated that the Yaw/Roll Model is accurate enough to predict the transient response of both single and double trailers during maneuvers which approach the rollover limit. Hence the model with the proper implementation of the constraint relationships can be extended to study the directional dynamics of other multiple-articulated vehicles.

# 3.0 PROGRAM INPUT

## 3.1 General

Program operation is effectively accomplished by input of a parametric data list, along with the necessary job control instructions. This section provides a detailed description of the input data required. Appendix A provides a ready reference list of input parameters. A sample input list, along with the output of the "run" is provided in Appendix B.

Depending on the vehicle configuration, the input data list will contain the following elements:

-Title Line (up to 80 characters)

-Simulation Operation Parameters

-Sprung Mass Parameters for Each Vehicle

-Axle Loading Parameters

-Unsprung Mass Parameters for Each Axle

-Suspension Parameters for Each Axle

-Hitch Parameters

-Suspension Spring Tables (optional)

-Tire Cornering Force Tables

-Tire Aligning Torque Tables

-Steering System Parameters

-Steering Control Parameters (Driver Model or Time/Steer Angle Control)

The input data is identified only by its position in the input list and hence must be ordered exactly to match the vehicles and options used in the simulation. Errors in the input list will result either in a read fault (with possible system interrupt and abort of the program), or in simulation of the wrong conditions. Every effort has been made to define the input sequence and its alteration with various options in this section. Example input lists are shown throughout the Manual for reference by the user in compiling an input data list.

3.1.1 Table Lookup Option. It is often desirable to include nonlinear characteristics of vehicle components (particularly for tires and springs) in the model simulated. For such parameters a table lookup option can be used, allowing the parameter to be described by a multiple point approximation over the range of interest rather than assigning to it a single valued linear characteristic. The program thence interprets the dependent variable's value when needed using linear interpolation methods. In the event the program exceeds the range of the table, the dependent variable is extrapolated from the last two entries in the table.

The table lookup option may be used with the following input parameters:

-Suspension spring rate

-Tire cornering stiffness

-Tire aligning torque

## 3.2 Data Input

Input of a data list to run a simulation follows a concise format. The individual lines of data are defined below.

Line #1

TITLE - The Title line is an alphanumeric field of up to 80 characters in length supplied by the user to identify the simulation run. The program reads the title in a 20A4 format.

Line #2

NUMBER OF SPRUNG MASS UNITS - The first variable defines the number of sprung mass units in the vehicle configuration. Sprung mass units are the tractor, any trailers, and any dollies on a full trailer combination. Up to 4 units are allowed. The number is entered in I2 format.

NUMBER OF AXLES - The second entry on this line is the total number of axles in the combination, also entered in I2 format. Up to 11 axles are allowed.

Line #3

FORWARD VELOCITY - The first entry on Line 3 is the forward velocity of the vehicle in units of feet/second. The format is F10.2.

MAXIMUM SIMULATION TIME - This variable is the second entry on the line, and defines the length of the simulation run in the absence of a default termination due to rollover. The time is entered in units of seconds using F10.2 format.

PRINTOUT INTERVAL - The printout interval defines the points in time (seconds) at which the instantaneous values for all motion variables will be printed. Typical intervals would be 0.1 seconds. The value is entered in F10.2 format.

ROLL ANGLE INCREMENT - Defines the roll angle increment at which the matrices are updated in the solution. Typically, this variable should be set at 0.02 radians. The format is F10.2.

Line #4

NUMBER OF AXLES PER UNIT - The number of axles on each unit of the vehicle are entered on this line. An entry for each unit is made in sequential order using I2 format. Therefore, the number of entries should match the number of units specified in Line 2, and the total number of axles should match the number of axles entered on Line 2.

Line #5

SPRUNG WEIGHT OF EACH UNIT - On this line the sprung weight in pounds for each unit is entered in sequential order. Each entry is F10.2 format, and the number of entries should match the number of units specified on Line 2. If the unit carries payload, this entry should include the weight of the payload.

Line #6

ROLL MOMENTS OF INERTIA - The roll moment of inertia (units of inch-pound-seconds squared) for each unit is entered in F10.2 format.

The entries are sequential by unit and should match the number of units specified in Line 2. The moment of inertia is defined as the total value for the sprung mass taken about the center of gravity of the unit. If payload is carried on the unit, the roll moment of inertia should include the contribution from the payload, and is referenced to the center of gravity of the vehicle/payload combination. Note that contributions from the axles (unsprung masses) are not included in this moment of inertia value.

Line #7

PITCH MOMENT OF INERTIA - The pitch moment of inertia (units of inch-pound-seconds squared) are entered in the same fashion as the roll moments of inertia. That is, sequential entries in F10.2 format are made for each unit of the combination. The pitch moments of inertia are for the vehicle/payload combination taken about the center of gravity for the total mass. The number of entries should match the number of vehicle units specified in Line 2.

Line #8

YAW MOMENTS OF INERTIA - The yaw moments of inertia (units of inch-pound-seconds squared) are likewise entered in the same fashion as the roll moments of inertia. Sequential entries in F10.2 format are made for each unit of the combination, including the payload in the value. Unsprung masses should be excluded in the determination of this parameter. The number of entries should match the number of units entered on Line 2.

Line #9

C.G. HEIGHT - The center of gravity height in inches above the ground for each unit of the vehicle combination is entered in sequential order using F10.2 format. The c.g. height should be determined for the sprung mass only, excluding the unsprung masses. The number of entries should match the number of vehicle units entered on Line 2.

Line #10

AXLE LOAD - The static load at the ground (in pounds) carried by each axle of the assembled vehicle is entered sequentially by axle using

F10.2 format. These loads would be analogous to the load per axle observed if the simulated vehicle were driven over an axle-by-axle load scale. The number of entries should match the number of axles entered on Line 2.

Line #11

UNSPRUNG MASSES - The unsprung mass in pounds for each axle is entered in sequential order in F10.2 format on this line. The number of entries should match the number of axles entered on Line 2.

Line #12

ROLL MOMENT OF INERTIA, AXLES - The roll moment of inertia for each unsprung mass (comprised of the axle/wheel/brakes/tires, etc.) is entered in F10.2 format. The roll moment of inertia is expressed in units of inch-pound-seconds squared. Entries are sequential by axle, and the number of entries should match the number of axles entered on Line 2.

Line #13

AXLE LOCATIONS - The location of each axle is defined on this line by its position relative to the sprung mass c.g. of the vehicle unit on which it is mounted. One entry is made on this line for each axle of the overall configuration. The format is F10.2, and the number of entries should match the number of axles entered on Line 2. The location is specified by the longitudinal distance in inches from the axle rearward to the c.g. of the unit on which it is mounted. Thus if the axle is in front of the c.g., the value is positive. If the axle is behind the c.g. of the vehicle unit, the entry is negative.

Line #14

UNSPRUNG MASS C.G. HEIGHT - The c.g. height in inches above the ground is entered for each unsprung mass using F10.2 format. The number of entries should match the number of axles entered on Line 2.

Line #15

ROLL CENTER HEIGHT - The roll center height in inches above the ground is entered for each axle. The format is F10.2, and the number of entries should match the number of axles entered on Line 2. The roll center height is fixed on the sprung mass and represents the effective location at which lateral forces are transferred between the sprung and unsprung masses. The roll center height should be determined for the fully assembled vehicle (all units coupled and at load).

Line #16

SUSPENSION LATERAL SPREAD - The lateral spread on the suspension is defined as the lateral distance from the centerline of the vehicle out to the spring (sometimes called the suspension half-spacing). The units are inches, using F10.2 format, and the number of entries should match the number of axles entered on Line 2. A suspension may consist of both springs and dampers. This entry should reflect the distance to the springs. If the dampers (shock absorbers) are located at a different lateral location, their damping values (entered on Line 22) are adjusted appropriately to yield the equivalent roll damping.

Line #17

TRACK WIDTH - The track width is defined as the lateral distance from the centerline of the vehicle to the centerline of the tire (sometimes called the half-track). The parameter unit is inches, entered in F10.2 format, with one entry required for each axle, and the number of entries matching the number of axles specified in Line 2. With dual tires, the track width is defined as the distance to the inside tire, and the distance to the outside tire is obtained from the dual tire spacing entered on the next line.

Line #18

DUAL TIRE SPACING - The program allows for dual tires on each axle. The distance (in inches) between the centerlines of the tires on one side of the axle is defined as the dual tire spacing. One entry is required for each axle, for the number of axles specified in Line 2, using F10.2 format. For axles without dual tires, the zero entry is required to tell the program that it is a single wheel.

Line #19

TIRE VERTICAL STIFFNESS - The tire vertical stiffness parameter defines the spring rate in pounds/inch for one tire. It is entered in

F10.2 format, with one entry for each of the axles specified in Line 2. The spring rate is adjusted inside of the program for the number of tires (single or dual) on each axle.

<u>Line #20</u>

ROLL STEER COEFFICIENT - The roll steer coefficient defines the degrees of steer angle produced on an axle for each degree of roll between the sprung mass and the axle. Positive roll corresponds to the sprung mass rolling to the right (as in a left-hand turn). Positive steer corresponds to the axle steering to the right. Thus a positive roll steer coefficient results in the axle steering to the right in a left-hand turn maneuver. One entry is required for each axle in accordance with the number of axles specified in Line 2. The parameter is dimensionless (i.e., deg/deg), and is entered in F10.2 format.

<u>Line #21</u>

AUXILIARY ROLL STIFFNESS - In some suspension systems, additional roll stiffness is provided by anti-roll bars, the twist in the leaf springs and other sources. Roll stiffness deriving from these sources, and not accounted for in the simple mechanism of the spring forces operating on a lateral spread, is accommodated in the auxiliary roll stiffness parameter. The parameter units are inch-pound/degree, and are entered in F10.2 format. One entry is required for each axle in accordance with the number of axles entered in Line 2.

<u>Line #22</u>

SUSPENSION COULOMB FRICTION - Dry friction in the suspension linkages or springs is assumed to be of constant magnitude regardless of suspension deflection. The friction results in a hysteresis loop in the force/deflection properties for the suspension system. The suspension force (at a given deflection point) will differ depending on whether the deflection is moving in a compression or extension direction. The total difference in force is twice the coulomb friction magnitude. The coulomb friction value for each side of the suspension on each axle is entered on this line. The value is expressed in pounds, and entered in F10.2 format. One entry is required for each axle.

Line #23

VISCOUS DAMPING - Shock absorbers or elastomeric bushings may produce velocity proportional damping in a suspension system. The viscous damping (in units of pound-seconds/inch) for one side of the suspension is entered in F10.2 format; one entry being required for each axle in accordance with the number specified in Line 2. It is assumed that the damping force acts at the lateral location of the suspension system as specified in Line 16. In the event the shock absorbers have a lateral spread that is significantly different than that of the springs, the damping values should be adjusted to achieve the same roll damping effect. The appropriate adjustment factor is the square of the ratio of the damper lateral spread/suspension lateral spread.

Line #24

ARTICULATION PARAMETER #1 - In the event more than one vehicle unit was specified in Line 2, the articulation points on each vehicle must be defined (otherwise, skip to line 28). The articulation point on the first vehicle is located by this parameter. Its value is the longitudinal distance (in inches) from the sprung mass c.g. rearward to the articulation point. A negative value places the articulation point behind the c.g. The entry is made in F10.2 format.

ARTICULATION PARAMETER #2 - This parameter, entered on the same line, establishes location of the forward articulation point on the second vehicle unit. The value is the longitudinal distance (in inches) from the articulation point rearward to the sprung mass c.g. location. A positive value places the articulation point ahead of the c.g. The entry is made in F10.2 format.

ARTICULATION PARAMETER #3 - This parameter, entered on the same line, locates the articulation point on the second vehicle unit for connection to a third unit. The value is the longitudinal distance (in inches) from the sprung mass c.g. rearward to the articulation point. A negative value places the articulation point behind the c.g. The entry is made in F10.2 format.

ARTICULATION PARAMETER #4 - This parameter, entered on the same line, locates the forward articulation point on the third vehicle unit.

The value is the longitudinal distance (in inches) from the articulation point rearward to the sprung mass c.g. location. A positive value places the articulation point ahead of the c.g. The entry is made in F10.2 format.

ARTICULATION PARAMETER #5 - This parameter, entered on the same line, locates the articulation point on the third vehicle unit for connection to a fourth unit. The value is the longitudinal distance (in inches) from the sprung mass c.g. rearward to the articulation point. A negative value places the articulation point behind the c.g. The entry is made in F10.2 format.

ARTICULATION PARAMETER #6 - This parameter, entered on the same line, locates the forward articulation point on the fourth vehicle unit. The value is the longitudinal distance (in inches) from the articulation point rearward to the sprung mass c.g. location. A positive value places the articulation point ahead of the c.g. The entry is made in F10.2 format.

Line #25

ARTICULATION HEIGHT - The set of parameters entered on this line sets the vertical height (in inches) above the ground for all the articulation points. The vertical heights of each of the articulation points are sequentially entered in F10.2 format. The number of entries should match the number of articulation points (maximum of three).

Line #26

ARTICULATION POINT ROLL STIFFNESS - The roll stiffness at each of the articulation points is set by the sequential entry of parameters on this line. The roll stiffness is specified in units of inch-pounds/degrees, entered in F12.2 format. The number of entries should match the number of articulation points (maximum of three).

Line #27 - For Multi-Unit Vehicles Only

ARTICULATION TYPE - The type of joint at each articulation point is defined by the entries on this line. The code is as follows:

01 - Conventional fifth wheel

02 - Inverted fifth wheel

03 - Pintle hook or ball hitch

04 - Kingpin-type turntable

Data is entered in I2 format, with the number of entries equal to the number of articulation points (maximum of three). Note: The articulation type 03 may not be used to support a vertical load--only a lateral force. In addition, the roll stiffness value entered on Line #26 for any articulation type 04 joint, also defines (internally) the pitch stiffness.

Line #28

NUMBER OF SPRING TABLES - Enter in I2 format the number of different spring tables to follow. The maximum number allowed is eleven.

Line #29

SPRING ASSIGNMENTS - On this line enter the identifier number of the spring table appropriate to each axle. Eleven entries, each in I2 format, are required.

Line #30

TABLE SIZE #1 - One entry is made on this line indicating the number of lines in Spring Table #1. Anywhere from 1 to 10 lines may be specified. The entry is made in I2 format.

Lines #31-40

TABLE #1 - Each of the lines up to a maximum of 10 contains two entries, a spring force value, and a deflection value. Both are entered in F10.2 format. The force value is in pounds, while the deflection is in inches. Deflection values are all relative, as the ride height of the c.g. is already established by data entered in Line 9. A positive force represents compression of the spring. Likewise, a positive deflection also represents compression of the spring. Begin the table at the tensile end of the force-deflection curve.

Lines #41-150

ADDITIONAL SPRING TABLES - The remainder of these lines are optionally used for definition of ten more spring tables. In each case, the table should begin with a parameter specifying the number of lines to be read in the table (per Line 30), followed by that number of lines of force-deflection values (per Lines 31-40). The number of tables entered must match the number called out in Line 28. Unused lines can be simply dropped from the input list (i.e., blank lines do not need to be entered to fill the input list to line number 150).

Line #151

NUMBER OF TIRE CORNERING FORCE TABLES - Tire cornering force properties are defined in the cornering force tables. Two options are available:

1) Linear tires - Linear tires may be specified by entering a zero value for the number of tables. If selected, on the next line the stiffness values in pounds/degree/tire should be entered for the tires on each axle (up to eleven). The values are entered sequentially by axle in F10.2 format. Thereafter, skip to the aligning torque table entries beginning on Line 263.

2) Nonlinear tires - Nonlinear tire properties are represented by tabular input. This option is called by entering a positive number between 1 and 11 on Line 151, indicating the number of tire cornering force tables to follow.

Line #152

TIRE ASSIGNMENTS - The assignment of the tire cornering force tables to the axles is specified on this line. The line consists of entries of the tire table identification number for each axle of the vehicle. Entries are made sequentially by axle, each in I2 format.

Line #153

TABLE #1, SIZE - The tire cornering force table begins with an entry line defining the number of rows and the number of columns in the table. Both numbers are entered on one line in I2 format. The number of rows is one plus the number of vertical load values at which data will be supplied. The number of columns is one plus the number of slip angles at which data will be supplied. Neither the number of rows, nor the number of columns may exceed nine.

Lines #154-162

TABLE #1, ROW #1 - The first row consists of entries of the slip angle values at which data is to be entered. The line consists of up to 9 entries, each in F10.2 format. The first value should be a null (0.0), followed by up to 8 values of slip angle, in degrees, entered in order of increasing value. The number of entries in this row, including the null, should equal the number of columns specified in Line 153.

TABLE #1, ROW #2 - The second row consists of an entry for the vertical load (pounds), followed by the cornering force values (pounds) for each of the slip angle values entered in Row #1. The entries are made in F10.2 format. The number of entries (load plus cornering force values) should equal the number of columns specified in Line 153.

TABLE #1, ROW #3 - The third and subsequent rows repeat the entry format defined for the second row, representing data input at a subsequent load condition. The rows should be in order of increasing load values. The number of rows should match the number called out in Line 153.

Lines #163-172

TIRE CORNERING FORCE TABLE #2 - Tire cornering force Table #2 is entered in the same fashion as Table #1. The first entry (Line #163) is the Table Size specification indicating the number of rows and columns. The subsequent lines (up to nine) represent entries paralleling Lines #154-162.

Lines #173-262

ADDITIONAL TIRE CORNERING FORCE TABLES - The remaining lines 173 to 262 provide for up to nine more tire cornering force tables constructed as the first two tables above. If fewer than the maximum number of tables are required, those lines are simply deleted from the input (i.e., blank lines need not be entered in the data list to fill these assigned line numbers).

Line #263

NUMBER OF ALIGNING TORQUE TABLES - The number of aligning torque tables to follow are entered on this line. Up to 11 are allowed. The number is entered in I2 format. Two options are available.

1) Linear tires - Linear tires may be specified by entering zero for the number of tables in I2 format. If selected, the next line should list the aligning torque stiffness values in foot-pounds/degree/tire for the tires on each axle. The entries are made in F10.2 format sequentially by axle for the number of axles specified in Line 2, then skip to Line 375.

2) Nonlinear tires - Nonlinear tire properties are represented by tabular input. This option is called by entering a positive number between 1 and 11 on Line 263, indicating the number of tire aligning torque tables to follow.

Line #264

TIRE ASSIGNMENTS - The assignment of the tire aligning torque tables to the axles is specified on this line. The line consists of entries of the tire table identification number for each axle of the vehicie. Entries are made sequentially by axle, each in I2 format.

Line #265

TABLE #1, SIZE - The tire aligning torque table begins with an entry line defining the number of rows and columns in the table. Both numbers are entered on one line in I2 format. The number of rows is one plus the number of vertical load values at which data will be supplied. The number of columns is one plus the number of slip angles at which data will be supplied. Neither the number of rows, nor the number of columns may exceed nine.

Lines #266-274

TABLE #1, ROW #1 - The first row consists of entries of the slip angle values at which data is to be entered. The line consists of up to nine entries, each in F10.2 format. The first value should be a null (0.0), followed by up to eight values of slip angle in degrees, entered in order of increasing values. The number of entries in this row, including the null, should equal the number of columns specified in Line 265.

TABLE #1, ROW #2 - The second row consists of an entry for the vertical load (pounds), followed by the aligning torque values (foot-pounds/degree) for each of the slip angle values entered in Row #1. The entries are made in F10.2 format. The number of entries (load plus aligning torque values) should equal the number of columns specified in Line 265.

TABLE #1, ROW #3 - The third and subsequent rows repeat the entry format defined for the second row, representing data input at subsequent load values. The number of rows should match the number called out in Line 265.

Lines #275-284

TIRE ALIGNING TORQUE TABLE #2 - Tire aligning torque Table #2 is entered in the same fashion as Table #1. The first entry (Line 275) is the Table Size specification indicating the number of rows and columns. The subsequent lines (up to nine) represent entries paralleling Lines 266-274 above.

Lines #285-374

ADDITIONAL ALIGNING TORQUE TABLES - The remaining lines 285 to 374 are up to nine or more tire aligning torque tables constructed as the first two tables above. If fewer than the maximum number of tables are required, those lines are simply deleted from the input (i.e., blank lines need not be entered in the data list to fill these assigned line numbers).

Line #375

STEERING RATIO - In the simulation, the steering input to the vehicle can be controlled either at the steering wheel or at the front road wheels. The type of control is indicated by the entry of the steering ratio in F10.2 format on this line. If the input is applied at the steering wheel, compliance in the steering system alters the actual front wheel steer angle obtained. If it is desired to apply the steering input at the steering wheel, a steering ratio (degrees steering wheel/degree road wheel) greater than one must be specified (typical ranges are 18:1 to 36:1). In that case, certain steering system properties must be entered on the following Line 376. If the steering input is to be applied directly at the road wheel, a unity value is entered for the ratio, and Line 376 is deleted from the input.

Line #376

STEERING SYSTEM STIFFNESS - Three parameters must be entered on this line to define the important steering system properties. F10.2 format is used. The first property is the steering system stiffness from the steering wheel to the left road wheel. The value describes the stiffness at the road wheel when the steering wheel is held fixed. The units for the entry are inch-pounds/degree of road wheel deflection.

TIE ROD LINKAGE STIFFNESS - The second parameter describes the stiffness of the tie rod linkage transfering the steer angle command from the left to the right road wheel. The value describes the stiffness at the right road wheel when the left road wheel remains stationary. The units for this parameter are inch-pounds/degree of right road wheel steer angle.

MECHANICAL TRAIL - In the steering system model, the major source of compliance steer (the action of the lateral forces on the front wheels) is modeled. Because of caster angle on the front axle, the lateral forces act behind the steer rotation axis. The torque created acts against the compliance of the steering system, allowing small steer deviations to occur. Even though the angles are small, they have been found to be significant to the handling behavior of vehicles. The point of action for the lateral forces is specified by the Mechanical Trail. The parameter is given in inches, and is nominally equal to the caster angle (radians) times the front tire radius. A positive value corresponds to positive caster.

Line #377

STEERING CONTROL KEY - Within the model, the steering of the vehicle can be controlled by either of two options:

1) Steer Angle - The steering input can be controlled by definition of a time versus steer angle table. If this

option is to be used, a positive value equal to the number of lines in the time/steer angle table is entered here. The entry is in I3 format. When choosing this option, the next line of entry (378) is skipped, going immediately to the first line of table entry on Line 379.

2) Driver Model - Alternatively, the steering can be controlled via a driver model to make the vehicle follow a prescribed trajectory. This option is activated by entering a negative number on this line with a numerical value equal to the number of lines in the table defining the desired trajectory. The negative sign is used to key the program to select this option. I3 format is used for the entry.

Line #378

DRIVER TRANSPORT LAG - The reaction characteristics of the driver model include a lag in the input of the desired steer angle. The lag is specified by this parameter. Driver transport lag is normally in the range of 0.2 - 0.4 seconds. The entry is made in F10.2 format.

PREVIEW INTERVAL - The second driver characteristic entered on this line is the Preview Interval, entered in F10.2 format. The preview interval defines the "look ahead" time interval over which the driver is observing the trajectory to be followed. The interval is expressed in units of seconds (the look ahead distance being equivalent to the interval times the velocity). The interval is normally in the range of 1-3 seconds. Shorter intervals elicit quicker response from the driver, resulting in more oscillatory steering correction inputs. Longer intervals produce a more damped steering input with greater deviations from the desired trajectory.

Line #379

STEER TABLE - The Steer Table entered at this point defines either steer angle inputs (if the Steer Angle option was selected) or the trajectory table (if the Driver Model option was selected). In either case, the table consists of a number of line inputs equal to the table length specified in Line 377 above. Depending on the option selected, the table is entered using the following conventions:

1) Steer Angle Table - The steer angle table consists of two or three entries on a line using F10.2 format. The first entry is the time in seconds, beginning with a value of zero on the first line. The second entry is the steering wheel angle (degrees) if input at the steering wheel was selected in Line 375 by choice of a steering ratio greater than unity. If input directly to the road wheels was selected in Line 375, then steer angle values for the left and right road wheels respectively, are entered. Steer angles are positive to the right. The length of the steer angle table (in time) should at least equal the maximum simulation time specified in Line 3.

2) Trajectory Table - The desired trajectory for the vehicle to follow is specified in lieu of a steer angle table if the Driver Model was selected in Line 377. The Trajectory Table consists of two entries to a line, each in F10.2 format, where those entries are the longitudinal and lateral points defining the trajectory. Both points are given in units of feet. The table should begin at 0,0 and extend for a longitudinal distance equal to or greater than the distance the vehicle will travel during the simulation, <u>plus the distance equivalent to the Driver Preview Interval</u>.

# 4.0 PROGRAM OUTPUT

## 4.1 General

Operation of the constant velocity Yaw/Roll program generates output in a format compatible with line printer systems with 132 or more characters per line. The output falls in two categories--echo of input data and time-based listing of simulation output variables.

4.1.1 Coordinate Systems. In order to interpret the vehicle motion parameters given in the simulation output, it is necessary to define the coordinate systems used. Two coordinate systems are necessary to describe the simulated motion of each vehicle; an inertial coordinate system and a body-fixed coordinate system, as shown in Figure 7.

The inertial coordinate system is a right-hand orthogonal system fixed in space that serves as the reference point from which vehicle motions and attitudes are defined. The origin is placed at the truck/tractor sprung mass center of gravity at the beginning of the simulation (time=0). The inertial coordinate system is aligned with the gravity vector and the horizontal projection of the truck/tractor longitudinal axis. The axes are defined according to SAE convention as follows:

X - horizontal out the front of the vehicle

Y - horizontal out the right side of the vehicle

Z - vertically downward in the direction of gravity

The body-fixed coordinate system is located and fixed in the vehicle and defines the vehicle location and attitude. Its origin is at the sprung mass center of gravity and is oriented as follows:

x - longitudinally out the front of the vehicle

y - laterally out the right side of the vehicle

z - vertically in the plane of the vehicle sprung mass

Each vehicle in the simulated combination has a separate body-fixed coordinate system.

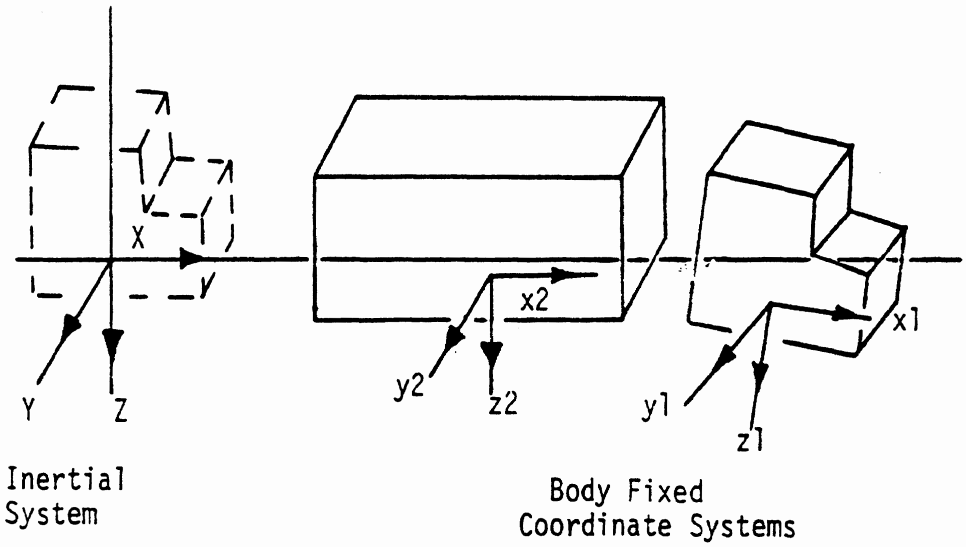



Figure 7. Illustration of coordinate system.

At the beginning of a simulation run, the origin of the truck/tractor body-fixed coordinate system is at the origin of the inertial coordinate system. Furthermore, the axes of the body-fixed system are coincident with those of the inertial system.

Since all vehicles in a combination are aligned on the inertial X axis at the beginning of a simulation, all trailers start off with a negative X coordinate and a zero Y coordinate. Since all vehicles may have a different sprung mass center of gravity height as well as different elevations due to road grade, the height of each vehicle in the inertial system is referenced from its initial height (i.e., the Z coordinate for each vehicle is defined by the change from its initial elevation).

During a simulation, the position and attitude of each vehicle is defined by the position and attitude of its body-fixed coordinate system in the inertial coordinate system. The vehicle position is given by the X, Y, and Z coordinates locating the origin of the body-fixed system. That is, at any instant of time, the vehicle attitude is defined by the following three rotations (Euler angles) going from the orientation of a translated inertial coordinate system to the orientation of the body-fixed system.

1) Yaw angle - rotation in the X-Y inertial plane about the Z axis; positive clockwise when viewed from above.

2) Pitch angle - rotation about the y body axis, out of the X-Y inertial plane; positive clockwise looking from left to right on the vehicle.

3) Roll angle - rotation about the x body axis; positive clockwise looking forward on the vehicle.

### 4.2 Input Echo

The first series of pages in the program output is an echo of the input data used to define the vehicle and simulation to be made. The order of the echo pages are as follows:

Simulation Operation Parameters and Steering Parameters

Truck/Tractor Parameters

Second Unit Parameters

Third Unit Parameters

Fourth Unit Parameters

As a minimum, pages 1 and 2 are always printed, while additional pages appear only if a tractor-trailer, or doubles, are being simulated.

## 4.3 Simulation Output

The simulation output pages are the product of the simulation run, providing a description of what happens to the vehicle combination in the course of the simulated maneuver. The output pages present lists of the selected vehicle motion variables and operating conditions at specified intervals of time throughout the maneuver. The variables and conditions are presented in columns with each line representing a point in time, measured in seconds, from the beginning of the simulation.

The output is identified by sprung mass number appearing on the top of each page. The output consists of blocks arising from the need to minimize computer memory requirements. Each page of output contains up to 41 time increments of output. If the duration of the maneuver and selected time interval for printing results in more than 41 lines of output, to minimize the number of output devices, output for the first 41 time increments (time block 1) is printed; then it continues with the second block of 41 (time block 2), etc. In order to minimize the number of time blocks and hence the bulk of the output pages, the user may want to choose carefully the Printout Interval specified in the Simulation Operation Parameters (Section 3.2), using the following information for guidance:

| Maneuver Direction | Time Increment of Output | No. of Time Blocks |
|---|---|---|
| 2 sec. | .05 sec. | 1 |
| 4 | .10 | 1 |
| 4 | .05 | 2 |
| 6 | .15 | 1 |
| 6 | .10 | 2 |
| 6 | .05 | 3 |
| 8 | .20 | 1 |
| 8 | .15 | 2 |
| 8 | .10 | 3 |
| 8 | .05 | 4 |

Up to sixteen output pages can be obtained for each simulation time block. The output follows the format described in the following sections.

4.3.1 <u>Sprung Mass Pages</u>. The Sprung Mass Page shown in Figure 8 describes the simulated vehicle motion by its position and rotational attitude in the inertial coordinate system. The inertial coordinate system is located at the truck/tractor sprung mass center of gravity at time zero in the simulation (see Section 4.1.1). The vehicle position is defined by forward, lateral, and vertical inertial coordinates of the vehicle sprung mass center of gravity during the simulation. For the truck/tractor, the initial coordinates are always zero. Trailers are always aligned behind the tractor so that they start from a negative forward position and zero lateral position. Positive lateral is to the right of the vehicle. To avoid confusion from the differing sprung mass heights, the vertical position always begins at zero and indicates relative change in elevation. Note that, by SAE convention, positive values of vertical position are downward, in the direction of gravity.

The attitude of the vehicle is given in the next three columns as defined by the Euler angle rotations (roll, pitch, and yaw) of the body-fixed coordinate system (see Section 4.1.1) in the inertial coordinate system.

In addition, the page lists the instantaneous values of linear and rotational velocities and the lateral acceleration. In the last column the steer angle is listed for the lead vehicle, whereas for towed vehicles, it lists the articulation angle, which is the difference between the yaw angles of the leading and trailing vehicles (leading minus trailing).

4.3.2 Constraint Page. The next page echos the calculated constraint forces at the articulation connections, as illustrated in Figure 9.

Constraint forces and moments are listed on this page for each articulation pivot on the vehicle. The first (left-hand) column is time. Depending on the type of articulation joint being used, the number of additional printout columns will vary. (a) For a single-unit vehicle no output will appear (no articulation pivots). (b) For a pintle hook connection only one column is printed--lateral constraint force. (c) For kingpin, conventional fifth wheel, and inverted fifth wheel type connections, four columns are printed for each articulation pivot: lateral force (lb), vertical force (lb), roll moment (in-lb), and pitch moment (in-lb).

4.3.3 Axle Page. Motion variables and conditions at each of the axles are listed on the Axle Page, as shown in Figure 10. The axle position is indicated by a roll angle and vertical (bounce) position. Thereafter, left and right side values for slip angle, vertical load, lateral force, aligning torque, and the suspension spring force are listed. One page is printed for each axle up to the maximum of eleven.

11 AXLE DOUBLE (MICH TANKER)

SPRUNG MASS # 1
****************

| TIME (SEC) | FORWARD POSITION (IN) | LATERAL POSITION (IN) | VERTICAL POSITION (IN) | ROLL ANGLE (DEG) | YAW ANGLE (DEG) | PITCH ANGLE (DEG) | FORWARD VEL IN/SEC | LATERAL VEL IN/SEC | ROLL RATE DEG/SEC | YAW RATE DEG/SEC | PITCH RATE DEG/SEC | LATERAL ACCN. IN/SEC**2 | STEER ANGLE DEG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 968.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.10 | 96.80 | 0.02 | 0.000 | -0.01 | 0.01 | -0.000 | 968.04 | 0.30 | -0.14 | 0.31 | 0.00 | 9.34 | 5.00 |
| 0.20 | 193.60 | 0.12 | 0.000 | -0.03 | 0.07 | 0.000 | 968.04 | 0.52 | -0.39 | 1.01 | -0.00 | 16.60 | 10.00 |
| 0.30 | 290.40 | 0.40 | 0.000 | -0.09 | 0.22 | 0.000 | 968.04 | 0.14 | -0.72 | 1.86 | -0.00 | 24.03 | 15.00 |
| 0.40 | 387.20 | 0.91 | -0.000 | -0.18 | 0.45 | 0.000 | 968.04 | -0.94 | -1.10 | 2.74 | -0.01 | 32.25 | 20.00 |
| 0.50 | 483.99 | 1.75 | -0.000 | -0.31 | 0.76 | 0.000 | 968.04 | -2.61 | -1.46 | 3.60 | -0.02 | 41.46 | 25.00 |
| 0.60 | 580.76 | 2.99 | -0.001 | -0.46 | 1.16 | 0.000 | 968.04 | -5.07 | -1.64 | 4.14 | -0.03 | 42.27 | 25.00 |
| 0.70 | 677.52 | 4.65 | -0.001 | -0.63 | 1.58 | 0.000 | 968.04 | -7.81 | -1.66 | 4.26 | -0.05 | 45.61 | 25.00 |
| 0.80 | 774.27 | 6.77 | -0.000 | -0.79 | 2.00 | 0.000 | 968.04 | -10.22 | -1.53 | 4.20 | -0.06 | 49.10 | 25.00 |
| 0.90 | 871.02 | 9.39 | -0.000 | -0.93 | 2.42 | 0.000 | 968.04 | -12.13 | -1.31 | 4.08 | -0.07 | 52.47 | 25.00 |
| 1.00 | 967.74 | 12.52 | 0.000 | -1.05 | 2.82 | 0.000 | 968.04 | -13.53 | -1.07 | 3.96 | -0.07 | 55.04 | 25.00 |
| 1.10 | 1064.45 | 16.21 | 0.001 | -1.14 | 3.21 | 0.000 | 968.04 | -14.40 | -0.77 | 3.79 | -0.08 | 59.93 | 25.00 |
| 1.20 | 1161.13 | 20.49 | -0.000 | -1.25 | 3.57 | 0.000 | 968.04 | -14.48 | -1.33 | 3.56 | -0.08 | 62.25 | 25.00 |
| 1.30 | 1257.79 | 25.39 | -0.004 | -1.42 | 3.92 | -0.000 | 968.04 | -14.14 | -2.14 | 3.43 | -0.08 | 61.59 | 25.00 |
| 1.40 | 1354.42 | 30.90 | -0.012 | -1.67 | 4.26 | 0.002 | 968.04 | -13.88 | -2.84 | 3.46 | -0.07 | 59.37 | 25.00 |
| 1.50 | 1451.01 | 37.01 | -0.019 | -1.98 | 4.62 | 0.004 | 968.04 | -13.96 | -3.35 | 3.56 | -0.11 | 57.77 | 25.00 |
| 1.60 | 1547.56 | 43.69 | -0.026 | -2.33 | 4.98 | 0.005 | 968.04 | -14.35 | -3.72 | 3.68 | -0.13 | 56.58 | 25.00 |
| 1.70 | 1644.07 | 50.94 | -0.035 | -2.71 | 5.35 | 0.008 | 968.04 | -15.08 | -3.86 | 3.81 | -0.15 | 55.63 | 25.00 |
| 1.80 | 1740.54 | 58.72 | -0.045 | -3.10 | 5.75 | 0.010 | 968.04 | -16.77 | -3.54 | 4.29 | -0.23 | 42.80 | 25.00 |
| 1.90 | 1836.97 | 66.98 | -0.059 | -3.25 | 6.21 | 0.015 | 968.04 | -19.63 | 0.04 | 4.68 | -0.17 | 56.04 | 25.00 |
| 2.00 | 1933.36 | 75.80 | -0.062 | -3.22 | 6.66 | 0.022 | 968.04 | -21.01 | 0.47 | 4.24 | -0.26 | 65.20 | 25.00 |
| 2.10 | 2029.69 | 85.26 | -0.059 | -3.15 | 7.06 | 0.015 | 968.04 | -21.10 | 0.96 | 3.89 | -0.25 | 71.01 | 25.00 |
| 2.20 | 2125.95 | 95.42 | -0.079 | -3.08 | 7.43 | 0.022 | 968.04 | -20.24 | 0.36 | 3.55 | -0.05 | 70.86 | 25.00 |
| 2.30 | 2222.13 | 106.28 | -0.074 | -3.08 | 7.78 | 0.027 | 968.04 | -19.30 | -0.15 | 3.49 | -0.26 | 65.83 | 25.00 |
| 2.40 | 2318.23 | 117.80 | -0.060 | -3.07 | 8.14 | 0.018 | 968.04 | -18.81 | 0.34 | 3.65 | -0.23 | 65.83 | 25.00 |
| 2.50 | 2414.25 | 129.97 | -0.069 | -3.04 | 8.51 | 0.022 | 968.04 | -18.34 | 0.14 | 3.61 | -0.13 | 65.69 | 25.00 |
| 2.60 | 2510.19 | 142.79 | -0.063 | -3.04 | 8.87 | 0.021 | 968.04 | -18.01 | 0.03 | 3.65 | -0.26 | 63.56 | 25.00 |
| 2.70 | 2606.03 | 156.25 | -0.062 | -3.02 | 9.24 | 0.018 | 968.04 | -17.84 | 0.27 | 3.70 | -0.17 | 64.68 | 25.00 |
| 2.80 | 2701.79 | 170.34 | -0.067 | -3.01 | 9.60 | 0.022 | 968.04 | -17.65 | -0.04 | 3.68 | -0.17 | 63.57 | 25.00 |
| 2.90 | 2797.45 | 185.06 | -0.059 | -3.01 | 9.97 | 0.019 | 968.04 | -17.58 | 0.00 | 3.72 | -0.25 | 62.71 | 25.00 |
| 3.00 | 2893.01 | 200.41 | -0.061 | -2.99 | 10.35 | 0.018 | 968.04 | -17.57 | 0.17 | 3.74 | -0.16 | 63.35 | 25.00 |
| 3.10 | 2988.47 | 216.37 | -0.064 | -2.99 | 10.72 | 0.021 | 968.04 | -17.56 | 0.06 | 3.72 | -0.19 | 63.05 | 25.00 |
| 3.20 | 3083.83 | 232.97 | -0.057 | -2.98 | 11.09 | 0.018 | 968.04 | -17.55 | 0.06 | 3.73 | -0.23 | 63.18 | 25.00 |
| 3.30 | 3179.07 | 250.18 | -0.060 | -2.97 | 11.47 | 0.018 | 968.04 | -17.53 | 0.10 | 3.74 | -0.16 | 63.25 | 25.00 |
| 3.40 | 3274.21 | 268.01 | -0.061 | -2.96 | 11.84 | 0.020 | 968.04 | -17.52 | 0.02 | 3.72 | -0.20 | 63.10 | 25.00 |
| 3.50 | 3369.22 | 286.46 | -0.056 | -2.96 | 12.21 | 0.018 | 968.04 | -17.49 | 0.04 | 3.72 | -0.22 | 63.12 | 25.00 |
| 3.60 | 3464.11 | 305.53 | -0.058 | -2.96 | 12.59 | 0.018 | 968.04 | -17.47 | 0.04 | 3.73 | -0.17 | 63.11 | 25.00 |
| 3.70 | 3558.87 | 325.22 | -0.059 | -2.96 | 12.96 | 0.019 | 968.04 | -17.46 | -0.03 | 3.72 | -0.20 | 62.96 | 25.00 |
| 3.80 | 3653.50 | 345.52 | -0.056 | -2.96 | 13.33 | 0.017 | 968.04 | -17.45 | -0.01 | 3.73 | -0.21 | 63.01 | 25.00 |
| 3.90 | 3748.00 | 366.44 | -0.058 | -2.96 | 13.70 | 0.018 | 968.04 | -17.45 | -0.01 | 3.73 | -0.17 | 62.99 | 25.00 |
| 4.00 | 3842.36 | 387.98 | -0.058 | -2.96 | 14.08 | 0.019 | 968.04 | -17.46 | -0.06 | 3.73 | -0.20 | 62.90 | 25.00 |

Figure 8. Sample sprung mass page.

11 AXLE DOUBLE (MICH TANKER)

## CONSTRAINT FORCES
*****************

NOTE: LATERAL FORCE ALONE IS PRINTED FOR PINTLE HOOK TYPE CONSTRAINT.
LOCATE FORCES & MOMENTS BASED ON CONSTRAINT TYPE

| TIME | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 32700.2 | 0.0 | 0.0 | 0.0 | 0.0 | 21134.6 | 0.0 | 0.0 | |
| 0.10 | -71.9 | 32699.7 | 3693.0 | 0.0 | -2.2 | -2.4 | 21127.1 | -1.4 | 27.3 | |
| 0.20 | -320.8 | 32700.1 | 7913.4 | 0.0 | 0.8 | -6.1 | 21128.0 | 57.0 | 26.4 | |
| 0.30 | -803.3 | 32698.3 | 14100.3 | 0.0 | 6.2 | -0.6 | 21134.2 | -50.5 | 7.3 | |
| 0.40 | -1502.2 | 32694.2 | 21193.7 | 0.0 | 10.4 | 28.3 | 21127.0 | -333.5 | 27.9 | |
| 0.50 | -2373.0 | 32684.8 | 28072.7 | 0.0 | 7.6 | 77.1 | 21128.8 | -472.0 | 32.6 | |
| 0.60 | -3301.5 | 32670.1 | 30419.0 | 0.0 | -4.4 | 112.3 | 21133.6 | 40.6 | 12.7 | |
| 0.70 | -4151.6 | 32652.6 | 31094.5 | 0.0 | -34.6 | 68.6 | 21127.6 | 1449.3 | 16.0 | |
| 0.80 | -4815.0 | 32636.1 | 28240.5 | 0.0 | -79.5 | -137.0 | 21128.7 | 3671.5 | -23.2 | |
| 0.90 | -5305.6 | 32620.7 | 23700.2 | 0.0 | -134.0 | -577.5 | 21132.5 | 5610.2 | -88.6 | |
| 1.00 | -5655.9 | 32606.5 | 18560.6 | 0.0 | -183.6 | -1274.3 | 21124.9 | 5114.1 | -114.6 | |
| 1.10 | -5707.6 | 32587.4 | 9817.5 | 0.0 | -250.4 | -2198.8 | 21120.7 | -838.3 | -175.6 | |
| 1.20 | -5561.9 | 32548.1 | -12041.0 | 0.0 | -287.1 | -3248.1 | 21111.1 | -14421.3 | -231.0 | |
| 1.30 | -5466.4 | 32424.3 | -43756.5 | 0.0 | -293.0 | -4298.7 | 21086.0 | -36641.0 | -224.4 | |
| 1.40 | -5559.5 | 32291.7 | -80209.8 | 0.0 | -279.5 | -5229.1 | 21063.2 | -66558.1 | -204.6 | |
| 1.50 | -5775.6 | 32181.3 | -120658.1 | 0.0 | -235.3 | -5859.6 | 21043.9 | -101170.4 | -128.6 | |
| 1.60 | -6090.8 | 32008.1 | -163664.9 | 0.0 | -199.9 | -6174.6 | 21026.6 | -133950.1 | -66.3 | |
| 1.70 | -6511.3 | 31817.6 | -205872.4 | 0.0 | -131.6 | -5987.4 | 20927.4 | -169005.8 | -300.3 | |
| 1.80 | -7954.0 | 31523.5 | -218227.5 | 0.0 | 29.7 | -5396.2 | 20671.5 | -224552.9 | -3255.5 | |
| 1.90 | -8425.2 | 31425.9 | -204839.9 | 0.0 | -65.8 | -4686.2 | 20678.6 | -293720.9 | -9812.2 | |
| 2.00 | -8332.0 | 31622.1 | -199401.2 | 0.0 | -150.2 | -4004.7 | 20771.6 | -332229.3 | -11548.5 | |
| 2.10 | -8038.8 | 31378.4 | -192760.7 | 0.0 | -186.2 | -3582.2 | 20679.5 | -316747.4 | -9971.0 | |
| 2.20 | -7589.1 | 31410.9 | -200577.9 | 0.0 | -227.8 | -3489.6 | 21068.3 | -247508.2 | -4056.3 | |
| 2.30 | -7636.3 | 31668.7 | -201629.0 | 0.0 | -85.6 | -2679.9 | 21196.0 | -180460.4 | 2296.5 | |
| 2.40 | -7575.9 | 31537.0 | -198678.6 | 0.0 | -227.7 | -3110.2 | 20873.7 | -159102.9 | -526.9 | |
| 2.50 | -7343.5 | 31605.3 | -203503.1 | 0.0 | -234.0 | -3437.5 | 21336.3 | -119908.3 | -2394.5 | |
| 2.60 | -7419.5 | 31650.3 | -200781.0 | 0.0 | -210.2 | -3753.7 | 21125.9 | -80365.6 | 1353.1 | |
| 2.70 | -7296.4 | 31548.9 | -200600.0 | 0.0 | -220.6 | -4138.3 | 20724.1 | -50298.9 | -904.7 | |
| 2.80 | -7265.8 | 31669.4 | -201613.8 | 0.0 | -194.3 | -4418.8 | 21487.2 | -31816.6 | -2057.6 | |
| 2.90 | -7330.7 | 31663.3 | -199849.9 | 0.0 | -183.8 | -4520.2 | 21009.9 | -40772.1 | 1195.2 | |
| 3.00 | -7264.8 | 31591.6 | -199758.1 | 0.0 | -188.1 | -4543.9 | 20703.4 | -62263.5 | -486.8 | |
| 3.10 | -7281.5 | 31689.7 | -198313.4 | 0.0 | -173.2 | -4559.5 | 21575.0 | -87500.0 | -1543.4 | |
| 3.20 | -7290.5 | 31669.9 | -196985.2 | 0.0 | -181.6 | -4435.7 | 20867.1 | -120159.2 | 858.4 | |
| 3.30 | -7256.8 | 31633.6 | -196610.4 | 0.0 | -177.4 | -4334.9 | 20769.2 | -140590.4 | -638.8 | |
| 3.40 | -7256.8 | 31711.2 | -196230.4 | 0.0 | -158.9 | -4192.9 | 21621.0 | -153964.8 | -1492.8 | |
| 3.50 | -7262.9 | 31685.1 | -195459.8 | 0.0 | -175.3 | -4017.9 | 20765.5 | -168565.1 | 697.4 | |
| 3.60 | -7238.2 | 31660.0 | -195617.7 | 0.0 | -166.4 | -3874.9 | 20899.9 | -168203.6 | -429.9 | |
| 3.70 | -7244.4 | 31713.3 | -195739.4 | 0.0 | -162.9 | -3773.1 | 21607.0 | -164577.3 | -1294.3 | |
| 3.80 | -7250.7 | 31682.8 | -195602.9 | 0.0 | -182.9 | -3694.9 | 20696.2 | -160617.0 | 439.3 | |
| 3.90 | -7236.2 | 31666.1 | -196193.3 | 0.0 | -175.8 | -3680.3 | 21020.1 | -144637.2 | -718.5 | |
| 4.00 | -7247.6 | 31700.1 | -196590.9 | 0.0 | -179.8 | -3750.8 | 21529.1 | -129021.1 | -1481.9 | |

Figure 9. Sample constraint forces page.

11 AXLE DOUBLE (MICH TANKER)

AXLE # 2
*********

| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 8000.0 | 0.0 | 0.0 | 6750.0 | 0.0 | 8000.0 | 0.0 | 0.0 | 6750.0 |
| 0.10 | -0.002 | -0.000 | -0.00 | 8013.6 | 4.2 | -0.57 | 6772.2 | -0.00 | 7986.1 | 4.2 | -0.57 | 6727.5 |
| 0.20 | -0.010 | -0.000 | -0.04 | 8064.3 | 42.8 | -5.86 | 6817.6 | -0.04 | 7935.7 | 42.3 | -5.74 | 6682.4 |
| 0.30 | -0.028 | -0.000 | -0.12 | 8176.2 | 130.6 | -18.13 | 6909.4 | -0.12 | 7823.4 | 126.6 | -17.09 | 6589.8 |
| 0.40 | -0.056 | 0.000 | -0.25 | 8352.0 | 266.8 | -37.73 | 7057.9 | -0.25 | 7647.2 | 250.0 | -33.50 | 6440.4 |
| 0.50 | -0.093 | 0.000 | -0.41 | 8583.6 | 446.4 | -64.65 | 7261.6 | -0.41 | 7414.3 | 400.1 | -53.04 | 6234.3 |
| 0.60 | -0.135 | 0.000 | -0.59 | 8848.0 | 659.0 | -97.93 | 7494.1 | -0.60 | 7148.3 | 560.5 | -73.34 | 5998.6 |
| 0.70 | -0.178 | 0.001 | -0.77 | 9114.0 | 865.2 | -131.71 | 7748.7 | -0.77 | 6881.5 | 697.2 | -89.92 | 5741.6 |
| 0.80 | -0.215 | 0.001 | -0.91 | 9348.2 | 1041.0 | -161.71 | 7989.6 | -0.91 | 6648.0 | 799.3 | -101.69 | 5499.4 |
| 0.90 | -0.245 | 0.001 | -1.01 | 9539.4 | 1178.6 | -185.69 | 8201.2 | -1.02 | 6457.6 | 868.3 | -108.92 | 5287.3 |
| 1.00 | -0.268 | 0.001 | -1.09 | 9682.6 | 1272.9 | -201.26 | 8377.8 | -1.10 | 6315.0 | 907.1 | -111.79 | 5110.1 |
| 1.10 | -0.283 | 0.001 | -1.14 | 9776.4 | 1329.0 | -210.76 | 8511.9 | -1.14 | 6217.8 | 925.9 | -112.84 | 4972.9 |
| 1.20 | -0.298 | 0.002 | -1.12 | 9862.0 | 1312.3 | -209.88 | 8721.1 | -1.12 | 6120.5 | 896.2 | -108.66 | 4750.4 |
| 1.30 | -0.321 | 0.004 | -1.07 | 9985.2 | 1275.4 | -206.70 | 9047.9 | -1.08 | 5951.9 | 842.9 | -101.32 | 4379.4 |
| 1.40 | -0.357 | 0.009 | -1.05 | 10184.8 | 1265.5 | -208.55 | 9496.8 | -1.05 | 5696.4 | 793.4 | -93.59 | 3874.8 |
| 1.50 | -0.403 | 0.013 | -1.05 | 10456.2 | 1292.7 | -216.90 | 10038.6 | -1.06 | 5386.9 | 756.1 | -86.58 | 3291.3 |
| 1.60 | -0.457 | 0.017 | -1.08 | 10763.1 | 1348.6 | -230.14 | 10633.8 | -1.08 | 5022.3 | 724.2 | -79.38 | 2636.7 |
| 1.70 | -0.515 | 0.023 | -1.13 | 11091.6 | 1436.0 | -248.68 | 11248.7 | -1.13 | 4621.9 | 697.8 | -71.97 | 1948.8 |
| 1.80 | -0.581 | 0.029 | -1.27 | 11468.5 | 1634.1 | -286.06 | 11808.4 | -1.27 | 4165.0 | 697.3 | -68.55 | 1297.2 |
| 1.90 | -0.604 | 0.036 | -1.53 | 11587.3 | 1957.5 | -339.59 | 11795.2 | -1.53 | 3991.5 | 787.7 | -74.36 | 1260.6 |
| 2.00 | -0.603 | 0.033 | -1.58 | 11614.9 | 2027.2 | -351.24 | 11740.1 | -1.59 | 4040.8 | 822.3 | -77.58 | 1382.0 |
| 2.10 | -0.589 | 0.034 | -1.57 | 11486.1 | 2000.6 | -343.60 | 11561.6 | -1.58 | 4084.6 | 825.0 | -78.11 | 1485.6 |
| 2.20 | -0.573 | 0.041 | -1.48 | 11355.8 | 1883.0 | -321.92 | 11461.2 | -1.49 | 4155.8 | 797.0 | -76.41 | 1537.9 |
| 2.30 | -0.571 | 0.036 | -1.41 | 11408.7 | 1804.6 | -311.10 | 11551.8 | -1.42 | 4230.2 | 777.4 | -75.52 | 1557.3 |
| 2.40 | -0.567 | 0.033 | -1.40 | 11368.1 | 1791.6 | -308.08 | 11503.6 | -1.41 | 4241.6 | 775.7 | -75.45 | 1585.9 |
| 2.50 | -0.560 | 0.035 | -1.37 | 11315.4 | 1744.2 | -299.75 | 11459.4 | -1.38 | 4283.0 | 766.0 | -74.97 | 1621.4 |
| 2.60 | -0.560 | 0.033 | -1.35 | 11337.1 | 1725.2 | -297.21 | 11484.1 | -1.36 | 4306.2 | 761.3 | -74.79 | 1633.4 |
| 2.70 | -0.555 | 0.034 | -1.35 | 11283.1 | 1716.9 | -294.95 | 11420.2 | -1.36 | 4313.0 | 761.5 | -74.82 | 1659.6 |
| 2.80 | -0.553 | 0.034 | -1.33 | 11290.0 | 1694.9 | -291.70 | 11433.1 | -1.34 | 4336.8 | 756.2 | -74.58 | 1673.2 |
| 2.90 | -0.554 | 0.031 | -1.33 | 11305.1 | 1696.1 | -292.16 | 11444.6 | -1.34 | 4346.8 | 757.7 | -74.80 | 1683.5 |
| 3.00 | -0.551 | 0.033 | -1.33 | 11264.6 | 1697.0 | -291.56 | 11395.4 | -1.34 | 4344.8 | 759.6 | -74.91 | 1697.5 |
| 3.10 | -0.550 | 0.033 | -1.33 | 11278.5 | 1694.1 | -291.38 | 11402.5 | -1.34 | 4363.4 | 760.9 | -75.17 | 1717.9 |
| 3.20 | -0.550 | 0.031 | -1.33 | 11280.8 | 1694.0 | -291.40 | 11398.8 | -1.34 | 4371.8 | 762.2 | -75.35 | 1731.8 |
| 3.30 | -0.548 | 0.032 | -1.33 | 11254.7 | 1691.6 | -290.56 | 11367.6 | -1.34 | 4370.6 | 762.2 | -75.32 | 1740.2 |
| 3.40 | -0.547 | 0.031 | -1.33 | 11265.5 | 1688.0 | -290.20 | 11374.2 | -1.33 | 4389.3 | 763.3 | -75.57 | 1759.3 |
| 3.50 | -0.547 | 0.030 | -1.33 | 11264.9 | 1687.2 | -290.06 | 11371.8 | -1.33 | 4392.4 | 763.5 | -75.61 | 1764.6 |
| 3.60 | -0.546 | 0.031 | -1.33 | 11248.1 | 1684.8 | -289.39 | 11354.2 | -1.33 | 4388.6 | 762.6 | -75.50 | 1764.6 |
| 3.70 | -0.546 | 0.031 | -1.32 | 11260.5 | 1682.9 | -289.33 | 11366.6 | -1.33 | 4398.2 | 762.9 | -75.60 | 1770.9 |
| 3.80 | -0.546 | 0.030 | -1.32 | 11260.9 | 1683.8 | -289.47 | 11368.1 | -1.33 | 4394.9 | 762.7 | -75.56 | 1766.8 |
| 3.90 | -0.546 | 0.031 | -1.32 | 11251.7 | 1683.0 | -289.19 | 11361.3 | -1.33 | 4388.1 | 761.6 | -75.41 | 1760.0 |
| 4.00 | -0.547 | 0.031 | -1.32 | 11264.6 | 1683.2 | -289.44 | 11376.7 | -1.33 | 4390.8 | 761.6 | -75.44 | 1757.6 |

Figure 10. Sample axle page.

# 5.0 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, Highway Safety Research Institute, The Univ. of Michigan, Ann Arbor, 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, Highway Safety Research Institute, The Univ.of Michigan, Ann Arbor, June 1, 1973.

3. Winkler, C.B., et al. "Predicting the Braking Performance of Trucks and Tractor-Trailers." Phase III Technical Report, Motor Truck Braking and Handling Performance Study, Highway Safety Research Institute, The Univ. of Michigan, Ann Arbor, June 1976.

4. Gillespie, T.D., et al. "Simulation of the Effects of Increased Truck Size and Weight." Final Rept., Contract No. DOT-FH-11-9330, Highway Safety Research Institute, The Univ. of Michigan, November 1979.

5. MacAdam, C.C., et al. "A Computerized Model for Simulating the Braking and Steering Dynamics of Trucks, Tractor-Semitrailers, Doubles, and Triples Combinations. User's Manual." Highway Safety Research Institute, The Univ. of Michigan, September 1, 1980.

6. MacAdam, C.C. "Application of an Optimal Preview Control for Simulation of Closed-Loop Automobile Driving." IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 6, June 1981, pp. 393-399.

7. Ervin, R.D., et al. "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers." Final Rept., Contract No. MPA-78-002A, Highway Safety Research Institute, The Univ. of Michigan, Report No. UM-HSRI-78-18, May 7, 1978.

8. Fancher, P. and MacAdam, C.C. "Computer Analysis of Antilock System Performance in the Braking of Commercial Vehicles." Proceedings of a Conference on Braking of Road Vehicles, The Inst. of Mech. Engrs., March 23-25, 1976.

9. Mallikarjunarao, C. "Road Tanker Design: Its Influence on the Risk and Economic Aspects of Transporting Gasoline in Michigan." Ph.D Dissertation, The University of Michigan, December 1981.

# APPENDIX A

## CONSTANT VELOCITY YAW/ROLL MODEL
Input Data List

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 1 | Title - Up to 80 characters | -- | 20A4 | HEAD |
| 2 | No. of Units - Not to exceed 4 | -- | I2 | NI |
| | No. of Axles - Not to exceed 11 | -- | I2 | NN |
| 3 | Forward velocity | Ft/sec | F10.2 | XVEL(1) |
| | Maximum simulation time | Sec | F10.2 | PRMT(2) |
| | Printout interval | Sec | F10.2 | XPRINT |
| | Roll angle increment - Typically 0.2 | Radians | F10.2 | UPDATE |
| 4 | No. of axles on Unit #1 | -- | I2 | NAXL(1) |
| | No. of axles on Unit #2 | -- | I2 | NAXL(2) |
| | No. of axles on Unit #3 | -- | I2 | NAXL(3) |
| | No. of axles on Unit #4 | -- | I2 | NAXL(4) |
| 5 | Sprung weight of Unit #1 | Lb. | F10.2 | WS(1) |
| | Sprunt weight of Unit #2 | Lb. | F10.2 | WS(2) |
| | Sprung weight of Unit #3 | Lb. | F10.2 | WS(3) |
| | Sprung weight of Unit #4 | Lb. | F10.2 | WS(4) |
| 6 | Spr. mass Roll M of I, Unit #1 | In-lb-sec^2 | F10.2 | IXXS(1) |
| | Spr. mass Roll M of I, Unit #2 | In-lb-sec^2 | F10.2 | IXXS(2) |
| | Spr. mass Roll M of I, Unit #3 | In-lb-sec^2 | F10.2 | IXXS(3) |
| | Spr. mass Roll M of I, Unit #4 | In-lb-sec^2 | F10.2 | IXXS(4) |
| 7 | Spr. mass Pitch M of I, Unit #1 | In-lb-sec^2 | F10.2 | IYYS(1) |
| | Spr. mass Pitch M of I, Unit #2 | In-lb-sec^2 | F10.2 | IYYS(2) |
| | Spr. mass Pitch M of I, Unit #3 | In-lb-sec^2 | F10.2 | IYYS(3) |
| | Spr. mass Pitch M of I, Unit #4 | In-lb-sec^2 | F10.2 | IYYS(4) |
| 8 | Spr. mass Yaw M of I, Unit #1 | In-lb-sec^2 | F10.2 | IZZS(1) |
| | Spr. mass Yaw M of I, Unit #2 | In-lb-sec^2 | F10.2 | IZZS(2) |
| | Spr. mass Yaw M of I, Unit #3 | In-lb-sec^2 | F10.2 | IZZS(3) |
| | Spr. mass Yaw M of I, UNit #4 | In-lb-sec^2 | F10.2 | IZZS(4) |

CONSTANT VELOCITY YAW/ROLL MODEL - Input Data List (Cont'd)

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 9 | Spr. mass CG height, Unit #1 | Inches | F10.2 | ZS(1) |
| | Spr. mass CG height, Unit #2 | Inches | F10.2 | ZS(2) |
| | Spr. mass CG height, Unit #3 | Inches | F10.2 | ZS(3) |
| | Spr. mass CG height, Unit #4 | Inches | F10.2 | ZS(4) |
| 10 | Ground load on Axle #1 (With all | Lb. | F10.2 | WINIT(1) |
| | Ground load on Axle #2 vehicles loaded | Lb. | F10.2 | WINIY(2) |
| | Ground load on Axle #3 and coupled) | Lb. | F10.2 | WINIT(3) |
| | (Etc. for the remaining axles) | | | WINIT(NN) |
| 11 | Unsprung weight of Axle #1 | Lb. | F10.2 | WU(1) |
| | Unsprung weight of Axle #2 | Lb. | F10.2 | WU(2) |
| | Unsprung weight of Axls #3 | Lb. | F10.2 | WU(3) |
| | (Etc. for the remaining axles) | | | WU(NN) |
| 12 | Roll M of I, Axle #1 | In-lb-sec^2 | F10.2 | IXXU(1) |
| | Roll M of I, Axle #2 | In-lb-sec^2 | F10.2 | IXXU(2) |
| | Roll M of I, Axle #3 | In-lb-sec^2 | F10.2 | IXXU(3) |
| | (Etc. for the remaining axles) | | | IXXU(NN) |
| 13 | Long. dist. from axle #1 to spr. mass CG | Inches | F10.2 | XU(1) |
| | Long. dist. from axle #2 to spr. mass CG | Inches | F10.2 | XU(2) |
| | Long. dist. from axle #3 to spr. mass CG | Inches | F10.2 | XU(3) |
| | (Etc. for the remaining axles) | | | XU(NN) |
| 14 | CG height, Axle #1 | Inches | F10.2 | ZU(1) |
| | CG height, Axle #2 | Inches | F10.2 | ZU(2) |
| | CG height, Axle #3 | Inches | F10.2 | ZU(3) |
| | (Etc. for the remaining axles) | | | ZU(NN) |
| 15 | Roll center height, Axle #1 | Inches | F10.2 | HR(1) |
| | Roll center height, Axle #2 | Inches | F10.2 | HR(2) |
| | Roll center height, Axle #3 | Inches | F10.2 | HR(3) |
| | (Etc. for the remaining axles) | | | HR(NN) |
| 16 | Suspension lateral half-spacing | Inches | F10.2 | SY(1) |
| | Suspension lateral half-spacing | Inches | F10.2 | SY(2) |
| | Suspension lateral half-spacing | Inches | F10.2 | SY(3) |
| | (Etc. for the remaining axles) | | | SY(NN) |

CONSTANT VELOCITY YAW/ROLL MODEL - Input Data List (Cont'd)

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 17 | Half-track dist. to inner tire, Axle #1 | Inches | F10.2 | TY(1) |
| | Half-track dist. to inner tire, Axle #2 | Inches | F10.2 | TY(2) |
| | Half-track dist. to inner tire, Axle #3 | Inches | F10.2 | TY(3) |
| | (Etc. for the remaining axles) | | | TY(NN) |
| 18 | Dual tire spacing, Axle #1 (Use 0.0 for | Inches | F10.2 | GY(1) |
| | Dual tire spacing, Axle #2 single tires) | Inches | F10.2 | GY(2) |
| | Dual tire spacing, Axle #3 | Inches | F10.2 | GY(3) |
| | (Etc. for the remaining axles) | | | GY(NN) |
| 19 | Vertical stiffness, one tire, Axle #1 | Lb/in | F10.2 | KT(1) |
| | Vertical stiffness, one tire, Axle #2 | Lb/in | F10.2 | KT(2) |
| | Vertical stiffness, one tire, Axle #3 | Lb/in | F10.2 | KT(3) |
| | (Etc. for the remaining axles) | | | KT(NN) |
| 20 | Roll steer coefficient, Axle #1 | -- | F10.2 | RSC(1) |
| | Roll steer coefficient, Axle #2 | -- | F10.2 | RSC(2) |
| | Roll steer coefficient, Axle #3 | -- | F10.2 | RSC(3) |
| | (Etc. for the remaining axles) | | | RSC(NN) |
| 21 | Auxiliary roll stiffness, Axle #1 | In-lb/deg | F10.2 | KRS(1) |
| | Auxiliary roll stiffness, Axle #2 | In-lb/deg | F10.2 | KRS(2) |
| | Auxiliary roll stiffness, Axle #3 | In-lb/deg | F10.2 | KRS(3) |
| | (Etc. for the remaining axles) | | | KRS(NN) |
| 22 | Coulomb friction, per spring, Axle #1 | Lb. | F10.2 | CF(1) |
| | Coulomb friction, per spring, Axle #2 | Lb. | F10.2 | CF(2) |
| | Coulomb friction, per spring, Axle #3 | Lb. | F10.2 | CF(3) |
| | (Etc. for the remaining axles) | | | CF(NN) |
| 23 | Viscous damping, per side, Axle #1 | Lb-sec/in | F10.2 | CV(1) |
| | Viscous damping, per side, Axle #2 | Lb-sec/in | F10.2 | CV(2) |
| | Viscous damping, per side, Axle #3 | Lb-sec/in | F10.2 | CV(3) |
| | (Etc. for the remaining axles) | | | CV(NN) |

CONSTANT VELOCITY YAW/ROLL MODEL - Input Data List (Cont'd)

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 24 | Aft hitch, dist. to CG, Unit #1 | Inches | F10.2 | XCON(1) |
| | Fwd hitch, dist. to CG, Unit #2 | Inches | F10.2 | XCON(2) |
| | Aft hitch, dist. to CG, Unit #2 | Inches | F10.2 | XCON(3) |
| | Fwd hitch, dist. to CG, Unit #3 | Inches | F10.2 | XCON(4) |
| | Aft hitch, dist. to CG, Unit #3 | Inches | F10.2 | XCON(5) |
| | Fwd hitch, dist. to CG, Unit #4 | Inches | F10.2 | XCON(6) |
| 25 | Height of Hitch #1 (With units | Inches | F10.2 | ZC(1) |
| | Height of Hitch #2 fully loaded | Inches | F10.2 | ZC(2) |
| | Height of Hitch #3 and hitched) | Inches | F10.2 | ZC(3) |
| 26 | Roll stiffness of Hitch #1 | In-lb/deg | F10.2 | KCON(1) |
| | Roll stiffness of Hitch #2 | In-lb/deg | F10.2 | KCON(2) |
| | Roll stiffness of Hitch #3 | In-lb/deg | F10.2 | KCON(3) |
| 27 | Type of Hitch #1 | -- | I2 | NCTYPE(1) |
| | Type of Hitch #2 | -- | I2 | NCTYPE(2) |
| | Type of Hitch #3 | -- | I2 | NCTYPE(3) |
| | - Conventional 5th wheel 01 | | | |
| | - Inverted 5th wheel 02 | | | |
| | - Pintle hook or ball hitch 03 | | | |
| | - Kingpin or turntable 04 | | | |
| 28 | No. of Spring Tables to be entered | -- | I2 | NSPR |
| 29 | Table # for springs on Axle #1 | -- | I2 | ISPR(1) |
| | Table # for springs on Axle #2 | -- | I2 | ISPR(2) |
| | Table # for springs on Axle #3 | -- | I2 | ISPR(2) |
| | (Etc. for the remaining axles ) | | | ISPR(NN) |

CONSTANT VELOCITY YAW/ROLL MODEL - Input Data List (Cont'd)

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 30 | No. of lines in Spring Table #1 | -- | I2 | ITEMP |
| 31 | First force value, Spring Table #1 | Lb. | F10.2 | FTABLE(-) |
| | First deflection value, Spring Table #1 | Inches | F10.2 | FTABLE(-) |
| 32 | Second force value, Spring Table #1 | Lb. | F10.2 | FTABLE(-) |
| | Second deflection value, Spring Table #1 | Inches | F10.2 | FTABLE(-) |
| 33-40 | Remaining lines of Spring Table #1 up to the number ITEMP | | | |
| 41 | No. of lines in Spring Table #2 | -- | I2 | ITEMP |
| 42 | First force value, Spring Table #2 | Lb. | F10.2 | FTABLE(-) |
| | First deflection value, Spring Table #2 | Inches | F10.2 | FTABLE(-) |
| 43 | Second force value, Spring Table #2 | Lb. | F10.2 | FTABLE(-) |
| | Second deflection value, Spring Table #2 | Inches | F10.2 | FTABLE(-) |
| 44-51 | Remaining lines of Spring Table #2 up to the number ITEMP | | | |
| 52-150 | Remaining Spring Tables up to the number NSPR | | | |
| 151 | No. of Tire Cornering Force Tables | -- | I2 | NFTAB |
| 152 | Cornering Force Table # for Axle #1 | -- | I2 | IFTAB(1) |
| | Cornering Force Table # for Axle #2 | -- | I2 | IFTAB(2) |
| | Cornering Force Table # for Axle #3 | -- | I2 | IFTAB(3) |
| | (Etc. for the remaining axles) | | | IFTAB(NN) |
| 153 | No. of rows in Cornering Force Table #1 | -- | I2 | |
| | No. of columns in Cornering Force Table #1 | -- | I2 | |
| 154 | Row #1, Table #1 (Slip angle values) | Deg. | F10.2 | |
| 155 | Row #2, Talbe #1 (Load and Force values) | Lb. | 9F10.2 | |
| 156 | Row #3, Table #1 (Load and Force values) | Lb. | 9F10.2 | |
| 157-162 | Remaining rows in Table #1 up to a maximum of 9 rows | | | |

CONSTANT VELOCITY YAW/ROLL MODEL - Input Data List (Cont'd)

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 163 | No. of rows in Cornering Force Table #2 | -- | I2 | |
| | No. of columns in Cornering Force Table #2 | -- | I2 | |
| 164 | Row #1, Table #2 (Slip angle values) | Deg. | F10.2 | |
| 165 | Row #2, Table #2 (Load and Force values) | Lb. | F10.2 | |
| 166 | Row #3, Table #2 (Load and Force valuea) | Lb. | F10.2 | |
| 167-172 | Remaining rows in Table #2 up to a maximum of 9 rows | | | |
| 173-262 | Remaining Cornering Force Tables to the number NFTAB | | | |
| 263 | No. of Aligning Torque Tables | -- | I2 | NATAB |
| 264 | Aligning Torque Table # for Axle #1 | -- | I2 | IATAB(1) |
| | Aligning Torque Table # for Axle #2 | -- | I2 | IATAB(2) |
| | Aligning Torque Table # for Axle #3 | -- | I2 | IATAB(3) |
| | (Etc. for the remaining axles) | | | IATAB(NN) |
| 265 | No. of rows in Aligning Torque Table #1 | -- | I2 | |
| | No. of columns in Aligning Torque Table #1 | -- | I2 | |
| 266 | Row #1, Table #1 (Slip angle values) | Deg. | F10.2 | |
| 267 | Row #2, Table #1 (Load and Torques) | Lb, Ft-lb | 9F10.2 | |
| 268 | Row #3, Table #1 (Load and Torques) | Lb, Ft-lb | 9F10.2 | |
| 269-274 | Remaining rows in Table #1 up to a maximum of 9 rows | | | |
| 275 | No. of rows in Aligning Torque Table #2 | -- | I2 | |
| | No. of columns in Aligning Torque Table #2 | -- | I2 | |
| 276 | Row #1, Table #2 (Slip angle values) | Deg. | F10.2 | |
| 277 | Row #2, Table #2 (Load and Torques) | Lb, Ft-lb | 9F10.2 | |
| 278 | Row #3, Table #2 (Load and Torques) | Lb, Ft-lb | 9F10.2 | |
| 279-284 | Remaining rows in Table #2 up to a maximum of 9 rows | | | |

CONSTANT VELOCITY YAW/ROLL MODEL - Input Data List (Cont'd)

| Line No. | Parameter Description | Units | Format | Program Symbol |
|---|---|---|---|---|
| 285-374 | Remaining Aligning Torque Tables to the number NATAB | | | |
| 375 | Steering Ratio (If > 1 calls the steering model, go to Line 376) | -- | F10.2 | GRATIO |
| 376 | Steering system stiffness | In-lb/deg | F10.2 | KSS |
| | Tie rod linkage stiffness | In-lb/deg | F10.2 | KTR |
| | Mechanical Trail | Inches | F10.2 | XM |
| 377 | No. of lines in Steer Table (Pos. sign calls Time/Steer Angle Table; skip to line 379) (Neg. sign calls Driver Model) | -- | I2 | NPOINT |
| 378 | Driver Transport Lag | Sec. | F10.2 | TAU |
| | Preview Interval | Sec. | F10.2 | PREV |
| 379 | Row #1 of Steer Table | | | |
| | Time | Sec. | F10.2 | TIME |
| | Steering Wheel Angle (If GRATIO > 1) | Deg. | F10.2 | DELL(1) |
| | - else - | | | |
| | Left Road Wheel Angle | Deg. | F10.2 | DELL(1) |
| | Right Road Wheel Angle | Deg. | F10.2 | DELR(1) |
| | - or - | | | |
| | Row #1 of Trajectory Table | | | |
| | Longitudinal distance | Ft. | F10.2 | XINP(1) |
| | Lateral distance | Ft. | F10.2 | YINP(1) |
| 380- | Additional Rows of Steer or Trajectory Table | | | |

END

# APPENDIX B

## SAMPLE LISTING OF INPUT AND OUTPUT

```
11 AXLE DOUBLE (MICH TANKER)
0411
80.67, 4.0,0.1,0.02
03030203
7800.0,67200.0,1515.0,55485.0
15500.0,75764.0,3082.0,58243.0
31332.0,1609673.0,5320.0,725165.0
31332.0,1609673.0,5320.0,725165.0
40.0,99.64,36.0,99.25
14500.,16000.,16000.,13000.,13000.,13000.,12825.,12825.,12950.,12950.,12950.
1200.0,2500.0,2300.,1500.,1500.,1500.,1500.,1500.,1500.,1500.,1500.0
3700.,4500.,4500.,4100.0,4100.,4100.,4100.,4100.,4100.,4100.,4100.0
35.0,-76.5,-126.5,-58.24,-100.24,-142.24,21.0,-21.0,-5.6,-47.6,-89.6
22.5,22.5,22.5,20.0,20.0,20.0,20.0,20.,20.,20.,20.0
22.0,29.0,29.0,29.0,29.0,29.0,29.0,29.0,29.0,29.0,29.0
16.3,19.0,19.0,19.0,19.0,19.0,19.0,19.0,19.0,19.0,19.0
40.25,29.5,29.5,29.5,29.5,29.5,30.0,30.0,30.0,30.0,30.0
0.0,13.0,13.0,13.0,13.0,13.0,13.0,13.0,13.0,13.0,13.0
5000.0,5000.000,5000.0,5000.,5000.,5000.,5000.,5000.,5000.,5000.,5000.0
0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
250.0,500.00,500.00,1000.0,1000.0,1000.0,1000.0,1000.0,1000.0,1000.0,1000.0
10.0,10.0,10.0,10.0,10.0,10.0,10.0,10.0,10.0,10.0,10.0
-70.345,105.7578,-158.44,68.5,0.0,77.4
50.,48.,50.
500000.0,0.0,500000.0
010304
03
0102020303030303030303
02
-5000.0,-5.0
5000.0,5.0
04
-3000.00,-1.0
0.0,0.00000
0.0,1.5
6000.00,2.5
04
-35000.0,-1.0
0.0,0.0
0.0,1.5
35000.0,2.5
03
0102020303030303030303
0507
0.0,1.0,2.0,4.0,8.0,12.0,16.0
2500.0,348.0,616.0,1036.0,1586.0,1859.0,1952.0
5000.0,662.0,1195.,2017.0,3121.0,3675.0,3812.0
7500.0,945.0,1712.,2944.0,4555.0,5221.0,5491.0
10000.,1139.,2112.,3715.0,5802.0,6618.0,6970.0
0507
0.0,1.0,2.0,4.0,8.0,12.0,16.0
2000.0,275.0,503.0,918.0,1445.,1668.,1818.0
4000.0,522.0,981.0,1765.,2721.,3118.,3335.0
6000.0,677.0,1307.,2391.,3707.,4245.,4401.0
8000.0,753.0,1477.,2767.,4437.,5080.,5357.0
0607
0.0,1.0,2.0,4.0,8.0,12.0,16.0
1400.0,238.0,440.0,718.0,1001.0,1263.0,1232.0
2800.0,391.0,743.0,1286.0,1898.0,2500.0,2431.0
```

```
61      4250.0,479.0,920.0,1631.0,2538.0,3082.0,3459.0
62      5600.0,509.0,987.0,1805.0,2943.0,3690.0,4227.0
63      6500.0,506.0,1005.,1856.0,3115.0,3990.0,4628.0
64      03
65      010202030303030303030303
66      0507
67      0.0,1.0,2.0,4.0,8.0,12.0,16.0
68      2500.0,27.0,40.0,46.0,36.0,17.0,4.0
69      5000.0,75.0,116.,144.,127.,65.0,14.0
70      7500.0,141.,225.,301.,259.,152.,48.0
71      10000.,208.,433.,483.,431.,239.,86.0
72      0507
73      0.0,1.0,2.0,4.0,8.0,12.0,16.0
74      2000.0,26.0,42.0,57.0,57.0,34.0,17.0
75      4000.0,71.0,127.,182.,184.,122.,73.0
76      6000.0,125.,225.,340.,344.,251.,140.0
77      8000.0,180.,333.,522.,528.,384.,215.0
78      0607
79      0.0,1.0,2.0,4.0,8.0,12.0,16.00
80      1400.0,20.0,33.0,38.0,20.0,6.00,0.0
81      2800.0,52.0,89.0,118.,87.0,49.0,19.0
82      4250.0,84.0,148.,213.,187.,118.,74.0
83      5600.0,114.,202.,306.,295.,208.,139.0
84      6500.0,135.,250.,382.,385.,279.,191.0
85      25.
86      25000.,25000.,1.
87      003
89      0.,0.
89.2    0.5,25.
89.4    10.,25.
End of file
```

*********************
*TANKER SAFETY STUDY*
*********************

*********************************
*DIRECTIONAL RESPONSE SIMULATION*
*********************************

11 AXLE DOUBLE (MICH TANKER)

# OF SPRUNG MASSES = 4

TOTAL # OF AXLES = 11

GROSS VEHICLE WEIGHT = 150000.00 LB.

FORWARD VELOCITY = 55.00 M.P.H

| | | DISTANCE AHEAD OF SPRUNG MASS C.G. (INCHES) | HEIGHT BELOW SPRUNG MASS C.G. (INCHES) | ROLL STIFFNESS (IN.LB/DEG) | TYPE OF CONSTRAINT |
|---|---|---|---|---|---|
| ARTICULATION PT # 1 | ON UNIT # 1 | -70.35 | -10.00 | 499999.75 | 1 |
| | ON UNIT # 2 | 105.76 | 49.64 | | |
| ARTICULATION PT # 2 | ON UNIT # 2 | -158.44 | 51.64 | 0.0 | 3 |
| | ON UNIT # 3 | 68.50 | -12.00 | | |
| ARTICULATION PT # 3 | ON UNIT # 3 | 0.0 | -14.00 | 499999.75 | 4 |
| | ON UNIT # 4 | 77.40 | 49.25 | | |

TYPE OF CONSTRAINT : 01 CONVENTIONAL 5TH WHEEL
02 INVERTED 5TH WHEEL
03 PINTLE HOOK
04 KING PIN(RIGID IN ROLL & PITCH)

OPEN LOOP STEER INPUT
*********************

STEERING GEAR RATIO = 25.00

STEERING STIFFNESS (IN.LB/DEG) = 25000.00

TIE ROD STIFFNESS (IN.LB/DEG) = 25000.00

MECHANICAL TRAIL (IN) = 1.00

# OF POINTS IN STEER TABLE = 3

| TIME SEC | STEERING WHEEL DEGREES |
|---|---|
| 0.0 | 0.0 |
| 0.50 | 25.00 |
| 10.00 | 25.00 |

11 AXLE DOUBLE (MICH TANKER)

UNIT # 1
*********

# OF AXLES ON THIS UNIT = 3

WEIGHT OF SPRUNG MASS = 7800.00 LB.

ROLL MOMENT OF INERTIA OF SPRUNG MASS = 15500.00 LB.IN.SEC**2

PITCH MOMENT OF INERTIA OF SPRUNG MASS = 31332.00 LB.IN.SEC**2

YAW MOMENT OF INERTIA OF SPRUNG MASS = 31332.00 LB.IN.SEC**2

HEIGHT OF SPRUNG MASS CG ABOVE GROUND = 40.00 INCHES

| | AXLE # 1 | AXLE # 2 | AXLE # 3 | AXLE # |
|---|---|---|---|---|
| LOAD ON EACH AXLE (LB.) | 14500.00 | 16000.00 | 16000.00 | |
| AXLE WEIGHT (LB.) | 1200.00 | 2500.00 | 2300.00 | |
| AXLE ROLL M.I (LB.IN.SEC**2) | 3700.00 | 4500.00 | 4500.00 | |
| X DIST FROM SP MASS CG (IN) | 35.00 | -76.50 | -126.50 | |
| HEIGHT OF AXLE C.G. ABOVE GROUND (INCHES) | 22.50 | 22.50 | 22.50 | |
| HEIGHT OF ROLL CENTER ABOVE GROUND (INCHES) | 22.00 | 29.00 | 29.00 | |
| HALF SPRING SPACING (IN) | 16.30 | 19.00 | 19.00 | |
| HALF TRACK - INNER TIRES (IN) | 40.25 | 29.50 | 29.50 | |
| DUAL TIRE SPACING (IN) | 0.0 | 13.00 | 13.00 | |
| STIFFNESS OF EACH TIRE (LB/IN) | 5000.00 | 5000.00 | 5000.00 | |
| ROLL STEER COEFFICIENT | 0.0 | 0.0 | 0.0 | |
| AUX ROLL STIFFNESS (IN.LB/DEG) | 0.0 | 0.0 | 0.0 | |
| SPRING COULOMB FRICTION - PER SPRING (LB) | 250.00 | 500.00 | 500.00 | |
| VISCOUS DAMPING PER SPRING (LB.SEC/IN) | 10.00 | 10.00 | 10.00 | |
| SPRING TABLE # | 1 | 2 | 2 | |
| CORNERING FORCE TABLE # | 1 | 2 | 2 | |
| ALIGNING TORQUE TABLE # | 1 | 2 | 2 | |

11 AXLE DOUBLE (MICH TANKER)

UNIT # 2
*********

# OF AXLES ON THIS UNIT = 3

WEIGHT OF SPRUNG MASS = 67200.00 LB.

ROLL MOMENT OF INERTIA OF SPRUNG MASS = 75764.00 LB.IN.SEC**2

PITCH MOMENT OF INERTIA OF SPRUNG MASS = 1609673.00 LB.IN.SEC**2

YAW MOMENT OF INERTIA OF SPRUNG MASS = 1609673.00 LB.IN.SEC**2

HEIGHT OF SPRUNG MASS CG ABOVE GROUND = 99.64 INCHES

| | AXLE # 4 | AXLE # 5 | AXLE # 6 | AXLE # | | | | |
|---|---|---|---|---|---|---|---|---|
| | ********* | ********* | ********* | ********* | ********* | ********* | ********* | ********* |
| LOAD ON EACH AXLE (LB.) | 13000.00 | 13000.00 | 13000.00 | | | | | |
| AXLE WEIGHT (LB.) | 1500.00 | 1500.00 | 1500.00 | | | | | |
| AXLE ROLL M.I (LB.IN.SEC**2) | 4100.00 | 4100.00 | 4100.00 | | | | | |
| X DIST FROM SP MASS CG (IN) | -58.24 | -100.24 | -142.24 | | | | | |
| HEIGHT OF AXLE C.G. ABOVE GROUND (INCHES) | 20.00 | 20.00 | 20.00 | | | | | |
| HEIGHT OF ROLL CENTER ABOVE GROUND (INCHES) | 29.00 | 29.00 | 29.00 | | | | | |
| HALF SPRING SPACING (IN) | 19.00 | 19.00 | 19.00 | | | | | |
| HALF TRACK - INNER TIRES (IN) | 29.50 | 29.50 | 29.50 | | | | | |
| DUAL TIRE SPACING (IN) | 13.00 | 13.00 | 13.00 | | | | | |
| STIFFNESS OF EACH TIRE (LB/IN) | 5000.00 | 5000.00 | 5000.00 | | | | | |
| ROLL STEER COEFFICIENT | 0.0 | 0.0 | 0.0 | | | | | |
| AUX ROLL STIFFNESS (IN.LB/DEG) | 0.0 | 0.0 | 0.0 | | | | | |
| SPRING COULOMB FRICTION - PER SPRING (LB) | 1000.00 | 1000.00 | 1000.00 | | | | | |
| VISCOUS DAMPING PER SPRING (LB.SEC/IN) | 10.00 | 10.00 | 10.00 | | | | | |
| SPRING TABLE # | 3 | 3 | 3 | | | | | |
| CORNERING FORCE TABLE # | 3 | 3 | 3 | | | | | |
| ALIGNING TORQUE TABLE # | 3 | 3 | 3 | | | | | |

11 AXLE DOUBLE (MICH TANKER)

UNIT # 3
*********

# OF AXLES ON THIS UNIT = 2

WEIGHT OF SPRUNG MASS = 1515.00 LB.

ROLL MOMENT OF INERTIA OF SPRUNG MASS = 3082.00 LB.IN.SEC**2

PITCH MOMENT OF INERTIA OF SPRUNG MASS = 5320.00 LB.IN.SEC**2

YAW MOMENT OF INERTIA OF SPRUNG MASS = 5320.00 LB.IN.SEC**2

HEIGHT OF SPRUNG MASS CG ABOVE GROUND = 36.00 INCHES

| | AXLE # 7 | AXLE # 8 | AXLE # | | | | | |
|---|---|---|---|---|---|---|---|---|
| | ********* | ********* | ********* | ********* | ********* | ********* | ********* | ********* |
| LOAD ON EACH AXLE (LB.) | 12825.00 | 12825.00 | | | | | | |
| AXLE WEIGHT (LB.) | 1500.00 | 1500.00 | | | | | | |
| AXLE ROLL M.I (LB.IN.SEC**2) | 4100.00 | 4100.00 | | | | | | |
| X DIST FROM SP MASS CG (IN) | 21.00 | -21.00 | | | | | | |
| HEIGHT OF AXLE C.G. ABOVE GROUND (INCHES) | 20.00 | 20.00 | | | | | | |
| HEIGHT OF ROLL CENTER ABOVE GROUND (INCHES) | 29.00 | 29.00 | | | | | | |
| HALF SPRING SPACING (IN) | 19.00 | 19.00 | | | | | | |
| HALF TRACK - INNER TIRES (IN) | 30.00 | 30.00 | | | | | | |
| DUAL TIRE SPACING (IN) | 13.00 | 13.00 | | | | | | |
| STIFFNESS OF EACH TIRE (LB/IN) | 5000.00 | 5000.00 | | | | | | |
| ROLL STEER COEFFICIENT | 0.0 | 0.0 | | | | | | |
| AUX ROLL STIFFNESS (IN.LB/DEG) | 0.0 | 0.0 | | | | | | |
| SPRING COULOMB FRICTION - PER SPRING (LB) | 1000.00 | 1000.00 | | | | | | |
| VISCOUS DAMPING PER SPRING (LB.SEC/IN) | 10.00 | 10.00 | | | | | | |
| SPRING TABLE # | 3 | 3 | | | | | | |
| CORNERING FORCE TABLE # | 3 | 3 | | | | | | |
| ALIGNING TORQUE TABLE # | 3 | 3 | | | | | | |

11 AXLE DOUBLE (MICH TANKER)

UNIT # 4
*********

# OF AXLES ON THIS UNIT = 3

WEIGHT OF SPRUNG MASS = 55485.00 LB.

ROLL MOMENT OF INERTIA OF SPRUNG MASS = 58243.00 LB.IN.SEC**2

PITCH MOMENT OF INERTIA OF SPRUNG MASS = 725165.00 LB.IN.SEC**2

YAW MOMENT OF INERTIA OF SPRUNG MASS = 725165.00 LB.IN.SEC**2

HEIGHT OF SPRUNG MASS CG ABOVE GROUND = 99.25 INCHES

| | AXLE # 9 | AXLE # 10 | AXLE # 11 | AXLE # | | | | |
|---|---|---|---|---|---|---|---|---|
| | ********* | ********* | ********* | ********* | ********* | ********* | ********* | ********* |
| LOAD ON EACH AXLE (LB.) | 12950.00 | 12950.00 | 12950.00 | | | | | |
| AXLE WEIGHT (LB.) | 1500.00 | 1500.00 | 1500.00 | | | | | |
| AXLE ROLL M.I (LB.IN.SEC**2) | 4100.00 | 4100.00 | 4100.00 | | | | | |
| X DIST FROM SP MASS CG (IN) | -5.60 | -47.60 | -89.60 | | | | | |
| HEIGHT OF AXLE C.G. ABOVE GROUND (INCHES) | 20.00 | 20.00 | 20.00 | | | | | |
| HEIGHT OF ROLL CENTER ABOVE GROUND (INCHES) | 29.00 | 29.00 | 29.00 | | | | | |
| HALF SPRING SPACING (IN) | 19.00 | 19.00 | 19.00 | | | | | |
| HALF TRACK - INNER TIRES (IN) | 30.00 | 30.00 | 30.00 | | | | | |
| DUAL TIRE SPACING (IN) | 13.00 | 13.00 | 13.00 | | | | | |
| STIFFNESS OF EACH TIRE (LB/IN) | 5000.00 | 5000.00 | 5000.00 | | | | | |
| ROLL STEER COEFFICIENT | 0.0 | 0.0 | 0.0 | | | | | |
| AUX ROLL STIFFNESS (IN.LB/DEG) | 0.0 | 0.0 | 0.0 | | | | | |
| SPRING COULOMB FRICTION - PER SPRING (LB) | 1000.00 | 1000.00 | 1000.00 | | | | | |
| VISCOUS DAMPING PER SPRING (LB.SEC/IN) | 10.00 | 10.00 | 10.00 | | | | | |
| SPRING TABLE # | 3 | 3 | 3 | | | | | |
| CORNERING FORCE TABLE # | 3 | 3 | 3 | | | | | |
| ALIGNING TORQUE TABLE # | 3 | 3 | 3 | | | | | |

SPRING TABLE # 1
****** *******

| FORCE LB | DEFLECTION INCHES |
|---|---|
| -5000.00 | -5.00 |
| 5000.00 | 5.00 |

SPRING TABLE # 2
****** *******

| FORCE LB | DEFLECTION INCHES |
| --- | --- |
| -3000.00 | -1.00 |
| 0.0 | 0.0 |
| 0.0 | 1.50 |
| 6000.00 | 2.50 |

SPRING TABLE # 3
****** *******

| FORCE LB | DEFLECTION INCHES |
|---|---|
| -35000.00 | -1.00 |
| 0.0 | 0.0 |
| 0.0 | 1.50 |
| 35000.00 | 2.50 |

CORNERING FORCE TABLE # 1
********* ***** *********
LATERAL FORCE VS. SLIP ANGLL

| 0.0 | 1.00 | 2.00 | 4.00 | 8.00 | 12.00 | 16.00 |
|---|---|---|---|---|---|---|
| 2500.00 | 348.00 | 616.00 | 1036.00 | 1586.00 | 1859.00 | 1952.00 |
| 5000.00 | 662.00 | 1195.00 | 2017.00 | 3121.00 | 3675.00 | 3812.00 |
| 7500.00 | 945.00 | 1712.00 | 2944.00 | 4555.00 | 5221.00 | 5491.00 |
| 10000.00 | 1139.00 | 2112.00 | 3715.00 | 5802.00 | 6618.00 | 6970.00 |

CORNERING FORCE TABLE # 2
********* ***** *********
LATERAL FORCE VS. SLIP ANGLL

| 0.0 | 1.00 | 2.00 | 4.00 | 8.00 | 12.00 | 16.00 |
|---|---|---|---|---|---|---|
| 2000.00 | 275.00 | 503.00 | 918.00 | 1445.00 | 1668.00 | 1818.00 |
| 4000.00 | 522.00 | 981.00 | 1765.00 | 2721.00 | 3118.00 | 3335.00 |
| 6000.00 | 677.00 | 1307.00 | 2391.00 | 3707.00 | 4245.00 | 4401.00 |
| 8000.00 | 753.00 | 1477.00 | 2767.00 | 4437.00 | 5080.00 | 5357.00 |

CORNERING FORCE TABLE # 3
********* ***** *********
LATERAL FORCE VS. SLIP ANGLL

| 0.0 | 1.00 | 2.00 | 4.00 | 8.00 | 12.00 | 16.00 |
|---|---|---|---|---|---|---|
| 1400.00 | 238.00 | 440.00 | 718.00 | 1001.00 | 1263.00 | 1232.00 |
| 2800.00 | 391.00 | 743.00 | 1286.00 | 1898.00 | 2500.00 | 2431.00 |
| 4250.00 | 479.00 | 920.00 | 1631.00 | 2538.00 | 3082.00 | 3459.00 |
| 5600.00 | 509.00 | 987.00 | 1805.00 | 2943.00 | 3690.00 | 4227.00 |
| 6500.00 | 506.00 | 1005.00 | 1856.00 | 3115.00 | 3990.00 | 4628.00 |

ALIGNING TORQUE TABLE # 1
******** ****** *********
ALIGNING TORQUE VS. SLIP ANGLE

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.0 | 1.00 | 2.00 | 4.00 | 8.00 | 12.00 | 16.00 |
| 2500.00 | 324.00 | 480.00 | 552.00 | 432.00 | 204.00 | 48.00 |
| 5000.00 | 900.00 | 1392.00 | 1728.00 | 1524.00 | 780.00 | 168.00 |
| 7500.00 | 1692.00 | 2700.00 | 3612.00 | 3108.00 | 1824.00 | 576.00 |
| 10000.00 | 2496.00 | 5196.00 | 5796.00 | 5172.00 | 2868.00 | 1032.00 |

ALIGNING TORQUE TABLE # 2
******** ****** *********
ALIGNING TORQUE VS. SLIP ANGLE

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.0 | 1.00 | 2.00 | 4.00 | 8.00 | 12.00 | 16.00 |
| 2000.00 | 312.00 | 504.00 | 684.00 | 684.00 | 408.00 | 204.00 |
| 4000.00 | 852.00 | 1524.00 | 2184.00 | 2208.00 | 1464.00 | 876.00 |
| 6000.00 | 1500.00 | 2700.00 | 4080.00 | 4128.00 | 3012.00 | 1680.00 |
| 8000.00 | 2160.00 | 3996.00 | 6264.00 | 6336.00 | 4608.00 | 2580.00 |

ALIGNING TORQUE TABLE # 3
******** ****** *********
ALIGNING TORQUE VS. SLIP ANGLE

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.0 | 1.00 | 2.00 | 4.00 | 8.00 | 12.00 | 16.00 |
| 1400.00 | 240.00 | 396.00 | 456.00 | 240.00 | 72.00 | 0.0 |
| 2800.00 | 624.00 | 1068.00 | 1416.00 | 1044.00 | 588.00 | 228.00 |
| 4250.00 | 1008.00 | 1776.00 | 2556.00 | 2244.00 | 1416.00 | 888.00 |
| 5600.00 | 1368.00 | 2424.00 | 3672.00 | 3540.00 | 2496.00 | 1668.00 |
| 6500.00 | 1620.00 | 3000.00 | 4584.00 | 4620.00 | 3348.00 | 2292.00 |

11 AXLE DOUBLE (MICH TANKER)

SPRUNG MASS # 1
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| TIME (SEC) | FORWARD POSITION (IN) | LATERAL POSITION (IN) | VERTICAL POSITION (IN) | ROLL ANGLE (DEG) | YAW ANGLE (DEG) | PITCH ANGLE (DEG) | FORWARD VEL IN/SEC | LATERAL VEL IN/SEC | ROLL RATE DEG/SEC | YAW RATE DEG/SEC | PITCH RATE DEG/SEC | LATERAL ACCN. IN/SEC**2 | STEER ANGLE DEG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 968.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.10 | 96.80 | 0.02 | 0.000 | -0.01 | 0.01 | -0.000 | 968.04 | 0.30 | -0.14 | 0.31 | 0.00 | 9.34 | 5.00 |
| 0.20 | 193.60 | 0.12 | 0.000 | -0.03 | 0.07 | 0.000 | 968.04 | 0.52 | -0.39 | 1.01 | -0.00 | 16.60 | 10.00 |
| 0.30 | 290.40 | 0.40 | 0.000 | -0.09 | 0.22 | 0.000 | 968.04 | 0.14 | -0.72 | 1.86 | -0.00 | 24.03 | 15.00 |
| 0.40 | 387.20 | 0.91 | -0.000 | -0.18 | 0.45 | 0.000 | 968.04 | -0.94 | -1.10 | 2.74 | -0.01 | 32.25 | 20.00 |
| 0.50 | 483.99 | 1.75 | -0.000 | -0.31 | 0.76 | 0.000 | 968.04 | -2.61 | -1.46 | 3.60 | -0.02 | 41.46 | 25.00 |
| 0.60 | 580.76 | 2.99 | -0.001 | -0.46 | 1.16 | 0.000 | 968.04 | -5.07 | -1.64 | 4.14 | -0.03 | 42.27 | 25.00 |
| 0.70 | 677.52 | 4.65 | -0.001 | -0.63 | 1.58 | 0.000 | 968.04 | -7.81 | -1.66 | 4.26 | -0.05 | 45.61 | 25.00 |
| 0.80 | 774.27 | 6.77 | -0.000 | -0.79 | 2.00 | 0.000 | 968.04 | -10.22 | -1.53 | 4.20 | -0.06 | 49.10 | 25.00 |
| 0.90 | 871.02 | 9.39 | -0.000 | -0.93 | 2.42 | 0.000 | 968.04 | -12.13 | -1.31 | 4.08 | -0.07 | 52.47 | 25.00 |
| 1.00 | 967.74 | 12.52 | 0.000 | -1.05 | 2.82 | 0.000 | 968.04 | -13.53 | -1.07 | 3.96 | -0.07 | 55.04 | 25.00 |
| 1.10 | 1064.45 | 16.21 | 0.001 | -1.14 | 3.21 | 0.000 | 968.04 | -14.40 | -0.77 | 3.79 | -0.08 | 59.93 | 25.00 |
| 1.20 | 1161.13 | 20.49 | -0.000 | -1.25 | 3.57 | 0.000 | 968.04 | -14.48 | -1.33 | 3.56 | -0.08 | 62.25 | 25.00 |
| 1.30 | 1257.79 | 25.39 | -0.004 | -1.42 | 3.92 | -0.000 | 968.04 | -14.14 | -2.14 | 3.43 | -0.08 | 61.59 | 25.00 |
| 1.40 | 1354.42 | 30.90 | -0.012 | -1.67 | 4.26 | 0.002 | 968.04 | -13.88 | -2.84 | 3.46 | -0.07 | 59.37 | 25.00 |
| 1.50 | 1451.01 | 37.01 | -0.019 | -1.98 | 4.62 | 0.004 | 968.04 | -13.96 | -3.35 | 3.56 | -0.11 | 57.77 | 25.00 |
| 1.60 | 1547.56 | 43.69 | -0.026 | -2.33 | 4.98 | 0.005 | 968.04 | -14.35 | -3.72 | 3.68 | -0.13 | 56.58 | 25.00 |
| 1.70 | 1644.07 | 50.94 | -0.035 | -2.71 | 5.35 | 0.008 | 968.04 | -15.08 | -3.86 | 3.81 | -0.15 | 55.63 | 25.00 |
| 1.80 | 1740.54 | 58.72 | -0.045 | -3.10 | 5.75 | 0.010 | 968.04 | -16.77 | -3.54 | 4.29 | -0.23 | 42.80 | 25.00 |
| 1.90 | 1836.97 | 66.98 | -0.059 | -3.25 | 6.21 | 0.015 | 968.04 | -19.63 | 0.04 | 4.68 | -0.17 | 56.04 | 25.00 |
| 2.00 | 1933.36 | 75.80 | -0.062 | -3.22 | 6.66 | 0.022 | 968.04 | -21.01 | 0.47 | 4.24 | -0.26 | 65.20 | 25.00 |
| 2.10 | 2029.69 | 85.26 | -0.059 | -3.15 | 7.06 | 0.015 | 968.04 | -21.10 | 0.96 | 3.89 | -0.25 | 71.01 | 25.00 |
| 2.20 | 2125.95 | 95.42 | -0.079 | -3.08 | 7.43 | 0.022 | 968.04 | -20.24 | 0.36 | 3.55 | -0.05 | 70.86 | 25.00 |
| 2.30 | 2222.13 | 106.28 | -0.074 | -3.08 | 7.78 | 0.027 | 968.04 | -19.30 | -0.15 | 3.49 | -0.26 | 65.83 | 25.00 |
| 2.40 | 2318.23 | 117.80 | -0.060 | -3.07 | 8.14 | 0.018 | 968.04 | -18.81 | 0.34 | 3.65 | -0.23 | 65.83 | 25.00 |
| 2.50 | 2414.25 | 129.97 | -0.069 | -3.04 | 8.51 | 0.022 | 968.04 | -18.34 | 0.14 | 3.61 | -0.13 | 65.69 | 25.00 |
| 2.60 | 2510.19 | 142.79 | -0.063 | -3.04 | 8.87 | 0.021 | 968.04 | -18.01 | 0.03 | 3.65 | -0.26 | 63.56 | 25.00 |
| 2.70 | 2606.03 | 156.25 | -0.062 | -3.02 | 9.24 | 0.018 | 968.04 | -17.84 | 0.27 | 3.70 | -0.17 | 64.68 | 25.00 |
| 2.80 | 2701.79 | 170.34 | -0.067 | -3.01 | 9.60 | 0.022 | 968.04 | -17.65 | -0.04 | 3.68 | -0.17 | 63.57 | 25.00 |
| 2.90 | 2797.45 | 185.06 | -0.059 | -3.01 | 9.97 | 0.019 | 968.04 | -17.58 | 0.00 | 3.72 | -0.25 | 62.71 | 25.00 |
| 3.00 | 2893.01 | 200.41 | -0.061 | -2.99 | 10.35 | 0.018 | 968.04 | -17.57 | 0.17 | 3.74 | -0.16 | 63.35 | 25.00 |
| 3.10 | 2988.47 | 216.37 | -0.064 | -2.99 | 10.72 | 0.021 | 968.04 | -17.56 | 0.06 | 3.72 | -0.19 | 63.05 | 25.00 |
| 3.20 | 3083.83 | 232.97 | -0.057 | -2.98 | 11.09 | 0.018 | 968.04 | -17.55 | 0.06 | 3.73 | -0.23 | 63.18 | 25.00 |
| 3.30 | 3179.07 | 250.18 | -0.060 | -2.97 | 11.47 | 0.018 | 968.04 | -17.53 | 0.10 | 3.74 | -0.16 | 63.25 | 25.00 |
| 3.40 | 3274.21 | 268.01 | -0.061 | -2.96 | 11.84 | 0.020 | 968.04 | -17.52 | 0.02 | 3.72 | -0.20 | 63.10 | 25.00 |
| 3.50 | 3369.22 | 286.46 | -0.056 | -2.96 | 12.21 | 0.018 | 968.04 | -17.49 | 0.04 | 3.72 | -0.22 | 63.12 | 25.00 |
| 3.60 | 3464.11 | 305.53 | -0.058 | -2.96 | 12.59 | 0.018 | 968.04 | -17.47 | 0.04 | 3.73 | -0.17 | 63.11 | 25.00 |
| 3.70 | 3558.87 | 325.22 | -0.059 | -2.96 | 12.96 | 0.019 | 968.04 | -17.46 | -0.03 | 3.72 | -0.20 | 62.96 | 25.00 |
| 3.80 | 3653.50 | 345.52 | -0.056 | -2.96 | 13.33 | 0.017 | 968.04 | -17.45 | -0.01 | 3.73 | -0.21 | 63.01 | 25.00 |
| 3.90 | 3748.00 | 366.44 | -0.058 | -2.96 | 13.70 | 0.018 | 968.04 | -17.45 | -0.01 | 3.73 | -0.17 | 62.99 | 25.00 |
| 4.00 | 3842.36 | 387.98 | -0.058 | -2.96 | 14.08 | 0.019 | 968.04 | -17.46 | -0.06 | 3.73 | -0.20 | 62.90 | 25.00 |

11 AXLE DOUBLE (MICH TANKER)

SPRUNG MASS # 2
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| TIME (SEC) | FORWARD POSITION (IN) | LATERAL POSITION (IN) | VERTICAL POSITION (IN) | ROLL ANGLE (DEG) | YAW ANGLE (DEG) | PITCH ANGLE (DEG) | FORWARD VEL IN/SEC | LATERAL VEL IN/SEC | ROLL RATE DEG/SEC | YAW RATE DEG/SEC | PITCH RATE DEG/SEC | LATERAL ACCN. IN/SEC**2 | ARTIC ANGLE DEG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | -176.10 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 968.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.10 | -79.30 | -0.00 | 0.000 | -0.00 | 0.00 | -0.000 | 968.04 | -0.00 | -0.06 | 0.01 | -0.00 | 0.14 | 0.01 |
| 0.20 | 17.51 | 0.00 | 0.000 | -0.02 | 0.00 | -0.000 | 968.04 | -0.02 | -0.27 | 0.10 | -0.00 | 1.25 | 0.07 |
| 0.30 | 114.31 | 0.02 | 0.000 | -0.06 | 0.02 | -0.000 | 968.04 | -0.12 | -0.59 | 0.33 | -0.00 | 3.85 | 0.19 |
| 0.40 | 211.11 | 0.07 | 0.000 | -0.14 | 0.08 | 0.000 | 968.05 | -0.40 | -0.96 | 0.73 | -0.00 | 8.24 | 0.37 |
| 0.50 | 307.91 | 0.21 | 0.001 | -0.25 | 0.18 | 0.000 | 968.06 | -1.00 | -1.33 | 1.33 | -0.01 | 14.48 | 0.59 |
| 0.60 | 404.71 | 0.50 | 0.001 | -0.40 | 0.35 | 0.000 | 968.09 | -2.04 | -1.61 | 2.09 | -0.01 | 22.30 | 0.81 |
| 0.70 | 501.50 | 1.01 | 0.003 | -0.57 | 0.60 | 0.000 | 968.13 | -3.62 | -1.71 | 2.91 | -0.03 | 30.67 | 0.98 |
| 0.80 | 598.28 | 1.83 | 0.005 | -0.73 | 0.93 | 0.000 | 968.16 | -5.74 | -1.61 | 3.69 | -0.05 | 38.73 | 1.07 |
| 0.90 | 695.06 | 3.03 | 0.008 | -0.89 | 1.33 | 0.000 | 968.19 | -8.30 | -1.42 | 4.34 | -0.07 | 45.92 | 1.08 |
| 1.00 | 791.84 | 4.69 | 0.011 | -1.02 | 1.79 | 0.000 | 968.22 | -11.15 | -1.16 | 4.82 | -0.08 | 51.93 | 1.03 |
| 1.10 | 888.62 | 6.87 | 0.012 | -1.12 | 2.29 | -0.000 | 968.22 | -14.18 | -1.17 | 5.12 | -0.14 | 55.39 | 0.92 |
| 1.20 | 985.38 | 9.60 | -0.007 | -1.27 | 2.81 | -0.012 | 968.21 | -17.32 | -1.85 | 5.19 | -0.31 | 56.44 | 0.77 |
| 1.30 | 1082.13 | 12.89 | -0.047 | -1.50 | 3.32 | -0.034 | 968.18 | -20.34 | -2.81 | 5.06 | -0.36 | 56.95 | 0.60 |
| 1.40 | 1178.86 | 16.76 | -0.089 | -1.83 | 3.82 | -0.058 | 968.16 | -22.91 | -3.61 | 4.77 | -0.43 | 58.29 | 0.45 |
| 1.50 | 1275.57 | 21.20 | -0.140 | -2.22 | 4.28 | -0.092 | 968.13 | -24.74 | -4.19 | 4.37 | -0.55 | 59.43 | 0.34 |
| 1.60 | 1372.25 | 26.24 | -0.200 | -2.66 | 4.69 | -0.132 | 968.12 | -25.78 | -4.56 | 3.94 | -0.58 | 60.14 | 0.29 |
| 1.70 | 1468.90 | 31.87 | -0.254 | -3.12 | 5.07 | -0.170 | 968.13 | -26.04 | -4.66 | 3.56 | -0.57 | 61.40 | 0.28 |
| 1.80 | 1565.52 | 38.12 | -0.290 | -3.54 | 5.41 | -0.199 | 968.16 | -25.42 | -2.83 | 3.37 | -0.28 | 68.88 | 0.34 |
| 1.90 | 1662.09 | 45.06 | -0.256 | -3.66 | 5.76 | -0.180 | 968.21 | -24.03 | -0.03 | 3.51 | 0.04 | 74.14 | 0.45 |
| 2.00 | 1758.60 | 52.72 | -0.255 | -3.62 | 6.11 | -0.182 | 968.24 | -22.61 | 0.70 | 3.54 | -0.48 | 72.32 | 0.55 |
| 2.10 | 1855.06 | 61.11 | -0.291 | -3.54 | 6.48 | -0.195 | 968.25 | -21.74 | 0.87 | 3.76 | -0.11 | 68.20 | 0.59 |
| 2.20 | 1951.45 | 70.18 | -0.266 | -3.48 | 6.86 | -0.174 | 968.24 | -21.44 | 0.23 | 3.83 | -0.11 | 67.27 | 0.58 |
| 2.30 | 2047.77 | 79.93 | -0.275 | -3.48 | 7.24 | -0.185 | 968.22 | -21.13 | -0.05 | 3.76 | -0.46 | 66.79 | 0.55 |
| 2.40 | 2144.02 | 90.33 | -0.283 | -3.47 | 7.62 | -0.190 | 968.21 | -20.92 | 0.30 | 3.83 | -0.08 | 65.54 | 0.52 |
| 2.50 | 2240.20 | 101.39 | -0.263 | -3.44 | 8.00 | -0.176 | 968.20 | -20.82 | 0.12 | 3.78 | -0.23 | 65.56 | 0.51 |
| 2.60 | 2336.30 | 113.10 | -0.280 | -3.44 | 8.37 | -0.188 | 968.20 | -20.61 | 0.13 | 3.71 | -0.34 | 64.52 | 0.49 |
| 2.70 | 2432.32 | 125.46 | -0.279 | -3.42 | 8.74 | -0.185 | 968.20 | -20.49 | 0.21 | 3.72 | -0.08 | 64.04 | 0.49 |
| 2.80 | 2528.25 | 138.45 | -0.267 | -3.41 | 9.11 | -0.178 | 968.19 | -20.27 | 0.02 | 3.63 | -0.28 | 64.36 | 0.49 |
| 2.90 | 2624.10 | 152.07 | -0.281 | -3.41 | 9.47 | -0.189 | 968.20 | -19.97 | 0.10 | 3.59 | -0.26 | 63.43 | 0.50 |
| 3.00 | 2719.86 | 166.32 | -0.275 | -3.39 | 9.83 | -0.183 | 968.20 | -19.73 | 0.14 | 3.60 | -0.11 | 63.38 | 0.52 |
| 3.10 | 2815.52 | 181.21 | -0.269 | -3.38 | 10.19 | -0.180 | 968.20 | -19.42 | 0.08 | 3.56 | -0.28 | 63.46 | 0.53 |
| 3.20 | 2911.07 | 196.71 | -0.280 | -3.37 | 10.55 | -0.187 | 968.21 | -19.13 | 0.11 | 3.57 | -0.23 | 62.56 | 0.55 |
| 3.30 | 3006.53 | 212.84 | -0.273 | -3.36 | 10.91 | -0.182 | 968.21 | -18.95 | 0.12 | 3.61 | -0.14 | 62.78 | 0.56 |
| 3.40 | 3101.88 | 229.59 | -0.270 | -3.36 | 11.27 | -0.181 | 968.21 | -18.76 | 0.05 | 3.60 | -0.27 | 62.74 | 0.57 |
| 3.50 | 3197.12 | 246.95 | -0.277 | -3.35 | 11.63 | -0.186 | 968.21 | -18.63 | 0.06 | 3.64 | -0.21 | 62.13 | 0.58 |
| 3.60 | 3292.25 | 264.92 | -0.271 | -3.35 | 12.00 | -0.182 | 968.22 | -18.59 | 0.05 | 3.68 | -0.16 | 62.46 | 0.59 |
| 3.70 | 3387.25 | 283.50 | -0.270 | -3.35 | 12.36 | -0.182 | 968.22 | -18.55 | -0.01 | 3.68 | -0.27 | 62.46 | 0.59 |
| 3.80 | 3482.14 | 302.70 | -0.276 | -3.35 | 12.73 | -0.186 | 968.22 | -18.57 | 0.00 | 3.72 | -0.21 | 62.13 | 0.60 |
| 3.90 | 3576.90 | 322.51 | -0.271 | -3.35 | 13.11 | -0.182 | 968.22 | -18.66 | -0.01 | 3.75 | -0.19 | 62.53 | 0.60 |
| 4.00 | 3671.53 | 342.92 | -0.271 | -3.35 | 13.48 | -0.183 | 968.22 | -18.73 | -0.05 | 3.75 | -0.26 | 62.57 | 0.59 |

11 AXLE DOUBLE (MICH TANKER)

SPRUNG MASS # 3
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| TIME (SEC) | FORWARD POSITION (IN) | LATERAL POSITION (IN) | VERTICAL POSITION (IN) | ROLL ANGLE (DEG) | YAW ANGLE (DEG) | PITCH ANGLE (DEG) | FORWARD VEL IN/SEC | LATERAL VEL IN/SEC | ROLL RATE DEG/SEC | YAW RATE DEG/SEC | PITCH RATE DEG/SEC | LATERAL ACCN. IN/SEC**2 | ARTIC ANGLE DEG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | -403.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 968.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.10 | -306.23 | 0.00 | -0.000 | -0.00 | 0.00 | 0.000 | 968.04 | -0.01 | -0.00 | 0.02 | 0.00 | 0.07 | -0.00 |
| 0.20 | -209.42 | 0.00 | -0.000 | -0.00 | 0.00 | 0.000 | 968.04 | -0.04 | -0.00 | 0.02 | -0.00 | 0.11 | 0.00 |
| 0.30 | -112.61 | 0.00 | -0.000 | -0.00 | 0.00 | 0.000 | 968.04 | -0.02 | 0.00 | -0.06 | -0.00 | -0.13 | 0.02 |
| 0.40 | -15.80 | 0.00 | -0.000 | 0.00 | -0.01 | 0.000 | 968.05 | 0.15 | 0.03 | -0.19 | 0.00 | -0.69 | 0.09 |
| 0.50 | 81.00 | -0.00 | -0.000 | 0.00 | -0.03 | 0.000 | 968.07 | 0.45 | 0.05 | -0.26 | -0.00 | -1.32 | 0.21 |
| 0.60 | 177.81 | -0.02 | -0.000 | 0.01 | -0.06 | 0.000 | 968.11 | 0.68 | 0.04 | -0.14 | 0.00 | -1.46 | 0.40 |
| 0.70 | 274.62 | -0.06 | -0.000 | 0.01 | -0.05 | 0.000 | 968.18 | 0.48 | -0.02 | 0.33 | 0.00 | -0.10 | 0.65 |
| 0.80 | 371.43 | -0.09 | -0.000 | 0.00 | 0.03 | 0.000 | 968.27 | -0.63 | -0.16 | 1.25 | 0.00 | 3.88 | 0.90 |
| 0.90 | 468.26 | -0.08 | -0.000 | -0.02 | 0.21 | 0.000 | 968.38 | -3.09 | -0.39 | 2.57 | 0.00 | 11.26 | 1.12 |
| 1.00 | 565.08 | 0.05 | -0.000 | -0.08 | 0.54 | 0.000 | 968.50 | -7.05 | -0.68 | 4.03 | -0.01 | 21.92 | 1.25 |
| 1.10 | 661.91 | 0.39 | -0.000 | -0.16 | 1.02 | 0.001 | 968.59 | -12.20 | -0.97 | 5.48 | -0.02 | 35.53 | 1.27 |
| 1.20 | 758.74 | 1.09 | -0.000 | -0.27 | 1.64 | 0.001 | 968.62 | -18.46 | -1.22 | 6.96 | -0.03 | 50.09 | 1.17 |
| 1.30 | 855.59 | 2.30 | -0.001 | -0.40 | 2.39 | 0.001 | 968.57 | -25.46 | -1.40 | 7.96 | -0.05 | 64.23 | 0.93 |
| 1.40 | 952.44 | 4.14 | -0.001 | -0.54 | 3.21 | 0.001 | 968.45 | -32.15 | -1.40 | 8.15 | -0.08 | 75.67 | 0.61 |
| 1.50 | 1049.27 | 6.74 | -0.001 | -0.67 | 4.01 | 0.001 | 968.28 | -37.73 | -1.16 | 7.75 | -0.09 | 82.74 | 0.27 |
| 1.60 | 1146.08 | 10.16 | -0.001 | -0.77 | 4.74 | 0.002 | 968.10 | -41.53 | -0.83 | 6.78 | -0.09 | 88.36 | -0.04 |
| 1.70 | 1242.85 | 14.47 | -0.003 | -0.84 | 5.33 | 0.001 | 967.97 | -42.25 | -0.67 | 4.96 | -0.11 | 98.78 | -0.26 |
| 1.80 | 1339.56 | 19.74 | -0.011 | -0.92 | 5.68 | -0.013 | 967.99 | -38.69 | -0.90 | 1.56 | -0.27 | 87.27 | -0.27 |
| 1.90 | 1436.20 | 25.88 | -0.011 | -1.01 | 5.66 | -0.041 | 968.26 | -30.73 | -0.59 | -1.28 | -0.22 | 63.52 | 0.09 |
| 2.00 | 1532.81 | 32.66 | -0.010 | -1.04 | 5.57 | -0.057 | 968.51 | -23.76 | 0.11 | -0.37 | 0.02 | 43.59 | 0.55 |
| 2.10 | 1629.38 | 39.89 | -0.013 | -0.96 | 5.61 | -0.039 | 968.64 | -20.26 | 1.16 | 1.28 | 0.21 | 42.97 | 0.87 |
| 2.20 | 1725.93 | 47.56 | -0.000 | -0.81 | 5.83 | -0.014 | 968.66 | -19.30 | 1.84 | 3.23 | 0.23 | 52.80 | 1.03 |
| 2.30 | 1822.43 | 55.80 | 0.004 | -0.62 | 6.19 | 0.013 | 968.63 | -18.22 | 1.33 | 3.22 | 0.09 | 91.12 | 1.05 |
| 2.40 | 1918.86 | 64.79 | -0.009 | -0.58 | 6.48 | 0.000 | 968.65 | -16.82 | 0.12 | 3.27 | -0.31 | 40.43 | 1.13 |
| 2.50 | 2015.24 | 74.27 | 0.008 | -0.53 | 6.91 | -0.009 | 968.62 | -19.37 | 0.74 | 5.05 | 0.13 | 58.09 | 1.09 |
| 2.60 | 2111.57 | 84.30 | 0.001 | -0.47 | 7.43 | 0.012 | 968.57 | -21.94 | 0.40 | 5.34 | 0.08 | 63.31 | 0.94 |
| 2.70 | 2207.83 | 94.97 | -0.015 | -0.43 | 7.97 | 0.001 | 968.52 | -24.70 | 0.31 | 5.43 | -0.27 | 66.07 | 0.77 |
| 2.80 | 2304.02 | 106.30 | 0.014 | -0.42 | 8.51 | -0.007 | 968.46 | -26.61 | -0.04 | 5.17 | 0.07 | 75.70 | 0.60 |
| 2.90 | 2400.11 | 118.37 | -0.003 | -0.44 | 8.99 | 0.009 | 968.41 | -27.40 | -0.40 | 4.45 | 0.03 | 69.84 | 0.48 |
| 3.00 | 2496.11 | 131.13 | -0.015 | -0.49 | 9.41 | -0.000 | 968.39 | -27.78 | -0.53 | 4.10 | -0.22 | 67.63 | 0.42 |
| 3.10 | 2592.02 | 144.56 | 0.018 | -0.54 | 9.81 | -0.006 | 968.38 | -27.47 | -0.61 | 3.72 | 0.08 | 70.28 | 0.39 |
| 3.20 | 2687.83 | 158.68 | -0.007 | -0.60 | 10.16 | 0.008 | 968.38 | -26.76 | -0.51 | 3.38 | 0.05 | 62.10 | 0.39 |
| 3.30 | 2783.54 | 173.42 | -0.012 | -0.64 | 10.49 | 0.001 | 968.39 | -26.36 | -0.25 | 3.39 | -0.19 | 63.56 | 0.41 |
| 3.40 | 2879.15 | 188.79 | 0.020 | -0.66 | 10.82 | -0.005 | 968.41 | -25.18 | -0.19 | 3.09 | 0.04 | 67.41 | 0.45 |
| 3.50 | 2974.66 | 204.82 | -0.011 | -0.68 | 11.12 | 0.007 | 968.43 | -23.97 | -0.05 | 2.99 | 0.01 | 57.90 | 0.51 |
| 3.60 | 3070.06 | 221.42 | -0.007 | -0.67 | 11.43 | -0.000 | 968.45 | -23.31 | 0.18 | 3.17 | -0.18 | 62.51 | 0.57 |
| 3.70 | 3165.36 | 238.64 | 0.019 | -0.65 | 11.74 | -0.005 | 968.47 | -22.18 | 0.13 | 3.07 | 0.05 | 62.54 | 0.62 |
| 3.80 | 3260.55 | 256.47 | -0.014 | -0.64 | 12.05 | 0.006 | 968.49 | -21.68 | 0.26 | 3.31 | 0.03 | 55.39 | 0.68 |
| 3.90 | 3355.63 | 274.84 | -0.003 | -0.60 | 12.40 | 0.000 | 968.50 | -21.80 | 0.34 | 3.62 | -0.15 | 61.51 | 0.70 |
| 4.00 | 3450.59 | 293.82 | 0.016 | -0.57 | 12.77 | -0.004 | 968.50 | -21.75 | 0.27 | 3.68 | 0.02 | 60.84 | 0.71 |

11 AXLE DOUBLE (MICH TANKER)

SPRUNG MASS # 4
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| TIME (SEC) | FORWARD POSITION (IN) | LATERAL POSITION (IN) | VERTICAL POSITION (IN) | ROLL ANGLE (DEG) | YAW ANGLE (DEG) | PITCH ANGLE (DEG) | FORWARD VEL IN/SEC | LATERAL VEL IN/SEC | ROLL RATE DEG/SEC | YAW RATE DEG/SEC | PITCH RATE DEG/SEC | LATERAL ACCN. IN/SEC**2 | ARTIC ANGLE DEG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | -480.44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 968.04 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.10 | -383.62 | 0.00 | 0.000 | -0.00 | 0.00 | 0.000 | 968.04 | 0.00 | -0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| 0.20 | -286.81 | 0.00 | 0.000 | -0.00 | 0.00 | 0.000 | 968.04 | -0.00 | -0.00 | 0.00 | -0.00 | 0.03 | 0.00 |
| 0.30 | -190.00 | 0.00 | 0.000 | -0.00 | 0.00 | 0.000 | 968.04 | -0.01 | -0.00 | 0.01 | 0.00 | 0.03 | 0.00 |
| 0.40 | -93.19 | 0.00 | 0.000 | 0.00 | 0.00 | 0.000 | 968.05 | -0.01 | 0.02 | -0.00 | 0.00 | -0.10 | -0.01 |
| 0.50 | 3.62 | 0.00 | 0.000 | 0.00 | -0.00 | 0.000 | 968.07 | -0.00 | 0.05 | -0.04 | -0.00 | -0.41 | -0.03 |
| 0.60 | 100.42 | -0.00 | 0.000 | 0.01 | -0.01 | 0.000 | 968.11 | 0.05 | 0.06 | -0.10 | 0.00 | -0.83 | -0.05 |
| 0.70 | 197.23 | -0.02 | 0.000 | 0.01 | -0.02 | 0.000 | 968.18 | 0.16 | 0.02 | -0.13 | 0.00 | -0.96 | -0.03 |
| 0.80 | 294.05 | -0.04 | 0.000 | 0.01 | -0.03 | 0.000 | 968.27 | 0.28 | -0.12 | -0.07 | -0.00 | -0.18 | 0.06 |
| 0.90 | 390.88 | -0.06 | -0.000 | -0.01 | -0.03 | 0.000 | 968.39 | 0.29 | -0.37 | 0.21 | 0.00 | 2.33 | 0.24 |
| 1.00 | 487.71 | -0.06 | 0.000 | -0.07 | 0.02 | 0.000 | 968.52 | -0.04 | -0.73 | 0.80 | 0.00 | 7.37 | 0.52 |
| 1.10 | 584.54 | 0.02 | 0.000 | -0.16 | 0.15 | 0.000 | 968.67 | -1.03 | -1.16 | 1.76 | -0.01 | 15.51 | 0.87 |
| 1.20 | 681.38 | 0.26 | 0.001 | -0.30 | 0.38 | 0.000 | 968.80 | -2.97 | -1.59 | 3.06 | -0.01 | 26.74 | 1.26 |
| 1.30 | 778.24 | 0.77 | 0.002 | -0.48 | 0.76 | 0.001 | 968.91 | -6.07 | -1.91 | 4.58 | -0.03 | 40.51 | 1.63 |
| 1.40 | 875.10 | 1.68 | 0.004 | -0.68 | 1.30 | 0.001 | 968.99 | -10.35 | -2.06 | 6.14 | -0.07 | 55.62 | 1.90 |
| 1.50 | 971.96 | 3.15 | 0.008 | -0.87 | 1.99 | 0.001 | 969.02 | -15.66 | -1.86 | 7.53 | -0.11 | 69.90 | 2.02 |
| 1.60 | 1068.82 | 5.32 | 0.011 | -1.04 | 2.80 | 0.002 | 968.96 | -21.73 | -1.44 | 8.57 | -0.15 | 81.54 | 1.94 |
| 1.70 | 1165.66 | 8.29 | 0.010 | -1.18 | 3.69 | 0.001 | 968.79 | -28.26 | -1.56 | 9.15 | -0.25 | 88.09 | 1.65 |
| 1.80 | 1262.47 | 12.15 | -0.022 | -1.37 | 4.60 | -0.020 | 968.55 | -34.78 | -2.23 | 9.06 | -0.57 | 90.80 | 1.08 |
| 1.90 | 1359.24 | 16.91 | -0.072 | -1.59 | 5.47 | -0.061 | 968.36 | -40.33 | -1.92 | 8.20 | -0.60 | 91.85 | 0.19 |
| 2.00 | 1455.96 | 22.58 | -0.094 | -1.70 | 6.22 | -0.080 | 968.18 | -43.72 | -0.07 | 6.60 | -0.16 | 91.98 | -0.65 |
| 2.10 | 1552.61 | 29.18 | -0.071 | -1.60 | 6.78 | -0.059 | 968.03 | -43.99 | 2.15 | 4.51 | 0.20 | 90.82 | -1.17 |
| 2.20 | 1649.18 | 36.68 | -0.015 | -1.30 | 7.12 | -0.022 | 967.99 | -40.91 | 3.55 | 2.43 | 0.36 | 86.89 | -1.29 |
| 2.30 | 1745.66 | 45.03 | 0.037 | -0.98 | 7.27 | 0.018 | 968.12 | -35.33 | 1.93 | 0.61 | 0.19 | 73.41 | -1.08 |
| 2.40 | 1842.08 | 54.13 | -0.002 | -0.90 | 7.25 | -0.001 | 968.34 | -28.11 | 0.67 | -0.81 | -0.38 | 66.02 | -0.77 |
| 2.50 | 1938.43 | 63.89 | -0.005 | -0.77 | 7.14 | -0.014 | 968.53 | -20.03 | 1.66 | -1.25 | 0.23 | 57.65 | -0.24 |
| 2.60 | 2034.72 | 74.21 | 0.026 | -0.63 | 7.03 | 0.015 | 968.70 | -12.78 | 1.08 | -0.91 | 0.14 | 48.90 | 0.41 |
| 2.70 | 2130.96 | 85.03 | -0.012 | -0.53 | 6.99 | -0.001 | 968.80 | -7.55 | 0.86 | 0.23 | -0.31 | 42.71 | 0.98 |
| 2.80 | 2227.16 | 96.27 | 0.002 | -0.48 | 7.09 | -0.011 | 968.82 | -5.21 | 0.05 | 1.92 | 0.16 | 40.26 | 1.41 |
| 2.90 | 2323.30 | 107.92 | 0.017 | -0.52 | 7.38 | 0.012 | 968.80 | -5.85 | -0.79 | 3.70 | 0.07 | 43.33 | 1.61 |
| 3.00 | 2419.40 | 120.00 | -0.011 | -0.61 | 7.82 | -0.001 | 968.79 | -8.75 | -0.96 | 5.15 | -0.30 | 49.53 | 1.59 |
| 3.10 | 2515.43 | 132.57 | 0.012 | -0.72 | 8.39 | -0.009 | 968.76 | -13.06 | -1.22 | 6.17 | 0.07 | 57.29 | 1.42 |
| 3.20 | 2611.39 | 145.71 | 0.014 | -0.84 | 9.03 | 0.010 | 968.72 | -17.83 | -1.11 | 6.63 | -0.01 | 65.23 | 1.12 |
| 3.30 | 2707.26 | 159.49 | -0.003 | -0.92 | 9.70 | -0.001 | 968.67 | -22.23 | -0.50 | 6.57 | -0.32 | 70.42 | 0.80 |
| 3.40 | 2803.03 | 173.97 | 0.020 | -0.97 | 10.34 | -0.008 | 968.58 | -25.84 | -0.52 | 6.19 | 0.01 | 73.84 | 0.48 |
| 3.50 | 2898.69 | 189.18 | 0.011 | -1.01 | 10.92 | 0.008 | 968.51 | -28.23 | -0.22 | 5.48 | -0.02 | 76.05 | 0.20 |
| 3.60 | 2994.23 | 205.13 | 0.003 | -1.00 | 11.43 | -0.001 | 968.45 | -29.16 | 0.30 | 4.60 | -0.26 | 75.30 | 0.00 |
| 3.70 | 3089.63 | 221.82 | 0.021 | -0.98 | 11.84 | -0.007 | 968.43 | -28.73 | 0.15 | 3.72 | 0.03 | 73.75 | -0.10 |
| 3.80 | 3184.90 | 239.24 | 0.006 | -0.96 | 12.17 | 0.007 | 968.44 | -27.03 | 0.47 | 2.88 | 0.02 | 71.35 | -0.12 |
| 3.90 | 3280.04 | 257.36 | 0.006 | -0.89 | 12.42 | -0.001 | 968.49 | -24.36 | 0.71 | 2.21 | -0.20 | 67.09 | -0.02 |
| 4.00 | 3375.05 | 276.13 | 0.017 | -0.83 | 12.62 | -0.007 | 968.55 | -21.25 | 0.52 | 1.86 | 0.06 | 63.02 | 0.15 |

11 AXLE DOUBLE (MICH TANKER)

## CONSTRAINT FORCES
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NOTE: LATERAL FORCE ALONE IS PRINTED FOR PINTLE HOOK TYPE CONSTRAINT.
LOCATE FORCES & MOMENTS BASED ON CONSTRAINT TYPE

| TIME | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 32700.2 | 0.0 | 0.0 | 0.0 | 0.0 | 21134.6 | 0.0 | 0.0 | |
| 0.10 | -71.9 | 32699.7 | 3693.0 | 0.0 | -2.2 | -2.4 | 21127.1 | -1.4 | 27.3 | |
| 0.20 | -320.8 | 32700.1 | 7913.4 | 0.0 | 0.8 | -6.1 | 21128.0 | 57.0 | 26.4 | |
| 0.30 | -803.3 | 32698.3 | 14100.3 | 0.0 | 6.2 | -0.6 | 21134.2 | -50.5 | 7.3 | |
| 0.40 | -1502.2 | 32694.2 | 21193.7 | 0.0 | 10.4 | 28.3 | 21127.0 | -333.5 | 27.9 | |
| 0.50 | -2373.0 | 32684.8 | 28072.7 | 0.0 | 7.6 | 77.1 | 21128.8 | -472.0 | 32.6 | |
| 0.60 | -3301.5 | 32670.1 | 30419.0 | 0.0 | -4.4 | 112.3 | 21133.6 | 40.6 | 12.7 | |
| 0.70 | -4151.6 | 32652.6 | 31094.5 | 0.0 | -34.6 | 68.6 | 21127.6 | 1449.3 | 16.0 | |
| 0.80 | -4815.0 | 32636.1 | 28240.5 | 0.0 | -79.5 | -137.0 | 21128.7 | 3671.5 | -23.2 | |
| 0.90 | -5305.6 | 32620.7 | 23700.2 | 0.0 | -134.0 | -577.5 | 21132.5 | 5610.2 | -88.6 | |
| 1.00 | -5655.9 | 32606.5 | 18560.6 | 0.0 | -183.6 | -1274.3 | 21124.9 | 5114.1 | -114.6 | |
| 1.10 | -5707.6 | 32587.4 | 9817.5 | 0.0 | -250.4 | -2198.8 | 21120.7 | -838.3 | -175.6 | |
| 1.20 | -5561.9 | 32548.1 | -12041.0 | 0.0 | -287.1 | -3248.1 | 21111.1 | -14421.3 | -231.0 | |
| 1.30 | -5466.4 | 32424.3 | -43756.5 | 0.0 | -293.0 | -4298.7 | 21086.0 | -36641.0 | -224.4 | |
| 1.40 | -5559.5 | 32291.7 | -80209.8 | 0.0 | -279.5 | -5229.1 | 21063.2 | -66558.1 | -204.6 | |
| 1.50 | -5775.6 | 32181.3 | -120658.1 | 0.0 | -235.3 | -5859.6 | 21043.9 | -101170.4 | -128.6 | |
| 1.60 | -6090.8 | 32008.1 | -163664.9 | 0.0 | -199.9 | -6174.6 | 21026.6 | -133950.1 | -66.3 | |
| 1.70 | -6511.3 | 31817.6 | -205872.4 | 0.0 | -131.6 | -5987.4 | 20927.4 | -169005.8 | -300.3 | |
| 1.80 | -7954.0 | 31523.5 | -218227.5 | 0.0 | 29.7 | -5396.2 | 20671.5 | -224552.9 | -3255.5 | |
| 1.90 | -8425.2 | 31425.9 | -204839.9 | 0.0 | -65.8 | -4686.2 | 20678.6 | -293720.9 | -9812.2 | |
| 2.00 | -8332.0 | 31622.1 | -199401.2 | 0.0 | -150.2 | -4004.7 | 20771.6 | -332229.3 | -11548.5 | |
| 2.10 | -8038.8 | 31378.4 | -192760.7 | 0.0 | -186.2 | -3582.2 | 20679.5 | -316747.4 | -9971.0 | |
| 2.20 | -7589.1 | 31410.9 | -200577.9 | 0.0 | -227.8 | -3489.6 | 21068.3 | -247508.2 | -4056.3 | |
| 2.30 | -7636.3 | 31668.7 | -201629.0 | 0.0 | -85.6 | -2679.9 | 21196.0 | -180460.4 | 2296.5 | |
| 2.40 | -7575.9 | 31537.0 | -198678.6 | 0.0 | -227.7 | -3110.2 | 20873.7 | -159102.9 | -526.9 | |
| 2.50 | -7343.5 | 31605.3 | -203503.1 | 0.0 | -234.0 | -3437.5 | 21336.3 | -119908.3 | -2394.5 | |
| 2.60 | -7419.5 | 31650.3 | -200781.0 | 0.0 | -210.2 | -3753.7 | 21125.9 | -80365.6 | 1353.1 | |
| 2.70 | -7296.4 | 31548.9 | -200600.0 | 0.0 | -220.6 | -4138.3 | 20724.1 | -50298.9 | -904.7 | |
| 2.80 | -7265.8 | 31669.4 | -201613.8 | 0.0 | -194.3 | -4418.8 | 21487.2 | -31816.6 | -2057.6 | |
| 2.90 | -7330.7 | 31663.3 | -199849.9 | 0.0 | -183.8 | -4520.2 | 21009.9 | -40772.1 | 1195.2 | |
| 3.00 | -7264.8 | 31591.6 | -199758.1 | 0.0 | -188.1 | -4543.9 | 20703.4 | -62263.5 | -486.8 | |
| 3.10 | -7281.5 | 31689.7 | -198313.4 | 0.0 | -173.2 | -4559.5 | 21575.0 | -87500.0 | -1543.4 | |
| 3.20 | -7290.5 | 31669.9 | -196985.2 | 0.0 | -181.6 | -4435.7 | 20867.1 | -120159.2 | 858.4 | |
| 3.30 | -7256.8 | 31633.6 | -196610.4 | 0.0 | -177.4 | -4334.9 | 20769.2 | -140590.4 | -638.8 | |
| 3.40 | -7256.8 | 31711.2 | -196230.4 | 0.0 | -158.9 | -4192.9 | 21621.0 | -153964.8 | -1492.8 | |
| 3.50 | -7262.9 | 31685.1 | -195459.8 | 0.0 | -175.3 | -4017.9 | 20765.5 | -168565.1 | 697.4 | |
| 3.60 | -7238.2 | 31660.0 | -195617.7 | 0.0 | -166.4 | -3874.9 | 20899.9 | -168203.6 | -429.9 | |
| 3.70 | -7244.4 | 31713.3 | -195739.4 | 0.0 | -162.9 | -3773.1 | 21607.0 | -164577.3 | -1294.3 | |
| 3.80 | -7250.7 | 31682.8 | -195602.9 | 0.0 | -182.9 | -3694.9 | 20696.2 | -160617.0 | 439.3 | |
| 3.90 | -7236.2 | 31666.1 | -196193.3 | 0.0 | -175.8 | -3680.3 | 21020.1 | -144637.2 | -718.5 | |
| 4.00 | -7247.6 | 31700.1 | -196590.9 | 0.0 | -179.8 | -3750.8 | 21529.1 | -129021.1 | -1481.9 | |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 1
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| | | | LEFT SIDE | | | | | RIGHT SIDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) |
| 0.0 | 0.0 | 0.0 | 0.0 | 7250.1 | 0.0 | 0.0 | 6650.0 | 0.0 | 7250.1 | 0.0 | 0.0 | 6650.0 |
| 0.10 | -0.019 | -0.000 | -0.14 | 7316.8 | 127.8 | -18.82 | 6646.9 | -0.13 | 7183.3 | 114.1 | -16.65 | 6653.1 |
| 0.20 | -0.038 | 0.0 | -0.27 | 7385.1 | 250.2 | -37.03 | 6658.5 | -0.24 | 7115.1 | 220.0 | -31.93 | 6641.5 |
| 0.30 | -0.063 | 0.000 | -0.42 | 7470.6 | 398.4 | -59.33 | 6681.9 | -0.39 | 7029.7 | 343.5 | -49.52 | 6617.6 |
| 0.40 | -0.093 | 0.000 | -0.61 | 7576.8 | 580.2 | -87.28 | 6716.9 | -0.56 | 6923.4 | 489.5 | -69.99 | 6581.7 |
| 0.50 | -0.128 | 0.001 | -0.83 | 7701.2 | 795.1 | -121.17 | 6760.0 | -0.76 | 6798.6 | 655.0 | -92.69 | 6536.7 |
| 0.60 | -0.149 | 0.001 | -0.93 | 7774.1 | 900.6 | -138.27 | 6813.3 | -0.85 | 6725.4 | 732.1 | -102.95 | 6481.8 |
| 0.70 | -0.172 | 0.002 | -1.07 | 7855.4 | 1025.1 | -157.39 | 6858.3 | -0.98 | 6644.1 | 830.1 | -115.89 | 6435.3 |
| 0.80 | -0.192 | 0.002 | -1.20 | 7923.3 | 1134.3 | -173.39 | 6893.7 | -1.10 | 6576.9 | 909.9 | -123.57 | 6399.5 |
| 0.90 | -0.207 | 0.003 | -1.30 | 7977.7 | 1225.3 | -187.27 | 6919.8 | -1.20 | 6523.7 | 972.4 | -128.94 | 6373.5 |
| 1.00 | -0.218 | 0.003 | -1.38 | 8018.3 | 1294.8 | -198.19 | 6938.6 | -1.28 | 6483.7 | 1019.1 | -132.89 | 6354.5 |
| 1.10 | -0.226 | 0.003 | -1.44 | 8044.3 | 1342.8 | -205.82 | 6948.0 | -1.33 | 6457.4 | 1051.1 | -135.59 | 6344.3 |
| 1.20 | -0.233 | 0.004 | -1.44 | 8065.7 | 1347.3 | -207.22 | 7002.7 | -1.34 | 6428.5 | 1048.7 | -134.84 | 6282.4 |
| 1.30 | -0.240 | 0.007 | -1.41 | 8082.1 | 1326.9 | -204.87 | 7083.7 | -1.31 | 6395.1 | 1027.0 | -132.11 | 6183.3 |
| 1.40 | -0.249 | 0.015 | -1.39 | 8095.1 | 1307.4 | -202.51 | 7172.5 | -1.29 | 6343.0 | 1004.2 | -128.96 | 6057.6 |
| 1.50 | -0.262 | 0.025 | -1.38 | 8130.0 | 1304.6 | -203.24 | 7275.7 | -1.28 | 6292.5 | 992.8 | -126.96 | 5936.8 |
| 1.60 | -0.276 | 0.034 | -1.39 | 8172.3 | 1317.6 | -206.52 | 7381.9 | -1.29 | 6231.6 | 991.4 | -125.74 | 5810.4 |
| 1.70 | -0.292 | 0.046 | -1.42 | 8208.0 | 1346.8 | -212.06 | 7472.2 | -1.32 | 6153.7 | 1000.2 | -125.17 | 5678.7 |
| 1.80 | -0.312 | 0.061 | -1.50 | 8262.2 | 1416.3 | -224.50 | 7541.8 | -1.40 | 6071.2 | 1036.0 | -126.99 | 5576.8 |
| 1.90 | -0.314 | 0.077 | -1.69 | 8251.6 | 1576.9 | -248.60 | 7371.2 | -1.59 | 6043.6 | 1150.2 | -137.14 | 5711.3 |
| 2.00 | -0.322 | 0.087 | -1.78 | 8301.7 | 1659.7 | -263.69 | 7358.7 | -1.67 | 6037.7 | 1203.9 | -142.03 | 5765.2 |
| 2.10 | -0.321 | 0.082 | -1.81 | 8309.5 | 1682.0 | -267.55 | 7327.3 | -1.70 | 6057.1 | 1222.1 | -144.16 | 5816.3 |
| 2.20 | -0.316 | 0.093 | -1.77 | 8229.9 | 1637.2 | -256.74 | 7286.2 | -1.66 | 6010.6 | 1190.0 | -140.16 | 5751.4 |
| 2.30 | -0.314 | 0.101 | -1.71 | 8278.4 | 1596.3 | -252.79 | 7362.3 | -1.60 | 6071.7 | 1165.0 | -139.11 | 5770.2 |
| 2.40 | -0.309 | 0.086 | -1.69 | 8279.5 | 1577.9 | -250.02 | 7355.5 | -1.58 | 6110.6 | 1157.6 | -139.22 | 5815.2 |
| 2.50 | -0.305 | 0.087 | -1.66 | 8220.0 | 1549.3 | -243.00 | 7316.4 | -1.56 | 6078.6 | 1137.6 | -136.68 | 5777.1 |
| 2.60 | -0.304 | 0.088 | -1.64 | 8253.3 | 1536.1 | -242.45 | 7352.3 | -1.54 | 6116.7 | 1130.4 | -136.78 | 5799.4 |
| 2.70 | -0.301 | 0.082 | -1.64 | 8230.1 | 1528.2 | -240.25 | 7325.4 | -1.53 | 6116.1 | 1126.8 | -136.43 | 5807.8 |
| 2.80 | -0.301 | 0.087 | -1.62 | 8215.8 | 1514.8 | -237.62 | 7326.1 | -1.52 | 6103.0 | 1116.4 | -135.18 | 5784.1 |
| 2.90 | -0.301 | 0.084 | -1.62 | 8247.7 | 1514.0 | -238.84 | 7352.7 | -1.51 | 6136.3 | 1117.7 | -135.97 | 5813.1 |
| 3.00 | -0.299 | 0.080 | -1.62 | 8218.0 | 1512.6 | -237.38 | 7321.1 | -1.51 | 6120.0 | 1117.1 | -135.59 | 5806.1 |
| 3.10 | -0.299 | 0.085 | -1.62 | 8218.1 | 1511.4 | -237.21 | 7323.7 | -1.51 | 6117.3 | 1115.8 | -135.41 | 5800.9 |
| 3.20 | -0.299 | 0.081 | -1.62 | 8240.8 | 1512.6 | -238.34 | 7341.3 | -1.51 | 6138.7 | 1117.7 | -136.02 | 5821.4 |
| 3.30 | -0.298 | 0.079 | -1.62 | 8217.5 | 1510.2 | -237.00 | 7319.6 | -1.51 | 6122.5 | 1115.8 | -135.51 | 5809.9 |
| 3.40 | -0.298 | 0.082 | -1.61 | 8222.5 | 1509.2 | -237.06 | 7325.4 | -1.51 | 6126.6 | 1115.1 | -135.53 | 5811.7 |
| 3.50 | -0.298 | 0.078 | -1.61 | 8236.1 | 1509.4 | -237.66 | 7336.6 | -1.51 | 6140.3 | 1116.0 | -135.89 | 5824.3 |
| 3.60 | -0.298 | 0.078 | -1.61 | 8217.7 | 1507.0 | -236.53 | 7321.0 | -1.51 | 6126.2 | 1113.9 | -135.41 | 5812.3 |
| 3.70 | -0.298 | 0.080 | -1.61 | 8224.1 | 1506.3 | -236.69 | 7328.4 | -1.51 | 6130.2 | 1113.4 | -135.44 | 5813.3 |
| 3.80 | -0.298 | 0.077 | -1.61 | 8232.5 | 1506.9 | -237.12 | 7335.5 | -1.51 | 6138.2 | 1114.2 | -135.67 | 5820.5 |
| 3.90 | -0.298 | 0.078 | -1.61 | 8218.8 | 1505.5 | -236.34 | 7324.5 | -1.51 | 6126.2 | 1112.7 | -135.30 | 5809.5 |
| 4.00 | -0.298 | 0.079 | -1.61 | 8225.6 | 1505.8 | -236.67 | 7332.0 | -1.51 | 6129.7 | 1112.8 | -135.37 | 5810.4 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 2
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| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 8000.0 | 0.0 | 0.0 | 6750.0 | 0.0 | 8000.0 | 0.0 | 0.0 | 6750.0 |
| 0.10 | -0.002 | -0.000 | -0.00 | 8013.6 | 4.2 | -0.57 | 6772.2 | -0.00 | 7986.1 | 4.2 | -0.57 | 6727.5 |
| 0.20 | -0.010 | -0.000 | -0.04 | 8064.3 | 42.8 | -5.86 | 6817.6 | -0.04 | 7935.7 | 42.3 | -5.74 | 6682.4 |
| 0.30 | -0.028 | -0.000 | -0.12 | 8176.2 | 130.6 | -18.13 | 6909.4 | -0.12 | 7823.4 | 126.6 | -17.09 | 6589.8 |
| 0.40 | -0.056 | 0.000 | -0.25 | 8352.0 | 266.8 | -37.73 | 7057.9 | -0.25 | 7647.2 | 250.0 | -33.50 | 6440.4 |
| 0.50 | -0.093 | 0.000 | -0.41 | 8583.6 | 446.4 | -64.65 | 7261.6 | -0.41 | 7414.3 | 400.1 | -53.04 | 6234.3 |
| 0.60 | -0.135 | 0.000 | -0.59 | 8848.0 | 659.0 | -97.93 | 7494.1 | -0.60 | 7148.3 | 560.5 | -73.34 | 5998.6 |
| 0.70 | -0.178 | 0.001 | -0.77 | 9114.0 | 865.2 | -131.71 | 7748.7 | -0.77 | 6881.5 | 697.2 | -89.92 | 5741.6 |
| 0.80 | -0.215 | 0.001 | -0.91 | 9348.2 | 1041.0 | -161.71 | 7989.6 | -0.91 | 6648.0 | 799.3 | -101.69 | 5499.4 |
| 0.90 | -0.245 | 0.001 | -1.01 | 9539.4 | 1178.6 | -185.69 | 8201.2 | -1.02 | 6457.6 | 868.3 | -108.92 | 5287.3 |
| 1.00 | -0.268 | 0.001 | -1.09 | 9682.6 | 1272.9 | -201.26 | 8377.8 | -1.10 | 6315.0 | 907.1 | -111.79 | 5110.1 |
| 1.10 | -0.283 | 0.001 | -1.14 | 9776.4 | 1329.0 | -210.76 | 8511.9 | -1.14 | 6217.8 | 925.9 | -112.84 | 4972.9 |
| 1.20 | -0.298 | 0.002 | -1.12 | 9862.0 | 1312.3 | -209.88 | 8721.1 | -1.12 | 6120.5 | 896.2 | -108.66 | 4750.4 |
| 1.30 | -0.321 | 0.004 | -1.07 | 9985.2 | 1275.4 | -206.70 | 9047.9 | -1.08 | 5951.9 | 842.9 | -101.32 | 4379.4 |
| 1.40 | -0.357 | 0.009 | -1.05 | 10184.8 | 1265.5 | -208.55 | 9496.8 | -1.05 | 5696.4 | 793.4 | -93.59 | 3874.8 |
| 1.50 | -0.403 | 0.013 | -1.05 | 10456.2 | 1292.7 | -216.90 | 10038.6 | -1.06 | 5386.9 | 756.1 | -86.58 | 3291.3 |
| 1.60 | -0.457 | 0.017 | -1.08 | 10763.1 | 1348.6 | -230.14 | 10633.8 | -1.08 | 5022.3 | 724.2 | -79.38 | 2636.7 |
| 1.70 | -0.515 | 0.023 | -1.13 | 11091.6 | 1436.0 | -248.68 | 11248.7 | -1.13 | 4621.9 | 697.8 | -71.97 | 1948.8 |
| 1.80 | -0.581 | 0.029 | -1.27 | 11468.5 | 1634.1 | -286.06 | 11808.4 | -1.27 | 4165.0 | 697.3 | -68.55 | 1297.2 |
| 1.90 | -0.604 | 0.036 | -1.53 | 11587.3 | 1957.5 | -339.59 | 11795.2 | -1.53 | 3991.5 | 787.7 | -74.36 | 1260.6 |
| 2.00 | -0.603 | 0.033 | -1.58 | 11614.9 | 2027.2 | -351.24 | 11740.1 | -1.59 | 4040.8 | 822.3 | -77.58 | 1382.0 |
| 2.10 | -0.589 | 0.034 | -1.57 | 11486.1 | 2000.6 | -343.60 | 11561.6 | -1.58 | 4084.6 | 825.0 | -78.11 | 1485.6 |
| 2.20 | -0.573 | 0.041 | -1.48 | 11355.8 | 1883.0 | -321.92 | 11461.2 | -1.49 | 4155.8 | 797.0 | -76.41 | 1537.9 |
| 2.30 | -0.571 | 0.036 | -1.41 | 11408.7 | 1804.6 | -311.10 | 11551.8 | -1.42 | 4230.2 | 777.4 | -75.52 | 1557.3 |
| 2.40 | -0.567 | 0.033 | -1.40 | 11368.1 | 1791.6 | -308.08 | 11503.6 | -1.41 | 4241.6 | 775.7 | -75.45 | 1585.9 |
| 2.50 | -0.560 | 0.035 | -1.37 | 11315.4 | 1744.2 | -299.75 | 11459.4 | -1.38 | 4283.0 | 766.0 | -74.97 | 1621.4 |
| 2.60 | -0.560 | 0.033 | -1.35 | 11337.1 | 1725.2 | -297.21 | 11484.1 | -1.36 | 4306.2 | 761.3 | -74.79 | 1633.4 |
| 2.70 | -0.555 | 0.034 | -1.35 | 11283.1 | 1716.9 | -294.95 | 11420.2 | -1.36 | 4313.0 | 761.5 | -74.82 | 1659.6 |
| 2.80 | -0.553 | 0.034 | -1.33 | 11290.0 | 1694.9 | -291.70 | 11433.1 | -1.34 | 4336.8 | 756.2 | -74.58 | 1673.2 |
| 2.90 | -0.554 | 0.031 | -1.33 | 11305.1 | 1696.1 | -292.16 | 11444.6 | -1.34 | 4346.8 | 757.7 | -74.80 | 1683.5 |
| 3.00 | -0.551 | 0.033 | -1.33 | 11264.6 | 1697.0 | -291.56 | 11395.4 | -1.34 | 4344.8 | 759.6 | -74.91 | 1697.5 |
| 3.10 | -0.550 | 0.033 | -1.33 | 11278.5 | 1694.1 | -291.38 | 11402.5 | -1.34 | 4363.4 | 760.9 | -75.17 | 1717.9 |
| 3.20 | -0.550 | 0.031 | -1.33 | 11280.8 | 1694.0 | -291.40 | 11398.8 | -1.34 | 4371.8 | 762.2 | -75.35 | 1731.8 |
| 3.30 | -0.548 | 0.032 | -1.33 | 11254.7 | 1691.6 | -290.56 | 11367.6 | -1.34 | 4370.6 | 762.2 | -75.32 | 1740.2 |
| 3.40 | -0.547 | 0.031 | -1.33 | 11265.5 | 1688.0 | -290.20 | 11374.2 | -1.33 | 4389.3 | 763.3 | -75.57 | 1759.3 |
| 3.50 | -0.547 | 0.030 | -1.33 | 11264.9 | 1687.2 | -290.06 | 11371.8 | -1.33 | 4392.4 | 763.5 | -75.61 | 1764.6 |
| 3.60 | -0.546 | 0.031 | -1.33 | 11248.1 | 1684.8 | -289.39 | 11354.2 | -1.33 | 4388.6 | 762.6 | -75.50 | 1764.6 |
| 3.70 | -0.546 | 0.031 | -1.32 | 11260.5 | 1682.9 | -289.33 | 11366.6 | -1.33 | 4398.2 | 762.9 | -75.60 | 1770.9 |
| 3.80 | -0.546 | 0.030 | -1.32 | 11260.9 | 1683.8 | -289.47 | 11368.1 | -1.33 | 4394.9 | 762.7 | -75.56 | 1766.8 |
| 3.90 | -0.546 | 0.031 | -1.32 | 11251.7 | 1683.0 | -289.19 | 11361.3 | -1.33 | 4388.1 | 761.6 | -75.41 | 1760.0 |
| 4.00 | -0.547 | 0.031 | -1.32 | 11264.6 | 1683.2 | -289.44 | 11376.7 | -1.33 | 4390.8 | 761.6 | -75.44 | 1757.6 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 3

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| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 8000.0 | 0.0 | 0.0 | 6850.0 | 0.0 | 8000.0 | 0.0 | 0.0 | 6850.0 |
| 0.10 | -0.004 | -0.000 | -0.02 | 8024.1 | 19.8 | -2.70 | 6864.2 | -0.02 | 7975.5 | 19.7 | -2.68 | 6835.7 |
| 0.20 | -0.016 | -0.000 | -0.09 | 8099.8 | 96.4 | -13.27 | 6897.3 | -0.09 | 7900.4 | 94.7 | -12.83 | 6802.7 |
| 0.30 | -0.038 | -0.000 | -0.22 | 8240.6 | 231.6 | -32.37 | 6974.3 | -0.22 | 7759.5 | 221.6 | -29.85 | 6725.3 |
| 0.40 | -0.071 | 0.000 | -0.39 | 8445.1 | 419.3 | -59.88 | 7106.6 | -0.39 | 7554.6 | 385.9 | -51.49 | 6591.8 |
| 0.50 | -0.112 | 0.000 | -0.59 | 8704.8 | 652.9 | -95.70 | 7294.8 | -0.60 | 7294.5 | 571.3 | -75.31 | 6401.6 |
| 0.60 | -0.157 | 0.000 | -0.81 | 8986.0 | 904.1 | -136.07 | 7520.9 | -0.81 | 7012.9 | 748.1 | -97.18 | 6173.1 |
| 0.70 | -0.200 | 0.001 | -0.98 | 9254.1 | 1123.7 | -173.17 | 7774.1 | -0.99 | 6745.0 | 880.3 | -112.64 | 5917.9 |
| 0.80 | -0.235 | 0.001 | -1.12 | 9477.0 | 1287.0 | -199.66 | 8021.5 | -1.13 | 6523.2 | 958.2 | -119.43 | 5669.6 |
| 0.90 | -0.264 | 0.001 | -1.22 | 9657.6 | 1410.7 | -220.14 | 8239.5 | -1.23 | 6343.8 | 1007.6 | -122.98 | 5451.0 |
| 1.00 | -0.286 | 0.001 | -1.30 | 9798.9 | 1501.5 | -235.55 | 8420.7 | -1.30 | 6202.6 | 1037.6 | -124.63 | 5269.0 |
| 1.10 | -0.301 | 0.001 | -1.33 | 9889.3 | 1550.5 | -244.23 | 8560.7 | -1.34 | 6107.7 | 1048.2 | -124.64 | 5124.9 |
| 1.20 | -0.314 | 0.002 | -1.30 | 9963.4 | 1520.8 | -241.41 | 8762.7 | -1.30 | 6023.8 | 1010.3 | -119.64 | 4910.5 |
| 1.30 | -0.335 | 0.005 | -1.25 | 10074.7 | 1476.9 | -237.18 | 9076.2 | -1.25 | 5866.1 | 951.0 | -111.59 | 4553.2 |
| 1.40 | -0.370 | 0.008 | -1.23 | 10277.5 | 1471.6 | -240.07 | 9519.2 | -1.23 | 5624.7 | 899.4 | -103.46 | 4070.3 |
| 1.50 | -0.416 | 0.011 | -1.24 | 10554.4 | 1509.4 | -250.55 | 10058.0 | -1.24 | 5324.3 | 860.3 | -95.89 | 3504.2 |
| 1.60 | -0.470 | 0.014 | -1.27 | 10864.8 | 1577.8 | -266.28 | 10649.8 | -1.27 | 4964.2 | 824.6 | -87.76 | 2861.6 |
| 1.70 | -0.528 | 0.019 | -1.33 | 11206.4 | 1680.5 | -287.99 | 11270.7 | -1.33 | 4571.9 | 793.8 | -79.48 | 2187.6 |
| 1.80 | -0.597 | 0.024 | -1.49 | 11605.1 | 1911.9 | -332.82 | 11839.6 | -1.49 | 4108.2 | 791.5 | -75.73 | 1540.9 |
| 1.90 | -0.627 | 0.029 | -1.77 | 11787.6 | 2271.7 | -394.89 | 11905.3 | -1.78 | 3907.3 | 879.3 | -80.90 | 1460.8 |
| 2.00 | -0.624 | 0.022 | -1.80 | 11821.7 | 2317.3 | -403.12 | 11875.6 | -1.81 | 3976.2 | 909.5 | -84.03 | 1580.9 |
| 2.10 | -0.609 | 0.026 | -1.77 | 11661.5 | 2262.8 | -389.71 | 11690.0 | -1.78 | 4007.1 | 902.1 | -83.62 | 1655.4 |
| 2.20 | -0.591 | 0.030 | -1.66 | 11557.0 | 2124.3 | -364.86 | 11613.1 | -1.67 | 4124.8 | 878.1 | -82.79 | 1747.8 |
| 2.30 | -0.589 | 0.021 | -1.59 | 11602.9 | 2040.5 | -352.91 | 11693.8 | -1.60 | 4203.6 | 859.4 | -82.07 | 1776.6 |
| 2.40 | -0.586 | 0.023 | -1.59 | 11539.3 | 2034.1 | -350.22 | 11627.9 | -1.60 | 4181.2 | 855.0 | -81.45 | 1772.4 |
| 2.50 | -0.578 | 0.024 | -1.56 | 11510.1 | 1987.7 | -342.15 | 11600.0 | -1.56 | 4244.5 | 850.1 | -81.61 | 1829.0 |
| 2.60 | -0.578 | 0.021 | -1.54 | 11518.7 | 1968.9 | -339.42 | 11612.6 | -1.55 | 4257.5 | 844.7 | -81.30 | 1834.4 |
| 2.70 | -0.574 | 0.024 | -1.54 | 11461.9 | 1964.6 | -337.27 | 11546.9 | -1.55 | 4254.9 | 844.7 | -81.23 | 1850.9 |
| 2.80 | -0.572 | 0.022 | -1.52 | 11483.8 | 1942.2 | -334.33 | 11568.6 | -1.53 | 4296.5 | 842.7 | -81.46 | 1883.5 |
| 2.90 | -0.572 | 0.020 | -1.52 | 11481.6 | 1944.2 | -334.58 | 11566.3 | -1.53 | 4289.7 | 842.4 | -81.36 | 1878.9 |
| 3.00 | -0.570 | 0.024 | -1.53 | 11445.9 | 1947.6 | -334.18 | 11521.1 | -1.53 | 4287.6 | 844.7 | -81.51 | 1891.7 |
| 3.10 | -0.569 | 0.021 | -1.52 | 11468.8 | 1944.2 | -334.24 | 11534.5 | -1.53 | 4316.2 | 847.9 | -82.04 | 1922.7 |
| 3.20 | -0.569 | 0.021 | -1.52 | 11456.6 | 1943.1 | -333.76 | 11519.6 | -1.53 | 4312.4 | 847.2 | -81.94 | 1924.7 |
| 3.30 | -0.567 | 0.023 | -1.52 | 11436.0 | 1942.0 | -333.05 | 11492.4 | -1.53 | 4314.2 | 847.9 | -82.00 | 1935.9 |
| 3.40 | -0.566 | 0.021 | -1.52 | 11450.9 | 1937.6 | -332.73 | 11501.8 | -1.53 | 4338.2 | 850.1 | -82.39 | 1960.3 |
| 3.50 | -0.566 | 0.020 | -1.52 | 11439.5 | 1936.1 | -332.20 | 11490.9 | -1.53 | 4332.3 | 848.7 | -82.23 | 1956.7 |
| 3.60 | -0.565 | 0.022 | -1.52 | 11427.7 | 1934.7 | -331.68 | 11476.8 | -1.53 | 4332.1 | 848.6 | -82.20 | 1960.3 |
| 3.70 | -0.565 | 0.020 | -1.51 | 11442.1 | 1932.2 | -331.66 | 11490.6 | -1.52 | 4344.7 | 849.4 | -82.39 | 1970.1 |
| 3.80 | -0.565 | 0.021 | -1.52 | 11434.9 | 1932.9 | -331.58 | 11486.2 | -1.52 | 4334.7 | 848.1 | -82.19 | 1959.5 |
| 3.90 | -0.565 | 0.022 | -1.52 | 11430.9 | 1932.9 | -331.49 | 11483.0 | -1.52 | 4332.0 | 847.7 | -82.13 | 1956.6 |
| 4.00 | -0.566 | 0.021 | -1.51 | 11444.6 | 1932.6 | -331.80 | 11498.9 | -1.52 | 4336.4 | 847.9 | -82.20 | 1956.2 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 4
*********

| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 6500.1 | 0.0 | 0.0 | 5750.0 | 0.0 | 6500.1 | 0.0 | 0.0 | 5750.0 |
| 0.10 | -0.001 | -0.000 | 0.00 | 6504.1 | -4.0 | 0.59 | 5767.6 | 0.00 | 6495.8 | -4.0 | 0.59 | 5732.5 |
| 0.20 | -0.009 | -0.000 | 0.02 | 6554.6 | -13.6 | 2.02 | 5881.6 | 0.02 | 6445.5 | -13.5 | 1.99 | 5618.5 |
| 0.30 | -0.030 | -0.000 | 0.03 | 6689.5 | -21.3 | 3.21 | 6155.8 | 0.03 | 6310.0 | -20.7 | 3.00 | 5343.4 |
| 0.40 | -0.070 | -0.000 | 0.02 | 6938.2 | -14.5 | 2.25 | 6628.4 | 0.02 | 6060.6 | -13.7 | 1.92 | 4870.2 |
| 0.50 | -0.129 | 0.0 | -0.02 | 7311.4 | 19.1 | -3.05 | 7303.7 | -0.02 | 5685.9 | 16.9 | -2.28 | 4193.3 |
| 0.60 | -0.208 | 0.000 | -0.10 | 7802.7 | 95.1 | -15.85 | 8150.2 | -0.10 | 5192.8 | 76.8 | -9.86 | 3345.3 |
| 0.70 | -0.296 | 0.000 | -0.24 | 8359.5 | 224.4 | -39.13 | 9064.8 | -0.24 | 4635.3 | 161.1 | -19.52 | 2428.0 |
| 0.80 | -0.386 | 0.000 | -0.42 | 8924.9 | 402.8 | -73.89 | 9949.0 | -0.42 | 4070.6 | 257.3 | -28.89 | 1541.7 |
| 0.90 | -0.469 | 0.000 | -0.62 | 9445.3 | 610.2 | -117.81 | 10728.5 | -0.63 | 3551.2 | 349.8 | -35.84 | 760.0 |
| 1.00 | -0.541 | 0.000 | -0.84 | 9895.0 | 833.7 | -167.76 | 11372.3 | -0.85 | 3102.3 | 423.8 | -40.92 | 113.1 |
| 1.10 | -0.572 | 0.015 | -1.04 | 10218.3 | 1034.8 | -212.77 | 11696.2 | -1.05 | 3024.5 | 508.0 | -48.48 | 0.0 |
| 1.20 | -0.593 | 0.052 | -1.19 | 10373.8 | 1177.9 | -240.45 | 11795.6 | -1.20 | 2918.6 | 553.0 | -51.10 | 0.0 |
| 1.30 | -0.603 | 0.125 | -1.30 | 10472.6 | 1280.1 | -260.31 | 11861.9 | -1.31 | 2891.8 | 591.2 | -53.78 | 0.0 |
| 1.40 | -0.621 | 0.219 | -1.37 | 10744.7 | 1353.6 | -280.71 | 12156.1 | -1.38 | 2938.9 | 628.6 | -57.18 | 0.0 |
| 1.50 | -0.638 | 0.335 | -1.41 | 10988.8 | 1397.9 | -295.85 | 12436.4 | -1.42 | 2972.8 | 651.4 | -59.39 | 0.0 |
| 1.60 | -0.650 | 0.470 | -1.42 | 11180.1 | 1409.9 | -303.73 | 12673.6 | -1.43 | 3009.6 | 661.3 | -60.61 | 0.0 |
| 1.70 | -0.666 | 0.609 | -1.41 | 11457.8 | 1400.5 | -310.04 | 13029.6 | -1.41 | 3092.9 | 669.8 | -62.21 | 0.0 |
| 1.80 | -0.695 | 0.724 | -1.46 | 11826.1 | 1459.2 | -332.55 | 13601.2 | -1.47 | 3087.7 | 690.3 | -64.04 | -598.2 |
| 1.90 | -0.763 | 0.716 | -1.63 | 12613.3 | 1631.8 | -397.57 | 14464.5 | -1.63 | 3026.8 | 744.9 | -68.42 | -365.2 |
| 2.00 | -0.738 | 0.711 | -1.61 | 12436.0 | 1612.2 | -386.30 | 14155.5 | -1.61 | 3165.6 | 768.8 | -71.36 | -112.1 |
| 2.10 | -0.693 | 0.722 | -1.58 | 11827.2 | 1579.1 | -356.76 | 13383.9 | -1.59 | 3124.7 | 751.4 | -69.10 | 87.3 |
| 2.20 | -0.705 | 0.692 | -1.50 | 12118.7 | 1505.3 | -351.56 | 13794.6 | -1.51 | 3255.0 | 742.5 | -69.78 | 0.0 |
| 2.30 | -0.696 | 0.697 | -1.47 | 11907.0 | 1472.0 | -337.56 | 13556.3 | -1.48 | 3155.3 | 708.9 | -66.13 | 0.0 |
| 2.40 | -0.690 | 0.702 | -1.48 | 11792.1 | 1481.4 | -335.98 | 13412.9 | -1.49 | 3121.5 | 707.7 | -65.65 | 0.0 |
| 2.50 | -0.701 | 0.683 | -1.46 | 12029.8 | 1468.5 | -340.72 | 13699.3 | -1.47 | 3221.0 | 719.3 | -67.59 | 0.0 |
| 2.60 | -0.684 | 0.693 | -1.45 | 11730.7 | 1450.0 | -327.83 | 13356.3 | -1.46 | 3138.7 | 697.9 | -64.98 | 0.0 |
| 2.70 | -0.685 | 0.689 | -1.44 | 11762.4 | 1440.9 | -326.94 | 13395.2 | -1.45 | 3151.6 | 696.0 | -64.97 | 0.0 |
| 2.80 | -0.691 | 0.678 | -1.42 | 11881.4 | 1420.8 | -326.38 | 13547.9 | -1.42 | 3201.0 | 695.1 | -65.41 | 0.0 |
| 2.90 | -0.677 | 0.688 | -1.40 | 11647.9 | 1401.4 | -315.72 | 13284.0 | -1.41 | 3146.3 | 678.4 | -63.47 | 0.0 |
| 3.00 | -0.681 | 0.682 | -1.39 | 11742.6 | 1386.8 | -315.51 | 13400.8 | -1.39 | 3185.6 | 678.3 | -63.86 | 0.0 |
| 3.10 | -0.682 | 0.675 | -1.37 | 11770.5 | 1369.2 | -312.78 | 13445.4 | -1.37 | 3203.8 | 673.4 | -63.65 | 0.0 |
| 3.20 | -0.671 | 0.681 | -1.35 | 11595.6 | 1351.6 | -304.36 | 13248.9 | -1.36 | 3163.6 | 659.8 | -62.13 | 0.0 |
| 3.30 | -0.675 | 0.674 | -1.34 | 11687.7 | 1342.1 | -305.04 | 13361.8 | -1.35 | 3200.2 | 661.3 | -62.61 | 0.0 |
| 3.40 | -0.675 | 0.670 | -1.33 | 11689.2 | 1330.1 | -302.70 | 13371.3 | -1.33 | 3208.6 | 657.3 | -62.37 | 0.0 |
| 3.50 | -0.668 | 0.675 | -1.32 | 11571.7 | 1321.2 | -297.71 | 13237.0 | -1.33 | 3178.4 | 649.0 | -61.39 | 0.0 |
| 3.60 | -0.673 | 0.671 | -1.32 | 11659.1 | 1320.2 | -299.90 | 13340.2 | -1.32 | 3205.8 | 652.6 | -61.96 | 0.0 |
| 3.70 | -0.672 | 0.669 | -1.32 | 11653.9 | 1317.6 | -299.24 | 13336.6 | -1.32 | 3206.4 | 651.6 | -61.89 | 0.0 |
| 3.80 | -0.668 | 0.674 | -1.32 | 11584.6 | 1318.5 | -297.53 | 13253.6 | -1.32 | 3184.8 | 648.9 | -61.44 | 0.0 |
| 3.90 | -0.673 | 0.671 | -1.32 | 11666.2 | 1324.5 | -300.94 | 13346.3 | -1.33 | 3205.0 | 654.4 | -62.10 | 0.0 |
| 4.00 | -0.673 | 0.672 | -1.33 | 11659.6 | 1328.8 | -301.62 | 13337.0 | -1.33 | 3199.8 | 655.6 | -62.14 | 0.0 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 5
*********

| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 6500.1 | 0.0 | 0.0 | 5750.0 | 0.0 | 6500.1 | 0.0 | 0.0 | 5750.0 |
| 0.10 | -0.001 | -0.000 | 0.00 | 6504.2 | -3.6 | 0.53 | 5767.2 | 0.00 | 6495.7 | -3.6 | 0.53 | 5733.4 |
| 0.20 | -0.009 | -0.000 | 0.01 | 6555.9 | -10.0 | 1.50 | 5877.8 | 0.01 | 6444.2 | -10.0 | 1.47 | 5622.4 |
| 0.30 | -0.031 | -0.000 | 0.01 | 6693.8 | -9.5 | 1.43 | 6144.4 | 0.01 | 6305.6 | -9.2 | 1.33 | 5354.8 |
| 0.40 | -0.071 | -0.000 | -0.01 | 6948.3 | 12.6 | -1.96 | 6604.4 | -0.01 | 6050.6 | 11.9 | -1.67 | 4894.3 |
| 0.50 | -0.132 | 0.0 | -0.08 | 7330.3 | 69.9 | -11.21 | 7262.0 | -0.08 | 5667.6 | 61.9 | -8.33 | 4235.3 |
| 0.60 | -0.212 | 0.000 | -0.19 | 7832.4 | 177.9 | -29.72 | 8087.8 | -0.19 | 5164.1 | 142.8 | -18.29 | 3408.3 |
| 0.70 | -0.303 | 0.000 | -0.36 | 8400.7 | 343.7 | -60.17 | 8982.0 | -0.36 | 4596.1 | 244.9 | -29.52 | 2511.2 |
| 0.80 | -0.394 | 0.000 | -0.58 | 8976.2 | 557.6 | -102.81 | 9849.5 | -0.58 | 4022.1 | 352.6 | -39.30 | 1641.8 |
| 0.90 | -0.478 | 0.000 | -0.81 | 9503.9 | 794.7 | -154.28 | 10617.6 | -0.82 | 3495.8 | 450.0 | -45.58 | 871.7 |
| 1.00 | -0.550 | 0.000 | -1.05 | 9957.1 | 1037.9 | -208.32 | 11259.1 | -1.06 | 3043.9 | 515.7 | -49.05 | 226.5 |
| 1.10 | -0.586 | 0.012 | -1.28 | 10274.3 | 1259.9 | -252.43 | 11612.3 | -1.29 | 2907.9 | 588.6 | -53.58 | 0.0 |
| 1.20 | -0.599 | 0.054 | -1.42 | 10345.5 | 1386.3 | -275.79 | 11621.8 | -1.42 | 2816.0 | 624.7 | -55.48 | 0.0 |
| 1.30 | -0.606 | 0.133 | -1.51 | 10315.9 | 1476.5 | -290.60 | 11525.5 | -1.52 | 2706.6 | 640.6 | -55.58 | 0.0 |
| 1.40 | -0.615 | 0.235 | -1.58 | 10435.9 | 1544.1 | -305.36 | 11627.9 | -1.59 | 2711.6 | 666.9 | -57.63 | 0.0 |
| 1.50 | -0.617 | 0.362 | -1.61 | 10464.1 | 1569.9 | -310.57 | 11647.7 | -1.62 | 2714.9 | 677.3 | -58.44 | 0.0 |
| 1.60 | -0.613 | 0.512 | -1.60 | 10402.3 | 1556.7 | -306.66 | 11578.4 | -1.60 | 2694.8 | 668.3 | -57.54 | 0.0 |
| 1.70 | -0.615 | 0.664 | -1.56 | 10443.4 | 1528.2 | -302.78 | 11641.5 | -1.57 | 2716.8 | 660.4 | -57.22 | 0.0 |
| 1.80 | -0.709 | 0.753 | -1.61 | 10740.9 | 1575.3 | -321.09 | 12548.5 | -1.61 | 1834.3 | 474.3 | -36.66 | -1342.9 |
| 1.90 | -0.760 | 0.746 | -1.78 | 11574.6 | 1759.2 | -384.79 | 13464.9 | -1.79 | 2021.7 | 568.9 | -44.24 | -1415.2 |
| 2.00 | -0.736 | 0.741 | -1.76 | 11383.0 | 1739.4 | -373.88 | 13145.0 | -1.77 | 2139.7 | 593.6 | -47.13 | -1183.0 |
| 2.10 | -0.690 | 0.753 | -1.75 | 10696.6 | 1704.9 | -342.71 | 12309.8 | -1.75 | 2030.2 | 565.3 | -43.30 | -1051.0 |
| 2.20 | -0.667 | 0.742 | -1.68 | 11106.5 | 1652.8 | -347.20 | 12462.3 | -1.69 | 2725.0 | 703.7 | -61.05 | -205.4 |
| 2.30 | -0.666 | 0.743 | -1.63 | 10829.2 | 1601.4 | -328.39 | 12294.7 | -1.64 | 2458.5 | 627.2 | -52.53 | -519.1 |
| 2.40 | -0.658 | 0.750 | -1.65 | 10673.9 | 1619.3 | -326.35 | 12091.1 | -1.66 | 2408.4 | 624.5 | -51.67 | -505.0 |
| 2.50 | -0.650 | 0.740 | -1.63 | 10991.5 | 1601.9 | -333.74 | 12276.4 | -1.64 | 2828.8 | 707.9 | -62.29 | -22.5 |
| 2.60 | -0.644 | 0.746 | -1.61 | 10628.0 | 1577.4 | -317.26 | 11981.3 | -1.62 | 2537.6 | 638.3 | -53.97 | -311.2 |
| 2.70 | -0.634 | 0.747 | -1.61 | 10667.4 | 1577.3 | -318.45 | 11932.6 | -1.62 | 2699.4 | 673.4 | -58.19 | -85.8 |
| 2.80 | -0.639 | 0.736 | -1.58 | 10830.8 | 1558.2 | -320.38 | 12102.0 | -1.59 | 2800.8 | 685.5 | -60.22 | 0.0 |
| 2.90 | -0.627 | 0.746 | -1.56 | 10536.0 | 1525.8 | -305.05 | 11832.6 | -1.57 | 2651.7 | 644.0 | -55.47 | -130.7 |
| 3.00 | -0.622 | 0.744 | -1.54 | 10656.4 | 1510.8 | -306.17 | 11926.7 | -1.55 | 2834.6 | 675.2 | -59.63 | 0.0 |
| 3.10 | -0.629 | 0.734 | -1.52 | 10706.6 | 1491.1 | -304.27 | 11991.6 | -1.52 | 2808.2 | 660.7 | -58.35 | 0.0 |
| 3.20 | -0.616 | 0.742 | -1.51 | 10489.4 | 1478.2 | -295.24 | 11741.5 | -1.52 | 2747.7 | 645.6 | -56.48 | 0.0 |
| 3.30 | -0.621 | 0.735 | -1.50 | 10615.6 | 1471.4 | -297.91 | 11895.0 | -1.50 | 2809.6 | 653.9 | -57.79 | 0.0 |
| 3.40 | -0.621 | 0.730 | -1.48 | 10618.4 | 1458.8 | -295.77 | 11906.6 | -1.49 | 2818.6 | 650.5 | -57.62 | 0.0 |
| 3.50 | -0.613 | 0.737 | -1.48 | 10471.8 | 1449.3 | -289.77 | 11737.1 | -1.49 | 2774.2 | 639.4 | -56.27 | 0.0 |
| 3.60 | -0.619 | 0.730 | -1.48 | 10590.2 | 1451.6 | -293.63 | 11874.5 | -1.48 | 2809.0 | 645.9 | -57.17 | 0.0 |
| 3.70 | -0.618 | 0.729 | -1.48 | 10579.8 | 1450.1 | -293.04 | 11864.6 | -1.48 | 2809.0 | 645.4 | -57.13 | 0.0 |
| 3.80 | -0.613 | 0.735 | -1.48 | 10489.7 | 1450.7 | -290.46 | 11757.2 | -1.49 | 2781.4 | 641.2 | -56.48 | 0.0 |
| 3.90 | -0.620 | 0.731 | -1.48 | 10595.1 | 1458.6 | -295.01 | 11876.5 | -1.49 | 2806.7 | 648.4 | -57.33 | 0.0 |
| 4.00 | -0.619 | 0.732 | -1.49 | 10580.5 | 1463.6 | -295.44 | 11857.7 | -1.50 | 2799.0 | 649.0 | -57.30 | 0.0 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 6
*********

| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 6500.1 | 0.0 | 0.0 | 5750.0 | 0.0 | 6500.1 | 0.0 | 0.0 | 5750.0 |
| 0.10 | -0.001 | -0.000 | 0.00 | 6504.3 | -3.1 | 0.47 | 5766.6 | 0.00 | 6495.5 | -3.1 | 0.46 | 5734.1 |
| 0.20 | -0.009 | -0.000 | 0.01 | 6557.1 | -6.5 | 0.97 | 5873.9 | 0.01 | 6442.9 | -6.4 | 0.95 | 5626.2 |
| 0.30 | -0.032 | -0.000 | -0.00 | 6698.3 | 2.4 | -0.36 | 6133.2 | -0.00 | 6301.3 | 2.3 | -0.33 | 5366.2 |
| 0.40 | -0.073 | -0.000 | -0.05 | 6958.5 | 39.9 | -6.18 | 6580.4 | -0.05 | 6040.5 | 37.3 | -5.25 | 4918.2 |
| 0.50 | -0.135 | 0.0 | -0.14 | 7349.3 | 120.9 | -19.42 | 7220.7 | -0.14 | 5649.2 | 106.7 | -14.33 | 4277.1 |
| 0.60 | -0.217 | 0.000 | -0.28 | 7862.3 | 261.1 | -43.72 | 8025.4 | -0.28 | 5135.5 | 208.3 | -26.59 | 3470.5 |
| 0.70 | -0.309 | 0.000 | -0.49 | 8441.9 | 463.5 | -81.45 | 8900.0 | -0.49 | 4557.0 | 327.5 | -39.30 | 2594.2 |
| 0.80 | -0.402 | 0.000 | -0.73 | 9027.3 | 712.7 | -132.09 | 9750.8 | -0.74 | 3973.8 | 446.3 | -49.35 | 1741.1 |
| 0.90 | -0.487 | 0.000 | -1.00 | 9562.2 | 979.7 | -191.23 | 10507.1 | -1.00 | 3440.7 | 547.8 | -54.78 | 982.1 |
| 1.00 | -0.559 | 0.000 | -1.26 | 10013.6 | 1231.6 | -241.90 | 11154.4 | -1.27 | 2991.0 | 594.9 | -54.57 | 331.7 |
| 1.10 | -0.609 | 0.006 | -1.51 | 10353.5 | 1473.9 | -291.10 | 11549.1 | -1.52 | 2700.9 | 637.7 | -55.34 | 0.0 |
| 1.20 | -0.608 | 0.055 | -1.65 | 10323.5 | 1607.0 | -313.25 | 11448.2 | -1.66 | 2685.2 | 689.2 | -58.88 | 0.0 |
| 1.30 | -0.604 | 0.142 | -1.73 | 10149.2 | 1673.3 | -319.79 | 11185.3 | -1.74 | 2556.9 | 689.4 | -57.36 | 0.0 |
| 1.40 | -0.607 | 0.251 | -1.79 | 10122.7 | 1723.7 | -327.58 | 11105.8 | -1.80 | 2497.7 | 695.0 | -57.07 | 0.0 |
| 1.50 | -0.595 | 0.390 | -1.80 | 9937.7 | 1729.1 | -323.13 | 10867.2 | -1.81 | 2457.0 | 690.6 | -56.12 | 0.0 |
| 1.60 | -0.575 | 0.554 | -1.77 | 9619.2 | 1687.3 | -307.02 | 10489.8 | -1.78 | 2391.7 | 665.1 | -53.31 | 0.0 |
| 1.70 | -0.562 | 0.720 | -1.72 | 9421.6 | 1633.0 | -292.63 | 10261.0 | -1.73 | 2358.2 | 640.5 | -51.06 | 0.0 |
| 1.80 | -0.699 | 0.784 | -1.75 | 9534.7 | 1665.1 | -301.00 | 11505.8 | -1.76 | 772.7 | 216.0 | -16.49 | -2574.2 |
| 1.90 | -0.754 | 0.776 | -1.93 | 10511.5 | 1872.1 | -366.10 | 12515.4 | -1.94 | 1036.5 | 316.7 | -23.85 | -2527.1 |
| 2.00 | -0.731 | 0.770 | -1.92 | 10312.2 | 1851.5 | -355.00 | 12170.0 | -1.92 | 1131.6 | 343.3 | -25.88 | -2287.4 |
| 2.10 | -0.683 | 0.785 | -1.91 | 9543.2 | 1807.9 | -324.22 | 11279.7 | -1.92 | 958.6 | 289.8 | -21.86 | -2232.0 |
| 2.20 | -0.664 | 0.770 | -1.84 | 10102.9 | 1774.2 | -335.54 | 11503.2 | -1.85 | 1759.9 | 515.6 | -39.07 | -1226.6 |
| 2.30 | -0.662 | 0.773 | -1.80 | 9745.9 | 1714.1 | -315.08 | 11292.1 | -1.80 | 1425.6 | 407.7 | -31.01 | -1627.6 |
| 2.40 | -0.653 | 0.781 | -1.82 | 9560.3 | 1728.2 | -311.92 | 11066.8 | -1.83 | 1357.2 | 393.0 | -29.83 | -1638.1 |
| 2.50 | -0.647 | 0.769 | -1.79 | 9971.3 | 1720.0 | -322.59 | 11302.0 | -1.80 | 1844.0 | 526.2 | -40.03 | -1061.2 |
| 2.60 | -0.640 | 0.776 | -1.77 | 9524.2 | 1683.6 | -303.67 | 10962.0 | -1.78 | 1487.5 | 420.5 | -32.04 | -1438.1 |
| 2.70 | -0.630 | 0.777 | -1.77 | 9590.6 | 1684.6 | -305.75 | 10924.2 | -1.78 | 1672.7 | 472.3 | -35.99 | -1179.5 |
| 2.80 | -0.628 | 0.769 | -1.73 | 9788.1 | 1656.2 | -306.77 | 11069.6 | -1.74 | 1896.5 | 524.4 | -40.09 | -937.6 |
| 2.90 | -0.623 | 0.777 | -1.71 | 9430.6 | 1626.5 | -291.87 | 10806.5 | -1.72 | 1598.8 | 438.3 | -33.56 | -1257.3 |
| 3.00 | -0.618 | 0.775 | -1.70 | 9594.3 | 1622.7 | -295.86 | 10869.1 | -1.71 | 1832.1 | 499.2 | -38.26 | -973.1 |
| 3.10 | -0.613 | 0.770 | -1.67 | 9652.8 | 1599.9 | -293.79 | 10897.9 | -1.68 | 1943.9 | 521.8 | -40.09 | -838.8 |
| 3.20 | -0.607 | 0.776 | -1.66 | 9392.6 | 1578.2 | -283.13 | 10679.0 | -1.67 | 1764.4 | 470.5 | -36.18 | -1018.7 |
| 3.30 | -0.603 | 0.773 | -1.66 | 9549.6 | 1579.0 | -287.57 | 10752.8 | -1.66 | 1971.6 | 524.1 | -40.32 | -761.1 |
| 3.40 | -0.600 | 0.770 | -1.64 | 9561.4 | 1563.9 | -285.46 | 10750.9 | -1.65 | 2021.0 | 532.2 | -41.01 | -698.5 |
| 3.50 | -0.597 | 0.774 | -1.64 | 9383.8 | 1554.9 | -279.19 | 10602.4 | -1.64 | 1887.2 | 496.4 | -38.26 | -833.5 |
| 3.60 | -0.596 | 0.772 | -1.64 | 9524.9 | 1562.1 | -284.17 | 10687.4 | -1.65 | 2039.6 | 537.0 | -41.38 | -652.3 |
| 3.70 | -0.596 | 0.771 | -1.63 | 9517.2 | 1556.8 | -283.11 | 10688.8 | -1.64 | 2030.6 | 533.0 | -41.10 | -666.3 |
| 3.80 | -0.596 | 0.774 | -1.64 | 9406.4 | 1559.1 | -280.46 | 10606.2 | -1.65 | 1921.2 | 506.4 | -39.02 | -785.3 |
| 3.90 | -0.597 | 0.772 | -1.65 | 9530.2 | 1571.0 | -285.75 | 10698.0 | -1.66 | 2022.1 | 535.3 | -41.21 | -674.4 |
| 4.00 | -0.600 | 0.771 | -1.65 | 9513.6 | 1572.7 | -285.57 | 10704.9 | -1.66 | 1977.2 | 524.1 | -40.34 | -736.3 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 7
*********

| | | | LEFT SIDE | | | | | RIGHT SIDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) |
| 0.0 | 0.0 | 0.0 | 0.0 | 6412.5 | 0.0 | 0.0 | 5662.5 | 0.0 | 6412.5 | 0.0 | 0.0 | 5662.5 |
| 0.10 | 0.000 | 0.000 | 0.00 | 6410.1 | -0.1 | 0.01 | 5660.6 | 0.00 | 6410.2 | -0.1 | 0.01 | 5659.7 |
| 0.20 | -0.000 | 0.000 | -0.00 | 6412.3 | 1.6 | -0.24 | 5661.7 | -0.00 | 6408.3 | 1.6 | -0.24 | 5659.0 |
| 0.30 | -0.000 | -0.000 | -0.00 | 6415.2 | 2.2 | -0.32 | 5663.9 | -0.00 | 6409.5 | 2.2 | -0.32 | 5660.9 |
| 0.40 | 0.001 | 0.000 | 0.00 | 6406.6 | -3.2 | 0.46 | 5656.5 | 0.00 | 6413.8 | -3.2 | 0.46 | 5663.8 |
| 0.50 | 0.003 | 0.000 | 0.02 | 6390.0 | -16.1 | 2.35 | 5643.5 | 0.02 | 6431.2 | -16.1 | 2.37 | 5677.7 |
| 0.60 | 0.006 | 0.0 | 0.04 | 6371.3 | -29.7 | 4.33 | 5627.3 | 0.04 | 6453.3 | -29.8 | 4.40 | 5697.0 |
| 0.70 | 0.007 | 0.000 | 0.04 | 6362.9 | -30.3 | 4.42 | 5618.4 | 0.04 | 6456.9 | -30.5 | 4.50 | 5701.9 |
| 0.80 | 0.001 | 0.000 | -0.01 | 6402.4 | 4.5 | -0.66 | 5648.6 | -0.01 | 6417.6 | 4.5 | -0.66 | 5671.6 |
| 0.90 | -0.018 | 0.000 | -0.12 | 6523.2 | 97.3 | -14.44 | 5752.1 | -0.12 | 6298.4 | 96.0 | -13.91 | 5569.4 |
| 1.00 | -0.054 | 0.000 | -0.31 | 6749.2 | 264.2 | -40.13 | 5959.1 | -0.31 | 6067.2 | 252.7 | -35.65 | 5357.0 |
| 1.10 | -0.107 | 0.000 | -0.58 | 7088.7 | 501.6 | -78.70 | 6299.2 | -0.58 | 5726.2 | 457.4 | -61.85 | 5014.1 |
| 1.20 | -0.177 | 0.000 | -0.91 | 7535.0 | 814.1 | -132.79 | 6773.3 | -0.91 | 5278.3 | 682.2 | -88.28 | 4535.6 |
| 1.30 | -0.258 | 0.000 | -1.29 | 8048.5 | 1179.0 | -192.81 | 7360.7 | -1.30 | 4756.7 | 876.6 | -102.85 | 3935.6 |
| 1.40 | -0.343 | 0.001 | -1.68 | 8583.4 | 1552.9 | -258.00 | 8013.7 | -1.70 | 4217.9 | 1019.8 | -107.59 | 3272.8 |
| 1.50 | -0.418 | 0.001 | -2.03 | 9063.2 | 1887.3 | -320.46 | 8629.2 | -2.05 | 3736.6 | 1100.0 | -104.08 | 2649.5 |
| 1.60 | -0.472 | 0.001 | -2.28 | 9407.0 | 2095.4 | -354.27 | 9145.2 | -2.30 | 3389.0 | 1108.3 | -92.59 | 2125.9 |
| 1.70 | -0.506 | 0.001 | -2.37 | 9604.7 | 2175.6 | -370.30 | 9532.8 | -2.39 | 3153.8 | 1066.3 | -85.37 | 1698.5 |
| 1.80 | -0.541 | 0.002 | -2.24 | 9798.9 | 2085.1 | -367.80 | 10079.1 | -2.24 | 2908.1 | 948.0 | -76.32 | 1107.8 |
| 1.90 | -0.566 | -0.000 | -1.84 | 10043.6 | 1769.7 | -333.04 | 10819.4 | -1.84 | 2827.6 | 791.8 | -67.48 | 528.3 |
| 2.00 | -0.564 | -0.002 | -1.42 | 10077.4 | 1380.6 | -268.42 | 11224.8 | -1.42 | 2893.9 | 638.6 | -56.93 | 215.5 |
| 2.10 | -0.518 | -0.000 | -1.20 | 9714.3 | 1165.5 | -224.48 | 10807.6 | -1.20 | 3112.9 | 588.0 | -54.79 | 515.6 |
| 2.20 | -0.439 | -0.001 | -1.11 | 9242.0 | 1073.2 | -199.93 | 9911.4 | -1.11 | 3644.9 | 624.8 | -63.93 | 1462.4 |
| 2.30 | -0.342 | 0.000 | -1.04 | 8583.4 | 985.9 | -174.57 | 8783.8 | -1.04 | 4222.6 | 654.1 | -74.57 | 2510.5 |
| 2.40 | -0.324 | 0.002 | -0.92 | 8402.5 | 873.8 | -153.06 | 8549.0 | -0.93 | 4275.4 | 590.6 | -68.32 | 2633.2 |
| 2.50 | -0.304 | -0.002 | -1.05 | 8437.8 | 989.7 | -172.59 | 8289.6 | -1.05 | 4566.8 | 701.0 | -83.41 | 3190.0 |
| 2.60 | -0.282 | 0.000 | -1.18 | 8176.4 | 1097.4 | -183.36 | 7758.6 | -1.19 | 4589.4 | 786.4 | -91.83 | 3501.0 |
| 2.70 | -0.271 | 0.003 | -1.34 | 8022.6 | 1221.7 | -198.35 | 7388.5 | -1.35 | 4569.3 | 878.8 | -100.32 | 3716.5 |
| 2.80 | -0.271 | -0.003 | -1.45 | 8268.7 | 1336.6 | -219.15 | 7449.2 | -1.46 | 4817.2 | 984.7 | -114.26 | 4102.7 |
| 2.90 | -0.285 | 0.001 | -1.51 | 8172.8 | 1378.9 | -223.12 | 7421.8 | -1.52 | 4543.4 | 973.9 | -108.93 | 3789.2 |
| 3.00 | -0.308 | 0.004 | -1.54 | 8258.1 | 1407.4 | -229.17 | 7646.5 | -1.55 | 4332.5 | 954.3 | -103.62 | 3450.6 |
| 3.10 | -0.337 | -0.004 | -1.53 | 8715.9 | 1426.7 | -242.35 | 8231.8 | -1.54 | 4423.4 | 962.8 | -105.92 | 3363.5 |
| 3.20 | -0.362 | 0.002 | -1.50 | 8625.9 | 1392.9 | -235.48 | 8399.0 | -1.50 | 4018.0 | 878.3 | -91.45 | 2746.5 |
| 3.30 | -0.378 | 0.003 | -1.48 | 8725.7 | 1381.2 | -235.97 | 8634.2 | -1.48 | 3904.7 | 849.4 | -86.99 | 2500.6 |
| 3.40 | -0.387 | -0.004 | -1.42 | 9045.4 | 1343.8 | -237.49 | 9012.4 | -1.42 | 4117.0 | 850.2 | -90.62 | 2605.8 |
| 3.50 | -0.389 | 0.003 | -1.35 | 8776.1 | 1272.3 | -220.79 | 8893.1 | -1.36 | 3814.8 | 769.7 | -78.66 | 2205.4 |
| 3.60 | -0.383 | 0.002 | -1.31 | 8795.8 | 1238.7 | -216.11 | 8904.5 | -1.32 | 3913.6 | 763.7 | -79.76 | 2301.0 |
| 3.70 | -0.374 | -0.004 | -1.25 | 8959.0 | 1188.7 | -211.76 | 9028.5 | -1.25 | 4191.5 | 767.2 | -84.34 | 2579.1 |
| 3.80 | -0.363 | 0.003 | -1.21 | 8587.2 | 1142.0 | -197.69 | 8682.8 | -1.22 | 3963.9 | 719.3 | -76.69 | 2381.9 |
| 3.90 | -0.347 | 0.001 | -1.21 | 8600.2 | 1143.6 | -198.11 | 8574.6 | -1.22 | 4175.1 | 747.9 | -82.37 | 2694.4 |
| 4.00 | -0.334 | -0.004 | -1.21 | 8678.6 | 1143.4 | -199.48 | 8535.2 | -1.22 | 4418.1 | 777.3 | -88.57 | 3027.0 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 8
*********

| | | | LEFT SIDE | | | | | RIGHT SIDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) |
| 0.0 | 0.0 | 0.0 | 0.0 | 6412.5 | 0.0 | 0.0 | 5662.5 | 0.0 | 6412.5 | 0.0 | 0.0 | 5662.5 |
| 0.10 | -0.000 | 0.000 | -0.00 | 6411.2 | 0.7 | -0.10 | 5660.6 | -0.00 | 6410.5 | 0.7 | -0.10 | 5661.1 |
| 0.20 | -0.000 | 0.000 | -0.00 | 6413.4 | 2.4 | -0.35 | 5662.1 | -0.00 | 6408.9 | 2.4 | -0.35 | 5660.1 |
| 0.30 | -0.000 | 0.0 | -0.00 | 6414.4 | 0.2 | -0.03 | 5665.8 | -0.00 | 6410.6 | 0.2 | -0.03 | 5658.9 |
| 0.40 | 0.001 | 0.000 | 0.01 | 6404.5 | -9.9 | 1.45 | 5662.7 | 0.01 | 6417.5 | -9.9 | 1.46 | 5659.0 |
| 0.50 | 0.004 | 0.000 | 0.03 | 6386.6 | -25.6 | 3.74 | 5651.1 | 0.03 | 6435.6 | -25.6 | 3.77 | 5671.3 |
| 0.60 | 0.007 | -0.000 | 0.04 | 6369.3 | -35.0 | 5.11 | 5630.4 | 0.04 | 6455.1 | -35.2 | 5.19 | 5694.2 |
| 0.70 | 0.007 | 0.000 | 0.02 | 6369.5 | -18.7 | 2.73 | 5607.8 | 0.02 | 6452.4 | -18.8 | 2.77 | 5714.1 |
| 0.80 | -0.002 | 0.000 | -0.06 | 6423.2 | 49.1 | -7.21 | 5612.2 | -0.06 | 6399.5 | 49.1 | -7.19 | 5710.2 |
| 0.90 | -0.024 | 0.0 | -0.23 | 6563.9 | 190.4 | -28.37 | 5679.7 | -0.23 | 6260.9 | 186.8 | -26.95 | 5644.5 |
| 1.00 | -0.063 | 0.000 | -0.48 | 6812.2 | 413.7 | -63.23 | 5849.2 | -0.49 | 6009.6 | 392.2 | -54.95 | 5471.6 |
| 1.10 | -0.120 | 0.000 | -0.81 | 7173.7 | 711.4 | -112.47 | 6151.0 | -0.82 | 5648.3 | 639.2 | -85.77 | 5168.1 |
| 1.20 | -0.192 | 0.000 | -1.21 | 7634.2 | 1075.6 | -171.86 | 6602.9 | -1.22 | 5187.8 | 879.7 | -109.06 | 4712.4 |
| 1.30 | -0.274 | 0.000 | -1.63 | 8156.4 | 1483.0 | -237.51 | 7179.4 | -1.65 | 4660.9 | 1072.3 | -120.24 | 4126.3 |
| 1.40 | -0.358 | 0.000 | -2.03 | 8690.2 | 1865.9 | -305.84 | 7841.0 | -2.06 | 4126.1 | 1189.6 | -119.96 | 3457.2 |
| 1.50 | -0.429 | 0.000 | -2.36 | 9142.3 | 2138.2 | -348.55 | 8510.0 | -2.39 | 3674.7 | 1208.5 | -105.81 | 2783.8 |
| 1.60 | -0.482 | 0.000 | -2.58 | 9478.5 | 2319.7 | -380.64 | 9045.6 | -2.60 | 3338.9 | 1193.0 | -93.39 | 2244.3 |
| 1.70 | -0.513 | 0.001 | -2.59 | 9653.5 | 2341.8 | -390.11 | 9464.5 | -2.60 | 3119.5 | 1122.3 | -86.15 | 1776.0 |
| 1.80 | -0.541 | 0.004 | -2.31 | 9724.4 | 2133.9 | -370.36 | 10002.5 | -2.31 | 2828.6 | 944.6 | -74.21 | 1028.8 |
| 1.90 | -0.562 | 0.006 | -1.79 | 9775.8 | 1706.8 | -314.74 | 10640.2 | -1.78 | 2620.0 | 720.7 | -59.83 | 239.3 |
| 2.00 | -0.551 | 0.012 | -1.41 | 9722.0 | 1357.1 | -255.99 | 10875.4 | -1.41 | 2702.4 | 597.6 | -51.89 | 0.0 |
| 2.10 | -0.519 | 0.007 | -1.25 | 9499.9 | 1206.4 | -226.48 | 10565.8 | -1.25 | 2886.8 | 571.6 | -51.53 | 313.5 |
| 2.20 | -0.445 | 0.002 | -1.25 | 9205.9 | 1197.2 | -218.54 | 9762.6 | -1.25 | 3532.5 | 678.3 | -66.51 | 1457.8 |
| 2.30 | -0.349 | -0.002 | -1.18 | 8701.6 | 1115.0 | -195.73 | 8783.8 | -1.18 | 4259.4 | 737.3 | -82.63 | 2654.1 |
| 2.40 | -0.331 | 0.002 | -1.06 | 8447.2 | 1003.8 | -174.89 | 8466.7 | -1.07 | 4230.1 | 670.1 | -76.11 | 2719.8 |
| 2.50 | -0.314 | -0.001 | -1.26 | 8447.5 | 1179.8 | -200.40 | 8124.9 | -1.27 | 4450.9 | 814.8 | -92.54 | 3257.9 |
| 2.60 | -0.293 | -0.001 | -1.42 | 8317.7 | 1304.6 | -215.70 | 7694.1 | -1.43 | 4590.6 | 925.1 | -105.04 | 3692.0 |
| 2.70 | -0.282 | 0.003 | -1.58 | 8093.2 | 1428.7 | -228.63 | 7264.3 | -1.59 | 4503.2 | 1007.8 | -111.46 | 3840.3 |
| 2.80 | -0.281 | -0.002 | -1.68 | 8290.9 | 1531.8 | -247.59 | 7296.8 | -1.69 | 4713.8 | 1105.5 | -124.33 | 4178.0 |
| 2.90 | -0.294 | -0.000 | -1.70 | 8284.9 | 1553.0 | -250.54 | 7368.8 | -1.71 | 4540.7 | 1087.9 | -119.67 | 3943.4 |
| 3.00 | -0.316 | 0.003 | -1.72 | 8305.4 | 1564.4 | -252.78 | 7555.8 | -1.73 | 4279.7 | 1046.0 | -111.10 | 3540.5 |
| 3.10 | -0.344 | -0.003 | -1.69 | 8726.0 | 1569.9 | -263.94 | 8121.6 | -1.70 | 4345.6 | 1042.1 | -111.93 | 3412.7 |
| 3.20 | -0.368 | 0.001 | -1.64 | 8717.4 | 1527.9 | -257.60 | 8363.3 | -1.65 | 4023.2 | 957.7 | -98.51 | 2868.5 |
| 3.30 | -0.385 | 0.003 | -1.62 | 8769.6 | 1514.1 | -256.84 | 8560.2 | -1.63 | 3866.1 | 919.7 | -92.33 | 2575.9 |
| 3.40 | -0.393 | -0.003 | -1.55 | 9054.3 | 1464.2 | -256.20 | 8920.1 | -1.56 | 4053.4 | 912.7 | -95.09 | 2645.0 |
| 3.50 | -0.395 | 0.002 | -1.48 | 8853.6 | 1391.6 | -240.35 | 8859.4 | -1.49 | 3816.1 | 836.4 | -84.34 | 2310.8 |
| 3.60 | -0.389 | 0.002 | -1.45 | 8832.5 | 1362.7 | -235.52 | 8834.3 | -1.46 | 3873.4 | 829.5 | -84.75 | 2370.3 |
| 3.70 | -0.380 | -0.003 | -1.38 | 8967.6 | 1307.6 | -230.06 | 8936.6 | -1.38 | 4126.8 | 831.1 | -89.08 | 2621.1 |
| 3.80 | -0.369 | 0.002 | -1.36 | 8663.4 | 1271.9 | -218.39 | 8636.0 | -1.36 | 3956.1 | 794.1 | -83.07 | 2489.8 |
| 3.90 | -0.354 | 0.001 | -1.37 | 8645.5 | 1283.9 | -219.74 | 8491.7 | -1.38 | 4130.9 | 828.1 | -88.88 | 2774.8 |
| 4.00 | -0.342 | -0.003 | -1.37 | 8700.9 | 1285.1 | -220.98 | 8429.5 | -1.38 | 4349.8 | 859.5 | -95.17 | 3086.9 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 9
*********

| | | | LEFT SIDE | | | | | RIGHT SIDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) |
| 0.0 | 0.0 | 0.0 | 0.0 | 6475.1 | 0.0 | 0.0 | 5725.0 | 0.0 | 6475.1 | 0.0 | 0.0 | 5725.0 |
| 0.10 | -0.000 | -0.000 | 0.00 | 6475.2 | -0.1 | 0.01 | 5725.6 | 0.00 | 6475.0 | -0.1 | 0.01 | 5724.8 |
| 0.20 | -0.000 | -0.000 | 0.00 | 6476.2 | -0.3 | 0.04 | 5727.7 | 0.00 | 6474.3 | -0.3 | 0.04 | 5723.0 |
| 0.30 | -0.000 | -0.000 | -0.00 | 6477.2 | 0.3 | -0.04 | 5728.7 | -0.00 | 6472.7 | 0.3 | -0.04 | 5721.1 |
| 0.40 | 0.000 | -0.000 | -0.00 | 6474.9 | 2.0 | -0.29 | 5720.8 | -0.00 | 6475.3 | 2.0 | -0.29 | 5729.0 |
| 0.50 | 0.002 | -0.000 | -0.00 | 6464.0 | 3.4 | -0.51 | 5697.1 | -0.00 | 6486.5 | 3.4 | -0.51 | 5753.3 |
| 0.60 | 0.005 | -0.000 | -0.00 | 6444.9 | 1.4 | -0.21 | 5663.5 | -0.00 | 6505.0 | 1.4 | -0.21 | 5786.4 |
| 0.70 | 0.007 | -0.000 | 0.01 | 6429.0 | -7.1 | 1.04 | 5646.7 | 0.01 | 6521.2 | -7.1 | 1.06 | 5803.6 |
| 0.80 | 0.006 | -0.000 | 0.03 | 6438.8 | -22.6 | 3.33 | 5692.7 | 0.03 | 6511.4 | -22.8 | 3.37 | 5757.8 |
| 0.90 | -0.005 | -0.000 | 0.05 | 6509.7 | -40.5 | 6.01 | 5863.2 | 0.05 | 6440.0 | -40.3 | 5.93 | 5586.4 |
| 1.00 | -0.033 | -0.000 | 0.06 | 6682.6 | -48.3 | 7.28 | 6218.8 | 0.06 | 6266.5 | -46.9 | 6.77 | 5230.3 |
| 1.10 | -0.081 | -0.000 | 0.03 | 6989.8 | -26.5 | 4.12 | 6794.8 | 0.03 | 5958.0 | -24.7 | 3.43 | 4653.1 |
| 1.20 | -0.153 | 0.000 | -0.05 | 7450.0 | 47.3 | -7.66 | 7597.8 | -0.05 | 5496.0 | 40.9 | -5.40 | 3848.5 |
| 1.30 | -0.248 | 0.000 | -0.22 | 8050.4 | 200.2 | -34.01 | 8578.8 | -0.22 | 4893.9 | 152.6 | -19.02 | 2863.6 |
| 1.40 | -0.357 | 0.000 | -0.46 | 8744.5 | 444.1 | -80.20 | 9651.1 | -0.47 | 4197.9 | 293.1 | -33.54 | 1787.1 |
| 1.50 | -0.467 | 0.000 | -0.80 | 9444.4 | 782.7 | -151.10 | 10647.5 | -0.81 | 3497.7 | 445.9 | -45.18 | 784.8 |
| 1.60 | -0.560 | 0.000 | -1.20 | 10039.9 | 1175.7 | -233.07 | 11432.5 | -1.21 | 2902.3 | 556.9 | -50.96 | -7.6 |
| 1.70 | -0.608 | 0.019 | -1.58 | 10484.9 | 1548.5 | -307.38 | 11755.2 | -1.60 | 2741.7 | 678.2 | -58.71 | 0.0 |
| 1.80 | -0.636 | 0.068 | -1.94 | 10763.2 | 1887.7 | -377.54 | 11898.7 | -1.96 | 2658.6 | 792.0 | -66.33 | 0.0 |
| 1.90 | -0.658 | 0.133 | -2.27 | 10936.8 | 2172.7 | -424.10 | 11940.1 | -2.30 | 2557.3 | 854.3 | -66.28 | 0.0 |
| 2.00 | -0.682 | 0.160 | -2.60 | 11087.7 | 2443.1 | -465.64 | 11959.3 | -2.62 | 2404.7 | 885.6 | -63.26 | 0.0 |
| 2.10 | -0.686 | 0.127 | -2.78 | 11063.9 | 2586.7 | -482.76 | 11848.3 | -2.80 | 2323.1 | 898.7 | -61.36 | 0.0 |
| 2.20 | -0.665 | 0.043 | -2.70 | 10788.4 | 2505.6 | -458.41 | 11554.4 | -2.71 | 2312.0 | 875.4 | -60.24 | 0.0 |
| 2.30 | -0.555 | -0.004 | -2.26 | 10246.7 | 2127.6 | -389.10 | 10597.6 | -2.26 | 3181.5 | 1031.7 | -85.66 | 1323.7 |
| 2.40 | -0.508 | 0.000 | -1.72 | 9607.5 | 1642.8 | -299.48 | 10096.3 | -1.72 | 3128.9 | 818.1 | -72.12 | 1126.7 |
| 2.50 | -0.424 | 0.004 | -1.33 | 9087.0 | 1266.4 | -226.57 | 9443.0 | -1.33 | 3685.5 | 735.7 | -73.69 | 1824.0 |
| 2.60 | -0.341 | -0.004 | -0.85 | 8829.7 | 819.8 | -149.06 | 9128.9 | -0.85 | 4491.0 | 561.1 | -66.79 | 2651.2 |
| 2.70 | -0.278 | 0.002 | -0.53 | 8108.8 | 491.6 | -83.87 | 8465.4 | -0.53 | 4567.4 | 352.2 | -42.32 | 2734.3 |
| 2.80 | -0.245 | 0.002 | -0.32 | 8037.9 | 301.5 | -51.16 | 8432.9 | -0.33 | 4913.7 | 229.8 | -28.70 | 3014.6 |
| 2.90 | -0.269 | -0.003 | -0.30 | 8304.4 | 279.5 | -48.46 | 8851.5 | -0.30 | 4882.3 | 209.3 | -26.06 | 2812.4 |
| 3.00 | -0.320 | 0.002 | -0.46 | 8384.5 | 434.1 | -75.92 | 9085.9 | -0.46 | 4304.4 | 295.8 | -34.36 | 2126.7 |
| 3.10 | -0.385 | 0.0 | -0.69 | 8981.2 | 672.7 | -124.09 | 9777.0 | -0.70 | 4081.0 | 431.2 | -48.50 | 1767.5 |
| 3.20 | -0.458 | -0.002 | -0.99 | 9446.5 | 967.3 | -186.78 | 10352.9 | -1.00 | 3610.3 | 562.7 | -58.33 | 1185.2 |
| 3.30 | -0.505 | 0.003 | -1.30 | 9591.0 | 1256.9 | -236.64 | 10521.9 | -1.31 | 3157.0 | 645.4 | -59.39 | 731.5 |
| 3.40 | -0.536 | -0.001 | -1.51 | 9972.6 | 1461.3 | -279.38 | 10863.3 | -1.52 | 3138.3 | 732.2 | -66.06 | 713.4 |
| 3.50 | -0.563 | -0.001 | -1.68 | 10061.9 | 1617.8 | -307.99 | 10976.9 | -1.69 | 2889.3 | 746.6 | -64.82 | 455.1 |
| 3.60 | -0.559 | 0.002 | -1.77 | 9974.5 | 1702.5 | -319.75 | 10795.5 | -1.78 | 2855.1 | 776.7 | -66.60 | 524.2 |
| 3.70 | -0.548 | -0.001 | -1.73 | 10049.5 | 1667.3 | -315.98 | 10796.1 | -1.74 | 3061.8 | 807.8 | -71.09 | 778.4 |
| 3.80 | -0.532 | 0.000 | -1.65 | 9835.0 | 1589.3 | -297.05 | 10567.5 | -1.66 | 3053.7 | 773.9 | -68.28 | 808.9 |
| 3.90 | -0.494 | 0.001 | -1.51 | 9605.6 | 1452.2 | -268.58 | 10228.4 | -1.52 | 3306.1 | 767.0 | -69.92 | 1170.0 |
| 4.00 | -0.459 | -0.002 | -1.31 | 9468.7 | 1264.1 | -235.01 | 10042.2 | -1.32 | 3617.8 | 720.9 | -71.35 | 1517.8 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 10
*********

| | | | LEFT SIDE | | | | | RIGHT SIDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) | SLIP ANGLE (DEG) | VERTICAL LOAD (LB.) | LATERAL FORCE (LB.) | ALIGNING TORQUE (FT.LB) | SPRING FORCE (LB.) |
| 0.0 | 0.0 | 0.0 | 0.0 | 6475.1 | 0.0 | 0.0 | 5725.0 | 0.0 | 6475.1 | 0.0 | 0.0 | 5725.0 |
| 0.10 | -0.000 | -0.000 | 0.00 | 6476.5 | -0.1 | 0.01 | 5726.8 | 0.00 | 6476.3 | -0.1 | 0.01 | 5726.1 |
| 0.20 | -0.000 | -0.000 | 0.00 | 6477.2 | -0.1 | 0.02 | 5728.6 | 0.00 | 6475.2 | -0.1 | 0.02 | 5724.0 |
| 0.30 | -0.000 | -0.000 | -0.00 | 6477.3 | 0.5 | -0.07 | 5728.7 | -0.00 | 6472.6 | 0.5 | -0.07 | 5721.4 |
| 0.40 | 0.000 | -0.000 | -0.00 | 6476.0 | 1.8 | -0.27 | 5722.5 | -0.00 | 6476.5 | 1.8 | -0.27 | 5730.2 |
| 0.50 | 0.002 | -0.000 | -0.00 | 6464.4 | 2.0 | -0.29 | 5699.5 | -0.00 | 6488.0 | 2.0 | -0.29 | 5752.8 |
| 0.60 | 0.005 | -0.000 | 0.00 | 6443.8 | -2.1 | 0.30 | 5666.9 | 0.00 | 6506.6 | -2.1 | 0.31 | 5783.8 |
| 0.70 | 0.008 | -0.000 | 0.01 | 6428.4 | -11.9 | 1.74 | 5651.5 | 0.01 | 6524.5 | -12.0 | 1.77 | 5801.2 |
| 0.80 | 0.006 | -0.000 | 0.03 | 6438.7 | -25.2 | 3.71 | 5694.3 | 0.03 | 6513.5 | -25.3 | 3.76 | 5757.7 |
| 0.90 | -0.006 | -0.000 | 0.04 | 6512.9 | -33.3 | 4.93 | 5855.2 | 0.04 | 6437.7 | -33.1 | 4.87 | 5595.2 |
| 1.00 | -0.034 | -0.000 | 0.02 | 6695.3 | -19.4 | 2.94 | 6193.5 | 0.02 | 6257.0 | -18.9 | 2.72 | 5258.4 |
| 1.10 | -0.085 | -0.000 | -0.04 | 7016.1 | 38.8 | -6.04 | 6741.0 | -0.04 | 5934.6 | 35.9 | -4.99 | 4709.5 |
| 1.20 | -0.160 | -0.000 | -0.18 | 7495.0 | 165.4 | -26.89 | 7507.1 | -0.19 | 5454.1 | 141.7 | -18.63 | 3941.3 |
| 1.30 | -0.258 | 0.0 | -0.41 | 8118.1 | 385.3 | -65.78 | 8450.7 | -0.41 | 4833.1 | 289.5 | -35.86 | 2997.1 |
| 1.40 | -0.370 | 0.000 | -0.73 | 8833.6 | 700.5 | -127.50 | 9489.2 | -0.73 | 4119.4 | 454.4 | -51.41 | 1956.1 |
| 1.50 | -0.482 | 0.000 | -1.12 | 9548.3 | 1094.6 | -209.54 | 10471.7 | -1.14 | 3408.9 | 606.2 | -58.86 | 970.7 |
| 1.60 | -0.575 | 0.000 | -1.57 | 10146.7 | 1521.1 | -293.90 | 11258.0 | -1.59 | 2816.1 | 689.1 | -59.95 | 181.8 |
| 1.70 | -0.621 | 0.018 | -1.98 | 10562.2 | 1920.5 | -375.26 | 11623.6 | -2.00 | 2649.1 | 805.9 | -67.00 | 0.0 |
| 1.80 | -0.651 | 0.070 | -2.32 | 10724.0 | 2198.4 | -417.48 | 11652.3 | -2.34 | 2435.9 | 830.2 | -62.42 | 0.0 |
| 1.90 | -0.655 | 0.148 | -2.64 | 10623.9 | 2450.3 | -443.31 | 11384.3 | -2.67 | 2281.9 | 857.2 | -58.87 | 0.0 |
| 2.00 | -0.662 | 0.186 | -2.89 | 10635.2 | 2649.0 | -467.97 | 11283.2 | -2.91 | 2199.7 | 883.4 | -57.15 | 0.0 |
| 2.10 | -0.673 | 0.146 | -2.97 | 10743.2 | 2718.6 | -482.31 | 11375.3 | -2.99 | 2168.7 | 887.3 | -56.47 | 0.0 |
| 2.20 | -0.663 | 0.050 | -2.80 | 10689.8 | 2582.2 | -462.74 | 11393.7 | -2.81 | 2237.7 | 873.6 | -58.07 | 0.0 |
| 2.30 | -0.557 | -0.006 | -2.28 | 10369.5 | 2155.8 | -396.92 | 10674.8 | -2.29 | 3277.7 | 1068.2 | -89.12 | 1433.9 |
| 2.40 | -0.507 | -0.000 | -1.69 | 9586.3 | 1611.0 | -293.74 | 10111.9 | -1.69 | 3125.5 | 802.7 | -70.91 | 1091.4 |
| 2.50 | -0.421 | 0.006 | -1.27 | 8990.0 | 1214.5 | -216.39 | 9405.3 | -1.27 | 3623.1 | 699.9 | -69.73 | 1717.0 |
| 2.60 | -0.339 | -0.006 | -0.81 | 8910.5 | 783.5 | -143.49 | 9228.1 | -0.81 | 4591.8 | 543.6 | -65.51 | 2718.2 |
| 2.70 | -0.279 | 0.001 | -0.54 | 8099.3 | 500.0 | -85.22 | 8441.7 | -0.54 | 4549.4 | 357.4 | -42.84 | 2734.0 |
| 2.80 | -0.249 | 0.004 | -0.41 | 8000.9 | 376.7 | -63.74 | 8315.7 | -0.41 | 4823.6 | 283.8 | -35.11 | 3014.2 |
| 2.90 | -0.277 | -0.005 | -0.45 | 8430.4 | 431.6 | -75.72 | 8807.7 | -0.46 | 4900.6 | 322.5 | -40.22 | 2987.0 |
| 3.00 | -0.331 | 0.002 | -0.68 | 8443.4 | 645.5 | -113.51 | 8938.5 | -0.69 | 4221.8 | 432.7 | -49.68 | 2251.3 |
| 3.10 | -0.397 | 0.002 | -0.96 | 9012.7 | 931.0 | -172.29 | 9572.2 | -0.97 | 3948.4 | 582.4 | -64.14 | 1876.6 |
| 3.20 | -0.471 | -0.003 | -1.27 | 9590.1 | 1232.8 | -232.72 | 10257.0 | -1.29 | 3589.1 | 701.9 | -69.34 | 1389.7 |
| 3.30 | -0.517 | 0.002 | -1.59 | 9657.6 | 1518.6 | -280.70 | 10379.3 | -1.60 | 3073.9 | 752.6 | -66.73 | 856.3 |
| 3.40 | -0.547 | 0.000 | -1.78 | 9995.3 | 1708.9 | -321.43 | 10698.9 | -1.79 | 3027.0 | 822.3 | -71.78 | 793.1 |
| 3.50 | -0.573 | -0.002 | -1.91 | 10175.7 | 1842.4 | -349.29 | 10907.8 | -1.93 | 2876.3 | 839.0 | -71.60 | 613.1 |
| 3.60 | -0.567 | 0.002 | -1.97 | 10016.2 | 1888.5 | -352.17 | 10700.5 | -1.98 | 2795.3 | 840.7 | -70.65 | 600.2 |
| 3.70 | -0.555 | -0.000 | -1.89 | 10046.0 | 1816.3 | -340.94 | 10688.3 | -1.90 | 2980.7 | 855.9 | -73.85 | 806.2 |
| 3.80 | -0.538 | -0.000 | -1.78 | 9911.3 | 1707.3 | -318.74 | 10544.8 | -1.79 | 3060.9 | 828.5 | -72.50 | 905.7 |
| 3.90 | -0.498 | 0.001 | -1.61 | 9620.4 | 1540.4 | -283.25 | 10176.9 | -1.62 | 3269.5 | 802.9 | -72.33 | 1200.3 |
| 4.00 | -0.462 | -0.000 | -1.39 | 9449.4 | 1336.7 | -246.15 | 9968.4 | -1.40 | 3557.3 | 751.5 | -72.79 | 1516.6 |

11 AXLE DOUBLE (MICH TANKER)

AXLE # 11

*********

| TIME (SEC) | ROLL (DEG) | BOUNCE (IN) | LEFT SIDE SLIP ANGLE (DEG) | LEFT SIDE VERTICAL LOAD (LB.) | LEFT SIDE LATERAL FORCE (LB.) | LEFT SIDE ALIGNING TORQUE (FT.LB) | LEFT SIDE SPRING FORCE (LB.) | RIGHT SIDE SLIP ANGLE (DEG) | RIGHT SIDE VERTICAL LOAD (LB.) | RIGHT SIDE LATERAL FORCE (LB.) | RIGHT SIDE ALIGNING TORQUE (FT.LB) | RIGHT SIDE SPRING FORCE (LB.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 | 6475.1 | 0.0 | 0.0 | 5725.0 | 0.0 | 6475.1 | 0.0 | 0.0 | 5725.0 |
| 0.10 | -0.000 | -0.000 | 0.00 | 6477.6 | -0.0 | 0.01 | 5727.8 | 0.00 | 6477.4 | -0.0 | 0.01 | 5727.1 |
| 0.20 | -0.000 | -0.000 | 0.00 | 6478.4 | -0.0 | 0.00 | 5729.6 | 0.00 | 6476.3 | -0.0 | 0.00 | 5725.3 |
| 0.30 | -0.000 | -0.000 | -0.00 | 6477.5 | 0.7 | -0.10 | 5728.6 | -0.00 | 6472.6 | 0.7 | -0.10 | 5721.6 |
| 0.40 | 0.000 | -0.000 | -0.00 | 6477.2 | 1.7 | -0.24 | 5723.8 | -0.00 | 6477.8 | 1.7 | -0.24 | 5730.8 |
| 0.50 | 0.002 | -0.000 | -0.00 | 6464.7 | 0.5 | -0.08 | 5701.9 | -0.00 | 6489.4 | 0.5 | -0.08 | 5752.3 |
| 0.60 | 0.005 | -0.000 | 0.01 | 6442.5 | -5.5 | 0.81 | 5669.9 | 0.01 | 6508.1 | -5.5 | 0.82 | 5780.9 |
| 0.70 | 0.008 | -0.000 | 0.02 | 6427.6 | -16.6 | 2.45 | 5656.1 | 0.02 | 6527.6 | -16.8 | 2.49 | 5798.7 |
| 0.80 | 0.006 | -0.000 | 0.03 | 6438.6 | -27.8 | 4.08 | 5696.1 | 0.03 | 6515.6 | -27.9 | 4.14 | 5757.9 |
| 0.90 | -0.006 | -0.000 | 0.03 | 6516.1 | -26.0 | 3.86 | 5847.5 | 0.03 | 6435.4 | -25.9 | 3.81 | 5604.1 |
| 1.00 | -0.036 | -0.000 | -0.01 | 6707.9 | 9.4 | -1.43 | 6168.4 | -0.01 | 6247.2 | 9.1 | -1.31 | 5286.4 |
| 1.10 | -0.089 | -0.000 | -0.12 | 7042.5 | 104.3 | -16.29 | 6687.5 | -0.12 | 5911.1 | 96.3 | -13.33 | 4765.5 |
| 1.20 | -0.167 | -0.000 | -0.32 | 7540.1 | 284.2 | -46.37 | 7417.0 | -0.32 | 5412.1 | 241.5 | -31.62 | 4033.7 |
| 1.30 | -0.268 | -0.000 | -0.61 | 8185.9 | 572.0 | -98.13 | 8323.4 | -0.61 | 4772.3 | 423.9 | -52.15 | 3129.8 |
| 1.40 | -0.383 | -0.000 | -0.99 | 8922.1 | 958.7 | -175.84 | 9328.6 | -1.00 | 4041.1 | 611.2 | -68.32 | 2123.6 |
| 1.50 | -0.496 | -0.000 | -1.45 | 9644.2 | 1393.2 | -259.98 | 10306.5 | -1.46 | 3327.8 | 745.6 | -68.51 | 1146.5 |
| 1.60 | -0.590 | -0.000 | -1.94 | 10252.2 | 1868.5 | -356.09 | 11085.7 | -1.96 | 2730.9 | 813.2 | -68.17 | 368.4 |
| 1.70 | -0.646 | 0.012 | -2.40 | 10659.7 | 2263.2 | -422.32 | 11535.4 | -2.43 | 2432.9 | 850.4 | -62.75 | 0.0 |
| 1.80 | -0.653 | 0.075 | -2.71 | 10648.8 | 2509.0 | -451.64 | 11382.5 | -2.74 | 2324.9 | 889.0 | -60.75 | 0.0 |
| 1.90 | -0.649 | 0.164 | -2.99 | 10303.5 | 2701.9 | -458.02 | 10838.8 | -3.02 | 2036.4 | 846.1 | -51.71 | 0.0 |
| 2.00 | -0.646 | 0.210 | -3.18 | 10188.9 | 2842.6 | -469.13 | 10624.4 | -3.21 | 1959.4 | 851.0 | -50.41 | 0.0 |
| 2.10 | -0.657 | 0.166 | -3.16 | 10413.2 | 2849.5 | -480.21 | 10896.7 | -3.18 | 2037.1 | 879.1 | -52.31 | 0.0 |
| 2.20 | -0.661 | 0.058 | -2.90 | 10588.0 | 2654.4 | -466.12 | 11231.8 | -2.91 | 2172.2 | 872.5 | -56.10 | 0.0 |
| 2.30 | -0.559 | -0.008 | -2.31 | 10493.9 | 2184.7 | -404.94 | 10760.9 | -2.31 | 3372.9 | 1104.9 | -92.58 | 1552.6 |
| 2.40 | -0.506 | -0.001 | -1.66 | 9565.3 | 1579.2 | -288.04 | 10127.6 | -1.65 | 3122.7 | 787.5 | -69.72 | 1056.7 |
| 2.50 | -0.418 | 0.009 | -1.22 | 8892.7 | 1161.0 | -206.38 | 9367.5 | -1.22 | 3561.0 | 664.9 | -65.89 | 1609.9 |
| 2.60 | -0.337 | -0.008 | -0.77 | 8990.6 | 746.2 | -137.78 | 9327.4 | -0.77 | 4692.3 | 525.2 | -64.04 | 2784.1 |
| 2.70 | -0.279 | 0.001 | -0.54 | 8089.9 | 508.3 | -86.58 | 8418.5 | -0.54 | 4531.6 | 362.5 | -43.36 | 2734.0 |
| 2.80 | -0.253 | 0.005 | -0.49 | 7963.6 | 451.5 | -76.19 | 8199.8 | -0.49 | 4733.8 | 336.2 | -41.19 | 3012.9 |
| 2.90 | -0.286 | -0.006 | -0.61 | 8556.9 | 585.4 | -103.86 | 8762.8 | -0.62 | 4918.3 | 436.2 | -54.51 | 3161.8 |
| 3.00 | -0.342 | 0.002 | -0.90 | 8502.6 | 858.0 | -151.71 | 8793.1 | -0.91 | 4139.9 | 565.6 | -64.18 | 2374.4 |
| 3.10 | -0.409 | 0.003 | -1.23 | 9036.9 | 1173.3 | -211.12 | 9384.2 | -1.24 | 3823.1 | 709.4 | -73.69 | 1969.1 |
| 3.20 | -0.484 | -0.004 | -1.56 | 9732.6 | 1499.1 | -279.49 | 10159.1 | -1.57 | 3569.1 | 839.6 | -80.10 | 1595.4 |
| 3.30 | -0.528 | 0.002 | -1.87 | 9723.5 | 1781.4 | -325.43 | 10238.7 | -1.89 | 2991.8 | 854.0 | -73.50 | 979.0 |
| 3.40 | -0.557 | 0.002 | -2.05 | 10014.7 | 1950.1 | -360.52 | 10543.5 | -2.06 | 2919.5 | 898.6 | -75.47 | 864.1 |
| 3.50 | -0.582 | -0.002 | -2.15 | 10281.5 | 2045.7 | -380.88 | 10853.4 | -2.17 | 2870.6 | 913.4 | -74.92 | 755.6 |
| 3.60 | -0.573 | 0.002 | -2.17 | 10048.0 | 2048.6 | -372.82 | 10622.7 | -2.18 | 2745.3 | 883.5 | -70.87 | 659.1 |
| 3.70 | -0.560 | 0.001 | -2.05 | 10038.0 | 1956.7 | -362.08 | 10585.8 | -2.06 | 2904.2 | 894.4 | -75.01 | 829.1 |
| 3.80 | -0.543 | -0.001 | -1.90 | 9987.4 | 1825.7 | -340.76 | 10521.4 | -1.91 | 3067.8 | 883.3 | -76.75 | 1002.7 |
| 3.90 | -0.502 | 0.001 | -1.71 | 9635.4 | 1628.7 | -297.98 | 10125.8 | -1.71 | 3233.5 | 838.1 | -74.67 | 1230.4 |
| 4.00 | -0.466 | 0.001 | -1.47 | 9429.8 | 1409.2 | -257.23 | 9895.1 | -1.48 | 3496.9 | 781.0 | -74.07 | 1515.0 |

APPENDIX C

# DERIVATION OF THE EQUATIONS OF MOTION FOR THE DYNAMIC MODEL OF MULTIPLE-ARTICULATED VEHICLES (YAW/ROLL MODEL)

The equations of motion are derived by the application of the Newton's laws of motion. The derivation is organized under the following sub-headings:

1) Axis Systems
2) Equations of Motion for the Sprung and Unsprung Masses
3) Suspension Forces
4) Constraint Forces and Moments
5) Tire Forces

A brief outline of the computer code is presented at the end of the appendix.

## C.1. Axis Systems

Three types of axis systems are used in the process of developing the equations of motion. They are: (1) an inertial axis system fixed in space, (2) an axis system fixed to each of the sprung masses, and (3) an axis system fixed to each of the unsprung masses. For example, Figure B.1 shows the axis systems for a four-axle, multiple-articulated vehicle with two articulation points, $C_1$ and $C_2$, respectively.

Euler angles are used to define the orientation of the sprung and unsprung masses with respect to the inertial axis system. Since all sprung mass axis systems are defined alike, the axis transformation equations are given below for only one sprung mass. For the same reason, the transformation equations for the unsprung mass axis systems are derived for a single unsprung mass.

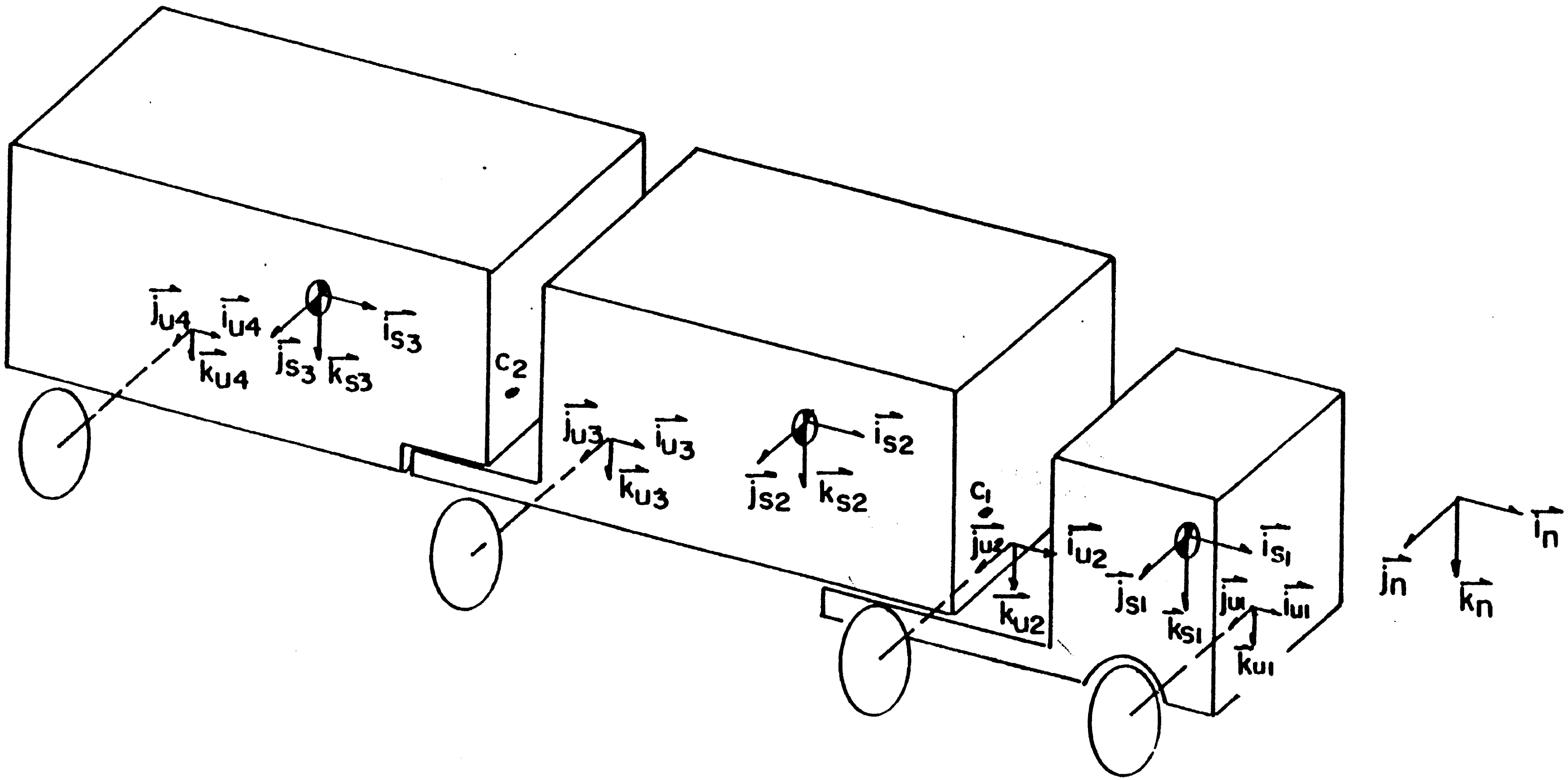



Figure C.1. Axis systems for an articulated vehicle with three sprung masses and four unsprung masses.

C.1.1 <u>Sprung Mass Axis System</u>. The three Euler angles of yaw ($\psi_s$), pitch ($\theta_s$), and roll ($\phi_s$) which are needed to describe the orientation of each of the sprung mass axis systems are shown in Figures C.2, C.3, and C.4, respectively.

The transformation equation between the inertial and sprung mass axis systems can be derived using the three sequential steps of rotation which are illustrated. For the yaw rotation, $\psi_s$

$$\begin{Bmatrix} \vec{i}_n \\ \vec{j}_n \\ \vec{k}_n \end{Bmatrix} = \begin{bmatrix} \cos\psi_s & -\sin\psi_s & 0 \\ \sin\psi_s & \cos\psi_s & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \vec{i}_1 \\ \vec{j}_1 \\ \vec{k}_1 \end{Bmatrix} \tag{1}$$

or

$$\{\vec{i}_n, \vec{j}_n, \vec{k}_n\}^T = [a_{ij}] \{\vec{i}_1, \vec{j}_1, \vec{k}_1\}^T \tag{2}$$

For the rotation, $\theta_s$, illustrated in Figure C.3,

$$\begin{Bmatrix} \vec{i}_1 \\ \vec{j}_1 \\ \vec{k}_1 \end{Bmatrix} = \begin{bmatrix} \cos\theta_s & 0 & \sin\theta_s \\ 0 & 1 & 0 \\ -\sin\theta_s & 0 & \cos\theta_s \end{bmatrix} \begin{Bmatrix} \vec{i}_2 \\ \vec{j}_2 \\ \vec{k}_2 \end{Bmatrix} \tag{3}$$

or

$$\{\vec{i}_1, \vec{j}_1, \vec{k}_1\}^T = [b_{ij}] \{\vec{i}_2, \vec{j}_2, \vec{k}_2\}^T \tag{4}$$

Proceeding along similar lines, the roll rotation illustrated in Figure C.4 yields

$$\begin{Bmatrix} \vec{i}_2 \\ \vec{j}_2 \\ \vec{k}_2 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_s & -\sin\phi_s \\ 0 & \sin\phi_s & \cos\phi_s \end{bmatrix} \begin{Bmatrix} \vec{i}_s \\ \vec{j}_s \\ \vec{k}_s \end{Bmatrix} \tag{5}$$

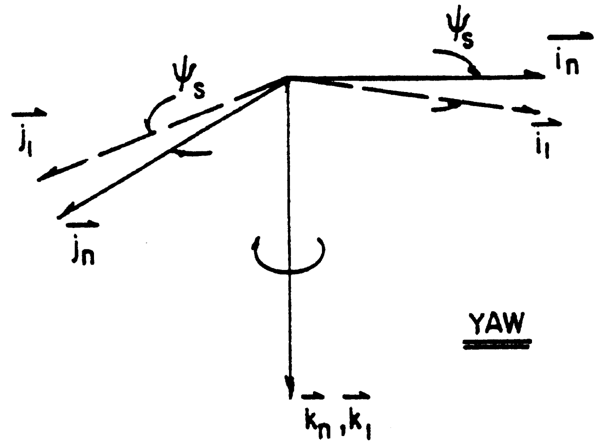



Figure C.2

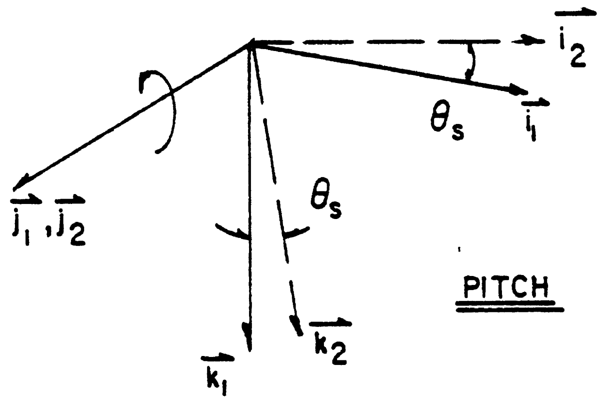



Figure C.3

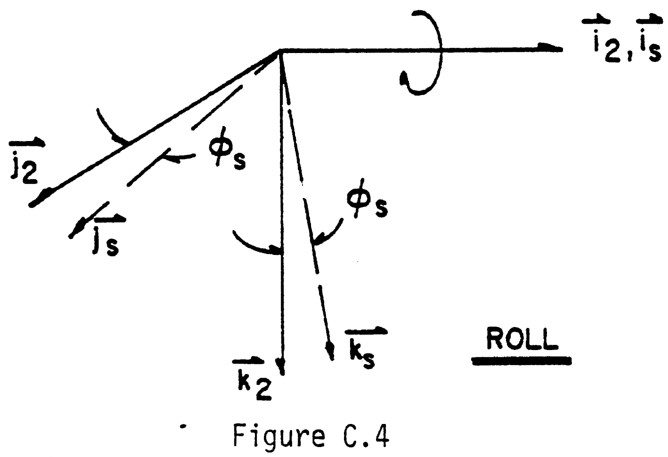



Figure C.4

Euler angles needed to define the orientation of each of the sprung mass axis systems.

or

$$\{\vec{i}_2,\vec{j}_2,\vec{k}_2\}^T = [c_{ij}]\{\vec{i}_s,\vec{j}_s,\vec{k}_s\}^T \tag{6}$$

The transformation matrix which is needed to relate the sprung mass axis system and the inertial axis system can now be obtained by combining (2), (4), and (6). Doing so, we get

$$\{\vec{i}_n,\vec{j}_n,\vec{k}_n\}^T = [A_{ij}]\{\vec{i}_s,\vec{j}_s,\vec{k}_s\}^T \tag{7}$$

where $[A_{ij}] = [a_{ij}]\,[b_{ij}]\,[c_{ij}]$

During directional maneuvers, the pitch angles of sprung masses are usually restricted to very small values, hence the transformation equations can be simplified by replacing sin $\theta_s$ by $\theta_s$ and cos $\theta_s$ by 1.0. Expanding Equation (7) and applying the small pitch angle assumption, we get:

$$\begin{Bmatrix}\vec{i}_n\\ \vec{j}_n\\ \vec{k}_n\end{Bmatrix} = \begin{bmatrix}\cos\psi_s & -\sin\psi_s\cos\phi_s+\cos\psi_s\theta_s\sin\phi_s & \sin\psi_s\sin\phi_s+\cos\psi_s\theta_s\cos\phi_s\\ \sin\psi_s & \cos\psi_s\cos\phi_s+\sin\psi_s\theta_s\sin\phi_s & -\cos\psi_s\sin\phi_s+\sin\psi_s\theta_s\cos\phi_s\\ -\theta_s & \sin\phi_s & \cos\phi_s\end{bmatrix}\begin{Bmatrix}\vec{i}_s\\ \vec{j}_s\\ \vec{k}_s\end{Bmatrix} \tag{8}$$

Also

$$\begin{Bmatrix} \vec{i}_s \\ \vec{j}_s \\ \vec{k}_s \end{Bmatrix} =$$

$$\begin{bmatrix} \cos\psi_s & \sin\psi_s & -\theta_s \\ -\sin\psi_s\cos\phi_s+\cos\psi_s\theta_s\sin\phi_s & \cos\psi_s\cos\phi_s+\sin\psi_s\theta_s\sin\phi_s & \sin\phi_s \\ \sin\psi_s\sin\phi_s+\cos\psi_s\theta_s\cos\phi_s & -\cos\psi_s\sin\phi_s+\sin\psi_s\theta_s\cos\phi_s & \cos\phi_s \end{bmatrix} \begin{Bmatrix} \vec{i}_n \\ \vec{j}_n \\ \vec{k}_n \end{Bmatrix} \tag{9}$$

Sprung Mass Angular Velocities:

The equations of motion of each sprung mass are written in terms of the body-fixed angular velocities $(p_s, q_s, r_s)$ and their derivatives. In order to determine the Euler angles, the Euler angular velocities $(\dot{\phi}_s, \dot{\theta}_s, \dot{\psi}_s)$ have to be calculated from the body-fixed angular velocities $(p_s, q_s, r_s)$ and then integrated numerically. The Euler angular velocities $(\dot{\phi}_s, \dot{\theta}_s, \dot{\psi}_s)$ are defined along the $(\vec{i}_s, \vec{j}_2, \vec{k}_n)$ directions. Therefore, equating the body-fixed and Euler angular velocities, we get

$$p_s\vec{i}_s + q_s\vec{j}_s + r_s\vec{k}_s = \dot{\phi}_s\vec{i}_s + \dot{\theta}_s\vec{j}_2 + \dot{\psi}_s\vec{k}_n \tag{10}$$

From Equation (5) we note that

$$\vec{j}_2 = \cos\phi_s\vec{j}_s - \sin\phi_s\vec{k}_s \tag{11}$$

Also, Equation (8) indicates that

$$\vec{k}_n = -\theta_s\vec{i}_s + \sin\phi_s\vec{j}_s + \cos\phi_s\vec{k}_s \tag{12}$$

Substituting Equations (11) and (12) back into (10) we get

$$p_s\vec{i}_s = (\dot{\phi}_s - \theta_s\dot{\psi}_s)\vec{i}_s \tag{13}$$

$$q_s\vec{j}_s = (\dot{\theta}_s \cos \phi_s + \sin \phi_s\dot{\psi}_s)\vec{j}_s \tag{14}$$

$$r_s\vec{k}_s = (-\dot{\theta}_s \sin \phi_s + \dot{\psi}_s \cos \phi_s)\vec{k}_s \tag{15}$$

The above three equations can also be written for solving the Euler angular velocities in terms of the body-fixed angular velocities $(p_s,q_s,r_s)$. In doing so, we get:

$$\dot{\phi}_s = p_s + (q_s \sin \phi_s + r_s \cos \phi_s)\theta_s \tag{16}$$

$$\dot{\theta}_s = q_s \cos \phi_s - r_s \sin \phi_s \tag{17}$$

$$\dot{\psi}_s = q_s \sin \phi_s + r_s \cos \phi_s \tag{18}$$

Therefore, Equations (16)-(18) can be numerically integrated to obtain the Euler angles at any time t of the simulation.

C.1.2 Unsprung Mass Axis System. Each unsprung mass is permitted only to roll and bounce with respect to the sprung mass to which it is attached. The orientation of the unsprung mass with respect to the inertial axis system is therefore defined by the yaw angle, $\psi_s$, and the roll angle, $\phi_u$, which are shown in Figures C.5 and C.6, respectively.

Figure C.6 indicates that

$$\begin{Bmatrix} \vec{i}_u \\ \vec{j}_u \\ \vec{k}_u \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi_u & \sin \phi_u \\ 0 & -\sin \phi_u & \cos \phi_u \end{bmatrix} \begin{Bmatrix} \vec{i}_1 \\ \vec{j}_1 \\ \vec{k}_1 \end{Bmatrix} \tag{19}$$

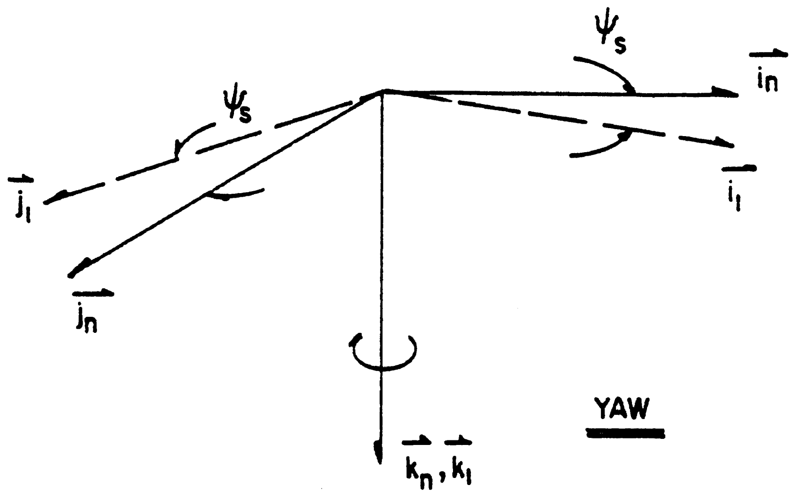



Figure C.5

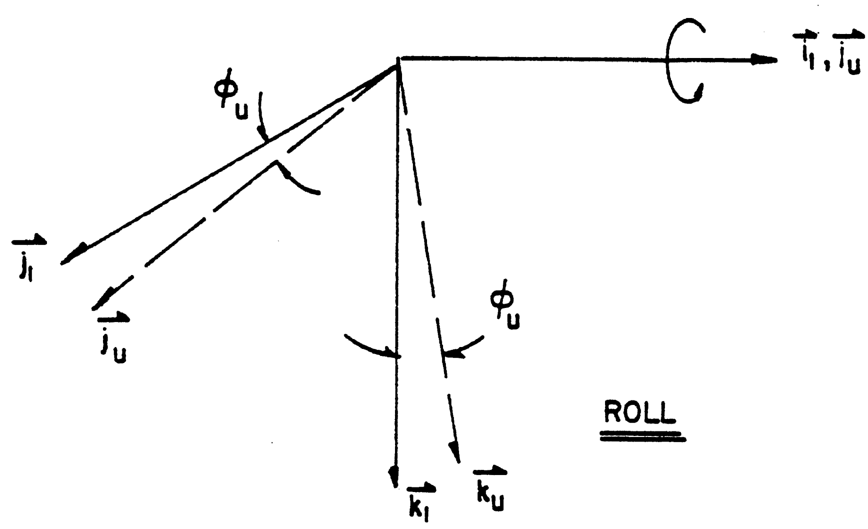



Figure C.6

Euler angles needed to define the orientation of each of the unsprung masses.

When Equations (3) and (5) are combined, we have

$$\begin{Bmatrix} \vec{i}_1 \\ \vec{j}_1 \\ \vec{k}_1 \end{Bmatrix} = [b_{ij}]\,[c_{ij}] \begin{Bmatrix} \vec{i}_s \\ \vec{j}_s \\ \vec{k}_s \end{Bmatrix} \tag{20}$$

Therefore, combining Equations (19) and (20) and substituting for $[b_{ij}]$ and $[c_{ij}]$, we get the transformation equation which relates the sprung and unsprung mass axis systems.

$$\begin{Bmatrix} \vec{i}_u \\ \vec{j}_u \\ \vec{k}_u \end{Bmatrix} = \begin{bmatrix} 1 & \theta_s \sin\phi_s & \theta_s \cos\phi_s \\ -\theta_s \sin\phi_u & \cos(\phi_s-\phi_u) & -\sin(\phi_s-\phi_u) \\ -\theta_s \cos\phi_u & \sin(\phi_s-\phi_u) & \cos(\phi_s-\phi_u) \end{bmatrix} \begin{Bmatrix} \vec{i}_s \\ \vec{j}_s \\ \vec{k}_s \end{Bmatrix} \tag{21}$$

## C.2. Equations of Motion

With each sprung mass assumed to possess five degrees of freedom and each unsprung mass assumed to possess two degrees of freedom, the number of differential equations required to describe the directional and roll behavior of a multiple-articulated vehicle is given by

$$k = 5n + 2m$$

where $n$ = number of sprung masses
$m$ = number of unsprung masses

C.2.1 Equations of Motion for the Sprung Masses. Application of Newton's laws of motion leads to five equations for each of the sprung masses possessed by the assumed vehicle system, viz.:

Lateral Force Equation:

$$m_s \dot{v}_s - m_s(p_s w_s - r_s u_s) = \Sigma\ \vec{j}_s \text{ component of constraint forces} + \Sigma\ \vec{j}_s \text{ component of the suspension forces} + m_s g \sin \phi_s \quad (22)$$

Vertical Force Equation:

$$m_s \dot{w}_s - m_s(q_s u_s - p_s v_s) = \Sigma\ \vec{k}_s \text{ component of constraint forces} + \Sigma\ \vec{k}_s \text{ component of the suspension forces} + m_s g \cos \phi_s \quad (23)$$

Rolling Moment Equation:

$$I_{xx_s} \dot{p}_s - (I_{yy_s} - I_{zz_s}) q_s r_s = \Sigma \text{ roll moments from the constraints} + \Sigma \text{ roll moments from the suspensions} \quad (24)$$

Pitching Moment Equation:

$$I_{yy_s} \dot{q}_s - (I_{zz_s} - I_{xx_s}) p_s r_s = \Sigma \text{ pitching moments from the constraints} + \Sigma \text{ pitching moments from the suspensions} \quad (25)$$

Yawing Moment Equation:

$$I_{zz} \dot{r}_s - (I_{xx_s} - I_{yy_s}) p_s q_s = \Sigma \text{ yawing moments from the constraints} + \Sigma \text{ yawing moments from the suspensions} \quad (26)$$

Note:

In the above equation, the "constraint forces" are the forces which arise at the points of connection between adjacent sprung masses. The "suspension forces" are defined as the forces acting between an axle and the sprung mass.

C.2.2 Equations of Motion for the Unsprung Masses. Two equations can be written for the roll and bounce degrees of freedom possessed by each of the unsprung masses:

$$I_{xx_{u_i}} \dot{p}_{u_i} = \text{roll moment produced by the suspension forces + roll moment produced by the tire forces} \quad (27)$$

$$m_{u_i} \vec{a}_{m_{u_i}} \cdot \vec{k}_{u_i} = \vec{k}_{u_i} \text{ component of suspension forces} + \vec{k}_{u_i} \text{ component of the tire forces} + m_{u_i} g \cos \phi_{u_i} \quad (28)$$

In order to evaluate the right-hand side of Equations (22) through (28), the forces produced by the suspension, hitching mechanisms and tires need to be determined. The manner in which these forces are treated is outlined in the following sections.

## C.3. Suspension Forces

Each suspension is assumed to consist of a pair of linear springs and linkages which establish a roll center, $R_i$. Figure C.7 is a schematic diagram showing that the suspension springs are assumed to remain parallel to the $\vec{k}_{u_i}$ axis of the unsprung mass, and are capable of transmitting either compressive or tensile forces only. All roll plane forces which are perpendicular to the suspension springs are assumed to act through the roll center, $R_i$. The roll center, $R_i$, is located at a fixed distance, $z_{R_i}$, beneath the sprung mass, and is permitted to slide along the $\vec{k}_{u_i}$ axis of the unsprung mass.

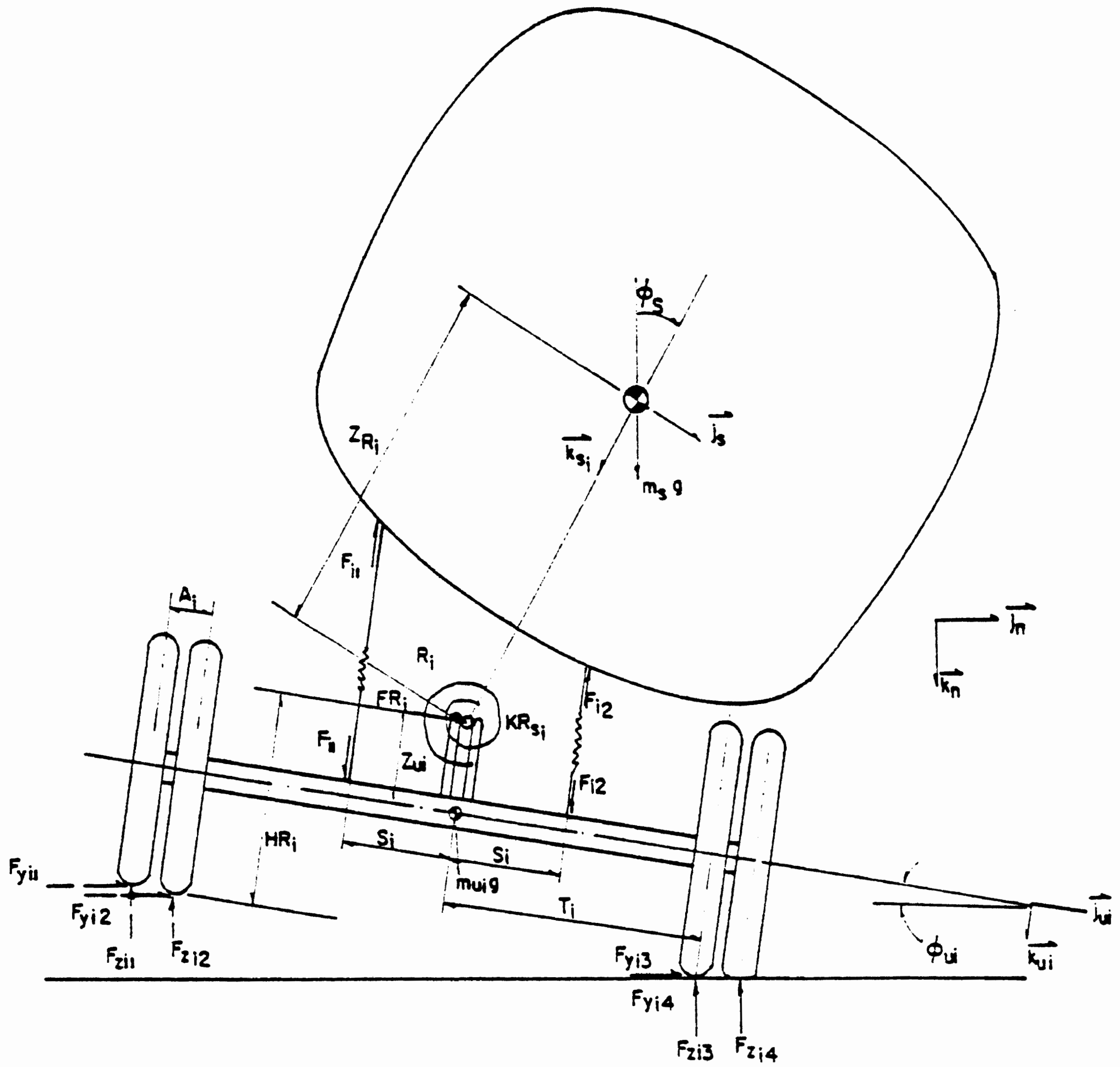



Figure C.7. Suspension and tire forces at each axle.

Figure C.7 shows that the suspension forces transmitted to the sprung mass from any given axle, i, are

$$F_{susp_i} = F_{R_i}\vec{j}_{u_i} - (F_{i1}+F_{i2})\vec{k}_{u_i} \tag{29}$$

The suspension forces can be defined in the sprung mass coordinate system by applying the coordinate transformation expressed by Equation (21). Upon applying the transformation, we get

$$\begin{aligned} F_{susp_i} = & [- F_{R_i}\theta_s \sin \phi_{u_i} + (F_{i1}+F_{i2})\theta_s \cos \phi_{u_i}]\vec{i}_s + [F_{R_i} \cos(\phi_s-\phi_{u_i}) \\ & - (F_{i1}+F_{i2})\sin(\phi_s-\phi_{u_i})]\vec{j}_s - [F_{R_i} \sin(\phi_s-\phi_{u_i}) \\ & + (F_{i1}+F_{i2})\cos(\phi_s-\phi_{u_i})]\vec{k}_s \end{aligned} \tag{30}$$

The compressive or tensile forces, $F_{ij}$, produced by the suspension springs are calculated using a suitable suspension spring model. On the other hand, the force, $F_{R_i}$, acting through the roll center, $R_i$, is an internal force which can be eliminated by inspecting the dynamic equilibrium of the axle in the $\vec{j}_{u_i}$ direction. Upon writing the equation for the lateral equilibrium of the axle, and rearranging, we get:

$$\begin{aligned} F_{R_i} = & - m_{u_i}[\vec{a}_{m_{u_i}} \cdot \vec{j}_{u_i}] + \sum_{j=1}^{4} F_{y_{ij}} \cos \phi_{u_i} \\ & - \sum_{j=1}^{4} F_{z_{ij}} \sin \phi_{u_i} + m_{u_i} g \sin \phi_{u_i} \end{aligned} \tag{31}$$

Of the terms in the right-hand side of (31), the only unknown is the acceleration, $\vec{a}_{m_{u_i}}$, of the unsprung mass. Since the acceleration of the unsprung mass can be defined relative to the sprung mass to which it is attached, it can be written as:

$$\vec{a}_{m_{u_i}} = \vec{a}_{m_s} + \vec{a}_{R_i/m_s} + \vec{a}_{m_{u_i}/R_i} \tag{32}$$

where $\vec{a}_{m_s}$ is the acceleration at the c.g. of the sprung mass

$\vec{a}_{R_i/m_s}$ is the relative acceleration at the roll center, $R_i$, with respect to the sprung mass c.g.

and $\vec{a}_{m_{u_i}/R_i}$ is the relative acceleration at the c.g. of the axle with respect to the roll center, $R_i$

We shall now derive expressions for each of the three terms in the right-hand side of (32).

The acceleration of the sprung mass along the body-fixed coordinates $(\vec{i}_s, \vec{j}_s, \vec{k}_s)$ is given by:

$$\vec{a}_{m_s} = (\dot{u}_s + q_s w_s - r_s v_s)\vec{i}_s + (\dot{v}_s + u_s r_s - p_s w_s)\vec{j}_s + (\dot{w}_s + p_s v_s - q_s u_s)\vec{k}_s \tag{33}$$

Since the roll center, $R_i$, is at a fixed distance from the sprung mass c.g., the acceleration of $R_i$ with respect to the sprung mass c.g. $(\vec{a}_{R_i/m_s})$ can be derived as follows:

$$\vec{r}_{R_i/m_s} = x_{R_i}\vec{i}_s + z_{R_i}\vec{k}_s \tag{34}$$

$$\vec{v}_{R_i/m_s} = \dot{\vec{r}}_{R_i/m_s} = (z_{R_i} q_s)\vec{i}_s + (-p_s z_{R_i} + x_{R_i} r_s)\vec{j}_s - x_{R_i} q_s \vec{k}_s \tag{35}$$

$$\vec{a}_{R_i/m_s} = \dot{\vec{v}}_{R_i/m_s} = [\dot{q}_s z_{R_i} - x_{R_i} q_s^2 + p_s r_s z_{R_i} - x_{R_i} r_s^2]\vec{i}_s + [-\dot{p}_s z_{R_i} + x_{R_i}\dot{r}_s + z_{R_i} q_s r_s + x_{R_i} q_s p_s]\vec{j}_s + [-p_s^2 z_{R_i} + x_{R_i} r_s p_s - z_{R_i} q_s^2 - x_{R_i}\dot{q}_s]\vec{k}_s \tag{36}$$

The third term in Equation (32), $\vec{a}_{m_{u_i}/R_i}$, can be derived along the same lines as $\vec{a}_{R_i/m_s}$, viz.:

$$\vec{r}_{m_{u_i}/R_i} = z_{u_i}\vec{k}_{u_i} \tag{37}$$

$$\vec{v}_{m_{u_i}/R_i} = \dot{\vec{r}}_{m_{u_i}/R_i} = \dot{z}_{u_i}\vec{k}_{u_i} - p_{u_i}z_{u_i}\vec{j}_{u_i} \tag{38}$$

$$\begin{aligned}\vec{a}_{m_{u_i}/R_i} = \dot{\vec{v}}_{m_{u_i}/R_i} &= \ddot{z}_{u_i}\vec{k}_{u_i} - (\dot{p}_{u_i}z_{u_i} + 2p_{u_i}\dot{z}_{u_i})\vec{j}_{u_i} \\ &- p^2_{u_i}z_{u_i}\vec{k}_{u_i} + p_{u_i}r_{u_i}z_{u_i}\vec{i}_{u_i}\end{aligned} \tag{39}$$

Hence, combining Equations (33), (36), and (39) and transforming the acceleration defined in the sprung mass coordinate system to the unsprung mass coordinate system, we get:

$$\begin{aligned}\vec{a}_{m_{u_i}} \cdot \vec{j}_{u_i} = &-(\dot{u}_s + q_s w_s - r_s v_s + \dot{q}_s z_{R_i} - x_{R_i} q_s^2 + p_s r_s z_{R_i} \\ &- x_{R_i} r_s^2)\theta_s \sin\phi_{u_i} + (\dot{v}_s + u_s r_s - p_s w_s - \dot{p}_s z_{R_i} \\ &+ x_{R_i}\dot{r}_s + z_{R_i} q_s r_s + x_{R_i} q_s p_s)\cos(\phi_s - \phi_u) \\ &- [\dot{w}_s + p_s v_s - q_s u_s - p_s^2 z_{R_i} + x_{R_i} r_s p_s \\ &- z_{R_i} q_s^2 - x_{R_i}\dot{q}_s]\sin(\phi_s - \phi_u) - \dot{p}_{u_i} z_{u_i} - 2p_{u_i}\dot{z}_{u_i}\end{aligned} \tag{40}$$

On substituting the right-hand side of (40) for the term $(\vec{a}_{m_{u_i}} \cdot \vec{j}_{u_i})$ in Equation (31), we get the following result for $F_{R_i}$:

$$
\begin{aligned}
F_{R_i} = -m_{u_i}\{&-[\dot{u}_s + q_s w_s - r_s v_s + \dot{q}_s z_{R_i} - x_{R_i} q_s^2 + p_s r_s z_{R_i} \\
&+ x_{R_i} r_s^2]\theta_s \sin\phi_{u_i} + (\dot{v}_s + u_s r_s - p_s w_s - \dot{p}_s z_{R_i} \\
&+ x_{R_i}\dot{r}_s + z_{R_i} q_s r_s + x_{R_i} q_s p_s]\cos(\phi_s - \phi_{u_i}) - (\dot{w}_s + p_s v_s \\
&- q_s u_s - p_s^2 z_{R_i} + x_{R_i} r_s p_s - z_{R_i} q_s^2 - x_{R_i}\dot{q}_s]\sin(\phi_s - \phi_{u_i}) \\
&- \dot{p}_{u_i} z_{u_i} - 2p_{u_i}\dot{z}_{u_i}\} + \sum_{j=1}^{4} F_{y_{ij}} \cos\phi_{u_i} - \sum_{j=1}^{4} F_{z_{ij}} \sin\phi_{u_i} \\
&+ m_{u_i} g \sin\phi_{u_i}
\end{aligned} \tag{41}
$$

## C.4. Constraint Equations

The differential equations which describe the motion of the sprung mass (Equations (22)-(26)) contain terms which are related to the forces and moments which arise at the points of connection between the various sprung masses. These forces and moments can be determined from the kinematic equations which define the constraints. Alternatively, the constraint forces and moments could be evaluated by considering the coupling mechanisms to be compliant such that the forces/moments transmitted through the coupling becomes a function of the relative displacement (linear and angular) between the lead and trailing elements of the coupling mechanism.

Examination of the geometric configuration of the coupling units used on heavy-duty trucks and the structures to which they are attached indicates that these coupling elements are relatively rigid with respect to translation but relatively compliant with respect to rotation. Accordingly, two different schemes were adopted to represent the constraint forces/moments that appear on the right-hand side of Equations (22) through (26). Specifically, the forces were determined from kinematic expressions which state, in effect, that the acceleration at a coupling point is the same for both the lead and the trailing units of the coupling. The moments, on the other hand, were calculated as a function of the angular displacement of the lead and trailing elements of a given coupling mechanism.

Four particular coupling mechanisms were of interest. These mechanisms are diagrammed in Figure C.8. Note that the fifth wheel and the inverted fifth wheel arrangement permit the lead and the trailing units to yaw and pitch with respect to one another, but are stiff in roll. The kingpin-type connection permits only yaw motions. In the case of the pintle hook connection, the trailing unit is permitted to roll, bounce, yaw, and pitch with respect to the lead unit, the only constraint being that which requires the lateral position of the lead coupler to be the same as the lateral position of the forward end of the drawbar.

Let us consider, first, the procedure by which the unknown constraint forces can be determined on the basis of the kinematic conditions which must be satisfied. If the set of k second-order differential equations of motion corresponding to n sprung masses and m unsprung masses are written in matrix notation (recall that $k = 5n + 2m$), we obtain:

$$M \ddot{\vec{x}} = \vec{y} + N \vec{f}_c \tag{42}$$

where

$M$ is the inertia matrix of size $k \times k$

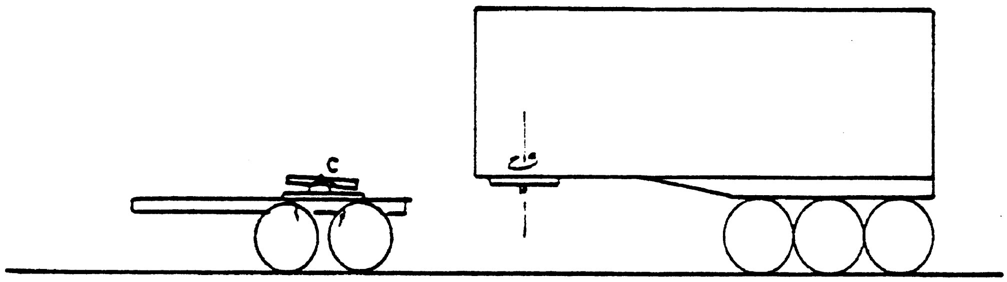
$\dot{\vec{x}}$ is a vector of the first derivative of the motion variables of size k:

$[(v_i, w_i, r_i, q_i, p_i)\ i=1,\ldots,n\ ,\ (p_{u_i}, z_{u_i})\ i=1,\ldots,m$

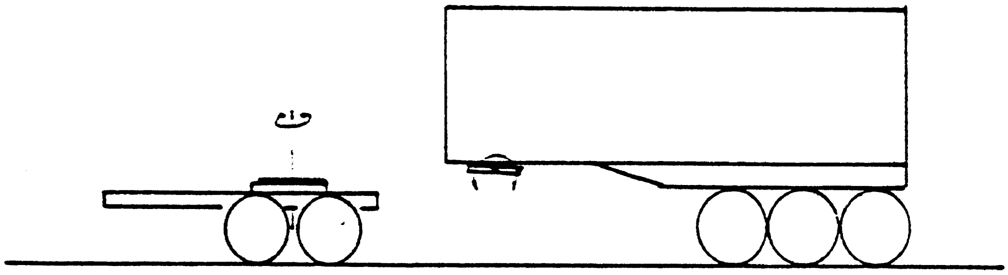
$\vec{y}$ is a vector of size k, which is a function of $\vec{x}$, $\dot{\vec{x}}$ and the dimension of the vehicle

$\vec{f}_c$ is a vector of j unknown constraint forces and moments

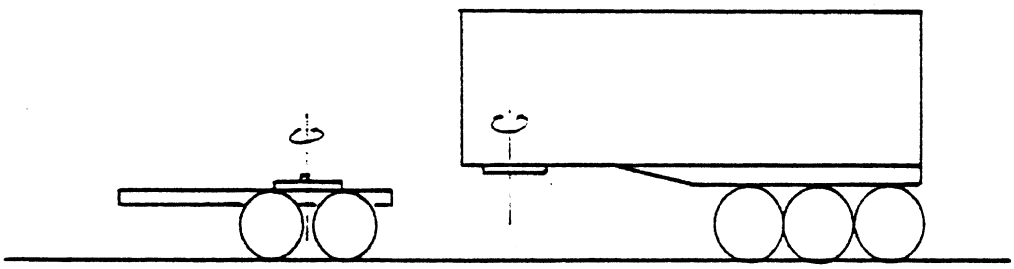
$N$ is a matrix of size $k \times k$ which is a function of vehicle dimensions and $\vec{x}$.



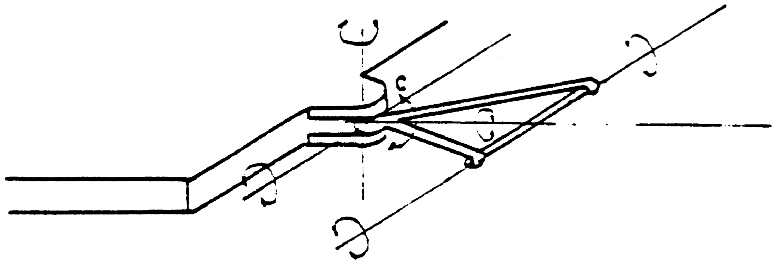
CONVENTIONAL FIFTH WHEEL



INVERTED FIFTH WHEEL



KINGPIN



PINTLE HOOK

Figure C.8. Schematic diagrams of four coupling mechanisms commonly used on commercial vehicles.

The kinematic constraints that exist at the various connecting points, when written as a set of acceleration constraint equations, are of the form:

$$C \ddot{\vec{x}} = \vec{d} \tag{43}$$

where

C is a matrix of size j×k, which is a function of the vehicle dimensions and $\vec{x}$

$\vec{d}$ is a vector of size j, which is a function of $\vec{x}$, $\dot{\vec{x}}$, and the dimensions of the vehicle.

If we solve Equation (42) for $\ddot{\vec{x}}$, we obtain

$$\ddot{\vec{x}} = M^{-1}\vec{y} + M^{-1}N \vec{f}_c \tag{44}$$

On substituting Equation (44) in (43), we get

$$C M^{-1}\vec{y} + C M^{-1}N \vec{f}_c = \vec{d} \tag{45}$$

which, on being solved for the constraint forces, yields:

$$\vec{f}_c = [C M^{-1}N]^{-1} \{\vec{d} - C M^{-1}\vec{y}\} \tag{46}$$

The set of differential equations given by Equation (42) can now be solved by substituting Equation (46) back into (42). Upon doing so, we obtain:

$$\ddot{\vec{x}} = M^{-1}\vec{y} + M^{-1}N[C M^{-1}N]^{-1} \{\vec{d} - C M^{-1}\vec{y}\} \tag{47}$$

Since all the terms in the right-hand side of (47) are known, Equation (47) can be integrated by any standard integration subroutine.

Each of the four connections considered here are single-point constraints. Specifically, there is a point C common to both the lead and the trailing units, about which articulation takes place. (See, for example, Figure C.9.) The required equations of constraint are obtained by equating the acceleration of point C on the lead unit to the acceleration of the same point on the trailing unit.

With reference to Figure C.9, the acceleration of point C on the lead unit is seen to be:

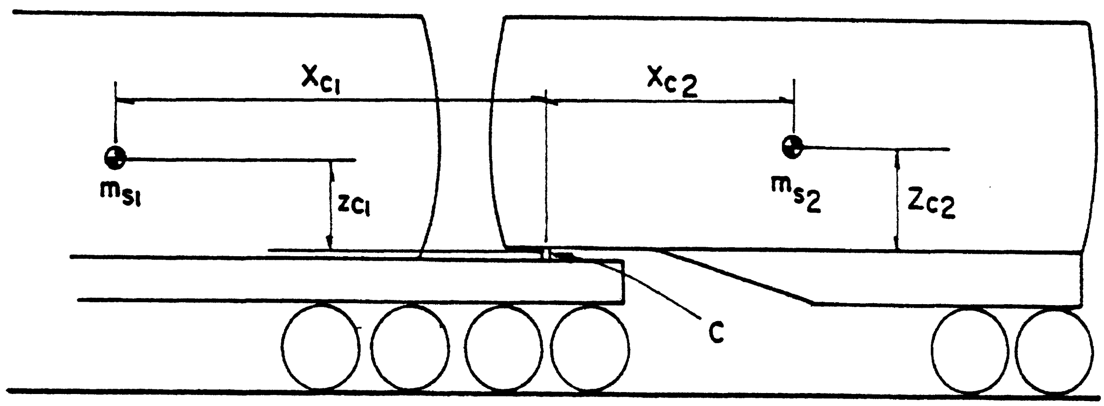



Figure C.9. A single point constraint in which the articulation takes place about point C.

$$\vec{a}_c = [\dot{u}_{s_1} + q_{s_1}w_{s_1} - r_{s_1}v_{s_1} + \dot{q}_{s_1}z_{c_1} - x_{c_1}q_{s_1}^2 + p_{s_1}r_{s_1}z_{c_1}$$

$$- x_{c_1}r_{s_1}^2]\vec{i}_{s_1} + [\dot{v}_{s_1} + u_{s_1}r_{s_1} - p_{s_1}w_{s_1} - \dot{p}_{s_1}z_{c_1} + x_{c_1}\dot{r}_{s_1}$$

$$+ z_{c_1}q_{s_1}r_{s_1} + z_{c_1}q_{s_1}r_{s_1} + x_{c_1}q_{s_1}r_{s_1}]\vec{j}_{s_1} + [\dot{w}_{s_1} + p_{s_1}v_{s_1}$$

$$- q_{s_1}u_{s_1} - x_{c_1}\dot{q}_{s_1} - p_{s_1}^2z_{c_1} + x_{c_1}r_{s_1}p_{s_1} - z_{c_1}q_{s_1}^2]\vec{k}_{s_1}$$

$$= a_1\vec{i}_{s_1} + b_1\vec{j}_{s_1} + c_1\vec{k}_{s_1} \tag{48}$$

The acceleration of the same point in terms of the motion variables of the trailing unit is:

$$\vec{a}_c = [\dot{u}_{s_2} + q_{s_2}w_{s_2} - r_{s_2}v_{s_2} + \dot{q}_{s_2}z_{c_2} - x_{c_2}q_{s_2}^2 + p_{s_2}r_{s_2}z_{c_2}$$

$$- x_{c_2}r_{s_2}^2]\vec{i}_{s_2} + [\dot{v}_{s_2} + u_{s_2}r_{s_2} - p_{s_2}w_{s_2} - \dot{p}_{s_2}z_{c_2} + x_{c_2}\dot{r}_{s_2}$$

$$+ z_{c_2}q_{s_2}r_{s_2} + x_{c_2}q_{s_2}p_{s_2}]\vec{j}_{s_2} + [\dot{w}_{s_2} + p_{s_2}v_{s_2} - q_{s_2}u_{s_2}$$

$$- x_{c_2}\dot{q}_{s_2} - p_{s_2}^2z_{c_2} + x_{c_2}r_{s_2}p_{s_2} - z_{c_2}q_{s_2}^2]\vec{k}_{s_2}$$

$$= a_2\vec{i}_{s_2} + b_2\vec{j}_{s_2} + c_2\vec{k}_{s_2} \tag{49}$$

Equations (48) and (49) can be equated to each other after transforming the coordinate system of the lead unit to that of the trailing unit, or vice versa.

Referring to Equation (7), we note that:

$$\begin{Bmatrix} \vec{i}_n \\ \vec{j}_n \\ \vec{k}_n \end{Bmatrix} = [A_{ij}]_1 \{\vec{i}_{s_1}, \vec{j}_{s_1}, \vec{k}_{s_1}\}^T \tag{50}$$

But

$$\begin{Bmatrix} \vec{i}_{s_2} \\ \vec{j}_{s_2} \\ \vec{k}_{s_2} \end{Bmatrix} = [A_{ij}]_2^T \{\vec{i}_n, \vec{j}_n, \vec{k}_n\}^T \quad (51)$$

Upon combining Equations (50) and (51), we get:

$$\begin{Bmatrix} \vec{i}_{s_2} \\ \vec{j}_{s_2} \\ \vec{k}_{s_2} \end{Bmatrix} = [A_{ij}]_2^T[A_{ij}]_1\{\vec{i}_{s_1}, \vec{j}_{s_1}, \vec{k}_{s_1}\}^T = [T_{ij}]\{\vec{i}_{s_1}, \vec{j}_{s_1}, \vec{k}_{s_1}\}^T \quad (52)$$

where:

$$T_{11} = \cos(\psi_{s_2}-\psi_{s_1})$$

$$T_{12} = \sin(\psi_{s_2}-\psi_{s_1})\cos\phi_{s_1} - \theta_{s_2}\sin\phi_{s_1} + \sin\phi_{s_1}\theta_{s_1}\cos(\psi_{s_2}-\psi_{s_1})$$

$$T_{13} = -\sin(\psi_{s_2}-\psi_{s_1})\sin\phi_{s_1} - \theta_{s_2}\cos\phi_{s_1} + \cos\phi_{s_1}\theta_{s_1}\cos(\psi_{s_2}-\psi_{s_1})$$

$$T_{21} = -\cos\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) - \theta_{s_1}\sin\phi_{s_2} + \sin\phi_{s_2}\theta_{s_2}\cos(\psi_{s_2}-\psi_{s_1})$$

$$\begin{aligned} T_{22} = {} & \cos\phi_{s_1}\cos\phi_{s_2}\cos(\psi_{s_2}-\psi_{s_1}) + \sin\phi_{s_1}\sin\phi_{s_2} \\ & - \sin\phi_{s_1}\theta_{s_1}\cos\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) \\ & + \sin\phi_{s_2}\theta_{s_2}\cos\phi_{s_1}\sin(\psi_{s_2}-\psi_{s_1}) \end{aligned}$$

$$\begin{aligned} T_{23} = {} & -\sin\phi_{s_1}\cos\phi_{s_2}\cos(\psi_{s_2}-\psi_{s_1}) + \cos\phi_{s_1}\sin\phi_{s_2} \\ & - \cos\phi_{s_1}\cos\phi_{s_2}\theta_{s_1}\sin(\psi_{s_2}-\psi_{s_1}) \\ & - \sin\phi_{s_1}\sin\phi_{s_2}\theta_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) \end{aligned}$$

$$T_{31} = \sin\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) - \cos\phi_{s_2}\theta_{s_1} + \cos\phi_{s_2}\theta_{s_2}\cos(\psi_{s_2}-\psi_{s_1})$$

$$T_{32} = -\cos\phi_{s_1}\sin\phi_{s_2}\cos(\psi_{s_2}-\psi_{s_1}) + \cos\phi_{s_2}\sin\phi_{s_1}$$

$$+ \sin\phi_{s_1}\sin\phi_{s_2}\theta_{s_1}\sin(\psi_{s_2}-\psi_{s_1})$$

$$+ \cos\phi_{s_1}\cos\phi_{s_2}\theta_{s_2}\sin(\psi_{s_2}-\psi_{s_1})$$

$$T_{33} = \sin\phi_{s_1}\sin\phi_{s_2}\cos(\psi_{s_2}-\psi_{s_1}) + \cos\phi_{s_1}\cos\phi_{s_2}$$

$$+ \cos\phi_{s_1}\sin\phi_{s_2}\theta_{s_1}\sin(\psi_{s_2}-\psi_{s_1})$$

$$- \sin\phi_{s_1}\cos\phi_{s_2}\theta_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) \tag{53}$$

After the transformation is applied to Equation (51), one obtains the following constraint equations:

$$b_2\vec{j}_{s_2} = (a_1T_{21} + b_1T_{22} + c_1T_{23})\vec{j}_{s_2} \tag{54}$$

$$c_2\vec{k}_{s_2} = (a_1T_{31} + b_1T_{32} + c_1T_{33})\vec{k}_{s_2} \tag{55}$$

Note that Equations (54) and (55) are equivalent to Equation (43) above, since the quantities, $a_1$, $b_1$, and $c_1$, etc., are accelerations. Equations (54) and (55) serve to determine the lateral and vertical forces acting at the coupling point C. In the case of the pintle hook connection, only Equation (54) is required since a constraint force cannot exist in the vertical direction.

C.4.1 Roll and Pitch Moments for a Conventional Fifth Wheel Connection. Figure C.10 presents both the side and rear views of a conventional fifth wheel arrangement. It is observed that the conventional fifth wheel arrangement permits free rotational motions of the trailing unit along the pitch axis, $\vec{j}_{s_1}$, of the lead unit, and along the yaw axis, $\vec{k}_{s_2}$, of the trailing unit. When the two units are in line, the pitch axis, $\vec{j}_{s_2}$, of the trailing unit coincides with the $\vec{j}_{s_1}$ axis. Therefore, when the relative yaw angle is zero,

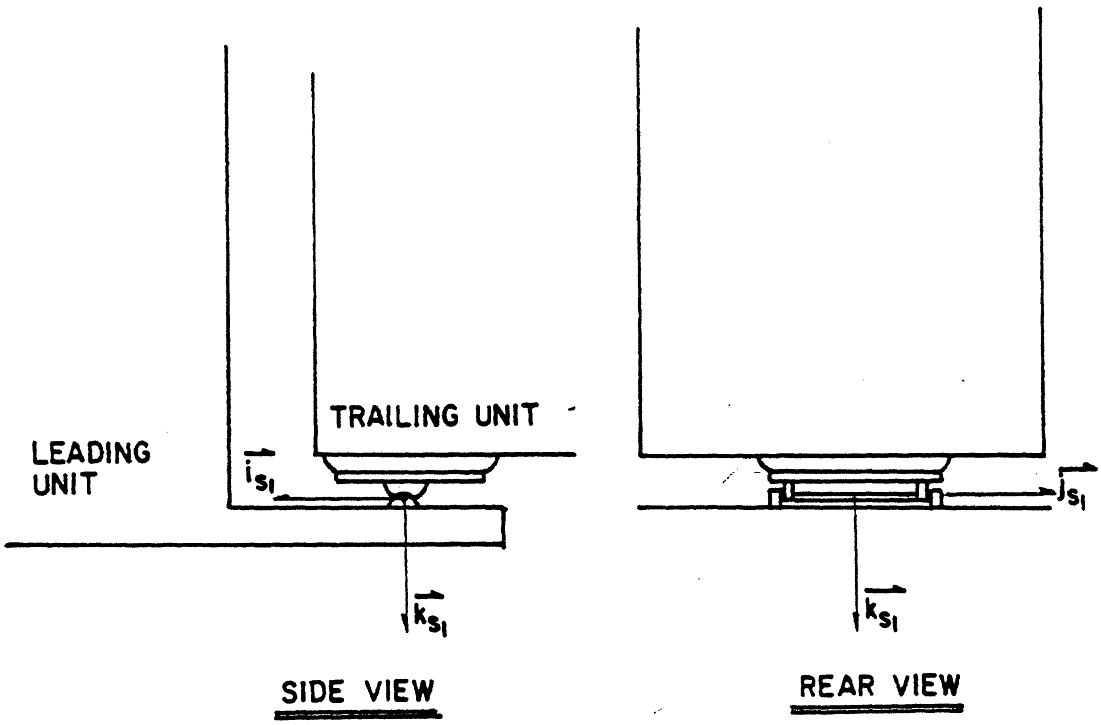



Figure C.10. Conventional fifth wheel arrangement.

the trailing unit is free to pitch with respect to the lead unit. When the relative yaw angle between the two units reaches 90 degrees, the roll axis, $\vec{i}_{s_2}$, of the trailing unit coincides with the pitch axis, $\vec{j}_{s_1}$, making the trailing unit free to roll with respect to the lead unit.

It is assumed that frictional couples which exist along the $\vec{j}_{s_1}$ and $\vec{k}_{s_2}$ directions are sufficiently small that they can be neglected. Thus, the only constraining moment that can act on the lead unit is a roll moment along the $\vec{i}_{s_1}$ direction. The roll compliance which exists both in the tractor and trailer structures and in the coupling device is lumped to constitute the torsional stiffness, $K_1$, shown in Figure C.11. A second set of axes $(\vec{i}'_{s1}, \vec{j}'_{s1}, \vec{k}'_{s1})$ affixed to the fifth wheel are also defined in Figure C.11. This axis system has the same yaw and pitch angles as those of the lead unit, but has a different roll angle, $\phi'_{s1}$. The

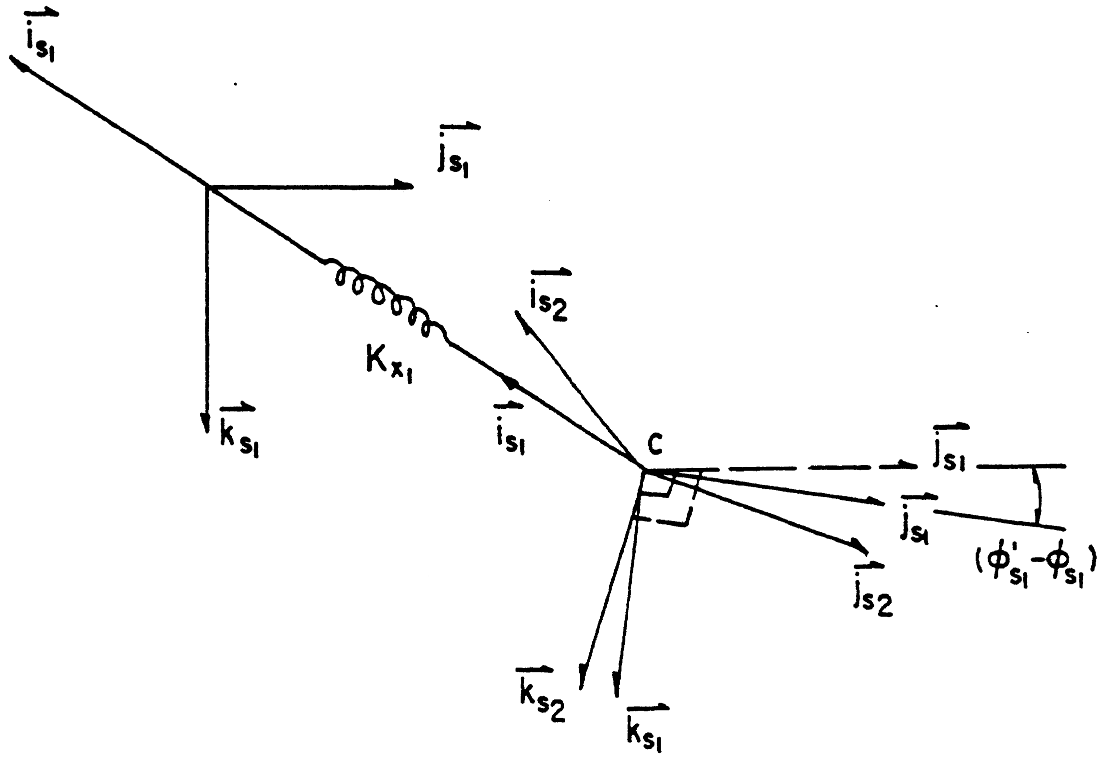



Figure C.11. Representation of the conventional fifth wheel arrangement in the yaw/roll model.

difference in the roll angle ($\phi'_{s_1}-\phi_{s_1}$) represents the structural compliance. The roll moment acting through the fifth wheel can therefore be expressed as:

$$M_{x_1} = K_1(\phi'_{s_1}-\phi_{s_1}) \tag{56}$$

The construction of the fifth wheel is such that the pitch axis, $\vec{j}'_{s_1}$, is always perpendicular to the yaw axis, $\vec{k}_{s_2}$. In terms of unit vectors, this condition can be written as:

$$\vec{j}'_{s_1} \cdot \vec{k}_{s_2} = 0 \tag{57}$$

Both $\vec{j}'_{s_1}$ and $\vec{k}_{s_2}$ can be expressed in terms of the inertial unit vector ($\vec{i}_n$, $\vec{j}_n$, $\vec{k}_n$) using the transform equation (9). Upon doing so, carrying out the dot product and solving for $\phi'_{s_1}$, we find that Equation (56) can be expressed as

$$M_{x_1} = K_{x_1}\left\{\tan^{-1}\left[\frac{\sin\phi_{s_2}\cos(\psi_{s_2}-\psi_{s_1})-\theta_{s_2}\cos\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1})}{\theta_{s_1}\sin\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) + \cos\phi_{s_2}}\right] - \phi_{s_1}\right\} \tag{58}$$

The constraining moments acting on the trailing unit are

$$M_{x_2} = - M_{x_1}T_{11} \tag{59}$$

and

$$M_{y_2} = - M_{x_1}T_{21} \tag{60}$$

where $T_{11}$ and $T_{21}$ are defined in Equation (53).

C.4.2 Roll and Pitch Moments for an Inverted Fifth Wheel Arrangement. The inverted fifth wheel is an arrangement in which the lower and upper halves of a conventional fifth wheel coupling are reversed. The inverted fifth wheel arrangement is shown in Figure C.12.

The coupler permits free rotational motion of the trailing unit along the pitch axis, $\vec{j}_{s_2}$, of the trailing unit and the yaw axis, $\vec{k}_{s_1}$, of the lead unit. Unlike the conventional fifth wheel arrangement, the pitch axis of the inverted coupler is always lined up with the pitch axis of the trailer for all values of articulation angles. The inverted fifth wheel coupling can therefore transmit a roll-resisting moment from the lead unit to the trailing unit for all values of the relative yaw angle between the lead and the trailing

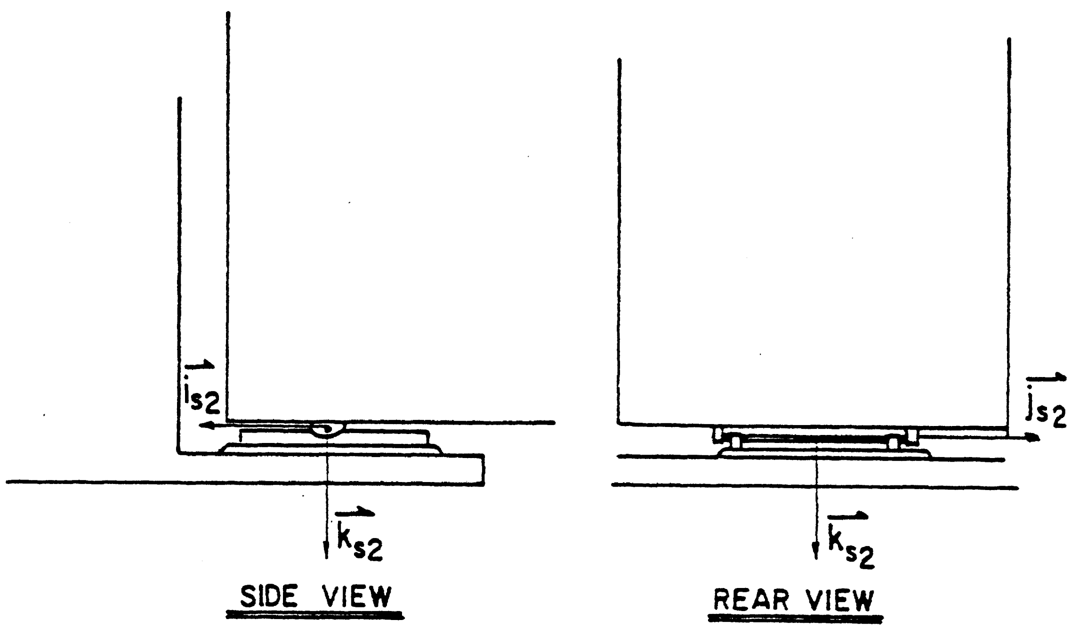



Figure C.12. The inverted fifth wheel arrangement.

units. In the case of the inverted fifth wheel, the structural compliance in roll is modeled by a torsional spring of stiffness $K_{x_1}$, oriented along the $\vec{i}_{s_2}$ axis of the trailing unit. Upon carrying out the derivation, we get:

$$M_{x_2} = K_{x_1}\left\{\tan^{-1}\left[\frac{\sin\phi_{s_1}\cos(\psi_{s_1}-\psi_{s_2})-\theta_{s_1}\cos\phi_{s_1}\sin(\psi_{s_1}-\psi_{s_2})}{\theta_{s_2}\sin\phi_{s_1}\sin(\psi_{s_1}-\psi_{s_2})+\cos\phi_{s_1}}\right]-\phi_{s_2}\right\} \tag{61}$$

The roll and pitch moment acting on the lead unit are given by

$$M_{x_1} = - M_{x_2}T_{11} \tag{62}$$

$$M_{y_1} = - M_{x_2}T_{12} \tag{63}$$

where $T_{11}$ and $T_{12}$ are once again defined in Equation (53).

C.4.3 Roll and Pitch Moments for a Kingpin-Type Connection. In a kingpin-type arrangement, only yaw motion is permitted between the lead and the trailing units. Hence, constraining moments act in both the pitch and yaw directions. The structural compliance is therefore represented by torsional springs, $K_{x_1}$ and $K_{y_1}$, along the pitch and roll axes. Shown in Figure C.13 is an axis system ($\vec{i}'_{s_1}$, $\vec{j}'_{s_1}$, $\vec{k}'_{s_1}$) which has the same yaw angle, $\psi_{s_1}$, as the lead unit, but different roll and pitch angles, $\phi'_{s_1}$ and $\theta'_{s_1}$, respectively. The axis system is so oriented that the $k'_{s_1}$ axis is parallel to the $\vec{k}_{s_2}$ axis of the trailing unit. Therefore, the vector equations

$$\vec{i}'_{s_1} \cdot \vec{k}_{s_2} = 0 \tag{64}$$

and

$$\vec{j}'_{s_1} \cdot \vec{k}_{s_2} = 0 \tag{65}$$

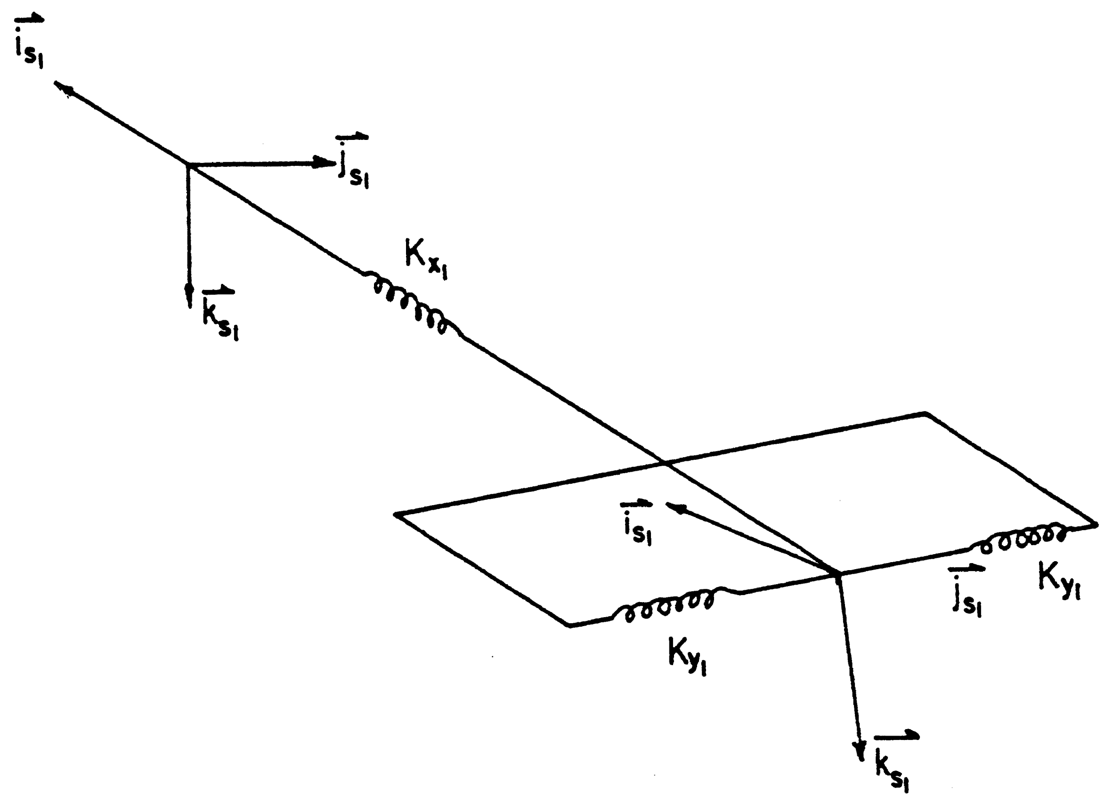



Figure C.13. Representation of the kingpin-type connection in the yaw/roll model.

have to be satisfied. Equation (64) yields the pitch angle

$$\theta'_{s_1} = \theta_{s_2}\cos(\psi_{s_2}-\psi_{s_1}) + \tan\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) \tag{66}$$

Therefore

$$\begin{aligned} M_{y_1} &= K_{y_1}(\theta'_{s_1}-\theta_{s_1}) \\ &= K_{y_1}[\theta_{s_2}\cos(\psi_{s_2}-\psi_{s_1}) + \tan\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) - \theta_{s_1}] \end{aligned} \tag{67}$$

Equation (65) yields a result which is identical to (58), therefore

$$M_{x_1} = K_{x_1}\left[\tan^{-1}\left(\frac{\sin\phi_{s_2}\cos(\psi_{s_2}-\psi_{s_1})-\theta_{s_2}\cos\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1})}{\theta'_{s_1}\sin\phi_{s_2}\sin(\psi_{s_2}-\psi_{s_1}) + \cos\phi_{s_2}}\right) - \phi_{s_1}\right] \quad (68)$$

The constraining moments, $M_{x_2}$ and $M_{y_2}$, which act on the trailing unit are now given by

$$M_{x_2} = - M_{x_1}T_{11} - M_{y_1}T_{12} \quad (69)$$

and

$$M_{y_2} = - M_{x_1}T_{21} - M_{y_1}T_{22} \quad (70)$$

where $T_{11}$, $T_{12}$, $T_{21}$, and $T_{22}$ are once again defined in Equation (53).

## C.5 Forces and Moments at the Tire-Road Interface

In order to obtain a high degree of accuracy in predicting roll/yaw behavior, the computer code utilizes measured tire data for computing the lateral forces and aligning moments generated at the tire-road interface. If the sideslip angle and the vertical load acting on a tire are known, the lateral force and aligning moment can be computed by a linear interpolation of the tabulated tire data. Expressions for the sideslip angle and the vertical load at the tire-road interface will now be derived in terms of the velocities and displacements of the sprung and unsprung masses.

C.5.1 Sideslip Angles. Let us first express the sideslip angle at the tire-road interface in terms of the body-fixed velocities of the sprung mass and the axle. The sideslip angle at the j-th tire on axle i is given by the expression:

$$\alpha_{ij} = \tan^{-1} (v_{axle_i}/u_{tire_{ij}}) - \delta_i \tag{71}$$

where

$$v_{axle_i} = [v_s - z_{R_i} p_s]\cos \phi_s + x_{u_i} r_s/\cos \phi_s - p_{u_i} HR_i \cos \phi_{u_i} \tag{72}$$

$$u_{tire_{i1}} = u_s + (T_i + A_i) r_s \tag{73}$$

$$u_{tire_{i2}} = u_s + T_i r_s \tag{74}$$

$$u_{tire_{i3}} = u_s - T_i r_s \tag{75}$$

$$u_{tire_{i4}} = u_s - (T_i + A_i) r_s \tag{76}$$

(Note that the term $\delta_i$ in Equation (71) represents the angle made by the wheel plane with respect to the longitudinal axis of the sprung mass coordinate system.)

C.5.2 Vertical Loads. The vertical compliance in the tires is modeled by linear springs, $KT_{ij}$. Therefore, if the vertical deflection, $\Delta_{ij}$, at the tire is known, the vertical tire load, $F_{z_{ij}}$, can be calculated from the expression:

$$F_{z_{ij}} = KT_{ij} \Delta_{ij} \tag{77}$$

The vertical deflection of the tires can be expressed in terms of the deflection of the sprung and unsprung masses. The deflection of the outer left tire on axle i is given by the equation:

$$\Delta_{i1} = \Delta_{i0} + \Delta z_s - z_{R_i}(1 - \cos \phi_s) + z_{u_i} \cos \phi_{u_i} - z_{u_{i0}} - (T_i + A_i) \sin \phi_{u_i} - x_{u_i} \theta_s \tag{78}$$

where

$\Delta z_s$ is the vertical deflection of the sprung mass c.g. along the inertial axis $\vec{k}_n$

$$\Delta z_s = 0.0 \text{ at time } t = 0.0$$

$z_{u_{i0}}$ is the vertical distance between the roll center, $R_i$, and the axle c.g. at time t = 0.0

$\Delta_{i0}$ is the static deflection of the tires at time t = 0.0.

The deflection of the other three tires on axle i is given by:

$$\Delta_{i2} = \Delta_{i1} + A_i \sin \phi_{u_i} \tag{79}$$

$$\Delta_{i3} = \Delta_{i2} + 2T_i \sin \phi_{u_i} \tag{80}$$

$$\Delta_{i4} = \Delta_{i3} + A_i \sin \phi_{u_i} \tag{81}$$

Equations (78) through (81) yield the vertical load on a given tire which, in combination with Equation (71), permits one to perform a linear interpolation of tabulated tire data to determine the value of lateral force and aligning moment corresponding to the prevailing load and slip angle.

## C.6 Computer Code for Solving the Equations of Motion

The discussions in Section C.3 through C.5 have outlined the manner in which one can compute the external forces acting on both the sprung and unsprung masses. The equations of motion, (22) through (28), together with Equations (16) through (18) which define the Euler angular velocities ($\dot{\phi}_s$, $\dot{\theta}_s$, $\dot{\psi}_s$) are sufficient to solve for $\ddot{\vec{x}}$, $\dot{\vec{x}}$, and $\vec{x}$ by numerical integration.

A summary description of the computer code in the form of flow charts is given below in Figures C.14 through C.17. The computer program consists of an INPUT subroutine which reads in the input variables. A subroutine called FUNCTN solves the equation and computes $\ddot{\vec{x}}$. During the simulation of closed-loop maneuvers, the subroutine FUNCTN calls the driver model (described in References [1] and [2]) for computing the steering-wheel angle. During open-loop maneuvers, the steering-wheel angle is calculated from a star table which is specified by the user of the program. The subroutine FUNCTN also calls subroutines which compute the lateral forces and aligning torques which are present at the tire-road interfaces. The necessary output variables are printed out through the OUTPUT subroutine at specified intervals of time—XPRINT. The numerical integration is performed using a predictor corrector method.

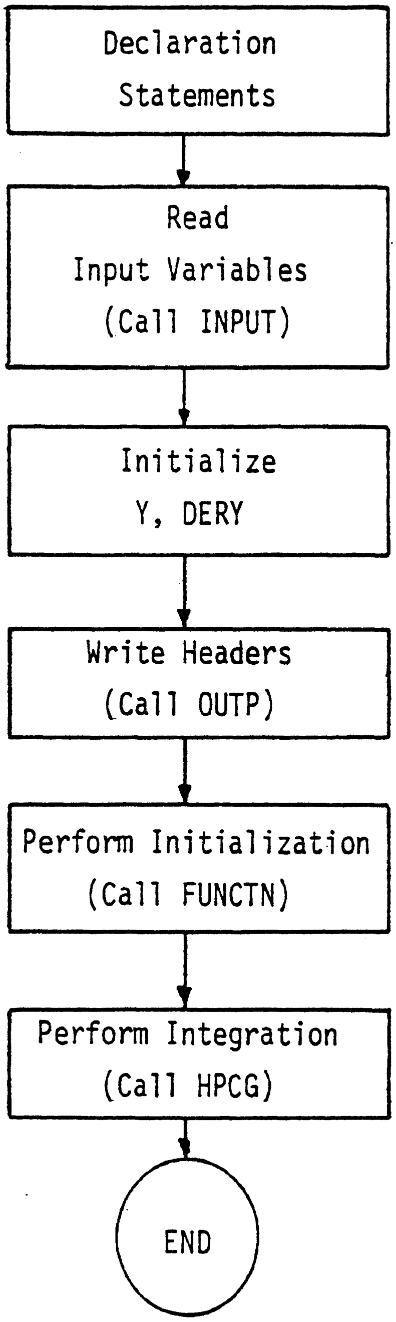



Figure C.14. Main

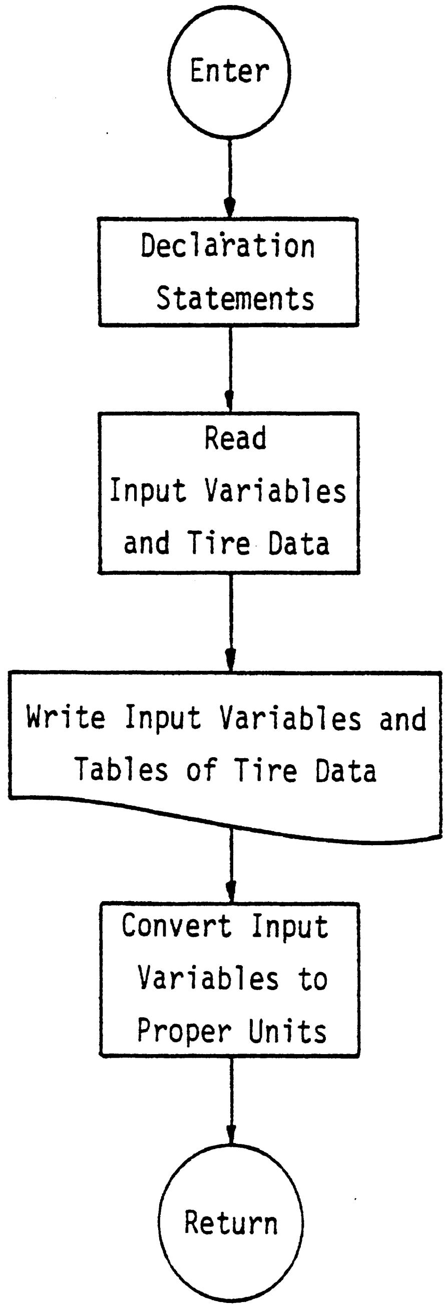



Figure C.15. Subroutine INPUT

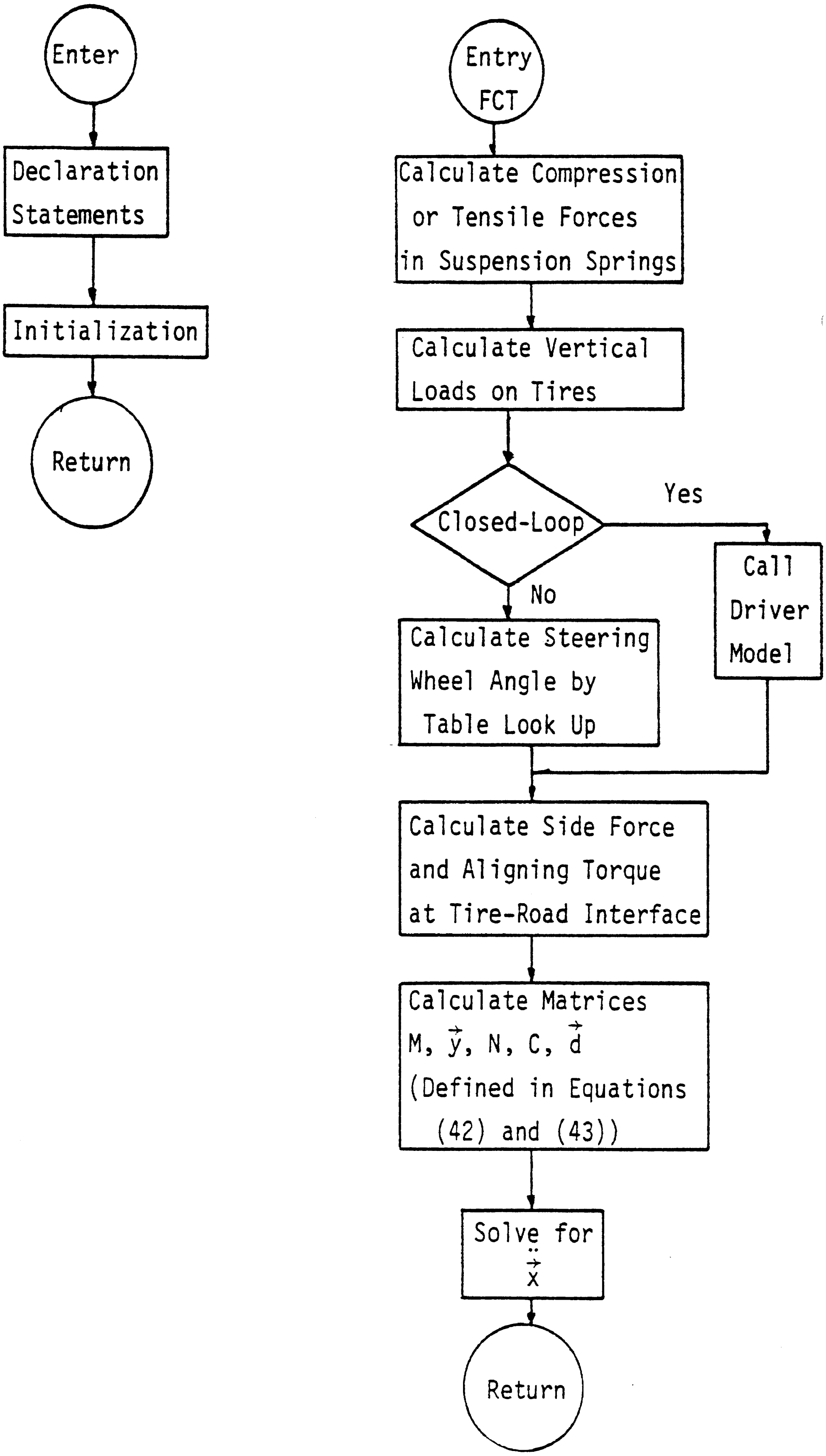



Figure C.16. Subroutine FUNCTN

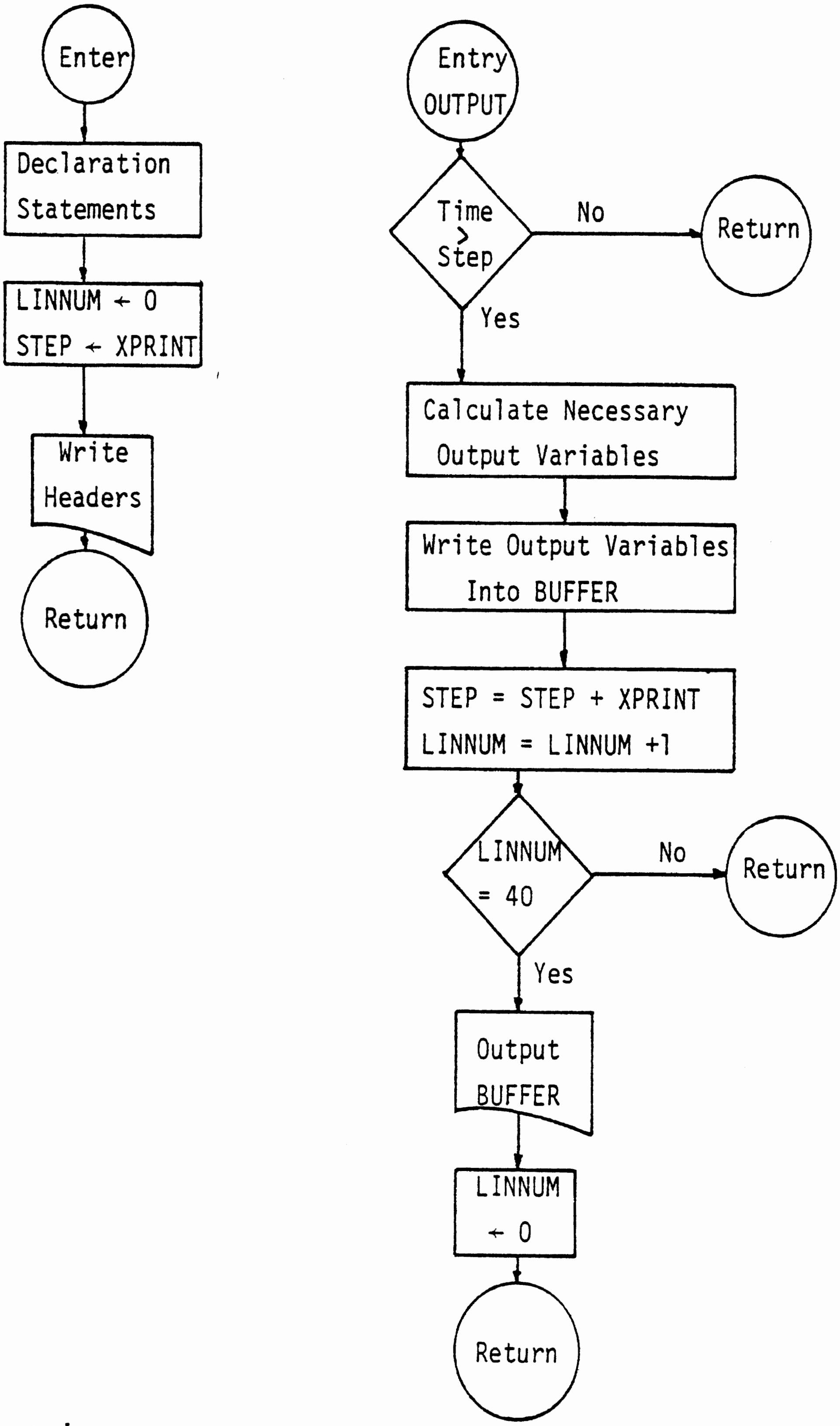



Figure C.17. Subroutine OUTP