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Centre for Surface Transportation Technology
Centre de technologie des transports de surface

TP 14344 E

# *A Computer Simulation for Assessment of Tank Truck Roll Stability*

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Technical Report
1 March 2005

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# A COMPUTER SIMULATION FOR ASSESSMENT OF TANK TRUCK ROLL STABILITY

# SIMULATION PAR ORDINATEUR POUR L'EVALUATION DE LA STABILITÉ AU ROULIS DE CAMIONS-CITERNES

J.R. Billing

Centre for Surface
Transportation Technology

Centre de technologie
des transports de surface

Technical Report

Rapport technique

CSTT-HVC-TR-071

CSTT-HVC-TR-071

1 March 2005

J. Coleman
General Manager/
Gestionnaire principal

This report reflects the views of its author, and not necessarily those of Transport Canada, Transport Dangerous Goods.

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This report describes Version 1.00 of the program SRMTT, implemented as SRMTT100.xls and SRMTT100.exe.

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17. Abstract

A computer simulation program has been developed to assess the rollover characteristics of heavy tank trucks. The program addresses straight trucks, tractor-semitrailers, B-trains, pony trailers and full trailers. Each vehicle unit may have one tank with up to five compartments that have a generalized elliptical cross-section. The model accounts for movement of the fluid centre of gravity within the tank as a consequence of tank roll and lateral acceleration.

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17. Résumé

Un programme de simulation par ordinateur a été développé pour évaluer les caractéristiques de renversement des camions-citernes lourds. Ce programme porte sur les camions-porteurs, les tracteurs semi-remorques, les trains B, les remorques semi-portées et les remorques classiques. Chaque véhicule peut avoir une citerne et jusqu'à cinq compartiments de section elliptique. Le modèle prend en compte les mouvements du centre de gravité du fluide dans la citerne suite au roulis et à l'accélération latérale.

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## EXECUTIVE SUMMARY

The Centre for Surface Transportation Technology of the National Research Council Canada (NRC/CSTT) conducted a series of tilt tests of tank trucks on behalf of Transport Canada's Dangerous Goods Directorate. An important part of this work was to develop a means to predict the roll threshold of tank trucks, including the effects of fluid movement on the rollover process.

This report describes a computer simulation developed to determine the rollover threshold of a tank truck. The model can represent a straight truck, tractor-semitrailer, A- or B-train double trailer combination, truck-full trailer or truck-pony trailer combination. Each vehicle unit may have one tank, and each tank may have up to five compartments, each filled to a different level with a different fluid. Each vehicle unit may have a suspension with non-linear characteristics, and may be fitted with a liftable axle, also with non-linear characteristics.

The simulation consists of a master Excel Workbook where the user prepares input data, and in which results are placed, and a stand-alone simulation program that computes the rollover response.

The simulation has been validated against a limited amount of existing data, and artificial test cases where the results can be determined analytically. It has also been used to simulate a large number of tilt tests of tank vehicles. The simulation appears able to match the principal responses of the vehicles tested with reasonable fidelity.

Reliable results and conclusions can only be expected when the user has sufficient understanding of vehicle configuration, vehicle component properties and vehicle dynamics to be able to distinguish between input data that are realistic and input data that are unrealistic, and between results that are reasonable and results that are unreasonable.

This report describes the current version of the computer simulation procedure. The version number of the program to which this document applies is identified on the reverse of the title page.

## SOMMAIRE

Le Centre de technologie des transports de surface, du Conseil national de recherches du Canada (CNRC/CTTS), a effectué une série d'essais d'inclinaison des camions-citernes pour le compte de la Direction générale des marchandises dangereuses de Transports Canada. Une partie importante de ce travail consistait à développer un moyen de prédire le seuil de renversement des camions-citernes, y compris les effets du mouvement du liquide sur le processus de renversement.

Ce rapport décrit une simulation par ordinateur mise au point pour déterminer le seuil de renversement d'un camion-citerne. Le modèle peut représenter un camion-porteur, un tracteur semi-remorque, un semi-remorque double de type A et B, un camion et remorque classique ou un camion et remorque semi-portée. Chaque véhicule peut avoir une citerne et chaque citerne peut avoir jusqu'à cinq compartiments contenant un fluide différent avec un niveau de remplissage différent. Chaque véhicule peut avoir une suspension avec des caractéristiques non linéaires, et peut être équipé d'un essieu relevable, également avec des caractéristiques non linéaires.

La simulation fait appel à un logiciel Excel Workbook maître où l'utilisateur prépare les données à entrer, et dans lequel sont consignés les résultats, et à un programme de simulation indépendant qui calcule la réponse au renversement.

La simulation a été validée en fonction d'un nombre limité de données existantes, et d'essais artificiels où les résultats peuvent être déterminés par l'analyse. Elle a également été utilisée pour simuler un grand nombre d'essais de renversement de véhicules-citernes. La simulation semble concorder avec les principales réponses des véhicules mis à l'essai avec une fidélité raisonnable.

Des résultats et des conclusions fiables ne sont possibles que lorsque l'utilisateur a une connaissance suffisante de la configuration du véhicule, des propriétés de ses composants et de sa dynamique pour être en mesure de distinguer entre données d'entrée réalistes et données d'entrée irréalistes, et entre résultats raisonnables et résultats déraisonnables.

Ce rapport décrit la version courante de la procédure de simulation. Le numéro de version du programme auquel ce document s'applique est identifié au dos de la page titre.

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# 1. INTRODUCTION

A heavy truck rollover is always a serious crash. When the truck is a tank truck carrying dangerous goods, there is additional risk of spill, fire or explosion. Transport Canada's Dangerous Goods Directorate is considering approaches that could improve the rollover stability of tank trucks used for transportation of dangerous goods on highways.

An initial series of tilt tests to characterize the rollover threshold of representative tank trucks and other trucks that operate around Ashcroft, B.C. was conducted by the Centre for Surface Transportation Technology of the National Research Council Canada (NRC/CSTT) in October 2001 [1]. A more comprehensive set of tilt tests was conducted using the NRC/CSTT tilt table in Ottawa, beginning in late 2002 [2].

An important part of the latter piece of work was to be able to predict the roll threshold of vehicles. This report describes the current version of a computer simulation procedure that may be used to estimate the roll threshold of a typical tank truck with several compartments, each of which may be full, partially full or empty. The version number of the program to which this document applies is identified on the reverse of the title page.

# 2. MODELING TANK TRUCK ROLLOVER

## 2.1 The Starting Point

Three simulation programs that compute the static roll threshold of a vehicle were evaluated. None considers the articulation that arises when a vehicle is driven in a curve, so each produces a result that corresponds to a tilt test. The three programs were:

1. The Static Roll Model, developed at the University of Michigan Transportation Research Institute (UMTRI) [3];
2. A simplified version of the Static Roll Model that had been translated for Microsoft Excel, and extended with a generalized model for a tank, and for fluid movement within that tank [4]; and
3. The Static Roll Threshold (SRT) Calculator, an on-line program developed in New Zealand [7].

The Static Roll Model was coded in FORTRAN [3], and was suitable for a straight truck, tractor-semitrailer, or full trailer or pony trailer towed by a pintle hook. It accommodated an A-train double or a truck-trailer combination in two separate runs, one for the towing vehicle, and another for the full trailer, because in each case there was no roll coupling between the full trailer and the vehicle that towed it. This model could not deal with a B-train double, where the second trailer was attached by a hitch that provided significant transfer of roll moment between the two trailers. The model grouped all axles on a vehicle unit into an equivalent single axle, so it could not accommodate a vehicle unit with more than one axle group when those axle groups had different suspensions. It allowed a non-linear suspension, fifth wheel separation, power unit frame flexibility and tire vertical, lateral and overturning stiffness. It lacked a fluid model. This model solved the equations of motion in a series of small sequential steps that increased the roll angle of the rear unit as the independent variable. It made a local linearization of suspension stiffness at each step, determined the linearized equations for a small increment in the independent variable, solved those equations for increments in other degrees of freedom, and accumulated all the responses. There was no control of error, so the accuracy of the result depended on the roll angle step size chosen by the user. A user therefore needed to make several runs using different roll angle step sizes to ensure results were consistent. Straight trucks were modeled as a tractor-semitrailer, with default characteristics given to the front axle.

The Static Roll Model had previously been modified by the author in a number of ways. The lateral acceleration and the roll angle of the rear unit were interchanged, so that the former became the independent variable. Changes were made to facilitate use of the model, including removing some redundancies in the input data, and modifying some data formats. The model was also extended to allow an initial difference in wheel loads between the left- and right-hand sides of each axle group, which is sometimes observed in tilt tests, and may have a significant effect on the roll threshold. This modified model was then used to compare simulation results with tilt test results for a number of flatbed semitrailer configurations tested by NRC/CSTT [5]. This work showed that this simple static roll model could produce results that came reasonably close to test results for a range of vehicle

configurations and payloads. The simulations not only predicted the roll thresholds, mostly within 0.01 g, but also exhibited closely similar trends of wheel load and roll angle, including fifth wheel separation, as a function of lateral acceleration. The correlation between test and simulation could certainly have been improved by refining the physical data for various vehicle components. However, this would not change the foregoing conclusion. A key factor in the correlation between test and simulation for the flatbed semitrailers was that the semitrailers were relatively stiff in torsion, so each vehicle rolled over as a unit. None of the modifications allowed the modified Static Roll Model to address the movement of a fluid load in a tank truck.

The Excel model [4] was a simplification of the Static Roll Model, extended to include a tank with a fluid load. It was a planar model, which combined the characteristics of all suspensions into a single linear suspension, without either tire lateral or overturning stiffness. The model allowed a tank with one compartment of uniform cross-section. It used a generalized ellipse to model the tank cross-section, which can come acceptably close to matching the cross-section of a wide range of tanks that are symmetric about both horizontal and vertical axes. It cannot handle a tank that is not vertically symmetric about a horizontal axis. It included a separate iterative procedure, coded in Excel's Visual Basic for Applications, which computed the free surface angle and the location of the centre of gravity of the fluid in a partially filled tank due to the combined effects of lateral acceleration and tank roll. However, a simplistic and very inefficient solution method did not appear able to produce consistent results. This model did address the movement of a fluid load in a tank with a single compartment. It did not address the range of vehicle configurations that exist in Canada.

The SRT Calculator was developed in New Zealand to address a regulated need to certify the roll threshold of its entire fleet of heavy vehicles [7]. It is an on-line program that deals with a straight truck, full trailer, pony trailer, pole trailer or semitrailer. Each is treated as a stand-alone vehicle. This is a significant simplification for a pole trailer or semitrailer, as it effectively equates lift-off of the trailer wheels to rollover, which may be quite conservative. This would not be an issue for many vehicles, which could pass the minimum specified roll threshold in the manner in which they would normally be operated. The SRT Calculator appears to be well-suited to provide a screen for vehicles that easily pass the roll threshold, or which can be loaded in such a manner that they will pass. The SRT Calculator does not deal with tank trucks, possibly because it does not need to. The low allowable axle and gross weights in New Zealand, and the low elliptical cross-section favoured by tank truck manufacturers, may well result in the top of the tank no higher than 2.8 m (110 in), when the vehicle is deemed to comply with the static roll threshold standard of 0.35 g. Vehicles that do not achieve 0.35 g by the SRT Calculator may still have an actual roll threshold over 0.35 g. New Zealand regulations allow other approved computational procedures to be used for these, which can provide a more accurate representation of the behaviour of the vehicle, such as by including non-linear characteristics of its components. The regulations also allow a tilt test to be used to demonstrate compliance.

NRC/CSTT tested straight trucks, tractor-semitrailers and B-trains, with both straight-bore and multiply-compartmented tanks [2]. It was clear that none of the three models could be

persuaded to be even reasonably representative of many of those vehicles. It was apparent that a new model would be necessary to conduct simulations for this range of vehicles, and to do it in a consistent manner.

Nevertheless, each of the three models each provided useful features. The original Static Roll Model [3] provided a sound solution procedure that could clearly be extended to represent an A- or B-train or a truck-trailer combination, with multiple axle groups on any vehicle unit. The Excel model [4] provided the Excel framework for input and pre-processing of vehicle and tank data, for post-processing and display of results, and the generalized tank and fluid model. The SRT Calculator provided a range of options for vehicles that did not meet a specified roll threshold, including additional runs at a series of downloads to determine the point at which the vehicle would meet the specified roll threshold.

## 2.2 Model Requirements

The following are the principal requirements of a static roll model of a tank truck for the purposes of this work:

1. The model must be able to represent the following vehicle configurations:
   - Straight truck;
   - Tractor-semitrailer;
   - A-train;
   - B-train;
   - Truck-full trailer; and
   - Truck-pony trailer.
2. Each vehicle unit may have up to three axle groups.
3. An axle group may be fitted with single or dual tires.
4. An axle group may have a suspension with non-linear force-displacement characteristics.
5. Each vehicle unit may have one tank with up to five compartments.
6. Each tank will have the same width and upper profile for all compartments.
7. The lower profile of the tank may vary between compartments.
8. Fill of any compartment may be specified by any two of weight of fluid, volume of fluid and density of fluid.

## 2.3 Assumptions

The following are the principal assumptions built into the model for the purposes of this work:

1. Each tank is rigid in torsion.
2. Each suspension has a roll centre.
3. The fluid has low viscosity and flows freely within the tank as the vehicle rolls
4. Roll angles are small, so the sine and cosine of a roll angle can be approximated by the angle and unity, respectively.

5. There is no articulation, so the simulation may represent the rollover that occurs in a tilt test more closely than the rollover that occurs in a high-speed circular turn.
6. The vertical load carried by each axle group does not change during the rollover process.
7. A tire can be represented by a separate linear spring that represents its vertical, later and overturning stiffness.

## 2.4 Tank Definition

A tank may be fitted on a vehicle unit, and may have from one to five compartments. Each compartment has a uniform cross-section along its length, and is symmetrical about the centre-line of the tank. Different compartments may have different cross-sections. The dimensions of the upper part of a tank are uniform along the length of the tank. The dimensions of the lower part of a compartment are uniform along the length of a compartment, but may differ between compartments. The lower part of each compartment has the same width as the upper part, but may have a different depth and/or shape.

**Figure 1: Tank and Compartment Cross-sections**

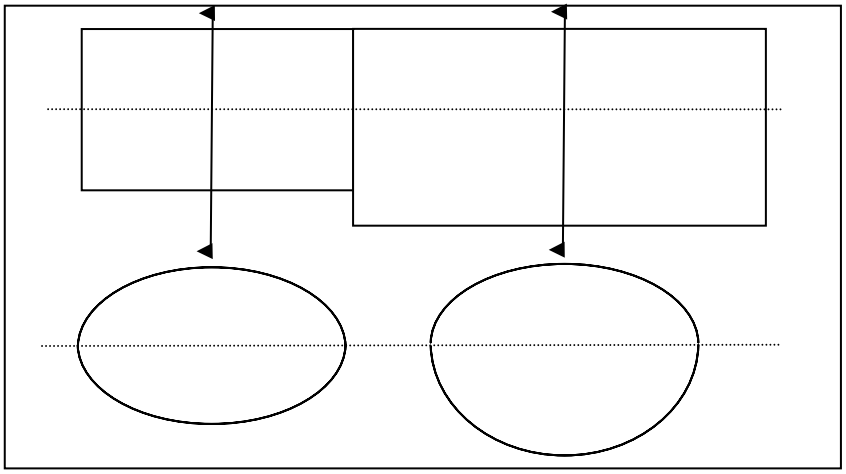


Figure 1 illustrates a tank with two compartments. The upper part of the tank has the same cross-section for the entire length of the tank. The cross-sections of the lower parts of each tank are different in both height and shape.

The upper part of the tank and the lower part of each compartment are each defined as a generalized ellipse given by the equation:

$$\left(\frac{y}{a}\right)^n + \left(\frac{z}{b}\right)^n = 1$$

Equation 1

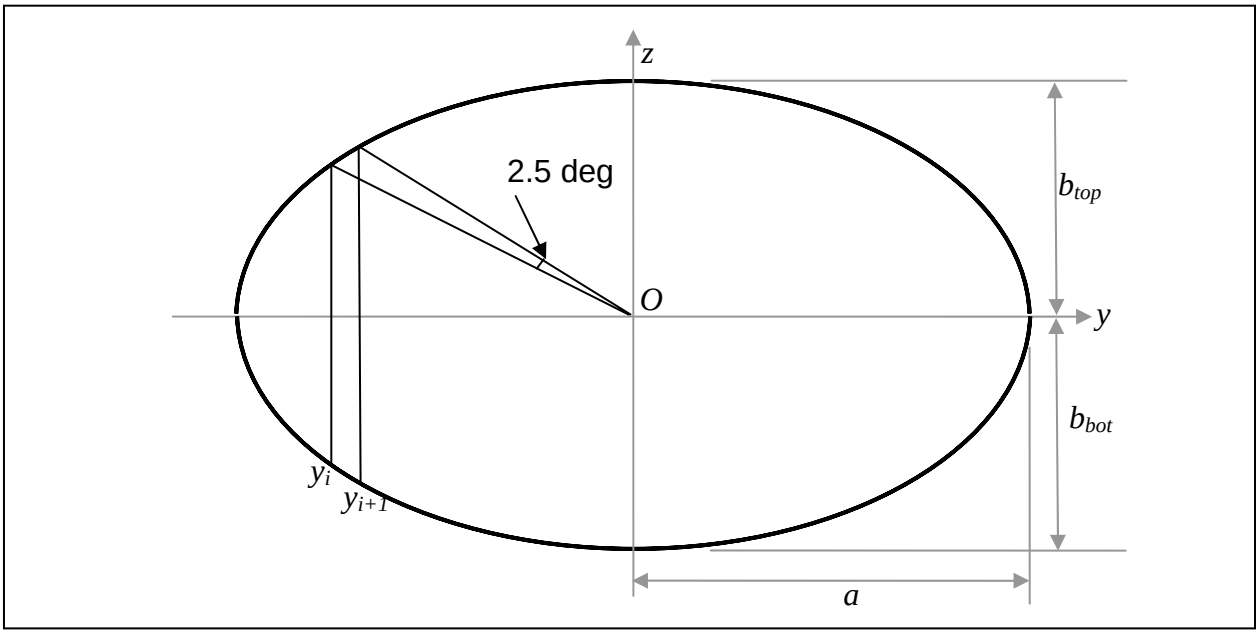
where $a$ = length of horizontal principal axis;
$b$ = length of vertical principal axis; and
$n$ = exponent.

All notation given in this chapter is summarized in a glossary at the end of the chapter.

The tank has a width of $2a$, and the distance from the horizontal principal axis to the top of the tank is $b_{top}$, and to the bottom of a compartment is $b_{bot}$. A compartment is circular if $a = b_{top} = b_{bot}$, and $n = 2$. A compartment is elliptical if $a \neq b_{top}$, $b_{top} = b_{bot}$, and $n = 2$. The tank takes on a generalized elliptical shape if $n > 2$. As the value of $n$ increases, the tank becomes increasingly rectangular with more tightly rounded corners. The highest practical value for $n$ is about 8. When the lower part of a compartment has a different cross-section than the upper part, the value of either $b$, or $n$, or both, differs between the upper and lower part of the tank.

The tank shell is defined by y-z coordinates with an origin $O$ at the centre of the horizontal principal axis, as shown in Figure 2. A series of radial lines is defined from the origin, with the first along the negative horizontal principal axis, and each succeeding line at an angle of 2.5 deg clockwise from the previous line, until the positive horizontal axis is reached. This results in a set of 73 points to define the tank shell. A radial distribution of points provides a better geometric definition of a tank than a uniformly spaced set of points along the y-axis. The intersection of the i'th radial line with the upper part of the tank shell defines a y-coordinate $y_i$ for both upper and lower parts of the tank. These y-coordinates are then used to compute z-coordinates for the upper and lower parts of the tank. A tank

**Figure 2: Tank Dimensions and Coordinate System**



cross-section is divided into a series of vertical slices between consecutive y-coordinates $y_i$ and $y_{i+1}$. Calculations are performed for each slice, and the results are summed to represent the entire cross-section. Since the shell is defined by a total of 73 points, from $-a$ to $a$, 72 transverse slices define the cross-section of the tank.

The end of each tank and compartment is assumed to be flat. This ignores any dome or radius in a bulkhead at the front or rear of a tank, or the end of a compartment. The volume contained by any such dome or radius may be accounted by adjusting the length of the compartment to ensure the actual volume of fill has the proper free surface height, and the location of the compartment to ensure that its longitudinal centre of gravity is in the correct position on the vehicle.

### 2.5 Fluid Calculations

The simulation requires that the centre of gravity of the fluid in a compartment be determined as the fluid moves and the tank rolls when subject to a lateral acceleration $a_y$. Figure 3 shows the free surface of the fluid subject to a lateral acceleration $a_y$ where the tank has taken up a roll angle $\theta$. The slope of the free surface relative to the tank axis system $m$ is given by:

$$m = \frac{(a_y + \theta)}{(1 - a_y \theta)} = \tan \alpha$$

Equation 2

The point at which the free surface meets the vertical principal axis of the compartment, identified as the free surface height in Figure 3, varies with the free surface angle $\alpha$. However, the area of fluid in any cross-section of the compartment does not change with lateral acceleration. The free surface height is easily determined by an iterative procedure comparing the fluid area for a current estimate of the free surface height to the initial fluid area. Once the free surface height is determined, the equation of the free surface is also determined, and the location of the centre of gravity of the fluid can be determined.

Figure 4 shows a vertical slice of a compartment between consecutive y-coordinates $y_1$ and $y_2$. The z-coordinates of the bottom of the compartment are $zb_1$ and $zb_2$ at $y_1$ and $y_2$ respectively, and the z-coordinates of the top of the compartment are $zt_1$ and $zt_2$. Let the plane of the free surface have z-coordinates $zs_1$ and $zs_2$ where it intersects the left- and right-hand sides of the slice at $y_1$ and $y_2$ respectively. There are three possible cases for the elevation of the free surface $zs_1$ on the left-hand side of the compartment slice:

L1: $zs_1 \leq zb_1$, below the bottom of the compartment;
L2: $zs_1 > zb_1$ and $zs_1 \leq zt_1$, within the compartment; or
L3: $zs_1 > zt_1$, above the top of the compartment.

Equation 3

**Figure 3: Tank and Fluid Contents Subject to Roll and Lateral Acceleration**

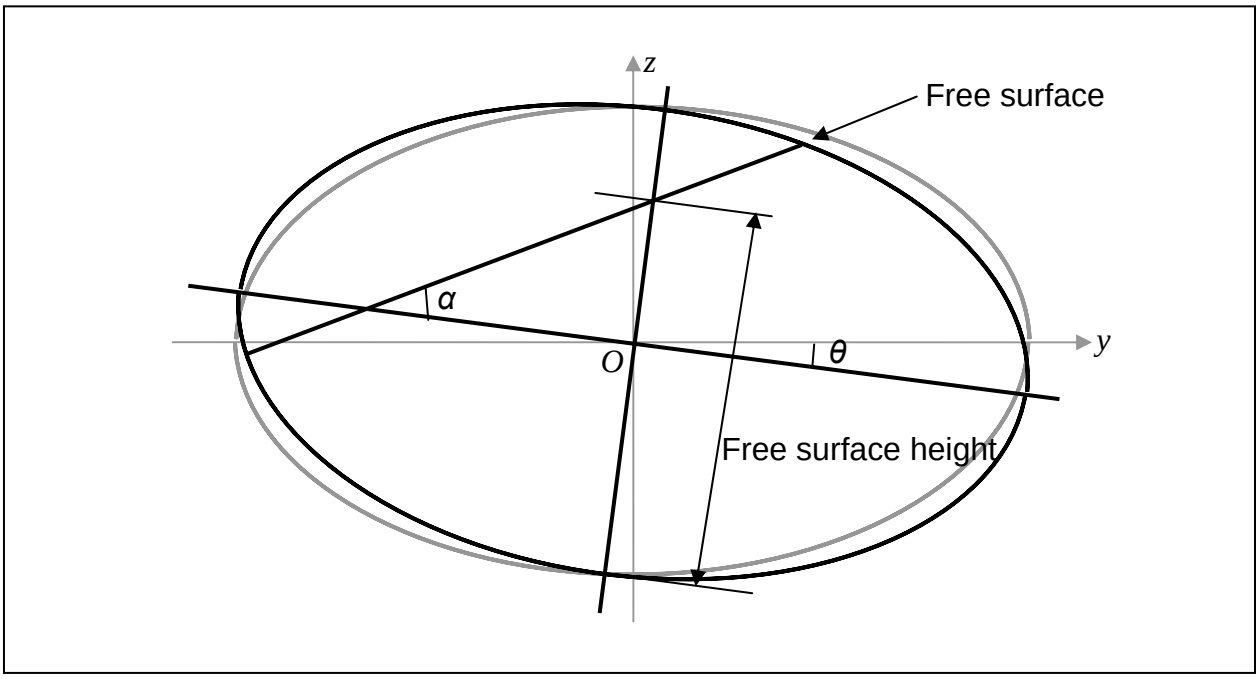
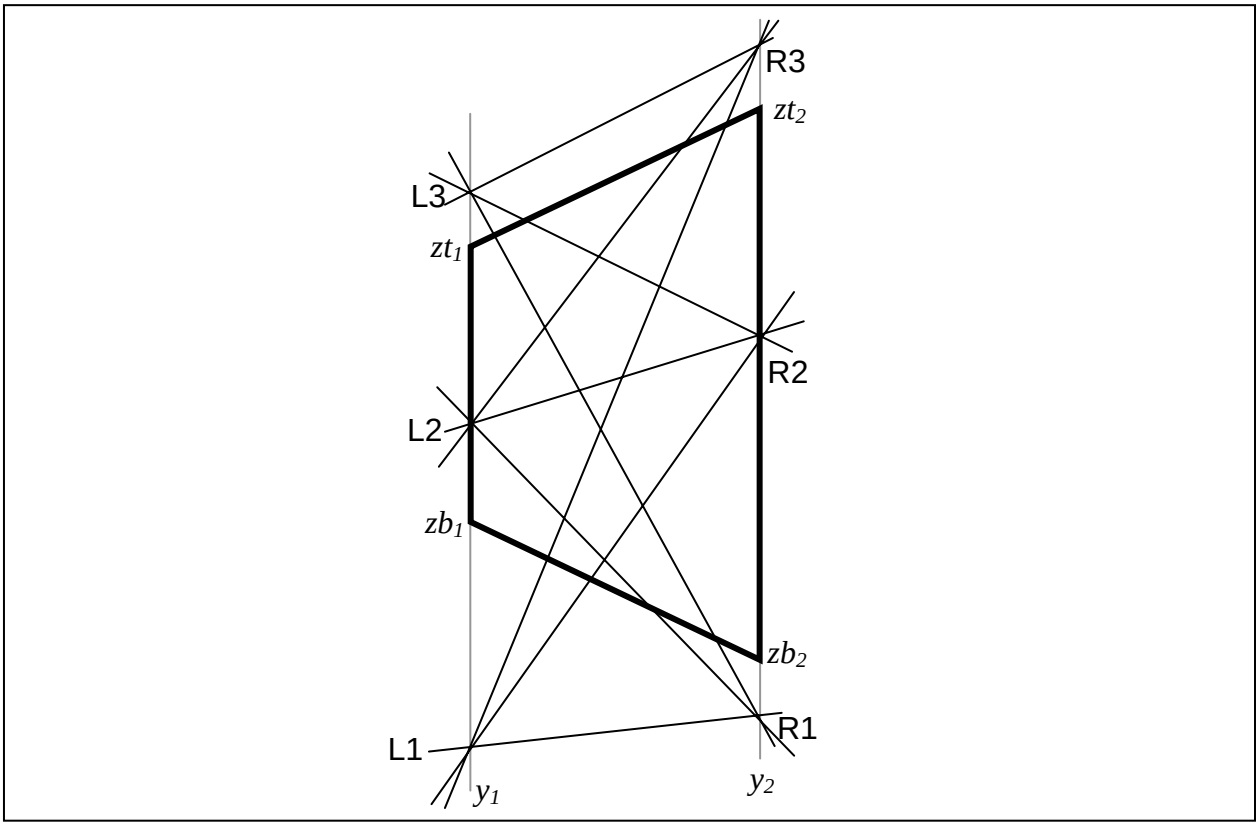
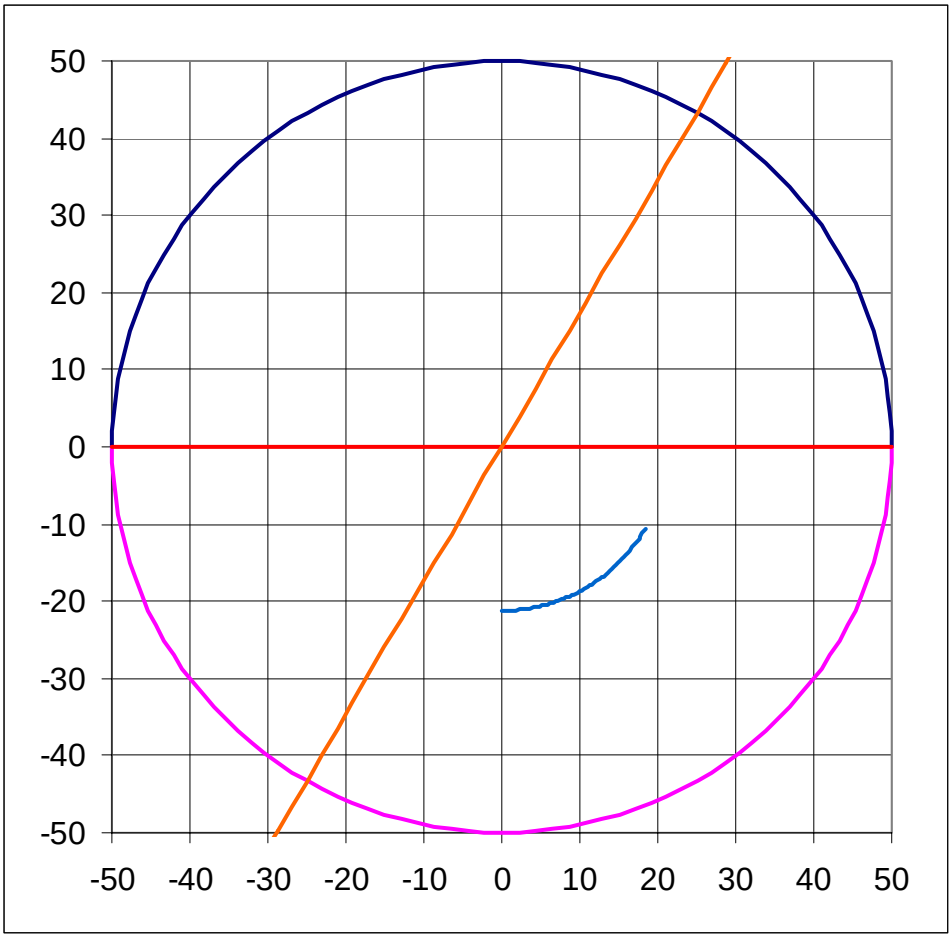



**Figure 4: Free Surface within a Tank Slice**



The same three cases apply to the right-hand side of the compartment slice, R1, R2 and R3, using subscript 2. Together, these give rise to nine possible intersections of the free surface with the left- and right-hand sides of a compartment slice, as shown in Figure 4. Case L1-R1 does not include any part of the compartment slice. Case L3-R3 includes the entire compartment slice. The other seven cases include part of the compartment slice, and enclose a triangular, quadrilateral or pentagonal area beneath the free surface and within the vertical sides and top of the compartment slice. The area and centre of gravity location of the fluid enclosed within the compartment slice are computed. The y- and z-moments of the fluid are computed about the vertical and horizontal principal axes respectively, and are accumulated for all compartment slices. The overall fluid centre of gravity is computed by dividing the sums of the y- and z-moments for all compartment slices by the total area of fluid. Figure 5 shows a typical result for the locus of the centre of gravity of the fluid in a circular tank with a diameter of 100 in. The upper and lower parts of the tank shell are shown as semi-circular arcs, the initial and final free surfaces (0 and 60 deg) are shown as straight lines, and the locus of the fluid centre of gravity as the free surface angle moves from 0 and 60 deg is shown as an arc.

**Figure 5: Locus of Fluid Centre of Gravity**



The calculation of the fluid centre of gravity in a tank compartment is time-consuming, as there are a large number of compartment slices, and it is necessary to use an iterative procedure to determine the free surface height. The simulation itself proceeds in a large number of small steps of lateral acceleration, and requires the location of the instantaneous centre of gravity of the fluid in each compartment as a function of free surface angle at each step. The centre of gravity of the fluid in each compartment is therefore generated for 1 deg increments in the free surface angle from zero to 60 deg, and the results are stored in tables. A free surface angle of 60 deg corresponds (for example) to a lateral acceleration of 1.00 g and a tank roll angle of about 15 deg, both of which are well beyond the capability of any tank truck.

A simulation run requires the location of the instantaneous centre of gravity of the fluid in each compartment for specific values of lateral acceleration and tank roll angle. These are used to compute the instantaneous free surface angle, and the centres of gravity are then determined by linear interpolation in the tables of centre of gravity for each compartment. This process is much faster than computing the centre of gravity directly as required, though it may be slightly less accurate. However, the parameters chosen, radii at 2.5 deg intervals, and a tight tolerance on the iteration for free surface height, result in a centre of gravity within 0.25 mm (0.01 in) of the exact location for all free surface angles for a circular tank, which is within 0.1% most of the time. By way of contrast, some of the physical parameters, like the suspension force-displacement relationship, and others, are of unknown accuracy, and may be within 10% some of the time.

## 2.6 Equations of Motion

The equations of motion follow those used in the Static Roll Model [3], with additional terms to reflect movement of the centre of gravity of the fluid [6], calculated as described above.

### 2.6.1 Vehicle Model

A schematic longitudinal vehicle model is shown in Figure 6. It consists of a power unit that is divided into two sprung masses, and may tow one or two semitrailers, each of which is an additional sprung mass. A power unit alone is a straight truck, and has two sprung masses. A tractor towing a semitrailer is a tractor-semitrailer, and has three sprung masses. A tractor towing a semitrailer that tows a second semitrailer is a B-train, and has four sprung masses. Sprung masses are numbered 1 through 4, from front to rear. All fixed axles on a vehicle unit are lumped together as a single equivalent axle. The power unit and any second semitrailer may also be equipped with a liftable axle, and the lead semitrailer may be equipped with up to three liftable axles, also lumped together as a single equivalent axle, all shown as in ghost images in Figure 6.

The power unit is divided into two sprung masses connected by a torsionally compliant frame, as shown in Figure 6. The frame has stiffness $KTR$ and Coulomb friction $CTR$, which results in the force-displacement relationship shown in Figure 7.

**Figure 6: Longitudinal Vehicle Model**

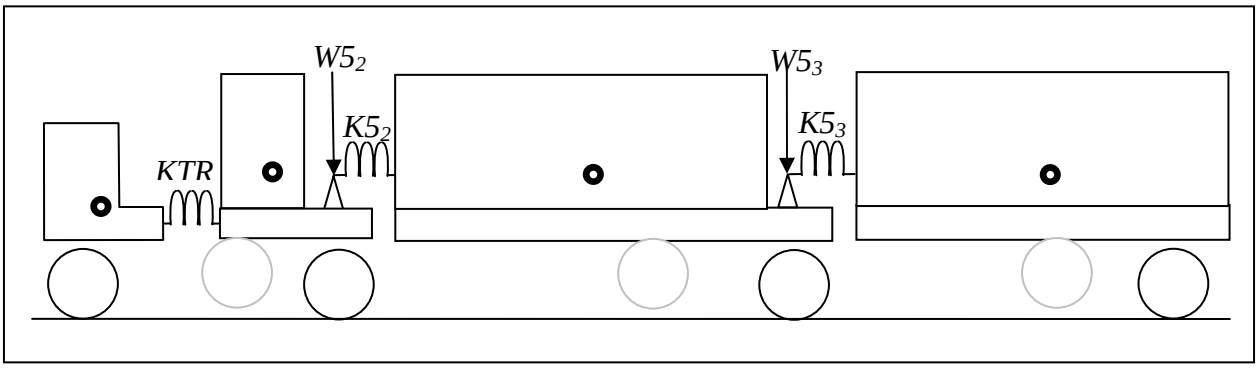



**Figure 7: Force-displacement Characteristic of Power Unit Frame**

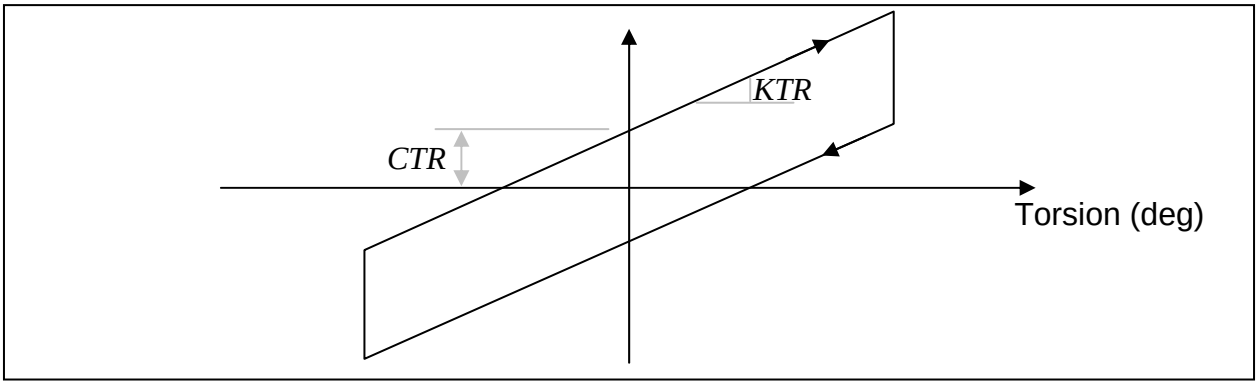
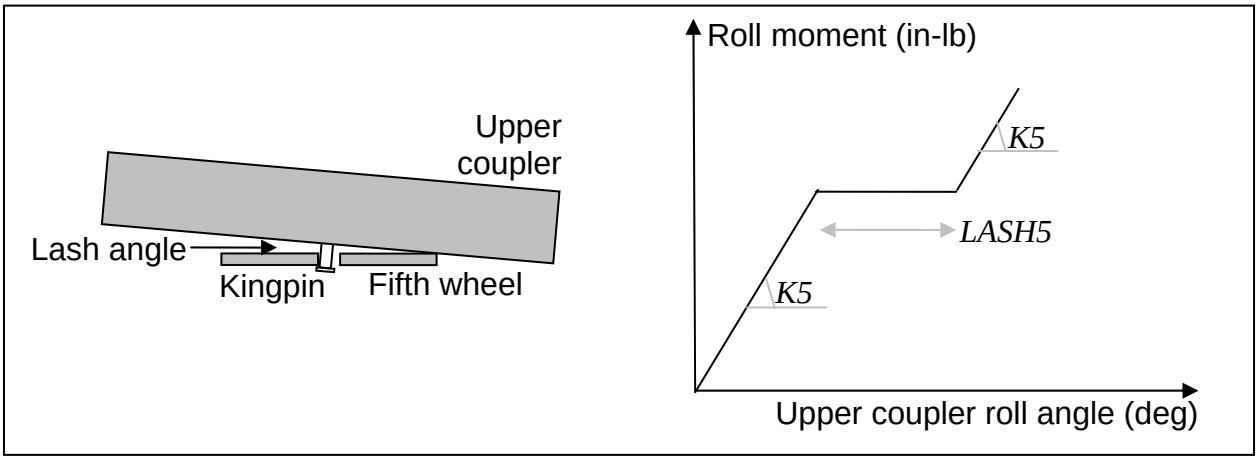


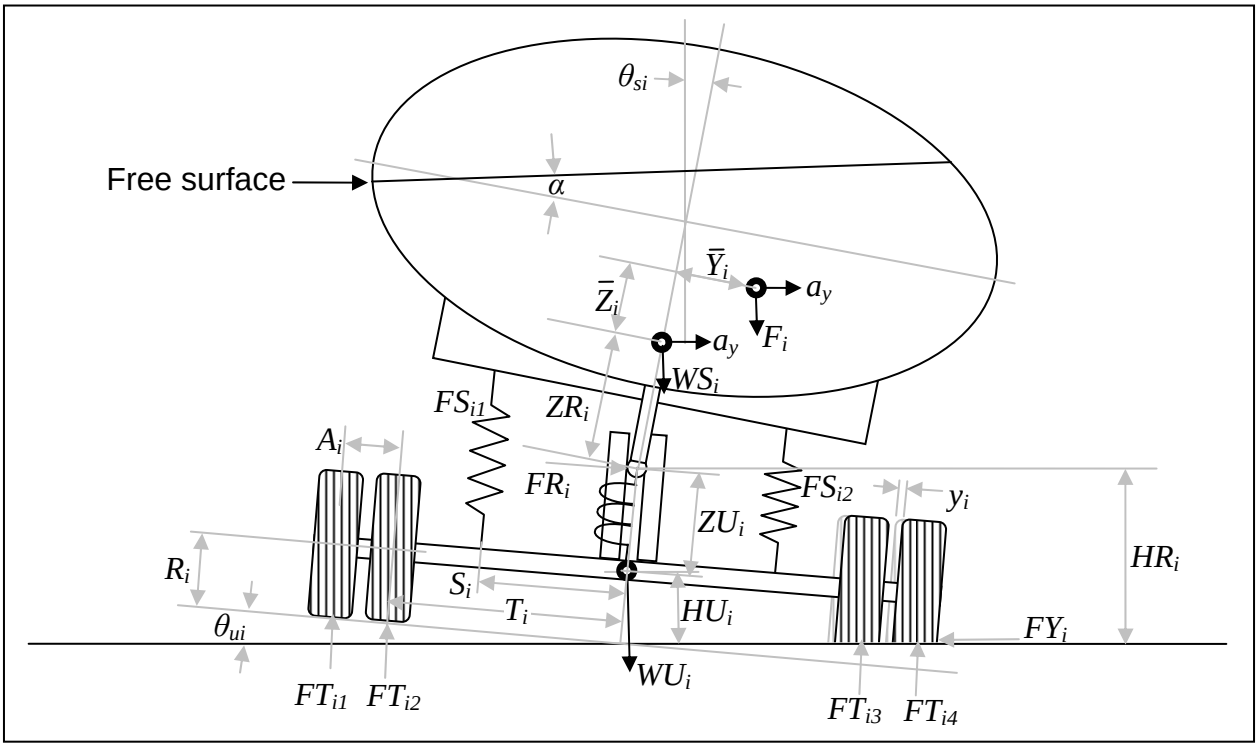

**Figure 8: Fifth Wheel Separation Lash**



A semitrailer that is vehicle unit $i+1$ is towed by a fifth wheel attached to vehicle unit $i$, as shown in Figure 6. The stiffness of a fifth wheel and the torsional compliance of the frame of the towed semitrailer are lumped together as a composite torsional stiffness $K5_i$. The upper coupler on a semitrailer is attached to the fifth wheel by means of a kingpin, which typically has some vertical lash. This lash allows the upper coupler to roll about the edge of the fifth wheel, as shown in Figure 8, which results in the force-displacement relationship also shown in Figure 8. When the moment due to lateral acceleration of the sprung mass exceeds the weight on the fifth wheel times half the width of the fifth wheel, the sprung mass rolls freely through the lash angle until the bottom of the kingpin engages its latch and prevents further roll.

A schematic roll model for one vehicle unit is shown in Figure 9. It consists of a fixed axle unit, referred to as the unsprung mass, and a body, referred to as the sprung mass. The sprung mass is constrained to roll about a roll centre which has freedom to move along a vertical normal to the centre-line of the axle, as indicated by dimension $ZU_i$ in Figure 9. The suspension consists of two main springs that are assumed to remain normal to the axle, in parallel with a torsion bar that represents the auxiliary roll stiffness of the suspension, whether or not the suspension is actually equipped with a torsion bar. The main springs may be non-linear, which represents hardening and lash in a steel suspension, and air spring characteristics in an air suspension. The torsion bar is assumed to be linear. The sprung mass has freedom to roll, as indicated by angle $\theta_{si}$.

**Figure 9: Roll Model**



The unsprung mass has freedom to move vertically relative to the ground, as indicated by dimension $HU_i$ in Figure 9, has freedom to move laterally relative to the ground against the lateral stiffness of the tires, as indicated by dimension $y_i$, and has freedom to roll, as indicated by angle $\theta_{ui}$.

### 2.6.2 Equations for Sprung Mass Roll Moment

The roll moment on the sprung mass of vehicle unit $i$ is:

$$F_{i1}(s_i + ZR_i \sin(\theta_{si} - \theta_{ui})) - F_{i2}(s_i - ZR_i \sin(\theta_{si} - \theta_{ui})) - FR_i ZR_i \cos(\theta_{si} - \theta_{ui}) + \alpha_i + \beta_i + \gamma_i + \delta_i + \varepsilon_i = 0$$

Equation 4

where $F_{ij}$ = vertical load on spring $j$ of the fixed axle group on vehicle unit $i$;

$s_i$ = distance of a spring of the fixed axle group on vehicle unit $i$ from the centre line of the vehicle;

$FR_i$ = lateral force acting through the roll centre parallel to the axle of vehicle unit $i$;

$ZR_i$ = vertical distance from the roll centre to the centre of gravity of the sprung mass of vehicle unit $i$;

$\theta_{si}$ = roll angle of the sprung mass of vehicle unit $i$;

$\theta_{ui}$ = roll angle of the fixed axle group of vehicle unit $i$;

$\alpha_i$ = roll moment due to torsional compliance of the power unit;

$\beta_i$ = roll moment due to shear force acting on the tractor frame;

$\gamma_i$ = roll moment due to fifth wheel load on a tractor;

$\delta_i$ = roll moment due to torsional compliance of a fifth wheel; and

$\varepsilon_i$ = roll moment due to movement of a fluid load on vehicle unit $i$.

Assuming the roll angles are small, and there are small deviations about an equilibrium position due to a small change in lateral acceleration $\Delta a_y$, the incremental roll moment on the sprung mass of vehicle unit $i$ is:

$$(\Delta F_{i1} - \Delta F_{i2})s_i + (\Delta F_{i1} + \Delta F_{i2})ZR_i(\theta_{si} - \theta_{ui}) + (F_{i1} + F_{i2})ZR_i(\Delta\theta_{si} - \Delta\theta_{ui}) + \Delta FR_i ZR_i + \Delta\alpha_i + \Delta\beta_i + \Delta\gamma_i + \Delta\delta_i + \Delta\varepsilon_i = 0$$

Equation 5

The suspension force $F_{ij}$ is given by:

$$F_{ij} = K_{ij}(ZU_i + (-1)^j s_i \sin(\theta_{si} - \theta_{ui}))$$

Equation 6

where $K_{ij}$ = vertical stiffness of spring $j$ of the fixed axle group on vehicle unit $i$; and
$ZU_i$ = vertical movement of the unsprung mass of the fixed axle group on vehicle unit $i$.

$$\therefore \Delta F_{ij} = K_{ij}(\Delta ZU_i + (-1)^j s_i(\Delta\theta_{si} - \Delta\theta_{ui}))$$

Equation 7

The lateral force $FR_i$ acting through the roll centre parallel to the axle of vehicle unit $i$ is given by:

$$FR_i = (WAXL_i - WU_i)(a_y - \theta_{ui})$$

Equation 8

where $WAXL_i$ = total weight on the fixed axle group of vehicle unit $i$; and
$WU_i$ = total unsprung weight of the fixed axle group on vehicle unit $i$.

$$\therefore \Delta FR_i = (WAXL_i - WU_i)(\Delta a_y - \Delta\theta_{ui})$$

Equation 9

The roll moment due to roll torsional compliance of the power unit frame $\alpha_i$ is:

$$\alpha_i = (-1)^i KTR(\theta_{si+1} - \theta_{si}) \quad \text{if } i = 1, \text{ and zero if } i > 1$$

Equation 10

where $KTR$ = torsional stiffness of power unit frame.

$$\therefore \Delta\alpha_i = (-1)^i KTR(\Delta\theta_{si+1} - \Delta\theta_{si}) \quad \text{if } i = 1, \text{ and zero if } i > 1$$

Equation 11

The roll moment due to shear force acting on the power unit frame $\beta_i$ is:

$$\beta_i = (-1)^{i+1} WFR.ZFR(a_y - \theta_{si}) \quad \text{if } i = 1 \text{ or } i = 2, \text{ and zero if } i > 2$$

Equation 12

where $WFR$ = shear force on power unit frame; and
$ZFR$ = distance from ground to top of power unit frame.

$$\therefore \Delta\beta_i = (-1)^{i+1} WFR.ZFR(\Delta a_y - \Delta\theta_{si})$$

Equation 13

The roll moment due to fifth wheel load on a tractor $\gamma_i$ is:

$\gamma_i = (-1)^i W5_i Z5_i (a_y - \theta_{si})$ if $i > 1$, and zero if $i = 1$ or $i = 4$

Equation 14

where $W5_i$ = vertical load on fifth wheel on vehicle unit $i$; and
$Z5_i$ = distance from ground to top of fifth wheel on vehicle unit $i$.

$\therefore \Delta\gamma_i = (-1)^i W5_i Z5_i (\Delta a_y - \Delta\theta_{si})$ if $i > 1$, and zero if $i = 1$ or $i = 4$

Equation 15

The roll moment due to torsional compliance of a fifth wheel $\delta_i$ is:

$\delta_i = (-1)^i K5_i (\theta_{si+1} - \theta_{si})$ if $i > 1$, and zero if $i = 1$ or $i = 4$

Equation 16

where $K5_i$ = roll stiffness of fifth wheel attached to vehicle unit $i$.

$\therefore \Delta\delta_i = (-1)^i K5_i (\Delta\theta_{si+1} - \Delta\theta_{si})$ if $i > 1$, and zero if $i = 1$ or $i = 4$

Equation 17

The roll moment due to fluid movement $\varepsilon_i$ is:

$\varepsilon_i = F_i \overline{Y_i}(1 + a_y\theta_{si}) - F_i \overline{Z_i}(\theta_{si} - a_y)$

Equation 18

where $F_i$ = total weight of all fluid in the tank of vehicle unit $i$;
$\overline{Y_i}$ = lateral centre of gravity of all fluid in the tank of vehicle unit $i$; and
$\overline{Z_i}$ = vertical centre of gravity of all fluid in the tank of vehicle unit $i$.

The incremental roll moment due to a small change in lateral acceleration $\Delta a_y$ is:

$\Delta\varepsilon_i = F_i \Delta\overline{Y_i}(1 + a_y\theta_{si}) + F_i \overline{Y}_i (\Delta a_y\theta_{si} + a_y\Delta\theta_{si}) - F_i \Delta\overline{Z_i}(\theta_{si} - a_y) - F_i \overline{Z_i}(\Delta\theta_{si} - \Delta a_y)$

Equation 19

$\Delta\overline{Y_i}$ is computed as the difference in $\overline{Y_i}$ between the last two steps of the simulation, and $\Delta\overline{Z_i}$ is computed similarly. These are approximations, but $\overline{Y_i}$ and $\overline{Z_i}$ both vary quite slowly with free surface angle, which itself changes slowly for the small steps in lateral acceleration used in the simulation.

Inserting results from Equation 6, Equation 7, Equation 9 and Equation 19 into Equation 5, the incremental roll moment on the sprung mass of vehicle unit $i$ due to a small change in

lateral acceleration $\Delta a_y$ is:

$$
\begin{aligned}
&-((K_{i1}s_i + K_{i2}s_i)s_i^2 + (K_{i1} - K_{i2})s_i ZR_i(\theta_{si} - \theta_{ui}) + (F_i\overline{Y}_i a_y - F_i\overline{Z_i}))\Delta\theta_{si} + \\
&((K_{i1}s_i + K_{i2}s_i)s_i^2 + (K_{i1} - K_{i2})s_i ZR_i(\theta_{si} - \theta_{ui}) - (WAXL_i - WU_i)ZR_i)\Delta\theta_{ui} + \\
&((K_{i1} - K_{i2})s_i + (K_{i1} + K_{i2})ZR_i(\theta_{si} - \theta_{ui}))\Delta ZU_i + \\
&\Delta\alpha_i + \Delta\beta_i + \Delta\gamma_i + \Delta\delta_i = \\
&-F_i\Delta\overline{Y_i}(1 + a_y\theta_{si}) + F_i\Delta\overline{Z_i}(\theta_{si} - a_y) - ((WAXL_i - WU_i)ZR_i + F_i\overline{Y}_i\theta_{si} + F_i\overline{Z_i})\Delta a_y
\end{aligned}
$$

Equation 20

The results from Equation 11, Equation 13, Equation 15 and Equation 17 can be inserted in Equation 20 as applicable to the vehicle unit.

### 2.6.3 Equations for Unsprung Mass Roll Moment

The roll moment for the sprung mass on vehicle unit $i$ is:

$$
\begin{aligned}
&-(F_{i1} - F_{i2})s_i + (FT_{i1} - FT_{i4})(T_i + A_i)\cos\theta_{ui} - (FT_{i3} + FT_{i4})y_i\cos\theta_{ui} + OVT_{i3} + OVT_{i4} + \\
&(FT_{i2} - FT_{i3})T_i\cos\theta_{ui} + FR_i ZU_i + FY_i HU_i + (FT_{i1} + FT_{i2} + FT_{i3} + FT_{i4})R_i\sin\theta_{ui} = 0
\end{aligned}
$$

Equation 21

where $FT_{ij}$ = vertical load on tire $j$ of the fixed axle group on vehicle unit $i$;

$T_i$ = distance of inner tire of the fixed axle group on vehicle unit $i$ from the centre line of the vehicle;

$A_i$ = distance between centre lines of dual tires of the fixed axle group on vehicle unit $i$;

$ZU_i$ = vertical distance from the roll centre to the centre of gravity of the unsprung mass of vehicle unit $i$;

$OVT_{ij}$ = overturning moment of tire $j$ of the fixed axle group on vehicle unit $i$;

$FY_i$ = lateral force acting through the roll centre parallel to the axle of vehicle unit $i$;

$HU_i$ = vertical distance from the ground to the centre of gravity of the unsprung mass of vehicle unit $i$; and

$R_i$ = rolling radius of tires of the fixed axle group on vehicle unit $i$.

Tire forces are given by:

$$
\begin{aligned}
FT_{i1} &= -KT_{i1}((T_i + A_i)\theta_{ui} - HU_i) \\
FT_{i2} &= -KT_{i2}(T_i\theta_{ui} - HU_i) \\
FT_{i3} &= KT_{i3}((T_i - y_i)\theta_{ui} + HU_i) \\
FT_{i4} &= KT_{i4}((T_i + A_i - y_i)\theta_{ui} + HU_i)
\end{aligned}
$$

Equation 22

Assuming the roll angles are small, and there are small deviations about an equilibrium position due to a small change in lateral acceleration $\Delta a_y$, the incremental roll moment on the sprung mass of vehicle unit $i$ is:

$$\Delta FT_{i1} = -KT_{i1}((T_i + A_i)\Delta\theta_{ui} - \Delta HU_i)$$
$$\Delta FT_{i2} = -KT_{i2}(T_i\Delta\theta_{ui} - \Delta HU_i)$$
$$\Delta FT_{i3} = KT_{i3}((T_i - y_i)\Delta\theta_{ui} - \Delta y_i\theta_{ui} + \Delta HU_i)$$
$$\Delta FT_{i4} = KT_{i4}((T_i + A_i - y_i)\Delta\theta_{ui} - \Delta y_i\theta_{ui} + \Delta HU_i)$$

Equation 23

The overturning moment of tire $j$ of the fixed axle group on vehicle unit $i$ is given by:

$$OVT_{ij} = KOVT_{ij}\theta_{ui}$$

Equation 24

where $KOVT_{ij}$ = overturning stiffness of tire $j$ of the fixed axle group on vehicle unit $i$.

$$\therefore \Delta OVT_{ij} = KOVT_{ij}\Delta\theta_{ui}$$

Equation 25

The lateral force on the fixed axle group on vehicle unit $i$ is given by:

$$FY_i = WAXL_i a_y$$

Equation 26

$$\therefore \Delta FY_i = WAXL_i \Delta a_y$$

Equation 27

Assuming the roll angles are small, and there are small deviations about an equilibrium position due to a small change in lateral acceleration $\Delta a_y$, the incremental roll moment on the sprung mass of vehicle unit $i$ is:

$$-(\Delta F_{i1} - \Delta F_{i2})s_i + (\Delta FT_{i1} - \Delta FT_{i4})(T_i + A_i) - (\Delta FT_{i3} + \Delta FT_{i4})y_i - (FT_{i3} + FT_{i4})\Delta y_i +$$
$$\Delta OVT_{i3} + \Delta OVT_{i4} + (\Delta FT_{i2} - \Delta FT_{i3})T_i + \Delta FR_i ZU_i + \Delta FY_i HU_i + FR_i \Delta ZU_i + FY_i \Delta HU_i +$$
$$(\Delta FT_{i1} + \Delta FT_{i2} + \Delta FT_{i3} + \Delta FT_{i4})R_i\theta_{ui} + (FT_{i1} + FT_{i2} + FT_{i3} + FT_{i4})R_i\Delta\theta_{ui} = 0$$

Equation 28

Inserting results from Equation 7, Equation 8, Equation 9, Equation 22, Equation 23, Equation 25, Equation 26 and Equation 27 Equation 26into Equation 28, and remembering

that:

$$(FT_{i1} + FT_{i2} + FT_{i3} + FT_{i4}) = WAXL_i$$

Equation 29

the incremental roll moment on the sprung mass of vehicle unit $i$ is:

$$\begin{aligned}
&(K_{i1} + K_{i2})s_i^2 \Delta\theta_{si} + \\
&(-(K_{i1} + K_{i2})s_i^2 - KT_{i1}(T_i + A_i)^2 - KT_{i2}T_i^2 - KT_{i3}(T_i - y_i)T_i - KT_{i4}((T_i + A_i - y_i)(T_i + A_i) + \\
&((-KT_{i1} + KT_{i4})(T_i + A_i) + (-KT_{i2} + KT_{i3})T_i - (KT_{i3} + KT_{i4})y_i)R_i\theta_{ui} - \\
&(KT_{i3}((T_i - y_i) + KT_{i4}((T_i + A_i - y_i))y_i\Delta\theta_{ui} + WAXL_iR_i - (WAXL_i - WU_i)ZU_i + \\
&KOVT_{i3} + KOVT_{i4})\Delta\theta_{ui} + \\
&(-(K_{i1} - K_{i2})s_i + (WAXL_i - WU_i)(a_y - \theta_{ui}))\Delta ZU_i + \\
&((KT_{i1} - KT_{i4})(T_i + A_i) + (KT_{i2} - KT_{i3})T_i + (KT_{i1} + KT_{i2} + KT_{i3} + KT_{i4})R_i\theta_{ui} - \\
&(KT_{i3} + KT_{i4})y_i + WAXL_ia_y)\Delta HU_i - \\
&(KT_{i3}((T_i - y_i)\theta_{ui} + HU_i) + KT_{i4}((T_i + A_i - y_i)\theta_{ui} + \\
&(KT_{i4}\theta_{ui}(T_i + A_i) + KT_{i3}\theta_{ui}T_i + (KT_{i3} + KT_{i4})\theta_{ui}y_i) + HU_i))\Delta y_i = \\
&-((WAXL_i - WU_i)ZU_i + WAXL_i.HU_i)\Delta a_y
\end{aligned}$$

Equation 30

When a vehicle unit has a liftable axle, and the axle is down, an additional equation similar to Equation 30 arises for the liftable axle.

### 2.6.4 Equations for Total Suspension Vertical Force

The total vertical force on the suspensions for the sprung mass on vehicle unit $i$ is:

$$(F_{i1} + F_{i2}) = (WAXL_i - WU_i)\cos\theta_{ui} + (WAXL_i - WU_i)a_y \sin\theta_{ui}$$

Equation 31

Inserting the suspension forces from Equation 6 in Equation 31 gives:

$$(K_{i1} + K_{i2})ZU_i - (K_{i1} - K_{i2})s_i \sin(\theta_{si} - \theta_{ui}) = (WAXL_i - WU_i)\cos\theta_{ui} + (WAXL_i - WU_i)a_y \sin\theta_{ui}$$

Equation 32

Assuming the roll angles are small and there are small deviations about an equilibrium position due to a small change in lateral acceleration $\Delta a_y$, then:

$$(K_{i1} + K_{i2})\Delta ZU_i - (K_{i1} - K_{i2})s_i(\Delta\theta_{si} - \Delta\theta_{ui}) - (WAXL_i - WU_i)a_y\Delta\theta_{ui} = (WAXL_i - WU_i)\theta_{ui}\Delta a_y$$

Equation 33

When a vehicle unit has a liftable axle, and the axle is down, an additional equation similar to Equation 33 arises for the liftable axle.

### 2.6.5 Equations for Tire Vertical Force

The vertical force on the tires for the fixed axle group on vehicle unit $i$, $WAXL_i$ is:

$$(FT_{i1} + FT_{i2} + FT_{i3} + FT_{i4}) = WAXL_i$$

Equation 34

Substituting from Equation 22 into Equation 34, and assuming the roll angles are small and there are small deviations about an equilibrium position due to a small change in lateral acceleration $\Delta a_y$, then:

$$((-KT_{i1} + KT_{i4})(T_i + A_i) + (-KT_{i2} + KT_{i3})T_i - (KT_{i3} + KT_{i4})y_i)\Delta\theta_{ui}$$
$$+ (KT_{i1} + KT_{i2} + KT_{i3} + KT_{i4})\Delta HU_i + (KT_{i3} + KT_{i4})\theta_{ui}\Delta y_i = 0$$

Equation 35

When a vehicle unit has a liftable axle, and the axle is down, an additional equation similar to Equation 35 arises for the liftable axle.

### 2.6.6 Equations for Lateral Forces on the Low-side Tires

The lateral force on the low-side tires for the fixed axle group on vehicle unit $i$, $F_{yi}$ is:

$$F_{yi} = (KYT_{i3} + KYT_{i4})y_i \cos\theta_{ui} = WAXL_i a_y$$

Equation 36

where $KYT_{ij}$ = the lateral stiffness of tire $j$ for the fixed axle group on vehicle unit $i$.

Assuming the roll angles are small and there are small deviations about an equilibrium position due to a small change in lateral acceleration $\Delta a_y$, the incremental lateral force on the low-side tires due to a small change in lateral acceleration $\Delta a_y$ is:

$$(KYT_{i3} + KYT_{i4})\Delta y_i = WAXL_i \Delta a_y$$

Equation 37

When a vehicle unit has a liftable axle, and the axle is down, an additional equation similar to Equation 37 arises for the liftable axle.

### 2.6.7 Equations of Motion

Each sprung mass is represented by one equation for $\Delta\theta_{si}$. Each unsprung mass, whether for a fixed or liftable axle, is represented by four equations, for $\Delta\theta_{ui}$, $\Delta ZU_i$, $\Delta HU_i$ and $\Delta y_i$. Each sprung mass is coupled to the unsprung masses attached to it, and is also coupled to the vehicle unit that tows it, if any, and the vehicle unit it tows, again, if any.

The equations of motion are a set of linear equations for the static roll equilibrium of the vehicle that are expressed in matrix form as:

$$[A]\langle \Delta x \rangle = \langle b \rangle \Delta a_y$$

Equation 38

$$\langle x_{i+1} \rangle = \langle x_i \rangle + (\Delta x)$$

Equation 39

where $[A]$ = matrix of coefficients;

$\langle \Delta x \rangle$ = vector of increments of independent variables;

$\langle b \rangle$ = vector of right-hand sides;

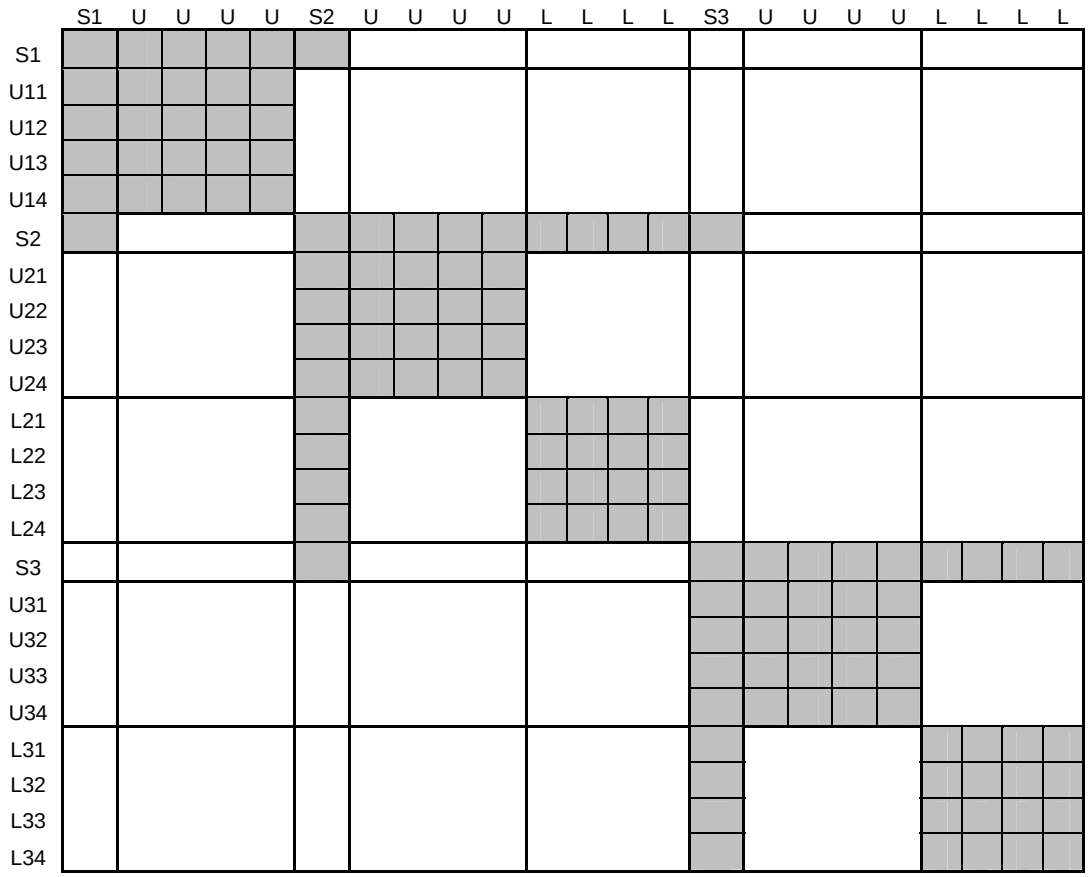
$\Delta a_y$ = increment of lateral acceleration, in g; and

$\langle x_i \rangle$ and $\langle x_{i+1} \rangle$ = values of independent variables at consecutive steps $i$ and $i+1$ during the simulation.

The number of equations in this system depends on the vehicle that is being modeled, as discussed in Section 5.6 below. Figure 10 illustrates the structure of the system of equations for a tractor-semitrailer, where each row represents one equation. The shaded cells have entries, the un-shaded cells are empty. The coding Si refers to the equation for sprung mass i. The coding Uij or Lij refers to the j'th equation for sprung mass i for a fixed or liftable axle respectively. A B-train would have nine extra equations, continuing the structure of those for S3, U3 and L3.

The vehicle is initially upright and not subject to any lateral acceleration. The coefficients of $[A]$ and $\langle b \rangle$ are determined for this state, Equation 38 is solved for the increments of independent variables $\langle \Delta x \rangle$ for a small increment in lateral acceleration $\Delta a_y$, and the independent variables are updated in accordance with Equation 39. The process is repeated for further small increments in lateral acceleration $\Delta a_y$ until all high-side wheels, except the front axle, lift off. The lateral acceleration at this point is considered the rollover threshold for the vehicle. Results are saved for the initial condition, for convenient regular steps in lateral acceleration, typically every 0.01 g, and for the final step.

**Figure 10: Structure of Equations of Motion**




## 2.7 Outputs

Outputs available from the model include:

- Load transfer ratio;
- Wheel loads;
- Sprung mass roll angles;
- Unsprung mass roll angles;
- Tire deflections;
- Tire loads;
- Spring deflections;
- Spring forces; and
- The locus of the composite fluid centre of gravity for each tank.

The load transfer ratio $LTR$ is a measure of vehicle rollover performance, computed continuously from low- and high-side wheel loads as:

$$LTR = (\sum L - \sum H) / \sum (L + H)$$

Equation 40

where $L$ = instantaneous low-side wheel loads;
$H$ = corresponding instantaneous high-side wheel loads; and
$\sum$ indicates summation over all wheels on one side of the vehicle, except for the front axle.

The front axle is excluded from the summations, because a typical heavy vehicle becomes unstable in roll well before the high-side front wheel lifts off. The load transfer ratio is initially zero when the lateral acceleration is zero, because $\sum L = \sum H$. The load transfer ratio rises to 1.0 when all high-side wheels considered have lifted, when $\sum H = 0$.

These outputs are computed at each output step, from an initial lateral acceleration of 0.00 g, then in specified steps, up to the exact rollover threshold when all high-side wheels have lifted off, to the nearest 0.0005 g. Roll angles are expressed in degrees, deflections in inches, and loads and forces in pounds. The load transfer ratio is non-dimensional.

## 2.8 Restrictions and Limitations

The model has at least the following restrictions and limitations:

1. The model does not include the effect of Coulomb friction in suspensions. It is assumed that a suspension will break out and allow the vehicle body to roll freely.
2. The model assumes that each tank is rigid in torsion.
3. The model may be run with no tanks defined, when it essentially defaults to the original UMTRI Static Roll Model extended to represent a B-train with the possibility of more than one axle group per vehicle unit.
4. Results will depend on the extent to which the configuration of the vehicle and the torsional stiffness of its body conform to the assumptions of the model.
5. The simulation will usually run with any input data set that passes the error checks. The results of the simulation depend critically on the validity of the input data.
6. Reliable results and conclusions can only be expected when the user has sufficient understanding of vehicle configuration, vehicle component properties and vehicle dynamics to be able to distinguish between input data that are realistic and input data that are unrealistic, and results that are reasonable and results that are unreasonable.

## 2.9 Nomenclature

This section collects together all variables used in equations developed in this Chapter, and presents them in alphabetical order.

$a$ = length of horizontal principal axis of a tank.
$a_y$ = lateral acceleration of vehicle.
$A_i$ = distance between centre lines of dual tires of the fixed axle group on vehicle unit $i$.
$b$ = length of vertical principal axis of a compartment.
$b_{top}$ = length of vertical principal axis of the top of a compartment.
$b_{bot}$ = length of vertical principal axis of the bottom of a compartment.
$F_i$ = total weight of all fluid in the tank of vehicle unit $i$.
$F_{ij}$ = vertical load on spring $j$ of the fixed axle group on vehicle unit $i$.
$FR_i$ = lateral force acting through the roll centre parallel to the axle of vehicle unit $i$.
$FT_{ij}$ = vertical load on tire $j$ of the fixed axle group on vehicle unit $i$.
$FY_i$ = lateral force acting through the roll centre parallel to the axle of vehicle unit $i$.
$HU_i$ = distance of the centre of gravity of the unsprung mass (axle) of vehicle unit $i$ above the ground.
$K_{ij}$ = vertical stiffness of spring $j$ of the fixed axle group on vehicle unit $i$.
$KOVT_{ij}$ = overturning stiffness of tire $j$ of the fixed axle group on vehicle unit $i$.
$KTR$ = torsional stiffness of power unit frame.
$KYT_{ij}$ = the lateral stiffness of tire $j$ for the fixed axle group on vehicle unit $i$.
$K5_i$ = roll stiffness of fifth wheel attached to vehicle unit $i$.
$LTR$ = load transfer ratio.
$n$ = exponent in generalized ellipse formula for tank cross-section.
$OVT_{ij}$ = overturning moment of tire $j$ of the fixed axle group on vehicle unit $i$.
$R_i$ = rolling radius of tires of the fixed axle group on vehicle unit $i$.
$s_i$ = distance of a spring of the fixed axle group on vehicle unit $i$ from the centre line of the vehicle.
$T_i$ = distance of inner tire of the fixed axle group on vehicle unit $i$ from the centre line of the vehicle.
$WAXL_i$ = total weight on the fixed axle group of vehicle unit $i$.
$WFR$ = shear force on power unit frame.
$WU_i$ = total unsprung weight of the fixed axle group on vehicle unit $i$.
$W5_i$ = vertical load on fifth wheel on vehicle unit $i$.
$y_i$ = lateral movement of the unsprung mass (axle) of vehicle unit $i$.
$\overline{Y_i}$ = lateral centre of gravity of all fluid in the tank of vehicle unit $i$.
$\overline{Z_i}$ = vertical centre of gravity of all fluid in the tank of vehicle unit $i$.
$ZFR$ = distance from ground to top of power unit frame.
$ZR_i$ = vertical distance from the roll centre to the centre of gravity of the sprung mass of vehicle unit $i$.
$ZU_i$ = distance of the roll centre of the sprung mass (body) of vehicle unit $i$ above its axle.

$Z5_i$ = distance from ground to top of fifth wheel on vehicle unit $i$.

$\alpha$ = free surface angle relative to compartment horizontal principal axis.

$\alpha_i$ = roll moment due to torsional compliance of the power unit.

$\beta_i$ = roll moment due to shear force acting on the tractor frame.

$\gamma_i$ = roll moment due to fifth wheel load on a tractor.

$\delta_i$ = roll moment due to torsional compliance of a fifth wheel.

$\varepsilon_i$ = roll moment due to movement of a fluid load on vehicle unit $i$.

$\theta_{si}$ = roll angle of the sprung mass (body) of vehicle unit $i$.

$\theta_{ui}$ = roll angle of the unsprung mass (axle) of vehicle unit $i$.

$[A]$ = matrix of coefficients.

$\langle \Delta x \rangle$ = vector of increments of independent variables.

$\langle b \rangle$ = vector of right-hand sides.

$\langle x_i \rangle$ = values of independent variables at step $i$ during the simulation.

# 3. MODEL IMPLEMENTATION

The model exists as two separate but co-operating modules, an Excel workbook for data entry and results, and a stand-alone program that does the rollover computations. The Excel workbook has a worksheet where a user enters data to describe the vehicle, its tanks, and the contents of those tanks. The user then clicks a button to execute a simple one-line Excel macro that starts the stand-alone simulation program. The simulation reads the input data from the Excel worksheet, conducts the simulation, and places results back into pre-assigned locations in other worksheets of the Excel Workbook, which include basic post-processing and display of results. There are several advantages to this approach:

1. The Excel data input worksheet is programmed with data consistency and data error checks on input data provided by the user.
2. The stand-alone program will not run unless the input data in the Excel worksheet are error-free. This eliminates the need for error checking in the stand-alone program, and eliminates runs that might be made with incomplete or seriously erroneous data.
3. Dropping the simulation results back into the Excel workbook for post-processing eliminates a substantial amount of programming in the stand-alone program, and is a step that many users would make anyway, for their own purposes.
4. Excel provides a user with a wide range of facilities of to compute inputs, additional outputs, or additional or alternative displays of results.
5. A user may cut and paste or link results from the Excel workbook into other programs.
6. Many users of the simulation will already be capable users of Excel, so can focus on the meaning of input data and outputs rather than having to learn how to use a stand-alone program that did data input, simulation and output.

The Excel Workbook was composed in Microsoft Excel 2002 from Microsoft Office XP (SP3). The stand-alone program was composed in Microsoft Visual Basic 6.0 (SP5) using the Microsoft Visual Studio programming environment, and is compiled for fast execution. The system is known to run under the Microsoft Windows 2000 and Windows XP Home Edition (SP2) operating systems, using both Excel 97 and Excel 2002. It has not been tested under other versions of Windows or for other versions of Excel.

The stand-alone program was based on the original Static Roll Model [3], translated from FORTRAN into Visual Basic, with the equations of motion re-arranged so that equivalent lateral acceleration is the independent variable, rather than trailer roll angle. The generalized tank model from the Excel model [4] was added, and its code was re-arranged and tightened to improve computational efficiency, accuracy and reliability, and extended to allow up to five compartments in each of two tanks, with each compartment allowed a different cross-section and fill level.

# 4. MODEL VALIDATION

The ultimate model, in all its generality, is rather complex, and there is no practical way to validate it. Validation was therefore conducted in a step-by-step manner, as the work progressed.

1. Check that base Visual Basic program produces the same results as the base FORTRAN version of the Static Roll Model for the examples given in [3].
2. Check that the modified Visual Basic program produces the same results as the base FORTRAN version of the Static Roll Model for the examples given in [3].
3. Construct a rigid block model, and check that the Visual Basic program produces rollover for T/2h.
4. Make tires flexible, and check that the Visual Basic program produces the correct rollover threshold for roll stiffness.
5. Check that the tank model produces correct tank area, fluid area and c.g. shift for circular and elliptical tanks with various levels of fill.
6. Construct a rigid block model with a circular tank, and check that the Visual Basic program produces the correct rollover threshold for various fill levels.
7. Compare axle group loads and body roll angles predicted by simulation with the results of tilt tests for a range of tank trucks recently tested at NRC/CSTT [2].

The model passed all of these checks. This outcome does not guarantee that it will produce a realistic estimate of the roll threshold of a particular vehicle, without validation of the input data for that vehicle.

# 5. USER'S GUIDE

## 5.1 The Excel Master Workbook

The Excel Master Workbook is the basis for the simulation. It has six worksheets:

1. **Start** contains a brief description of the other worksheets;
2. **Data** is for entry of vehicle, simulation, tank and tank payload data;
3. **Tank** receives intermediate tank compartment calculations;
4. **Simulation** receives the simulation results;
5. **Plots** displays graphs of selected static roll simulation results; and
6. **Summary** combines key information from other worksheets onto a single sheet that can be printed.

## 5.2 Execution

The following steps are necessary to conduct a simulation:

1. Ensure that a copy of the Excel Master Workbook and the stand-alone program are both in the subdirectory for the project to be conducted.
2. Open the Excel Master Workbook by using the "Open" option of the Excel "File" menu, which ensures that the project subdirectory becomes the active subdirectory. The Master Workbook includes a macro, so when a dialogue box comes up asking about macros, click "Enable Macros". A simulation cannot be run if macros are disabled.
3. Select the **Data** worksheet.
4. Enter a file name that identifies the run to be made in Cell C5. This must be different than the file name of the Master Workbook. The program does not allow data to be saved into the Master Workbook.
5. Enter vehicle, tank and simulation data into the **Data** worksheet.
6. The simulation will not run if the data are not error-free. Cell M4 of the **Data** worksheet indicates the number of errors in the data as input. Edit cells until all data are correct and the built-in error checks show that the data are error-free.
7. Click the button labeled "Run" to execute the stand-alone program. Cell M5 will indicate that the stand-alone program is "Running".
8. When the stand-alone program finishes normally, Cell M5 indicates that the run is "Done". The tank calculations are found in the **Tank** worksheet of the Excel Workbook, the simulation results are found in the **Simulation** worksheet, and built-in graphs in the **Plots** worksheet display certain simulation results.
9. If the stand-alone program terminates with an internal error condition, Cell M5 will indicate "Error". Any results up to that point placed in the **Tank** or **Simulation** worksheets may or may not be meaningful.

A simulation is intended to be run only as described above. If the stand-alone program is executed independently, it will not be able to find the active Workbook, and will crash. The Excel Master Workbook SRMTT*mnn*.xls, and the stand-alone program SRMTT*mnn*.exe

each have their version number *mnn* included in the file name. The stand-alone program will only run when executed from an Excel workbook saved from the Excel Master Workbook with the same version number.

### 5.3 Data Input

Data are entered in the **Data** worksheet, shown in Figure 11. The **Data** worksheet has eight data blocks:

1. The **Run Identification** data block identifies the run;
2. The **Vehicle Identification** data block identifies the vehicle;
3. The **Weight Distribution** data block computes the axle weights of the vehicle;
4. The **Vehicle** data block describes the vehicle for simulation;
5. The **Suspension** data block contains the force-displacement relationship for one spring in each suspension;
6. The **Tank** data block contains the tank geometry and any content information;
7. The **Simulation Condition** data block contains information to control the simulation; and
8. The **User Calculation Area** allows a user all the facilities of Excel to make any preliminary calculations of inputs that the user considers necessary.

Data may be entered in cells with a grey background, and the data entered appear in blue. Data that appear in black in a cell with a white background are computed internally within the worksheet, and cannot be over-ridden. Other cells are not available to the user, except for the **User Calculation Area**, described below.

Data must be entered in inches and pounds. Any original data that occur in metric or other units may be converted using the following built-in named constants

- UTF, to convert U.S. gallons to cubic feet;
- ITF, to convert Imperial gallons to cubic feet;
- LTF, to convert litres to cubic feet;
- KTP, to convert kilograms to pounds; and
- MTI, to convert metres to inches.

The **Data** worksheet contains validity checks in columns L through P, with one cell corresponding to each cell in which the user may enter data. The error check indicates “OK” if the data in the field passes the check, and it indicates “Error” if the data do not pass the check. The total number of fields with an error appears in Cell M4. The validity of data in some cells may depend on data in other cells. The **Data** worksheet in the Master Workbook is initially empty, and the absence of data from those fields that constitute the minimum valid run provokes a number of “Error” indicators. As a user enters valid data in these fields, “Error” indicators are replaced by “OK” indicators. As the user starts to enter data for a trailer, this will provoke “Error” indicators in a number of fields without data. Again, as valid data are entered in these fields, “Error” indicators are replaced by “OK” indicators.

## Figure 11: Data Workbook

**NRC/CSTT STATIC ROLL MODEL FOR TANK TRUCKS** Version 1.00 21-Feb-2005

| | | |
|---|---|---|
| Title | | |
| Save file name | | 24-Feb-05 1:54 PM |

**VEHICLE IDENTIFICATION**

| Information | Power Unit | Lead trailer | Rear trailer |
|---|---|---|---|
| Vehicle manufacturer | | | |
| Model | | | |
| Vehicle model year | | | |
| VIN | | | |
| License plate, province | | | |
| Owner | | | |
| Owner's address | | | |
| Tank manufacturer | | | |
| Tank specification | | | |
| Tank model year | | | |

**WEIGHT DISTRIBUTION DATA**

| Power Unit Data | Units | | Trailer Data | Units | Lead | Rear |
|---|---|---|---|---|---|---|
| BBC | in | | Length | in | | |
| Front axle setback | in | | Kingpin setback | in | | |
| Wheelbase | in | | Wheelbase | in | | |
| Number of drive axles | in | | Number of fixed axles | in | | |
| Drive axle spread | in | | Axle spread | in | | |
| Fifth wheel setting | in | | Fifth wheel setting | in | | |
| Sprung weight | lb | | Sprung weight | lb | | |
| Unsprung front axle weight | lb | | Unsprung fixed axle we | lb | | |
| Unsprung drive axle weight | lb | | | | | |
| Front axle tare weight | lb | | Trailer axle tare weight | lb | | |
| Liftable axle location | in | | Liftable axle 1 location | in | | |
| Liftable axle weight | lb | | Liftable axle 1 weight | lb | | |
| Liftable axle load | lb | | Liftable axle 1 load | lb | | |
| Gap from cab to tank | in | | Liftable axle 2 location | in | | |
| | | | Liftable axle 2 weight | lb | | |
| | | | Liftable axle 2 load | lb | | |
| | | | Liftable axle 3 location | in | | |
| | | | Liftable axle 3 weight | lb | | |
| | | | Liftable axle 3 load | lb | | |
| | | | Equalize axle loads | | | |

| Weights Summary | | Allowable (lb) | Maximum (lb) | Tare (lb) | Loaded (lb) | Loaded (kg) | Status |
|---|---|---|---|---|---|---|---|
| Axles | Steer | | 12000 | 0 | 0 | 0 | OK |
| | PU lift | | 0 | 0 | 0 | 0 | OK |
| | Drive | | 0 | 0 | 0 | 0 | OK |
| | Lead lift 1 | | 0 | 0 | 0 | 0 | OK |
| | Lead lift 2 | | 0 | 0 | 0 | 0 | OK |
| | Lead lift 3 | | 0 | 0 | 0 | 0 | OK |
| | Lead | | 0 | 0 | 0 | 0 | OK |
| | Rear lift | | 0 | 0 | 0 | 0 | OK |
| | Rear | | 0 | 0 | 0 | 0 | OK |
| Gross weight | | | 12000 | 0 | 0 | 0 | OK |
| Payload | | | 12000 | | 0 | 0 | 0.00% |

**VEHICLE DATA**

| Vehicle Data | Units | PU Front Axle | PU Drive Axle | Lead Trlr Fixed Axle | Rear Trlr Fixed Axle | PU Lift Axle | Lead Trlr Lift Axle | Rear Trlr Lift Axle |
|---|---|---|---|---|---|---|---|---|
| Number of axles | | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Axle group weight | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Left-right axle group weight differen | lb | | | | | | | |
| Unsprung weight, per axle | lb | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Unsprung weight c.g. height | in | | | | | | | |
| Inner tire offset | in | | | | | | | |
| Centre line - centre line of dual tires | in | 0 | | | | | | |
| Spring offset | in | | | | | | | |
| Tire vertical stiffness, per tire | lb/in | | | | | | | |
| Tire lateral stiffness, per tire | lb/in | | | | | | | |
| Tire overturning stiffness, per tire | in-lb/deg | | | | | | | |
| Sprung weight, empty | lb | 0 | 0 | 0 | 0 | | | |
| Sprung weight c.g. height | in | | | | | | | |
| Power unit frame torsional stiffness | in-lb/deg | | | | | | | |
| Power unit frame Coulomb friction | in-lb | | | | | | | |
| Fifth wheel torsional stiffness | in-lb/deg | | | | | | | |
| Fifth wheel, half width | in | | | | | | | |
| Fifth wheel separation lash | deg | | | | | | | |
| Fifth wheel load | lb | | 0 | 0 | | | | |
| Fifth wheel height | in | | | | | | | |
| Frame height at fifth wheel | in | | | | | | | |

**SUSPENSION DATA**

| FIXED AXLES | PU Front Axle | | PU Drive Axle | | Lead Trailer | | Rear Trailer | |
|---|---|---|---|---|---|---|---|---|
| Spring Table (per spring) | Force (lb) | Deflection (in) | Force (lb) | Deflection (in) | Force (lb) | Deflection (in) | Force (lb) | Deflection (in) |
| Roll center height | | | | | | | | |
| Aux roll stiffness, per axle | | | | | | | | |
| Number of points | | | | | | | | |
| 1 | | | | | | | | |
| 2 | | | | | | | | |
| 3 | | | | | | | | |
| 4 | | | | | | | | |
| 5 | | | | | | | | |
| 6 | | | | | | | | |
| 7 | | | | | | | | |
| 8 | | | | | | | | |
| 9 | | | | | | | | |
| 10 | | | | | | | | |

| LIFTABLE AXLES | Power Unit | | Lead Trailer | | Rear Trailer | |
|---|---|---|---|---|---|---|
| Spring Table (per spring) | Force (lb) | Deflection (in) | Force (lb) | Deflection (in) | Force (lb) | Deflection (in) |
| Roll center height | | | | | | |
| Aux roll stiffness, per axle | | | | | | |
| Number of points | | | | | | |
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |
| 7 | | | | | | |
| 8 | | | | | | |
| 9 | | | | | | |
| 10 | | | | | | |

## TANK DATA

| Power Unit Tank | Units | Comp 1 | Comp 2 | Comp 3 | Comp 4 | Comp 5 |
|---|---|---|---|---|---|---|
| a for Tank | in | | | | | |
| b-top for Tank | in | | | | | |
| n-top for Tank | | | | | | |
| Height of top of Tank from ground | in | | | | | |
| b-bottom for Compartment | in | | | | | |
| n-bottom for Compartment | | | | | | |
| Length of Void before Compartment | in | | | | | |
| Length of Compartment | in | | | | | |
| Fluid weight in Compartment | lb | | | | | |
| Fluid volume in Compartment | cu ft | | | | | |
| Fluid density in Compartment | lb/cu ft | | | | | |
| Commodity in compartment | | | | | | |

| Lead Trailer Tank | Units | Comp 1 | Comp 2 | Comp 3 | Comp 4 | Comp 5 |
|---|---|---|---|---|---|---|
| a for Tank | in | | | | | |
| b-top for Tank | in | | | | | |
| n-top for Tank | | | | | | |
| Height of top of Tank from ground | in | | | | | |
| b-bottom for Compartment | in | | | | | |
| n-bottom for Compartment | | | | | | |
| Gap before Compartment | in | | | | | |
| Length of Compartment | in | | | | | |
| Fluid weight in Compartment | lb | | | | | |
| Fluid volume in Compartment | cu ft | | | | | |
| Fluid density in Compartment | lb/cu ft | | | | | |
| Commodity in compartment | | | | | | |

| Rear Trailer Tank | Units | Comp 1 | Comp 2 | Comp 3 | Comp 4 | Comp 5 |
|---|---|---|---|---|---|---|
| a for Tank | in | | | | | |
| b-top for Tank | in | | | | | |
| n-top for Tank | | | | | | |
| Height of top of Tank from ground | in | | | | | |
| b-bottom for Compartment | in | | | | | |
| n-bottom for Compartment | | | | | | |
| Gap before Compartment | in | | | | | |
| Length of Compartment | in | | | | | |
| Fluid weight in Compartment | lb | | | | | |
| Fluid volume in Compartment | cu ft | | | | | |
| Fluid density in Compartment | lb/cu ft | | | | | |
| Commodity in compartment | | | | | | |

## SIMULATION CONDITION DATA

| Simulation Conditions | Units | | | | |
|---|---|---|---|---|---|
| Lateral acceleration calculation step | g | 0.0001 | | | |
| Lateral acceleration print step | g | 0.01 | | | |
| Run tank calculations only if 1 | | 0 | | | |
| Treat fluid load as solid if 1 | | 0 | | | |
| Screen updating off if 1 | | 1 | | | |
| Run even if error if 1 | | 0 | | | |
| Fixed axle suspension factor | | 1 | 1 | | |
| Liftable axle suspension factor | | | | | |

### 5.3.1 Run Identification Data Block

The **Run Identification** data block identifies the run. The data in this block are read for use in the simulation. The entries are defined in Table 1.

The file name must exclude the path and file type. The file is saved in the current working directory, which is presumed to be the project directory. The file type is assumed to be .xls, an Excel worksheet.

### 5.3.2 Vehicle Identification Data Block

The **Vehicle Identification** data block identifies the vehicle. The data in this block are only for identification of the Excel workbook, and are not read for use in the simulation, so are optional. This data block should be filled out as completely as possible when a specific vehicle is being studied. However, most fields may be inapplicable or unknown when a generic vehicle is being studied, and may be left empty. All inputs are character strings. The power unit entries in Cells C9:C18 are defined in Table 2. Corresponding entries for the lead and rear trailer entries are placed in Cells F9:F18 and I9:I18, respectively.

### 5.3.3 Weight Distribution Data Block

The **Weight Distribution** data block defines the vehicle configuration, and computes the empty and loaded axle weights of the vehicle. The data in this block are not read for use in the simulation, but certain results are reflected into the **Vehicle** data block, where they are read for use in the simulation. Payload weights are calculated from data entered in the **Tank** data block, and are used in the weight distribution calculation. All inputs are numeric. The power unit entries for Cells E23:E36 are defined in Table 3, and Figure 12 identifies the dimensions required. Note that the distance from the back of cab to the front of the tank is measured to the effective front of the tank, as discussed in Section 5.3.6 below. Trailer entries for Cells I23:I42 and J23:J35 are defined in Table 4, and Figure 13 identifies the dimensions required. Note that the fifth wheel setting for the lead semitrailer of a B-train is measured forward from the centre of the rearmost axle of the semitrailer. Allowable axle load entries for Cells C46:C55 are defined in Table 5. The allowable load defaults to the load allowed in Ontario if a cell is zero or left blank. Other jurisdictions have different allowable loads.

### 5.3.4 Vehicle Data Block

The **Vehicle** data block describes the vehicle for simulation. The data in this block are read for use in the simulation. All inputs are numeric. The entries are defined in Table 6. Figure 14 shows the transverse dimensions related to an axle.

Data in Cells E62:E74 refer to the power unit front axle. Data in the same range in columns F through K refer respectively to the power unit drive axle group, the lead trailer fixed axle group, the rear trailer fixed axle group, any power unit liftable axle, any lead trailer liftable axles, and any rear trailer liftable axle, respectively.

Data in Cells F75:F76 refer to the power unit frame. Data in Cells F77:F82 refer to the power unit fifth wheel, when the power unit is a tractor. Data in Cells G77:G82 refer to the lead trailer fifth wheel, when the vehicle is a B-train.

### 5.3.5 Suspension Data Block

The **Suspension** data block contains the force-displacement characteristic for one spring in each suspension. The data in this block are read for use in the simulation. All inputs are numeric. The entries are defined in Table 7.

A spring table must contain at least two data points. The force and displacement must also each increase monotonically, i.e. the i+1'th force entry must be greater than or equal to the i'th force entry, and the same for the displacements.

Data in cells C89:D101 refer to the power unit front axle spring table. Data in the same range in columns E through J refer to the power unit drive axle group spring table, the lead trailer fixed axle group spring table, and the rear trailer fixed axle group spring table, respectively. Data in Cells C106:H118 refer to any power unit liftable axle spring table, any lead trailer liftable axle spring table, and any rear trailer liftable axle spring table, respectively.

### 5.3.6 Tank Data Block

The **Tank** data block contains the tank geometry and contents. The data in this block are read for use in the simulation. All inputs are numeric, except for the fluid commodity, which is character. The entries are defined in Table 8. Dimensions related to the cross-section of a compartment are shown in Figure 15, and longitudinal dimensions related to a tank are shown in Figure 16. A tank is composed of a series of voids and compartments. A void is simply an empty space that a manufacturer uses to separate compartments and locate them so that the payload weight is properly distributed to the axles. A void contains no payload. The foremost void is measured from the front of the trailer to the front of the foremost compartment, so that the simulation can position the compartments properly along the length of the trailer. If there is no void, the void length is zero. A tank or compartment is assumed to be flat at each end. However, many tanks and compartments have a dome on each end, while others have a circular radius on one end, or each end. The user should adjust the length of a compartment to account for the capacity of any dome or radius, so that the compartment has the correct volume. The user should also make a corresponding adjustment in void length so that the centre of gravity of the compartment is in the correct location within the tank.

The first four items in Cells E123:E126 apply to the entire tank. The remaining items in rows 127 through 134 apply for each compartment that makes up the tank.

Data in Cells E123:I134 apply to any power unit tank. Data in Cells E137:I148 apply to any lead trailer tank. Data in Cells E151:I162 apply to any rear trailer tank.

Only two of the fluid weight, fluid volume and fluid density need be entered. The third is calculated from whichever two items are entered. It is better not to enter the third, because the value entered will likely differ slightly from the value calculated by the program.

The commodity identification is not read by the program. If a specific vehicle with a specific load is being studied, this field allows the commodity in each compartment to be identified. It may not be relevant when a generic vehicle is being studied.

### 5.3.7 Simulation Condition Data Block

The **Simulation Condition** data block allows the user to control certain aspects of the simulation. The data in this block are read for use in the simulation. All inputs are numeric. The entries are defined in Table 9.

The lateral acceleration calculation step determines, to some extent, the accuracy of the simulation. A smaller value will result in less difference between a calculation step and an internal non-linearity in the vehicle, such as a suspension data point. However, a smaller value will cause the simulation to take longer to run. This is not an issue for a straight truck, but it may be an issue for a B-train with liftable axles and multiple compartments. The default value of 0.0001 g has generally been found to give consistent and close results.

The lateral acceleration print step defines the output increment, so determines the number of output steps. It has no effect on the run time. The default value of 0.01 g has generally been found to give adequate definition of responses. The simulation ends whenever the high-side drive axle and all high-side trailer wheel loads become zero. The lateral acceleration at this calculation step is recorded, and the corresponding results are output, even if the lateral acceleration does not correspond to a print step.

Options are provided to allow a user to run:

- Only the tank calculations, with no rollover simulation;
- As if the fluid load were solid;
- With screen updating turned off, to make the run go faster; and
- Even if Cell M4 indicates there are errors in data fields, which may occur if a real vehicle should be outside the range of reality checks that cover normal legal vehicles.

### 5.3.8 User Calculation Area

The **User Calculation Area** allows a user all the facilities of Excel to make any preliminary calculations of inputs that the user considers necessary. Row 177 of the worksheet, and below, is available to a user for any calculations that might simplify preparation of input data for a specific vehicle.

**Table 1: Run Identification Data Block Entries**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| C3 | Title | None | Run title. | |
| C4 | Save file name | None | Name of file to be saved. Must be different than Master Workbook file name. | A valid file name, without path or type. |

**Table 2: Vehicle Identification Data Block Entries**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| C9 | Vehicle manufacturer | None | Name of vehicle manufacturer. | |
| C10 | Model | None | Manufacturer’s designation of vehicle model. | |
| C11 | Date of manufacture of vehicle | None | Date of manufacture, from vehicle data plate. | |
| C12 | VIN | None | Vehicle identification number, usually 17 digits. | |
| C13 | License plate, jurisdiction | None | Number on license plate, and jurisdiction (province or state) that issued the plate. | |
| C14 | Owner | None | Owner of vehicle. | |
| C15 | Owner's address | None | Address of owner. | |
| C16 | Tank manufacturer | None | Name of tank manufacturer. | |
| C17 | Tank specification | None | Specification to which tank was manufactured. | |
| C18 | Date of manufacture of tank | None | Date of manufacture of tank. | |

**Table 3: Weight Distribution Data Block Entries, Power Unit Data**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| E23 | BBC | in | Distance from front bumper to back of cab. | >70 in, <201 in |
| E24 | Front axle setback | in | Distance from front bumper to centre of front axle. | >25 in, <73 in |
| E25 | Wheelbase | in | Distance from centre of front axle to centre of drive axle group. | >100 in, <330 in |
| E26 | Number of drive axles | None | Number of axles in drive axle group. | 1, 2 or 3 |
| E27 | Drive axle spread | in | Spread of drive axle group. | Axle spacing >47 in, <73 in |
| E28 | Fifth wheel setting | in | Distance of fifth wheel ahead of centre of drive axle group. | >-15 in, <40 in |
| E29 | Sprung weight | lb | Total sprung weight of power unit. | >4,999 lb, <30,001 lb |
| E30 | Unsprung front axle weight | lb | Unsprung weight of front axle. | >999 lb, <3,001 lb |
| E31 | Unsprung drive axle weight | lb | Unsprung weight of drive axle group. | >999 lb, <3,001 lb per axle |
| E32 | Front axle tare weight | lb | Weight on front axle of power unit, empty, with any liftable axle raised. | >2,499 lb, <20,001 lb |
| E33 | Liftable axle location | in | Distance of any liftable axle ahead of foremost axle of drive axle group. | Zero if none, or between front and drive axles, or no more than 121 in behind the rearmost drive axle |
| E34 | Liftable axle weight | lb | Unsprung weight of liftable axle. | Zero if none, or >999 lb, <3,001 lb |
| E35 | Liftable axle load | lb | Total load on liftable axle. | Zero if none, or <30,001 lb |
| E36 | Gap from cab to tank | in | Distance from rear of cab to front of tank, when there is a tank on the power unit. | >=0, <73 in |

**Figure 12: Power Unit Dimensions**

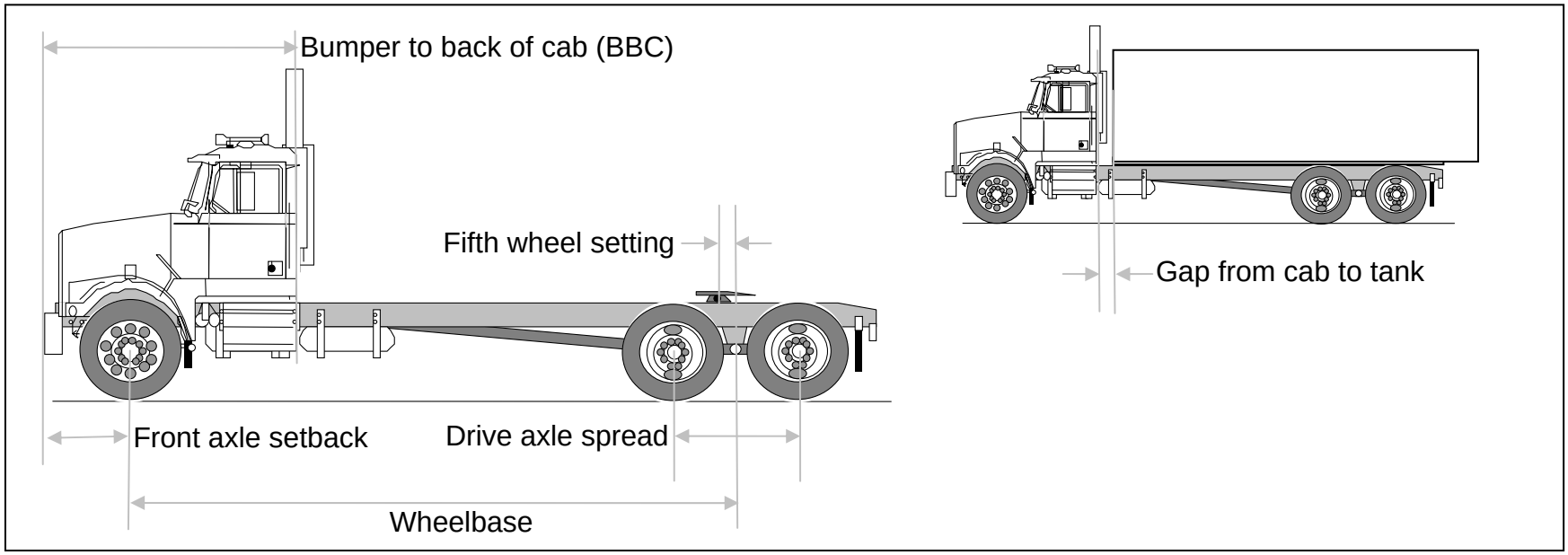



**Table 4: Weight Distribution Data Block Entries, Trailer Data**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| I23 | Length | in | Length of trailer. | >200 in, <640 in |
| I24 | Kingpin setback | in | Distance of kingpin/hitch rearward from front of trailer. | >11in, <85 in |
| I25 | Wheelbase | in | Distance from centre of kingpin/hitch to centre of trailer fixed axle group. | >20 in, <550 in |
| I26 | Number of fixed axles | None | Number of axles in trailer fixed axle group. | 1, 2, 3 or 4 |
| I27 | Axle spread | in | Spread of trailer fixed axle group. | Axle spacing >40 in, <125 in |

| | | | | |
|---|---|---|---|---|
| I28 | Fifth wheel setting | in | Distance of lead trailer fifth wheel ahead of rearmost fixed axle of that trailer, for a B-train. | >-15 in, <121 in |
| I29 | Sprung weight | lb | Sprung weight of trailer. | >6,999 lb, <100,001 lb |
| I30 | Unsprung fixed axle weight | lb | Unsprung weight of trailer fixed axle group. | >999 lb, <3,001 lb |
| I31 | None | | Empty | |
| I32 | Trailer axle tare weight | lb | Weight on trailer fixed axle group with trailer coupled and any liftable axles raised. | >999 lb, <20,001 lb, per axle |
| I33 | Liftable axle 1 location | in | Distance of liftable axle 1 ahead of foremost axle of drive axle group, negative if behind. | Zero if none, or within the trailer, outside the fixed axle group, |
| I34 | Liftable axle 1 weight | lb | Unsprung weight of liftable axle 1. | Zero if none, or >999 lb, <3,001 lb |
| I35 | Liftable axle 1 load | lb | Total load on liftable axle 1. | Zero if none, or <30,001 lb |
| I36 | Liftable axle 2 location | in | Distance of liftable axle 2 ahead of foremost axle of drive axle group, negative if behind. | Zero if none, or within the trailer, outside the fixed axle group, |
| I37 | Liftable axle 2 weight | lb | Unsprung weight of liftable axle 2. | Zero if none, or >999 lb, <3,001 lb |
| I38 | Liftable axle 2 load | lb | Total load on liftable axle 2. | Zero if none, or <30,001 lb |
| I39 | Liftable axle 3 location | in | Distance of liftable axle 3 ahead of foremost axle of drive axle group, negative if behind. | Zero if none, or within the trailer, outside the fixed axle group, |
| I40 | Liftable axle 3 weight | lb | Unsprung weight of liftable axle 3. | Zero if none, or >999 lb, <3,001 lb |
| I41 | Liftable axle 3 load | lb | Total load on liftable axle 3. | Zero if none, or <30,001 lb |
| I42 | Equalize axle loads | None | Indicator, use specified liftable axle loads if zero or blank, equalize all trailer axle loads otherwise. | 0 or 1 |

**Figure 13: Semitrailer Dimensions**

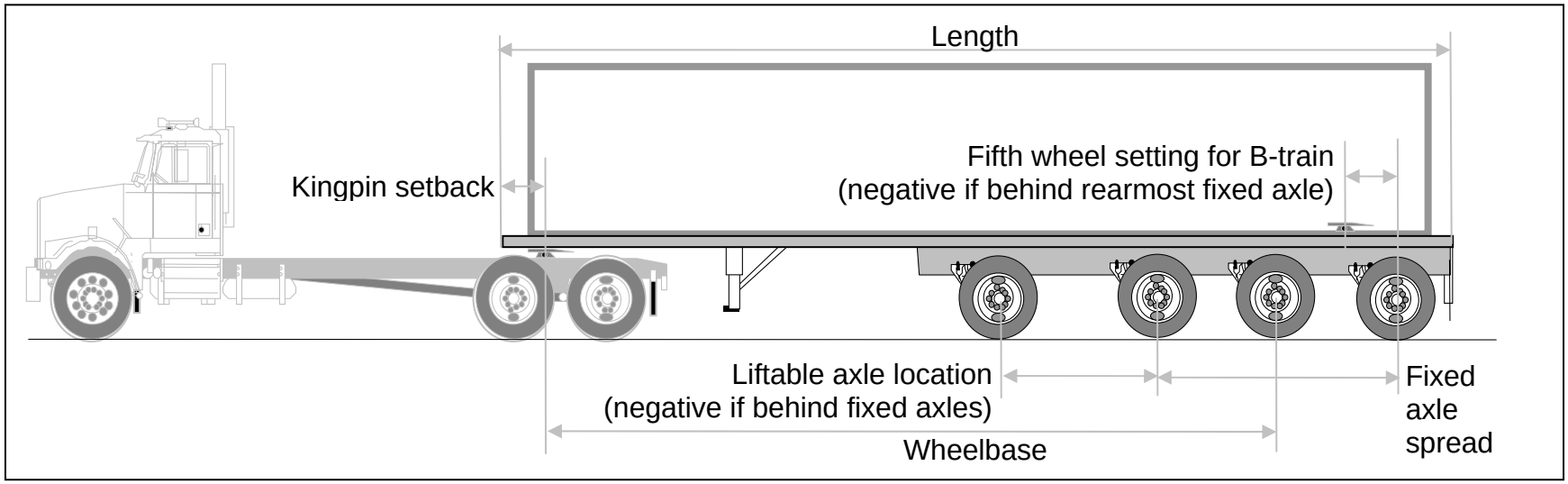



**Table 5: Weight Distribution Data Block Entries, Allowable Axle Loads**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| C46 | Steer | lb | Allowable load on power unit front axle | None |
| C47 | PU lift | lb | Allowable load on any power unit liftable axle | None |
| C48 | Drive | lb | Allowable load on power unit drive axle group | None |
| C49 | Lead lift 1 | lb | Allowable load on lead trailer liftable axle 1 | None |
| C50 | Lead lift 2 | lb | Allowable load on lead trailer liftable axle 2 | None |
| C51 | Lead lift 3 | lb | Allowable load on lead trailer liftable axle 3 | None |
| C52 | Lead | lb | Allowable load on lead trailer fixed axle group | None |
| C53 | Rear lift | lb | Allowable load on any rear trailer liftable axle | None |
| C54 | Rear | lb | Allowable load on rear trailer fixed axle group | None |
| C55 | Gross weight | lb | Allowable gross weight | None |

**Table 6: Vehicle Data Block Entries**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| E62 | Number of axles | None | Number of axles in each axle group | None, from Weight Distribution data block |
| E63 | Axle group weight | lb | Weight on each axle group | None, from Weight Distribution data block |
| E64 | Left-right axle group weight difference | lb | Weight on left-hand side wheels of axle group minus weight on right-hand side wheels of axle group, so negative if left-hand side is lightest, positive if right-hand side is lightest. | <20% of axle weight |
| E65 | Unsprung weight, per axle | lb | Unsprung weight of each axle in axle group | None, from Weight Distribution data block |
| E66 | Unsprung weight c.g. height | in | Height of centre of gravity of unsprung weight, above road | >15 in, <31 in |
| E67 | Inner tire offset | in | Distance from the centre-line of the vehicle to the centre-line of an inner tire, see Figure 14 | >12 in, <51 in |
| E68 | Dual tire spacing | in | Distance between the centre lines of the inner and outer tires for dual tires, see Figure 14 | Zero if single tires, >10 in, <15 in for dual tires |
| E69 | Spring offset | in | Distance from the centre-line of the vehicle to the centre-line of a spring, see Figure 14 | > 0 in |
| E70 | Tire vertical stiffness, per tire | lb/in | Vertical stiffness of one tire of axle group | >0 lb/in |
| E71 | Tire lateral stiffness, per tire | lb/in | Lateral stiffness of one tire of axle group | >0 lb/in |
| E72 | Tire overturning stiffness, per tire | in-lb/ deg | Overturning stiffness of one tire of axle group | >0 in-lb/deg |
| E73 | Sprung weight, empty | lb | Sprung weight on axle group | None, from Weight Distribution data block |
| E74 | Sprung weight c.g. height | in | Height of centre of gravity of sprung weight, above road | >19 in, <151 in |
| E75 | Power unit frame torsional stiffness | in-lb/ deg | Torsional stiffness of power unit frame | >0 in-lb/deg |

| | | | | |
|---|---|---|---|---|
| F76 | Power unit frame Coulomb friction | in-lb | Coulomb friction of power unit frame, which must be overcome before frame will twist | >0 in-lb |
| F77 | Fifth wheel torsional stiffness | in-lb/ deg | Torsional stiffness of fifth wheel | >0 in-lb/deg |
| F78 | Fifth wheel, half width | in | Half width of fifth wheel, from centre to edge | >6 in, <25 in |
| F79 | Fifth wheel separation lash | deg | Angle between upper coupler plate and fifth wheel when body has rolled about an edge of the fifth wheel and the kingpin has reached maximum extension | >=0 deg |
| F80 | Fifth wheel load | lb | Load on fifth wheel | None, from Weight Distribution data block |
| F81 | Fifth wheel height | in | Height of top of fifth wheel from ground, with power unit unloaded, and fifth wheel level | >30 in, <61 in |
| F82 | Frame height at fifth wheel | in | Height of top of frame from ground at fifth wheel location, with power unit unloaded | >30 in, <61 in |

**Figure 14: Axle Dimensions**

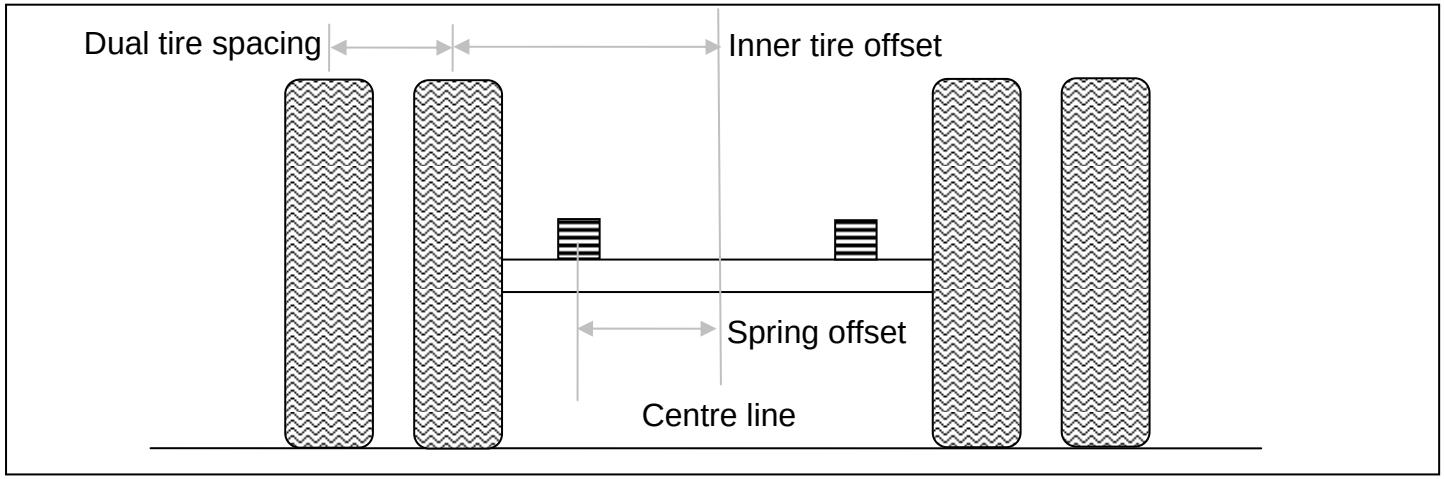


**Table 7: Suspension Data Block Entries**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| C89 | Suspension roll centre height | in | Height of roll centre of suspension above ground | > 0 in |
| C90 | Suspension auxiliary roll stiffness, per axle | in-lb/ deg | Additional roll stiffness of the suspension, beyond that generated simply by the spring offset and the vertical stiffness of the springs, for one axle | >0 in-lb/deg |
| C91 | Number of points | None | Number of data points in suspension table | > 1, < 11 |
| C92 | Force | lb | Spring force for given suspension displacement | Must be monotonic increasing from point to point |
| D92 | Displacement | in | Displacement for given spring force | Must be monotonic increasing from point to point |

**Table 8: Tank Data Block Entries**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| E123 | a for Tank | in | Half width of tank, see Figure 15. | >20 in, < 52 in |
| E124 | b-top for Tank | in | Height of upper principal axis for top of tank, see Figure 15. | >20 in, < 52 in |
| E125 | n-top for Tank | None | Index for top of tank, see Equation 1. | >= 2, <= 8 |
| E126 | Height of top of Tank from ground | in | Height of top of tank from ground, each assumed horizontal, see Figure 15. | > 44 in, < 163 in |
| E127 | b-bottom for Compartment | in | Height of lower principal axis for compartment, see Figure 15. | >20 in, < 52 in |
| E128 | n-bottom for Compartment | None | Index for bottom of compartment, see Equation 1. | >= 2, <= 8 |
| E129 | Length of Void before Compartment | in | Length of void ahead of this compartment. | >= 0 in, < 100 in |

| | | | | |
|---|---|---|---|---|
| E130 | Length of Compartment | in | Length of this compartment. | >0 in, < 636 in |
| E131 | Fluid weight in Compartment | lb | Fluid weight in this compartment. | >= 0 lb |
| E132 | Fluid volume in Compartment | cu in | Fluid volume in this compartment. | >= 0 cu ft |
| E133 | Fluid density in Compartment | lb/cu ft | Fluid density in this compartment. | >= 0 lb/cu ft |
| E134 | Commodity in Compartment | None | Identification of commodity in this compartment. | Optional |

**Table 9: Simulation Condition Data Block Entries**

| Cell | Data item | Units | Definition | Limits |
|---|---|---|---|---|
| E167 | Lateral acceleration calculation step | g | Small increment in lateral acceleration used to step through the simulation. | >= 0.00005 g,<= 0.005 g Default is 0.0001 g, if zero or left blank |
| E168 | Lateral acceleration output step | g | Increment in lateral acceleration used to output results through the simulation. | >= 0.005 g, <= 0.05 g. Default is 0.01 g, if zero or left blank. |
| E169 | Run tank calculations only | None | Indicator, run simulation if zero or blank, only run tank calculations otherwise. | 0 or 1 |
| E170 | Treat fluid load as rigid if 1 | None | Run simulation as if any fluid load is rigid | 0 or 1 |
| E171 | Screen updating off if 1 | None | Turn off screen updating if 1, to make the run go faster | 0 or 1 |
| E172 | Run even if error if 1 | None | Override the error check, and make a run even if Cell M4 indicates the presence of errors in the data | 0 or 1 |
| E173 | Fixed axle suspension factor | None | Factor that multiplies the suspension spring force and auxiliary roll stiffness for a fixed axle group spring table | >0, < 3. Default is 1 if zero or left blank. |
| E174 | Liftable axle suspension factor | None | Factor that multiplies the suspension spring force and auxiliary roll stiffness for a liftable axle spring table | >0, < 3. Default is 1 if zero or left blank. |

**Figure 15: Tank Cross-section Dimensions**

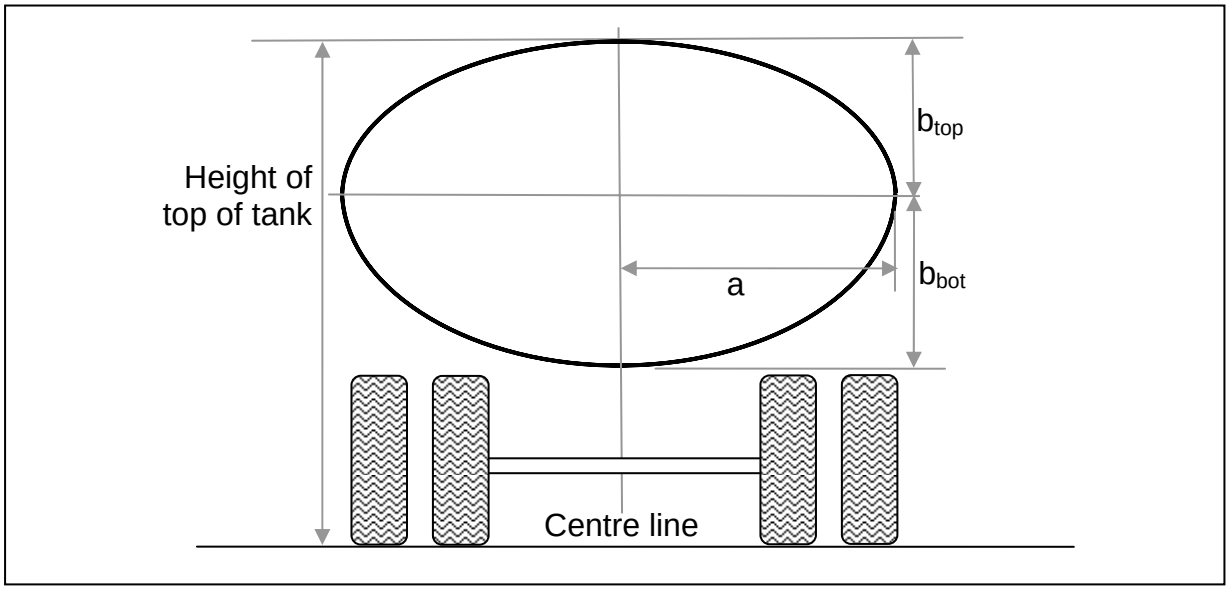
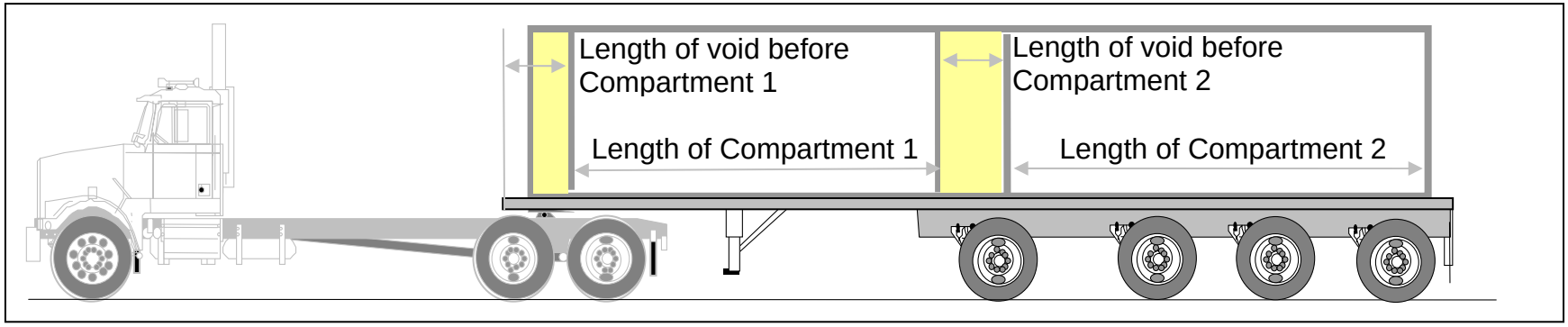



**Figure 16: Tank Longitudinal Dimensions**



## 5.4 Program Output

The Excel Master Workbook has six worksheets:

1. **Start** contains a description of the other worksheets;
2. **Data** is for entry of vehicle, simulation, tank and tank payload data;
3. **Tank** receives intermediate calculations of tank cross-section and the locus of the fluid centre of gravity for various free surface angles;
4. **Simulation** receives the simulation results;
5. **Plots** displays graphs of selected static roll simulation results; and
6. **Summary** summarizes key information from other worksheets onto a single sheet that can be printed.

The **Start** worksheet receives no output. The **Data** worksheet receives only the run status ("Running", "Done", or "Error"), and the elapsed (clock) time needed for preparation, tank calculations, simulation, and the entire run.

The **Tank** worksheet receives intermediate calculations of tank cross-section and the locus of the fluid centre of gravity for various free surface angles. A block at the top receives a summary of tank dimensions and capacity, and fill capacity. Blocks beneath, for each compartment, receive the y- and z-coordinates of the upper and lower parts of the compartment shell, the free surface coordinates for free surface angles from zero to 60 deg, in 1 deg increments, and the free surface height and y- and z-coordinates of the fluid centre of gravity for the same set of free surface angles. For each compartment, a plot shows the shape of the compartment, the free surface at zero and 60 deg, and the locus of the fluid centre of gravity fro free surface angles from zero to 60 deg, in 1 deg increments.

The **Simulation** worksheet receives the simulation results. The roll threshold appears in Cell C3, in g. Column A contains the equivalent lateral acceleration, in g, in steps as specified in the **Simulation Condition** data block. The last entry is the roll threshold, which generally does not occur at a designated output step. It is reflected to Cell C3, as noted above. Subsequent columns contain the load transfer ratio, loads for the left- and right-hand side wheels in each axle group and liftable axle group, sprung mass roll angles, unsprung mass roll angles, forces for each tire, deflections for each tire, forces for each suspension, and deflections for each suspension, and the locus of the composite fluid centre of gravity for all compartments of each tank.

The **Plots** worksheet receives its input from the **Simulation** workbook. It includes four plots, showing sprung mass roll angle, wheel loads, load transfer ratio and the locus of the fluid centre of gravity against equivalent lateral acceleration. The x-axis scale for these three plots is in steps of 0.05 g, and the maximum adjusts automatically to one increment beyond the largest necessary to show the responses. The y-axis maximum scales for the sprung mass roll angle, wheel load and centre of gravity locus plots also adjust automatically. The maximum scale for the y-axis of the load transfer ratio plot is set at 1.0, and does not need to adjust.

## 5.5 Modeling Vehicle Configurations

The model is able to represent the following vehicle configurations:

- Straight truck;
- Tractor-semitrailer;
- A-train;
- B-train;
- Truck-full trailer; and
- Truck-pony trailer.

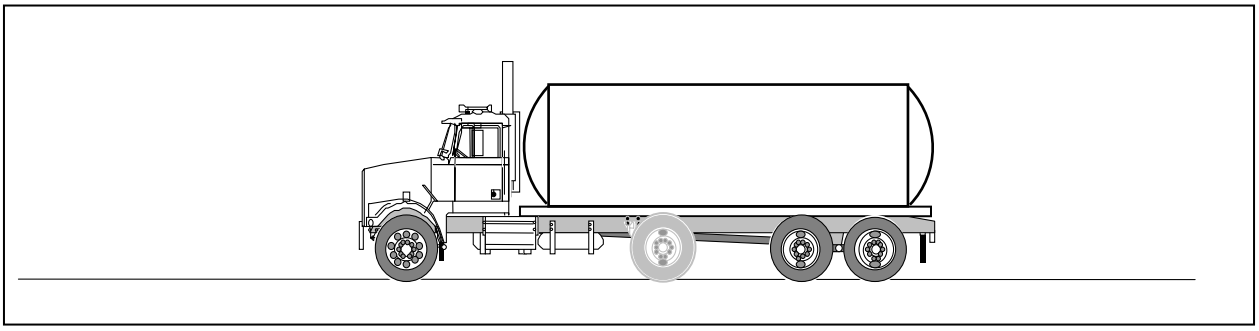
The following sub-sections describe how each of these configurations should be modeled.

### 5.5.1 Straight truck

Figure 17 shows a typical straight truck tank truck. The truck may be equipped with a liftable axle, as indicated by the ghost image.

A straight truck, or any other power unit, is described by data in Cells E23 through E36, E63 though F77 and C90 through F102 of the **Data** worksheet. Suspension characteristics for any liftable axle are described by data in Cells C107 through D119. Tank dimensions and contents are described by data in Cells E124 through I135.

**Figure 17: Straight Truck**



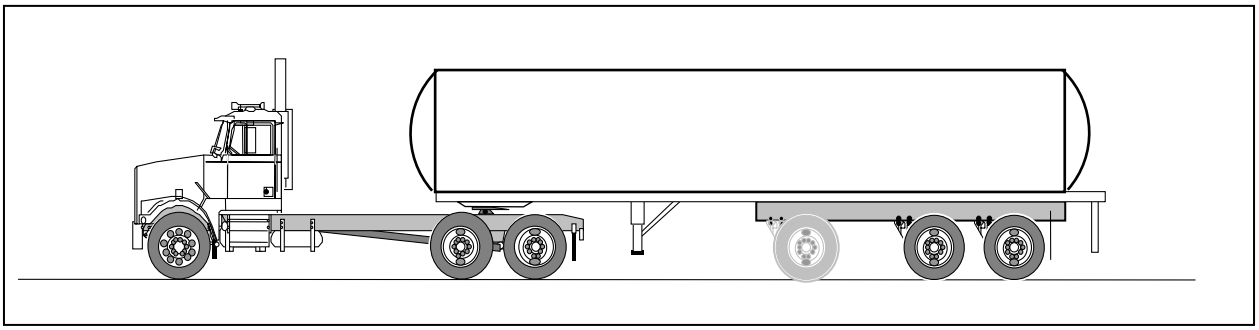
### 5.5.2 Tractor-semitrailer

Figure 18 shows a typical tractor-semitrailer tank truck. The tractor usually does not carry a tank, but the program does allow one. The semitrailer is towed by a fifth wheel on the tractor. The tractor may be equipped with a liftable axle, as shown for the straight truck. The semitrailer may be equipped with up to three liftable axles, with one indicated as a ghost image in Figure 18. If a semitrailer has more than one liftable axle, each is assumed to have the same number of tires, axle dimensions and suspension.

A tractor is described by data in Cells E23 through E36, E63 though F77 and C90 through F102 of the **Data** worksheet. Suspension characteristics for any liftable axle are described by data in Cells C107 through D119. Dimensions and contents of any tank are described by data in Cells E124 through I135. The tractor fifth wheel is described by data in Cells F78 through F83.

A semitrailer is described by data in Cells I23 through I42, G63 though G75 and G90 through H102 of the **Data** worksheet. Suspension characteristics for any liftable axle are described by data in Cells E107 through F119. Dimensions and contents of any tank are described by data in Cells E138 through I149.

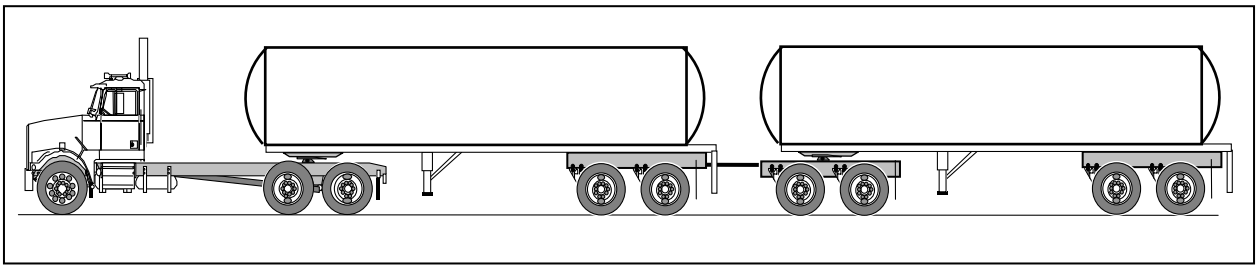
**Figure 18: Tractor-semitrailer**



### 5.5.3 A-train

Figure 19 shows a typical A-train double trailer tank truck. This consists of a tractor-semitrailer towing a full trailer by means of a pintle hook. The pintle hook does not allow any roll moment to be transferred between the semitrailer and full trailer, so each vehicle unit can roll over independently of the other. An A-train should be run in two stages, first the tractor-semitrailer, then the full trailer. The roll threshold for the vehicle is the lower of the two roll thresholds. The full trailer may have a converter dolly at the front, which couples to the semitrailer with a fifth wheel, or the two may be permanently coupled with a turntable. A turntable has very high roll stiffness, and no vertical free play, so the lash separation is zero. The full trailer should be modeled as a tractor-semitrailer, with data

**Figure 19: A-train Double**

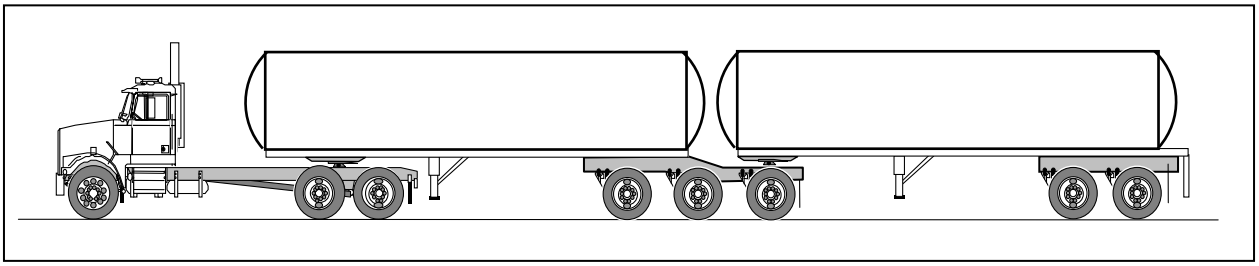


selected to eliminate the effect of the front axle. The tractor sprung mass, front axle unsprung mass, front axle tare weight, front axle tire stiffnesses, front axle suspension stiffnesses, front axle suspension roll centre, power unit frame torsional stiffness and Coulomb friction should all be low. This will effectively and artificially decouple the front axle from the rest of the vehicle, which will now have the roll characteristic of a full trailer.

### 5.5.4 B-train

Figure 20 shows a typical B-train double trailer tank truck. This consists of a tractor-semitrailer towing a second semitrailer by means of a fifth wheel mounted on the rear frame of the lead semitrailer. The fifth wheel allows roll moment to be transferred between the two semitrailers, so the entire vehicle unit rolls over as a unit. The fifth wheel on the lead semitrailer is often a compensating type, which is designed to provide some roll flexibility about a high roll centre, to reduce the torsional loads transferred into the relatively flexible rear frame of the lead semitrailer. Even if a standard fifth wheel is used, torsional flexibility of the rear frame of the lead semitrailer significantly reduces the effective torsional stiffness of the fifth wheel.

**Figure 20: B-train Double**

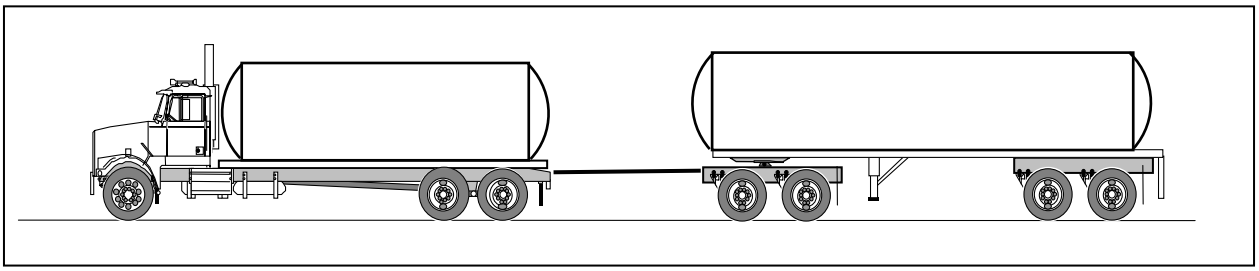


The rear semitrailer is described by data in Cells J23 through J42, H63 though H75 and I90 through J102 of the **Data** worksheet. Suspension characteristics for any liftable axle are described by data in Cells G107 through H119. Dimensions and contents of any tank are described by data in Cells E152 through I163. The lead semitrailer fifth wheel is described by data in Cells G78 through G83.

### 5.5.5 Truck-full Trailer

Figure 21 shows a typical truck-full trailer tank truck. This consists of a straight truck towing a full trailer by means of a pintle hook. The pintle hook does not allow any roll moment to be transferred between the truck and full trailer, so each vehicle unit can roll over independently of the other. A truck-full trailer should also be run in two stages, first the straight truck, then the full trailer. The roll threshold for the vehicle is the lower of the two roll thresholds. The full trailer should be modeled as a tractor-semitrailer, as described for the A-train in Section 5.5.3 above.

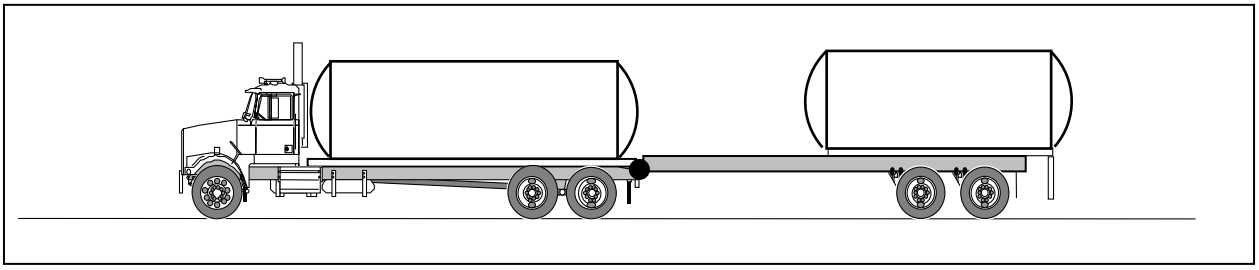
**Figure 21: Truck-full Trailer**



### 5.5.6 Truck-pony Trailer

Figure 22 shows a typical truck-pony trailer tank truck. This consists of a straight truck towing a pony trailer by means of a pintle hook. The pony trailer has a rigid drawbar and stands on its own axles, so there is very little load transfer between the pony trailer and the truck. The pintle hook does not allow any roll moment to be transferred between the truck and pony trailer, so each vehicle unit can roll over independently of the other. A truck-pony trailer should also be run in two stages, first the straight truck, then the pony trailer. The roll threshold for the vehicle is the lower of the two roll thresholds. The pony trailer should be modeled as a straight truck, as described for the tractor for an A-train full trailer in Section 5.5.3 above.

**Figure 22: Truck-pony Trailer**



## 5.6 Run Time

The time required to run any particular simulation depends on the complexity of the vehicle model, the speed of computer being used, and what else the computer is trying to do while the simulation is running. It is possible to construct a run that may be quite time-consuming, so the user should be aware of the relationship between run time and model complexity. The basic relationship between run time and model complexity is:

$$T = A + Bm + CRn^3$$

Equation 41

where $T$ is the run time, in seconds;
$A, B, C$ are constants, in seconds;
$m$ is the total number of tank compartments on the vehicle;
$R$ is the roll threshold, in g; and
$n$ is the number of degrees of freedom in the model, given by

$$n = 5*(2+S)+4*L$$

Equation 42

where $S$ is the number of trailers; and
$L$ is the number of liftable axles.

Equation 41 shows that a simulation takes longer when the tank has multiple compartments, when the vehicle has a higher rollover threshold, and when the vehicle is more complicated and has a greater number of degrees of freedom. Table 10 shows the number of degrees of freedom $n$ for each vehicle configuration. The simulation phase for a tractor-semitrailer takes about 3.4 times longer to run than a straight truck, and a double trailer combination takes about 8 times longer, for vehicles without any liftable axles, and the same rollover threshold. A double trailer combination with a liftable axle on each vehicle unit could take about 32 times longer to run than a straight truck with no liftable axle.

**Table 10: Number of Degrees of Freedom of Vehicle Configurations**

| Configuration | Number of Vehicle Units with a Liftable Axle | | | |
|---|---|---|---|---|
| | 0 | 1 | 2 | 3 |
| Straight truck | 10 | 14 | | |
| Tractor-semitrailer | 15 | 19 | 23 | |
| Full trailer | 15 | 19 | | |
| B-train | 20 | 24 | 28 | 32 |

For a typical run, $A$ in Equation 41 is about 6 s, $B$ is about 30 s per compartment, and $C$ is about 0.06 s. These values apply for a 2.0 GHz Pentium 4 processor, with no other applications running, and screen updates and internal re-calculations turned off, and a lateral acceleration calculation step of 0.0001 g.

The tank calculations often take a significant proportion of a run, particularly if the there are multiple compartments. Since a particular vehicle may often be run repeatedly with the same tank dimensions and fill, the program saves the contents of the Tank Data Block after each run. When a new run is made, the program checks the new input in the Tank Data Block against that saved from the previous run. If the data are the same, the movement of the fluid centre of gravity is not re-calculated, the results are simply read back from the

**Tank** worksheet. This reduces the value of $B$ from about 30 s per compartment for the original calculations to about 2 s per compartment to read back the results in subsequent runs.

The values of $A$, $B$ and $C$ are reduced with a faster computer. Regardless of the speed of a particular computer, these runs are shortest when no other applications are running. A run may take much longer when the computer has other processes running in the background, or other Excel workbooks are open, apparently regardless of whether the other processes are consuming a significant amount of the computer's resources, or not. The values of $A$, $B$ and $C$ change in proportion to the lateral acceleration calculation step.

The Simulation Conditions Data Block has an input that allows a user to freeze Excel screen updates and internal re-calculations during a run, which significantly reduces the run time. However, if the stand-alone program should crash during a run, it simply ends, and Excel is left frozen. It can be unfrozen by activating the Windows Task Manager with the Ctrl-Alt-Delete key combination, selecting the Applications tab, selecting Excel, and clicking End Task. A dialogue box pops up, asking whether Excel is to be terminated. Click Cancel, and Excel is unfrozen.

### 5.7 Error Messages

Error conditions that arise from input data checks in the **Data** worksheet are not covered here.

The following additional error messages may arise from conditions that occur during running of the stand-alone program:

1. "Excel Workbook Version mnn and Stand-alone Program Version pqq are incompatible" means the user is attempting to run the stand-alone program with an incompatible version of the Excel Workbook.
2. "Cannot run, input data has n errors" means the user attempted to run the stand-alone program while the input data in the Excel Workbook **Data** worksheet still contained n (an integer greater than 0) errors. Error indicators in the Excel Workbook **Data** worksheet identify those data fields with errors.
3. "Cannot save over Master Workbook SRMTTmnn.xls" means the user is attempting to save data into the Master Workbook, which is not allowed. A save file name should be entered in Cell C4.
4. "Height iteration failed for compartment j of tank n for angle x" means the simulation was unable to determine the free surface height of the fluid on the vertical principal axis of compartment j of tank n for free surface angle x to the horizontal after 30 iterations.
5. "SIMQ finds matrix AA singular for lateral acceleration a" means the simulation failed internally. There is probably a fundamental error in the structure of the input data, even though it passes the error checks.
6. "Cannot interpolate CG for free surface angle over 60 deg for compartment j of tank n" means the free surface angle exceeded 60 deg to the horizontal principal

axis for the j’th compartment of the n’th tank. There is probably something wrong with the input data, even though it passes the error checks. A free surface angle of 60 deg corresponds (for example) to a lateral acceleration of 1.00 g and a vehicle roll angle of 15 deg, both of which are well beyond the capability of normal vehicles.

# 6. CONCLUSIONS

This report describes a computer simulation developed to determine the rollover threshold of a tank truck. The model may represent a straight truck, tractor-semitrailer, A- or B-train double trailer combination, truck-full trailer or truck-pony trailer combination. Each vehicle unit may have one tank, and each tank may have up to five compartments, each filled to a different level with a different fluid.

The simulation consists of a master Excel Workbook where the user prepares input data, and in which results are placed, and a stand-alone simulation program that computes the rollover response.

The simulation has been validated against a limited amount of existing data, and artificial test cases where the results can be determined analytically. It has also been used to simulate a large number of tilt tests of tank vehicles. The simulation appears able to match the principal responses of the vehicles tested with reasonable fidelity.

The simulation will usually run with any input data set that passes the error checks. The validity of the results depends critically on the extent to which the input data represent the vehicle being modeled. Reliable results and conclusions can only be expected when the user has sufficient understanding of vehicle configuration, vehicle component properties and vehicle dynamics to be able to distinguish between input data that are realistic and input data that are unrealistic, and between results that are reasonable and results that are unreasonable.

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