Application of HVE SIMON to the Analysis of Lateral Wind Loadings on High-sided Vehicles

William Blythe, P.E., Ph.D.
William Blythe, Inc.

ABSTRACT

The SIMON simulation model [1,2][1], part of the HVE simulation environment, automatically calculates longitudinal wind forces as a function of vehicle speed and user-specified drag coefficients. Lateral wind loads are not calculated at the present time, but may be constructed by the user. Modifications to the SIMON program are suggested.

Tractor-trailer rollover due to high crosswinds is a well-recognized accident type. Some highway jurisdictions limit high-profile vehicle travel under certain weather conditions in certain locations to reduce the probability of rollover or other loss of control. The research literature relating to this issue has been reviewed and reported [3].

INTRODUCTION

Most of the published research relating to the potential for high-sided vehicle rollover in crosswinds dates to the decade of the 1990s. The most recent publication found was from 2003. The published research generally focuses on the characterization of wind flow patterns and the resulting wind loads on the vehicle, but the vehicle models themselves vary from “solid blocks” (the 2003 paper) to rudimentary six-degree-of-freedom four-wheeled single-mass vehicles without suspension or tire compliance.

By contrast, the SIMON model includes, in addition to the six equations of motion for each mass, two degrees of freedom for each wheel or dual pair, with suspension and tire compliance. Driver input is represented by steer, throttle and brake tables in the time domain.

A tractor with a single trailer is studied to determine critical lateral wind speeds for windward wheel lift-off.

Parameters studied include vehicle speed, wind speed and aerodynamic coefficients. Roadway cross-slope was fixed, as were vehicle properties (detailed in the Appendix). No low-coefficient road surfaces are included.

Empty or lightly-loaded trailers are expected to be most susceptible to rollover or dangerous lane excursions due to lateral wind loads, so the analysis presented utilizes an empty trailer.

LITERATURE REVIEW

In 1984, Cooper [4] developed a random-process model for turbulent wind normal to the direction of motion of a vehicle, with particular concern for rail vehicles and with no results immediately applicable to tractor-trailers. Concern about the quality of information available relating to aerodynamic forces was expressed.

C.J. Baker of Nottingham University, Great Britain, has published extensively on the subject. In a 1986 Paper [5] he developed a four-wheeled single-mass vehicle model, applied it to a bus accident, and noted that the least well-defined parameters were the aerodynamic coefficients.

In a 1987 Paper, Baker [6] proposed a “two-level” system of traffic control, with high-sided vehicle speed being restricted to 35 kph (22 mph) at a wind gust speed of 64 kph (40 mph) and road closure to occur at a wind gust speed of 80 kph (50 mph). This analysis was based upon his four-wheeled single-mass vehicle model and he states that “…for the articulated tractor-trailer… this must be a doubtful assumption… [and] should be borne in mind… .”

In 1988, Baker [7] extended his simple vehicle model to include road curvature and camber effects as well as driver inputs. The model application to articulated vehicles was justified by the observation that in most cases the cab and trailer are blown over as a unit and therefore act as a single-mass vehicle.

In a three-part Paper published in 1991, Baker [8] reviewed and summarized his previous work. In Part 1

---

[1] Numbers in brackets refer to references at the end of the Paper.

considerable experimental data on wind force and moment coefficients are presented, which must be interpreted carefully. For example, the coefficients for high-sided road vehicles are referenced to the frontal area[2], rather than the side area, which makes the side coefficients appear vary large. He also states that "…the force and moment coefficients show quite a large degree of sensitivity to changes in modeling technique." It also was noted that there were similarities in wind flow patterns over high-sided road vehicles to wind patterns observed on building roofs.

In Part III Baker [8] plotted accident wind speed for a high-sided road vehicle against wind angle and vehicle speed, where accident wind speed is defined as the speed causing any windward wheel reaction to go to zero. These results are shown in Figure 1.

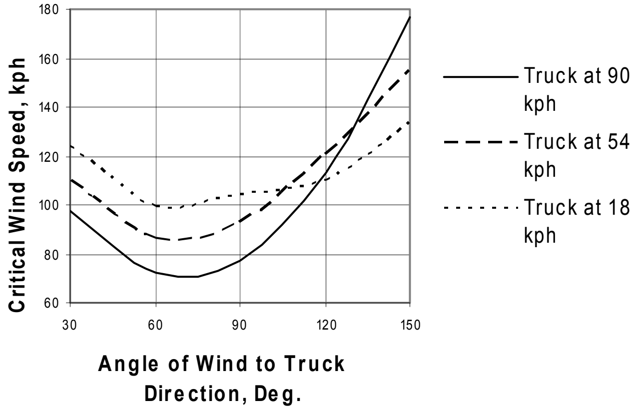

Figure 1: From Baker [8, Part III]

For the wind direction at 90 degrees to the truck direction of travel, these data can be recast as in Figure 2.

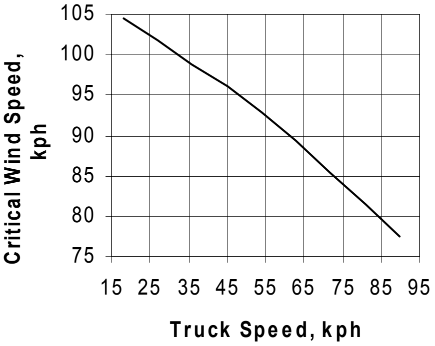

Figure 2

These results (Fig. 2), deduced from Reference 8, Part III, indicate a significant increase in critical wind speed as the truck speed is lowered. These data indicate that the critical wind speed for a truck at 75 kph (47 mph) is about 84 kph (52 mph) while the critical wind speed for a truck at 45 kph (28 mph) is about 96 kph (60 mph).

A severe storm in January of 1990, occurring in southern and central England, was reviewed in a 1992 Paper [9]. Two rollover accidents of "box vans" had enough data to be analyzed and the critical wind speeds were estimated to be between approximately 80 kph (50 mph) and 120 kph (75 mph). Plots similar to Figure 1 are presented.

In 1994 Baker [10] presented a method "…which allows some appreciation … of accident risk in situations where there are physical parameters that are difficult to specify… ." An attempt was made to include driver response but it was admitted that "…the parameters that specify driver behavior are almost impossible to quantify with any precision."

Recognizing that understanding the nature of air flow and the resulting aerodynamic forces on high-sided vehicles was important, Baker and Coleman [11] in 1994 published the results of wind tunnel studies on an articulated high-sided tractor-trailer. It was shown that "…the major flow mechanism is… similar to… the roof of low rise buildings."

SAE, in 1995 [19], published a compilation of Standards and Special Publications relating primarily to passenger car aerodynamics. In that compilation is SP-1109, "Crosswind Facilities and Procedures," in which resultant wind yaw angles of ± 40 degrees are investigated. It is noted that lift forces increase as yaw angle increases.

A 1998 Paper [12] applies a general approach to a specific bus accident and relates vehicle speed and accident risk to road camber (superelevation), surface friction, wind velocity and turning radius. One result was that instability, in this particular case, would be reached when the wind velocity was about 80 kph (50 mph) and the bus speed was about 72 kph (45 mph).

J. Bettle, et al. [13], in 2003, published a study whose stated objective was "…to establish a relationship between wind speed, truck speed and propensity for truck rollover…". The tractor and trailer were modeled as a series of solid "blocks." Figure 3 shows data extracted from that study, where the aerodynamic moment is a measure of the tendency of the wind to overturn the vehicle model. It was admitted that "…a complete dynamic rollover analysis would be required to obtain accurate safety limits."

Selected data from Figure 16 in [13] are shown in Figure 4, which highlights the effect of truck speed on the amount of aerodynamic overturning moment produced by a given wind speed.

---

[2] Referencing aerodynamic coefficients to the projected frontal area is automotive standard practice. See [18].

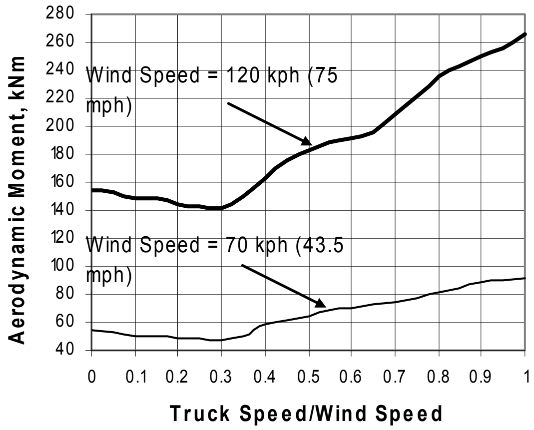

Figure 3

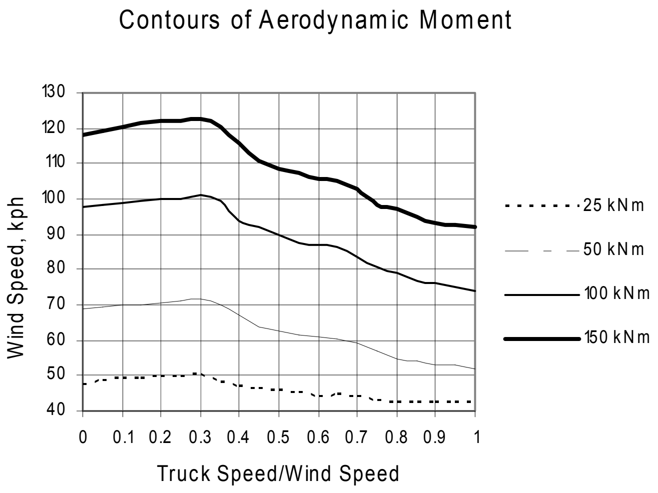

Figure 4: From Bettle, et al. [13]

An interesting Paper [14] by Young and Liesman in 2006 "correlates overturning freight vehicle crash records in Wyoming to measured wind speeds at nearby weather stations." The results "…indicate that weather station data can be used as a predictor of overturning crashes." No vehicle model was employed or needed for the purposes of that study.

In 1995 a Report was produced for the Nevada Department of Transportation [15] that concluded the critical wind speed for truck overturning was 64 kph (40 mph) and, for sliding on a slick surface (a tire/pavement friction coefficient of 0.1), a critical wind speed of 47 kph (29 mph). These results were based upon an empty 13.7 m (45 ft.) trailer, 4.3 m (14 ft.) high, and a static analysis without suspension or tire compliance. The criterion for critical wind for overturning was equality between the computed overturning moment and the restoring moment. No aerodynamic lift forces were considered.

One important consideration in this study [15] was the recognition that the trailer could overturn independently of the tractor and that a roll axis could be defined by the outboard leeward trailer tires and the fifth wheel location. Figure 5 illustrates this. The dimension $b_{effective}$ would be chosen as an approximation to the effective location of the roll axis and, ideally, should consider the lateral and vertical compliance of the suspension and tires. The maximum value of $b_{effective}$ would be the outside track width, b.

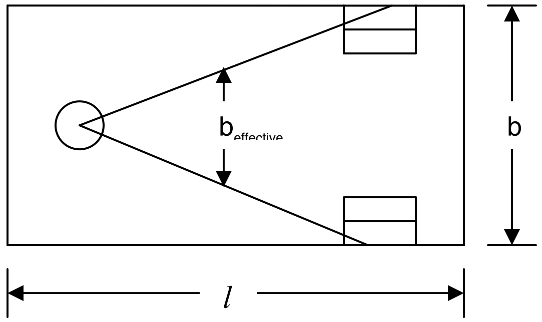

Figure 5

STATIC COMPUTATIONS

The simplest rollover analysis is based upon a rigid vehicle model and a static balance between overturning moment and resisting moment. This section reviews basic considerations of wind load, presents the critical wind speed equation developed by Saiidi and Maragakis [15], gives an alternate static analysis derived by the author and, following a discussion of relevant aerodynamic coefficients, gives some numerical results.

BERNOULLI EQUATION

The fundamental equation for dynamic fluid pressure is the Bernoulli equation [16]:

$$p_s = \frac{1}{2}\rho v^2 \qquad (1)$$

where $p_s =$ stagnation pressure

$\rho =$ mass density of the fluid = 1.2245 kg_m/m^3 (0.002376 slugs/ft.^{3}), for air (standard atmosphere), and

$v =$ velocity of the fluid.

The pertinent aerodynamic forces per unit area of surface are

Drag force $= D' = C_d p_s$ (2a)

Lift Force = $L' = C_l p_s$ (2b)

where, in the case of a trailer, the unit drag force is applied to the side perpendicular to the wind direction and the unit lift force is applied to the top, each at its center of pressure[3].

THE SAIIDI CRITICAL WIND SPEED EQUATION [15]

Letting $v =$ critical wind speed for rollover

$W =$ trailer weight, lbs.

$b_{effective}$ = effective roll restoring moment arm, ft.

$l =$ trailer box length, ft.

$h =$ trailer height, from ground, ft.

$h_2 =$ trailer tire diameter, ft.,

$C_d =$ drag coefficient,

$A_s =$ trailer side area, ft.^{2}, and

$d =$ moment arm for the side force, ft.,

the critical wind speed formula for overturning developed in [15] is derived from equating an overturning moment of

$$C_d p_s A_s d = \frac{0.002376}{2}(l)\left(h - \frac{h_2}{2}\right)C_d\left(\frac{h}{2} + \frac{h_2}{4}\right)v^2,$$

where v is in fps, to a resisting moment of $W\dfrac{b_{effective}}{2}$.

Thus, $$v = \left\{W\frac{b_{effective}}{0.002376(l)\left(h - \frac{h_2}{2}\right)C_d\left(\frac{h}{2} + \frac{h_2}{4}\right)}\right\}^{0.5}$$

for v in fps, and

$$v = \left\{W\frac{b_{effective}}{0.00512(l)\left(h - \frac{h_2}{2}\right)C_d\left(\frac{h}{2} + \frac{h_2}{4}\right)}\right\}^{0.5} \quad (3)$$

for v in mph. In this formula the effective trailer height is taken as the total trailer height less one-half of the tire diameter and no lift forces are considered.

AN ALTERNATE STATIC EQUATION

In this Section an alternate equation to (3) is derived, using slightly different assumptions and including the effect of aerodynamic lift on the trailer roof. The same notation is used as in the Saiidi Equation derivation.

In this derivation the overturning moment is

$$C_d p_s A_s d + C_l p_s A_r d_r =$$

$$\frac{0.002376}{2}(l)\left[\begin{array}{l} C_d\left(\dfrac{h^2 - h_2^2}{2}\right)v_{wind}^2 + \\ C_l(b)\left(\dfrac{b_{effective}}{2}\right)\left(v_{wind}^2 + v_{truck}^2\right) \end{array}\right]$$

where the velocities are in fps or

$$0.00256(l)\left[\begin{array}{l} C_d\left(\dfrac{h^2 - h_2^2}{2}\right)v_{wind}^2 + \\ C_l(b)\left(\dfrac{b_{effective}}{2}\right)\left(v_{wind}^2 + v_{truck}^2\right) \end{array}\right]$$

where the velocities are in mph.

Equating to the resisting moment of $W\left(\dfrac{b_{effective}}{2}\right)$ gives, for the critical wind speed,

$$v_{wind} =$$

$$\left\{W\frac{b_{effective}}{0.00256(l)\left[C_d\left(h^2 - h_2^2\right) + C_l(b)\left(b_{effective}\right)\left(1 + \dfrac{v_{truck}^2}{v_{wind}^2}\right)\right]}\right\}^{0.5}$$

(4)

---

[3] Due to lack of available data on aerodynamic pressure distributions, the centers of pressure for side force and for lift force are taken at the geometric center of their respective surfaces. Also, no aerodynamic roll or yaw moments are considered, except those produced by the drag and lift forces themselves. Further, no lateral aerodynamic force is computed on the leeward side of a trailer.

with the velocities in mph and where

$C_l =$ lift coefficient

$A_r =$ trailer roof area, ft.^{2}

$d_r =$ moment arm for the lift force, ft.

$b =$ trailer width, ft.

In this formula[4] the effective trailer height is the total height minus the wheel diameter. The consideration of aerodynamic lift brings in the truck speed, v_{truck}. Clearly, as v_{truck} increases, the critical wind speed for overturning decreases.

AERODYNAMIC COEFFICIENTS

A review of the literature makes it apparent that the aerodynamic coefficients for wind forces on tractor-trailers are somewhat less than well understood [4, 5, 8]. It can be expected that longitudinal drag forces have been examined more thoroughly than side and lift forces, due to concern over fuel economy.

Reference [7] provides experimentally-determined aerodynamic coefficients for 1/25th scale "standard articulated lorry" models. They are referenced to a "frontal area" of 11.5 m^2 (124 sq. ft.). The maximum side force coefficient (C_S) is given as 5.2. The "standard articulated lorry" side area is not given; if it is assumed to be 4.3m x 13.7m (14 ft. x 45 ft.), the given maximum side coefficient can be referred from the frontal area to the side by 5.2(11.5/(4.3)(13.7)) = 5.2(0.195) • 1. The maximum lift force coefficient (C_L) is given as 2.2 and, if the top area of the vehicle is taken as 2.4m x 13.7m (8 ft. by 45 ft.), becomes 2.2(11.5/(2.4)(13.7)) = 2.2(0.35) = 0.77 when referred to the top. None of these tests involved a *moving* vehicle, and the author states that "…to be fully representative… these tests should be carried out by propelling models across a wind tunnel in which the atmospheric wind has been simulated." It is expected, however, that such *static* tests would provide an upper bound to the aerodynamic coefficients and thus be conservative.

In reference [11] aerodynamic coefficients are presented which were derived from wind tunnel tests on a 1/50th scale model of an "articulated lorry" on a bridge deck. The geometry of the bridge was not presented, but the deck was said to have "a faired leading edge to prevent flow separation." The coefficients are referred to the vehicle model frontal area (given as 4500 mm^2), and are very similar in value to those of [7]. Enough dimensional data on the model are given to refer the aerodynamic coefficients to the side and top of the trailer. When thus referred, there results a side drag coefficient (C_d) of about 2.0 and a lift coefficient (C_l) of about 1.0, with variations for wind angle and amount of turbulence.

A 1998 SAE publication, "Aerodynamics of Road Vehicles" [20] contains a chapter on commercial vehicles. Primarily concerned with drag, wind yaw angles of just ± 14 degrees are considered. Furthermore, it is asserted that wind tunnel models of scale smaller than 1:2.5 will not produce reliable results. This is an excellent reference, but it does not address the central question of this research.

Reference [13] gives aerodynamic coefficients for a tractor-trailer on a bridge, based upon computational fluid mechanics. For a lateral wind direction and the truck in the windward lane, the side coefficient is given as 1.56 and the lift coefficient is given as 0.40. With a bridge edge vertical barrier of 1.1 m (3.6 ft.), it is likely that the bridge model has significantly influenced these values.

Both references [11] and [8] indicate that the air flow over a tractor-trailer has characteristics similar to that over a low-rise building. The Uniform Building Code [17] provides values for "design wind pressures" for buildings. The aerodynamic coefficient is composed of three values:

$C_e =$ combined height, exposure and gust factor = 1.39 (max.)

$C_q =$ pressure coefficient for the structure under consideration = 1.3 for walls, 0.7 for roofs

$I_w =$ importance factor = 1.15 (maximum)

The unit wind load then is $F' = C_e C_q I_w p_s$ or

the drag coefficient $C_d =$ (1.39)(1.3)(1.15) = 2.08 and the lift coefficient $C_l =$ (1.39)(0.7)(1.15) = 1.12.

Based upon the available information, it appears that these values are reasonable. They also agree well with the data from reference [11].

Reference [13] applies computational aerodynamics to a very special case which cannot be extended to general applicability. It appears likely that a general investigation of lateral wind loads on vehicles by means of computational aerodynamics would lead to more definitive values of drag and lift coefficients than presently are available.

---

[4] Clearly, because the wind speed appears on both sides of the equation, an iterative solution is necessary.

NUMERICAL EXAMPLE

Using the following values:

W = 16,680 lbs

$b_{effective} = 4.0$ ft. (probably the *smallest* reasonable value)

$l = 45$ ft.

$h = 13.65$ ft.

$h_2 = 4.15$ ft.

$C_d = 2.0$

$A_s = 427.5$ sq. ft.

$C_l = 1.0$

$b = 8$ ft. and

$v_{truck} = 55$ mph,

there is obtained, from Eq. (3), a critical wind speed of 40 mph.

From Eq. (4), the result is 36 mph.

In these calculations, $b_{effective} = 4$ ft.; an upper limit value would be 8 ft. Using that value, Eq. (3) yields 56.5 mph and Eq. (4) gives 49 mph for the critical wind speed. Obviously, for these static calculations, the assumed location of the roll axis is critical.

The results for a given value of $b_{effective}$ differ primarily due to lift considered in Eq, (4), generated both by the the wind and by the truck speed, with Eq. (4) producing a lower critical wind speed, as is expected.

DYNAMIC SIMULATIONS

COMPUTATIONAL ENVIRONMENT

SIMON

SIMON is an HVE-compatible 3-dimensional simulation model [22], modeling the response of one or more vehicles to driver inputs and terrain variations and including some capability for considering wind and other externally-applied loads. The model allows multiple sprung masses, each with six degrees of freedom, and multiple axles with up to five degrees of freedom per axle. Power units and trailers can be connected by a variety of realistic methods.

The application of aerodynamic loads to tractor-trailers modeled in SIMON represents an advance over previous analyses, which have concentrated on the investigation of the magnitude of aerodynamic loads and have used very simple vehicle models to determine vehicle response to those loads.

Presently SIMON automatically computes longitudinal aerodynamic loads, based upon vehicle speed and user-entered aerodynamic drag coefficient and projected surface area, input in HVE's vehicle editor. Center of pressure is also user-entered.

The treatment of lateral aerodynamic loads in SIMON is now under development and is not automatic. Hand-computed wind loads can be applied however, with whatever direction, location and time history the analyst desires, by use of the "collision pulse" option in HVE's event set-up dialogue.

TEST SURFACE

The test surface employed in this investigation has two 12 foot lanes each direction, with zero grade and 1.5 percent cross-slope down to the right, for right-hand traffic. The maximum friction coefficient between the tires and the roadway is given by the tire properties[5], presented with all of the vehicle data, in the Appendix. These friction properties are load and speed dependent, and the simulation program linearly interpolates between the given data points as load and speed change at each tire or tire group.

TEST VEHICLE

The test vehicle utilized is a tractor pulling a 45-foot box trailer. The specifications on this tractor-trailer model are presented in the Appendix. The mechanical details, including dimensions, weights, weight distribution and suspension and tire compliance derive from actual measurements on representative equipment.

FURTHER ANALYTICAL CONSIDERATIONS

The trailer in this study was unloaded, since light trailers are considered to be most susceptible to wind loads. Its weight was 16,680 lbs. Cross-winds were considered to act at 90 degrees to the trailer.

---

[5] The total friction between the tires and the road surface in the model is set by the product of three input variables: the road surface friction factor (here set to 1.0), the tire friction properties, specified for the test vehicle, and an "in-use" factor, which also is set to 1.0 here.

Lateral wind loads were not applied to the tractor. Lateral aerodynamic coefficients for such vehicles have not been well-studied, and the lack of such loads probably has little effect on the initial rollover behavior of the trailer. Absence of lateral tractor loads will affect the trajectory of the assembled rig, and probably increase the tractor yaw to windward.

Vehicle speed was considered when calculating lift on the top of the trailer; its effect on the trailer sides was considered self-equilibrating and therefore was ignored.

Vehicle longitudinal drag, based upon the frontal area of the power unit, is automatically calculated by SIMON, but does not contribute in any way to trailer rollover potential.

WIND LOADS ON THE 45-FOOT BOX TRAILER

Lateral Drag – The side area of the trailer was taken as (45)(9.5) = 427.5 sq. ft. Stagnation pressure was taken as

$$p_s = \frac{1}{2}\rho v^2 = \frac{1}{2}(0.00512)v^2$$

and the total drag force is computed as

$$D = C_d p_s A = 1.094 C_d v^2$$

for v in mph.

Thus, for $C_d = 2$, $D = 2.188v^2$ and at a wind speed of 55 mph, for example, $D = 6{,}620$ lbs. and is applied at the geometric center of the side area of the trailer.

Vertical Lift – The top area of the trailer was taken as (45)(8) = 360 sq. ft. The total lift force is computed as

$$L = C_l p_s A = 0.922 C_l v^2$$

for v in mph.

Thus, for $C_l = 1$, $L = 0.922v^2$ and at 55 mph for *both* the wind and the truck, for example, $L = 2(0.922v^2) = 5{,}580$ lbs. and is applied at the geometric center of the top area of the trailer.

The application of these aerodynamic loads begins at one second into the simulation run, and builds up over one-half second to the maximum value, which then is maintained for the entire run. Reference [8], Part III, suggests that a wind loading (gust) of 0.5 to 1.0 seconds would be of sufficient duration to overturn a road vehicle. This cannot be confirmed by the present analysis, since the criterion for termination was zero vertical force on any windward wheel.

RESULTS

As previously stated, the criterion for critical wind speed was zero vertical load on any windward trailer tire.[6] The results for the vehicle studied are presented in Figure 6.

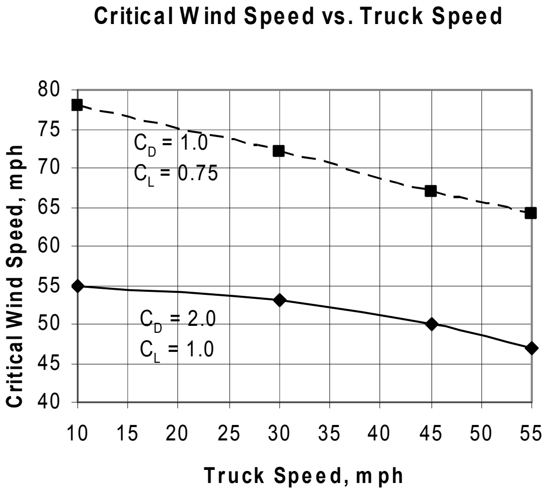

Figure 6

Because of the lack of clarity in evaluating aerodynamic coefficients, results for two different sets of drag and lift coefficients are presented. It is the belief of the author that, until better aerodynamic data become available, use of the more conservative results is justified.

A comparison of the results of the present research, for the 45 foot trailer, with data derived from Reference [8] as previously presented in Figure 2, is shown in Figure 7. This is a very general comparison, because weights, weight distribution, vehicle dimensions and even aerodynamic coefficients vary between the two investigations in unknown ways.

Comparison of the results of the dynamic simulations to static calculations by Equation (4), with all vehicle dimensions, weights and aerodynamic parameters having the same values in each calculation, is presented in Figure 8. Two examples of static calculations are shown, for the two limiting cases of the assumed position of the roll axis.

---

[6] This approach has been used consistently by other researchers. The wind load (and speed) related to that criterion may well not produce roll large enough to bring the trailer center of gravity over the pivot point and lead to rollover. Although the vehicle models used in SIMON are not restricted to small-angle displacements, the value of drag and lift coefficients can be expected to change with roll angle, and such changes have not been studied, to the knowledge of this investigator.

This comparison indicates that use of the outside roll axis position, rather than an axis being influenced by the fifth-wheel location, is in closer agreement with the dynamic simulation, although other differences in the two analyses should be kept in mind.

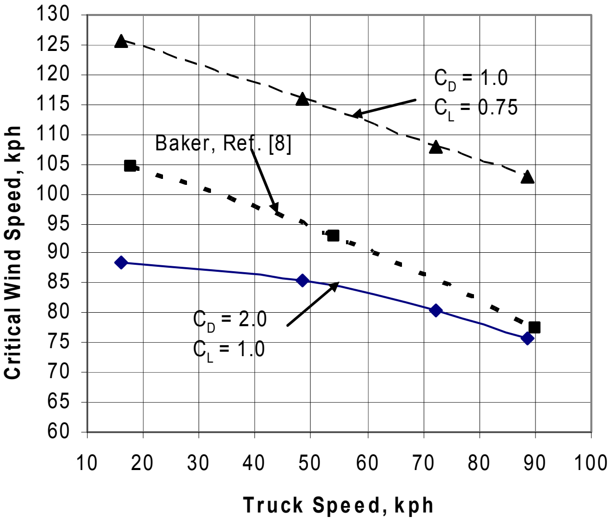

Figure 7: Ref.[8] vs. Current Research

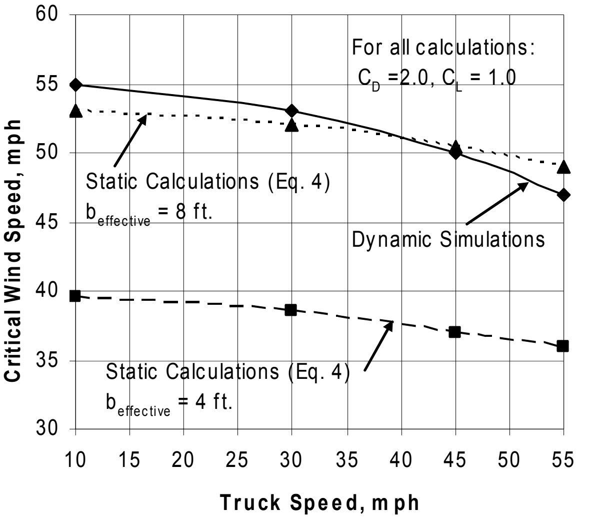

Figure 8: Comparison of Static Calculations with Dynamic Simulations

The criterion for critical wind speed in the static calculations is different from that used in the dynamic simulations. Balance between overturning and resisting moment (the static criterion) is not the same as the development of zero vertical force on any windward tire (the dynamic criterion).

Due to suspension and tire compliance, the tire patch will remain in contact with the road surface as the trailer rolls, until sufficient roll is developed to lift the tire. In these simulations, a trailer roll of between two and 2.5 degrees[7] is developed when a windward tire vertical force goes to zero, and the tire contact patch has dropped about two inches, from its loaded equilibrium position, relative to the trailer body. This tire movement, which of course is not considered in the static analysis, will likely affect the critical wind speed calculation.

CONCLUSIONS

1. Values of aerodynamic coefficients for high-sided road vehicles are not well established. The suggestion that aerodynamic flow patterns are similar to those over low-rise buildings, as reported by some researchers, is a useful observation. Wind loads on buildings have been studied extensively. Based upon such observations, a drag coefficient of approximately two and a lift coefficient of approximately one are suggested for box trailers, until more specific data are available.

2. Static calculations which do not consider suspension and tire compliance will predict critical wind speeds highly dependent upon the assumed location of the trailer roll axis. Dynamic simulations establish the roll axis automatically and are considered to be more realistic.

3. The SIMON simulation model, within the Engineering Dynamics Corporation HVE suite of analysis programs, is a valuable tool for studying tractor-trailer response to wind loading.

4. Vehicle speed has a relatively minor but still significant effect on critical wind speed. Significantly reducing vehicle speed in high winds is an appropriate driver response.

5. Based upon the limited analysis presented, in a truck speed zone of 55 mph, a wind (gust) speed of 40 mph is a reasonable level at which to initiate road closure for high-sided vehicles.

RECOMMENDATIONS

The HVE event editor could be made to allow designation of windward sides of a vehicle, with wind speed and direction input as a function of time. Aerodynamic coefficients, projected surface area and center of pressure should be user-entered. In a similar

---

[7] Before the wind loading, the trailer has an equilibrium roll angle, with respect to a horizontal earth-fixed plane, of 0.86 degrees, due to the cross-slope of the roadway of 1.5 percent. The wind produces a roll angle in the opposite direction of approximately 1.3 to 1.5 degrees, for a total roll excursion of between two and 2.5 degrees.

manner, to allow for uplift on, for example, box trailers, the top trailer surface could allow negative (outward) pressure.

Aerodynamic coefficients can be expected to change with vehicle roll (and yaw) angle, but no research known to the author has developed such information. Progress in this area might best be made by application of computational fluid dynamics. It probably is not reasonable to expect developments in SIMON to allow for the effects of roll on wind loads, when no data is expected to be available in the near future.

CONTACT

William Blythe, P.E., Ph.D.
1545 University Ave.
Palo Alto, California 94301-3140
650-323-2062
wbinc8831@sbcglobal.net

REFERENCES

1. Day, T.D., Roberts, S.G. and York, A.R., "SIMON: A New Vehicle Simulation Model for Vehicle Design and Safety Research," SAE Paper No. 2001-01-0503, Society of Automotive Engineers, Warrendale, PA, 2001.

2. Day, T.D., "Validation of the SIMON Model for Vehicle Handling and Collision Simulation – Comparison of Results with Experiments and Other Models," SAE Paper No. 2004-01-1207, SAE International, Warrendale, PA., 2004.

3. Blythe, W., "Tractor-trailer Response to High Crosswinds; Static Computations and Dynamic Simulations," SAE Paper No. 2007-01-4255, SAE International, Warrendale, PA., 2007.

4. Cooper, R., "Atmospheric Turbulence with Respect to Moving Ground Vehicles," *Journal of Wind Engineering and Industrial Aerodynamics*, 17 (1984) 215-238. Elsevier Science Publishers B. V., Amsterdam.

5. Baker, C. J., "A Simplified Analysis of Various Types of Wind-induced Road Vehicle Accidents," *Journal of Wind Engineering and Industrial Aerodynamics, 22 (1986) 69-85.* Elsevier Science Publishers B. V., Amsterdam.

6. Baker, C. J., "Measures to Control Vehicle Movement at Exposed Sites during Windy Periods," *Journal of Wind Engineering and Industrial Aerodynamics,* 25 (1987) 151-161. Elsevier Science Publishers B. V., Amsterdam.

7. Baker, C. J., "High Sided Articulated Road Vehicles in Strong Cross Winds," *Journal of Wind Engineering and Industrial Aerodynamics,* 31 (1988) 67-85, Elsevier Science Publishers B. V., Amsterdam.

8. Baker, C. J., "Ground Vehicles in High Cross Winds," Parts I, II and III. *Journal of Fluids and Structures* (1991) **5**, 69-90. Academic Press Limited.

9. Baker, C. J. and Reynolds S., "Wind-induced Accidents of Road Vehicles," *Accident Analysis & Prevention,* Vol. 24, No. 6, pp. 559-575 (1992). Pergamon Press.

10. Baker, C. J., "The Quantification of Accident Risk for Road Vehicles in Cross Winds," *Journal of Wind Engineering and Industrial Aerodynamics,* 51 (1994) 93-107. Elsevier Science Publishers B. V., Amsterdam.

11. Coleman, S. A., and Baker, C. J., "An Experimental Study of the Aerodynamic Behaviour of High Sided Lorries in Cross Winds," *Journal of Wind Engineering and Industrial Aerodynamics,* 53 (1994) 401-429. Elsevier Science Publishers B.V., Amsterdam.

12. Sigbjornsson, R. and Snaebjornsson, J., "Probabilistic Assesment of Wind Related Accidents of Road Vehicles," *Journal of Wind Engineering and Industrial Aerodynamics,* 74-76 (1998) 1079-1090. Elsevier Science Publishers B.V., Amsterdam.

13. Bettle, J., Holloway, A. G. L., and Venart, J .E. S., "A Computational Study of the Aerodynamic Forces Acting on a Tractor-trailer on a Bridge in Cross-wind," *Journal of Wind Engineering and Industrial Aerodynamics,* 91 (2003) 573-592. Elsevier Science Publishers B.V., Amsterdam.

14. Young, R. K. and Liesman, J., "Estimating the Relationship between Measured Wind Speed and Overturning Truck Crashes Using a Binary Logit Model," *Accident Analysis & Prevention,* in press, 2006, doi:10.1016/j.aap.2006.10.002.

15. Saiidi, M. and Maragakis, E., "Identification of Trigger Wind Velocities to Cause Vehicle Instability," Final Report to the Nevada Department of Transportation, District II, Agreement No. P206-95-201, Reno, Nevada, September 1995.

16. Streeter, V. L., Fluid Mechanics, Third Edition, McGraw-Hill Book Company, Inc. 1962.

17. Uniform Building Code, 1997, by the International Conference of Building Officials (ICBO). Published by the International Code Council (ICC).

18. Vehicle Aerodynamic Terminology, SAE J1594, SAE International, Warrendale, PA., 1994.

19. SAE Vehicle Aerodynamics Packet, 2006 Edition, SAE International, Warrendale, PA., 2005.

20. "Commercial Vehicles," Chapter 9 in Aerodynamics of Road Vehicles, 4th Edition, Wolf-Heinrich Hucho, Ed., SAE International, Warrendale, PA., 1998.

21. HVE Engineering Simulation User's Manual, Engineering Dynamics Corporation, Beaverton, Oregon, 2004.

22. SIMON Simulation Model Non-linear User's Manual, Engineering Dynamics Corporation, Beaverton, Oregon, 2002.

APPENDIX

VEHICLE DATA

TRACTOR DATA

General Information

Number of Axles:	3
Driver Location:	Left Side
Engine Location:	Front Engine
Drive Axle(s):	Axles 2 and 3

Sprung Mass Dimensional Data:

Overall Length (in):	265.75
Overall Width (in):	96.00
Overall Height (in):	103.35
Ground Clearance (in):	21.35
Wheelbase (in):	179.50
CG to Front Axle (in):	79.40
CG to Back Axle (in):	-100.10
CG Height (in):	45.35
Front Overhang (in):	48.00
Rear Overhang (in):	38.25

Sprung Mass Inertial Data:

Total Weight (lb):	16940.00
Sprung Weight (lb):	11755.09
Sprung Mass (lb-sec^2/in):	30.42

Sprg Mass Rot Inertia (lb-sec^2-in) -	Roll:	27284.07
	Pitch:	77963.84
	Yaw:	81064.75
	XZ Product:	0.00

Inter-Vehicle Connection Parameters:

Connection Location:	Rear
Type:	Fifth Wheel
Coordinates (in) - x:	-99.60
y:	0.00
z:	-3.00
Maximum Articulation (deg):	90.00
Connection Friction:	0.05
Friction Radius (in):	18.00

Steering System Parameters

First Axle:	Steerable
Steering Gear Ratio (deg/deg):	28.00

		Right Side	Left Side
		----------	----------
Caster (deg):		0.00	0.00
Inclination Angle (deg):		0.00	0.00
Steering Offset (in):		0.00	0.00
Stub Axle Length (in):		0.00	0.00
Initial Steer Axis Coord (in) -	x:	79.40	79.40
	y:	39.75	-39.75
	z:	24.00	24.00

Second Axle:	Not Steerable
Third Axle:	Not Steerable

Drivetrain Parameters

Engine Description: Generic Drivetrain
Maximum Power (HP): 350
Maximum Torque (ft-lb): 1350
Transmission Forward Speeds: 6
Differential Speeds: 2

Wide-open Throttle,	Speed (RPM):	200	800	1000	1200	1400	1600	1800
	Power (HP):	23	183	248	308	350	350	326
	Torque (ft-lb):	599	1200	1300	1350	1313	1149	950

Closed Throttle,	Speed (RPM):	250	800	1200	1600	2200
	Power (HP):	-1	-11	-24	-43	-82
	Torque (ft-lb):	-22	-71	-107	-142	-196

Transmission Gear:	Rev	1st	2nd	3rd	4th	5th	6th
Numerical Ratio:	-4.80	3.51	1.91	1.43	1.00	0.74	0.64

Differential Gear:	High	Low
Numerical Ratio:	3.55	4.83

Tractor First Axle

Wheel Location Information, First Axle ---

	Right Side	Left Side
Initial Wheel Coordinates (in) - x:	79.40	79.40
y:	39.75	-39.75
z:	24.00	24.00

Suspension Information:

Suspension Type:	Solid Axle
Axle Roll/Yaw Inertia (lb-sec^2-in):	5000.00
Axle Roll Ctr Ht Below CG (in):	21.00
Axle Roll Steer (deg/deg):	0.00
Lateral Spring Spacing (in):	36.00
Nominal Track Width (in):	79.50
Total Unsprung Weight (Axle+Wheels, lb):	1152.94
Auxiliary Roll Stiffness (in-lb/deg):	0.00

	Right Side	Left Side
Spring Rate (lb/in):	1125.00	1125.00
Viscous Damping (lb-sec/in):	5.00	5.00
Coulomb Friction (lb):	500.00	500.00
Friction Null Band (in/sec):	5.00	5.00
Deflection to Jounce Stop (in):	-5.00	-5.00
Stop Linear Rate (lb/in):	500.00	500.00
Stop Cubic Rate (lb/in^3):	5000.00	5000.00
Stop Energy Ratio (%/100):	0.50	0.50
Deflection to Jounce Stop (in):	5.00	5.00
Stop Linear Rate (lb/in):	500.00	500.00
Stop Cubic Rate (lb/in^3):	5000.00	5000.00
Stop Energy Ratio (%/100):	0.50	0.50
Camber Constant (deg):	0.00	0.00

```
Tire Information:
                                                  Right Side     Left Side
                                                  ----------     ----------
          Tire Model:                             Generic        Generic
          Tire Size:                              11.00R20H      11.00R20H
         Unloaded Radius (in):                    21.35          21.35
         Init. Radial Stiffness (lb/in/tire):     5000.00        5000.00
         2nd Radial Stiffness (lb/in/tire):       50000.00       50000.00
         Defl. @ 2nd Stiffness (in):              9.08           9.08
         Max Deflection (in):                     11.35          11.35
         Rebound Energy Ratio (%/100):            1.00           1.00
         Spin Inertia (Tire+Whl+Brk, lb-sec^2-in/ 182.21         182.21
         Steer Inertia (Tire+Whl+Brk, lb-sec^2-in 73.43          73.43
         Weight (Tire+Whl+Brk, lb/tire):          249.00         249.00
         Roll Resistance Const:                   0.01           0.01
         Roll Resististance Linear Coef (sec/in): 0.00           0.00
         Pneumatic Trail (in):                    -2.10          -2.10
         Lateral Stiffness (lb/in):               5000.00        5000.00

Cornering Stiffness (lb/deg/tire):     Right Side                 Left Side
                      --------------------- ---------------------------------------------------------
        Loads (lb):              2000.0  4000.0  6000.0     2000.0  4000.0  6000.0
        Speed (in/sec):              704.0                      704.0
        Load No.:                  1        2       3         1        2       3
                                 321.9   581.0   823.0      321.9   581.0   823.0

Camber Stiffness (lb/deg/tire):        Right Side                 Left Side
                      --------------------- --------------------- ------------------------------

        Loads (lb):              2000.0  4000.0  6000.0       2000.0  4000.0  6000.0
      Speed (in/sec):                704.0                            704.0
         Load No.:                 1        2       3           1       2       3
                                 40.0     60.0    80.0        40.0    60.0    80.0


Tire Friction Table:                       Right Side                   Left Side
                      --------------------- ------------------------------------------------------
        Loads (lb):                   3900.0  7200.0 10800.0       3900.0  7200.0 10800.0
        Speeds (in/sec):                  352.0   704.0                352.0   704.0
        Speed No. 1, Load No.:        1        2          3        1          2          3
        Peak Mu:                      0.80  0.76  0.73             0.80      0.76       0.73
        Slide Mu:                     0.60  0.55  0.50             0.60      0.55       0.50
         Slip @ Peak Mu (%/100):      0.35  0.30  0.25             0.35      0.30       0.25
         Long. Stiffness (lb/slip):  18000.0 35000.0 60000.0      18000.0 35000.0 60000.0
         Speed No. 2, Load No.:        1        2         3        1          2          3
          Peak Mu:                    0.80  0.74  0.68             0.80      0.74       0.68
          Slide Mu:                   0.50  0.44  0.39             0.50      0.44       0.39
         Slip @ Peak Mu (%/100):      0.25  0.18  0.16             0.25      0.18       0.16
         Long. Stiffness (lb/slip):   29800.0  69220.0 119850.0 29800.0  69220.0  119850.0

 Brake Information:
                                           Right Side      Left Side
                                             ----------     ----------
            Brake Assembly Type:         Generic Brake    Generic Brake
            Brake Time Lag (sec):            0.1000         0.1000
            Brake Time Rise (sec):           0.2000         0.2000
            Pushout Pressure (psi):            0.00           0.00
 Nominal Brake Torque Ratio (in-lb/psi):    1000.00        1000.00
```

Tractor Second Axle

Wheel Location Information:

	Right Side	Left Side
Initial Wheel Coordinates (in) -x:	-74.60	-74.60
Y:	36.00	-36.00
z:	24.00	24.00
Inter-dual Spacing (in):	13.50	13.50

Suspension Information:

Suspension Type:	4-Spring
Axle Roll/Yaw Inertia (lb-sec^2-in):	12230.00
Axle Roll Ctr Ht Below CG (in):	21.00
Axle Roll Steer (deg/deg):	0.00
Lateral Spring Spacing (in):	41.00
Nominal Track Width (in):	72.00
Total Unsprung Weight (Axle+Wheels, lb):	2103.99
Auxiliary Roll Stiffness (in-lb/deg):	0.00

	Right Side	Left Side
Spring Rate (lb/in):	5500.00	5500.00
Viscous Damping (lb-sec/in):	5.00	5.00
Coulomb Friction (lb):	1000.00	1000.00
Friction Null Band (in/sec):	5.00	5.00
Deflection to Jounce Stop (in):	-5.00	-5.00
Stop Linear Rate (lb/in):	300.00	300.00
Stop Cubic Rate (lb/in^3):	600.00	600.00
Stop Energy Ratio (%/100):	0.50	0.50
Deflection to Jounce Stop (in):	5.00	5.00
Stop Linear Rate (lb/in):	300.00	300.00
Stop Cubic Rate (lb/in^3):	600.00	600.00
Stop Energy Ratio (%/100):	0.50	0.50
Camber Constant (deg):	0.00	0.00

Tire Information:

	Right Side	Left Side
Tire Model:	Generic	Generic
Tire Size:	11.00R20H	11.00R20H
Unloaded Radius (in):	21.35	21.35
Init. Radial Stiffness (lb/in/tire):	5000.00	5000.00
2nd Radial Stiffness (lb/in/tire):	50000.00	50000.00
Defl. @ 2nd Stiffness (in):	9.08	9.08
Max Deflection (in):	11.35	11.35
Rebound Energy Ratio (%/100):	1.00	1.00
Spin Inertia (Tire+Whl+Brk, lb-sec^2-in	182.21	182.21
Steer Inertia (Tire+Whl+Brk, lb-sec^2-in	73.43	73.43
Weight (Tire+Whl+Brk, lb/tire):	249.00	249.00
Roll Resistance Const:	0.01	0.01
Roll Resististance Linear Coef (sec/in):	0.00	0.00
Min Fz For Skidmark (lb):	1900.00	1900.00
Pneumatic Trail (in):	-2.10	-2.10
Lateral Stiffness (lb/in):	5000.00	5000.00

Cornering Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):		704.0			704.0	
Load No.:	1	2	3	1	2	3

Speed No. 1:	321.9	581.0	823.0	321.9	581.0	823.0

Camber Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):		704.0			704.0	
Load No.:	1	2	3	1	2	3
Speed No. 1:	40.0	60.0	80.0	40.0	60.0	80.0

Tire Friction Table:	Right Side			Left Side		
Loads (lb):	3900.0	7200.0	10800.0	3900.0	7200.0	10800.0
Speeds (in/sec):		352.0	704.0		352.0	704.0
Speed No. 1, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7600	0.7300	0.8000	0.7600	0.7300
Slide Mu:	0.6000	0.5500	0.5000	0.6000	0.5500	0.5000
Slip @ Peak Mu (%/100):	0.3500	0.3000	0.2500	0.3500	0.3000	0.2500
Long. Stiffness (lb/slip):	18000.0	35000.0	60000.0	18000.0	35000.0	60000.0
Speed No. 2, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7400	0.6800	0.8000	0.7400	0.6800
Slide Mu:	0.5000	0.4400	0.3900	0.5000	0.4400	0.3900
Slip @ Peak Mu (%/100):	0.2500	0.1800	0.1600	0.2500	0.1800	0.1600
Long. Stiffness (lb/slip):	29800.0	69220.0	119850.0	29800.0	69220.0	119850.0

Brake Information:

	Right Side	Left Side
Brake Assembly Type:	Generic Brake	Generic Brake
Brake Time Lag (sec):	0.1000	0.1000
Brake Time Rise (sec):	0.2000	0.2000
Pushout Pressure (psi):	0.00	0.00
Nominal Brake Torque Ratio (in-lb/psi):	1500.00	1500.00

<u>Tractor Third Axle</u>

Same as tractor second axle except:

Wheel Location Information:

	Right Side	Left Side
Initial Wheel Coordinates (in) - x:	-125.60	-125.60
Total Unsprung Weight (Axle+Wheels, lb):	1927.98	

TRAILER DATA

<u>General Information:</u>

Vehicle Make: Generic
Number of Axles: 2

Sprung Mass Dimensional Data:
Overall Length (in): 540.00
Overall Width (in): 96.00
Overall Height (in): 163.74
Ground Clearance (in): 49.74
Wheelbase (in): 49.00
CG to Front Axle (in): -35.40
CG to Back Axle (in): -84.40
CG Height (in): 61.74
Front Overhang (in): 377.00
Rear Overhang (in): 114.00

```
          Sprung Mass Inertial Data:
          Total Weight (lb):           16680.00
          Sprung Weight (lb):          12488.18
          Sprung Mass (lb-sec^2/in):   32.32
          Sprg Mass Rot Inertia (lb-sec^2-in):
                                       Roll:          103213.54
                                       Pitch:         888296.88
                                       Yaw:           890662.88
                                       XZ Product:    0.00

Inter-Vehicle Connection Parameters:
               Connection Location:          Front
                          Type:              King Pin
               Coordinates (in) x:           305.60
                                y:           0.00
                                z:           12.50
```

<u>Trailer First Axle</u>

```
Wheel Location Information:
                                       Right Side      Left Side
                                       ----------      ----------
Initial Wheel Coordinates (in) x:        -35.40          -35.40
                               y:         36.00          -36.00
                               z:         40.00           40.00
Inter-dual Spacing (in):                  13.50           13.50

Suspension Information:
          Suspension Type:                        4-Spring
          Axle Roll/Yaw Inertia (lb-sec^2-in):    4746.00
          Axle Roll Ctr Ht Below CG (in):         37.00
          Axle Roll Steer (deg/deg):              0.00
          Lateral Spring Spacing (in):            38.00
          Nominal Track Width (in):               72.00
          Total Unsprung Weight (Axle+Wheels, lb): 2095.91
          Auxiliary Roll Stiffness (in-lb/deg):   0.00

                                        Right Side      Left Side
                                        ----------      ----------
          Spring Rate (lb/in):          5500.00         5500.00
          Viscous Damping (lb-sec/in):  5.00            5.00
          Coulomb Friction (lb):        1000.00         1000.00
          Friction Null Band (in/sec):  5.00            5.00
          Deflection to Jounce Stop (in): -5.00         -5.00
          Stop Linear Rate (lb/in):     500.00          500.00
         Stop Cubic Rate (lb/in^3):     5000.00         5000.00
         Stop Energy Ratio (%/100):     0.50            0.50
          Deflection to Jounce Stop (in): 5.00          5.00
          Stop Linear Rate (lb/in):     500.00          500.00
         Stop Cubic Rate (lb/in^3):     5000.00         5000.00
         Stop Energy Ratio (%/100):     0.50            0.50
          Camber Constant (deg):        0.00            0.00

Tire Information:
                                        Right Side      Left Side
                                        ----------      ----------
          Tire Model:                   Generic         Generic
          Tire Size:                    11.00R24.5H     11.00R24.5H
          Unloaded Radius (in):         21.74           21.74
          Init. Radial Stiffness (lb/in/tire): 5000.00  5000.00
          2nd Radial Stiffness (lb/in/tire): 50000.00   50000.00
          Defl. @ 2nd Stiffness (in):   9.08            9.08
```

Max Deflection (in):	11.35	11.35
Rebound Energy Ratio (%/100):	1.00	1.00
Spin Inertia (Tire+Whl+Brk, lb-sec^2-in	241.46	241.46
Steer Inertia (Tire+Whl+Brk, lb-sec^2-in	120.73	120.73
Weight (Tire+Whl+Brk, lb/tire):	299.00	299.00
Roll Resistance Const:	0.01	0.01
Roll Resististance Linear Coef (sec/in):	0.00	0.00
Min Fz For Skidmark (lb):	1900.00	1900.00
Pneumatic Trail (in):	-2.10	-2.10
Lateral Stiffness (lb/in):	5000.00	5000.00

Cornering Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):	704.0			704.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	321.9	581.0	823.0	321.9	581.0	823.0

Camber Stiffness (lb/deg/tire):	Right Side			Left Side		
Loads (lb):	2000.0	4000.0	6000.0	2000.0	4000.0	6000.0
Speeds (in/sec):	704.0			704.0		
Load No.:	1	2	3	1	2	3
Speed No. 1:	40.0	60.0	80.0	40.0	60.0	80.0

Tire Friction Table:	Right Side			Left Side		
Loads (lb):	3900.0	7200.0	10800.0	3900.0	7200.0	10800.0
Speeds (in/sec):	352.0	704.0		352.0	704.0	
Speed No. 1, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7600	0.7300	0.8000	0.7600	0.7300
Slide Mu:	0.6000	0.5500	0.5000	0.6000	0.5500	0.5000
Slip @ Peak Mu (%/100):	0.3500	0.3000	0.2500	0.3500	0.3000	0.2500
Long. Stiffness (lb/slip):	18000.0	35000.0	60000.0	18000.0	35000.0	60000.0
Speed No. 2, Load No.:	1	2	3	1	2	3
Peak Mu:	0.8000	0.7400	0.6800	0.8000	0.7400	0.6800
Slide Mu:	0.5000	0.4400	0.3900	0.5000	0.4400	0.3900
Slip @ Peak Mu (%/100):	0.2500	0.1800	0.1600	0.2500	0.1800	0.1600
Long. Stiffness (lb/slip):	29800.0	69220.0	119850.0	29800.0	69220.0	119850.0

Brake Information:

	Right Side	Left Side
Brake Assembly Type:	Generic Brake	Generic Brake
Brake Time Lag (sec):	0.1750	0.1750
Brake Time Rise (sec):	0.2500	0.2500
Pushout Pressure (psi):	0.00	0.00
Nominal Brake Torque Ratio (in-lb/psi):	1500.00	1500.00

Trailer Second Axle

Same as first axle except:

Wheel Location Information:	Right Side	Left Side
Initial Wheel Coordinates (in) - x:	-84.40	-84.40