

Integration of a Torsional Stiffness Model into an Existing Heavy Truck Vehicle Dynamics Model

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ABSTRACT

Torsional stiffness properties were developed for both a 53-foot box trailer and a 28-foot flatbed control trailer based on experimental measurements. In order to study the effect of torsional stiffness on the dynamics of a heavy truck vehicle dynamics computer model, static maneuvers were conducted comparing different torsional stiffness values to the original rigid vehicle model. Stiffness properties were first developed for a truck tractor model. It was found that the incorporation of a torsional stiffness model had only a minor effect on the overall tractor response for steady-state maneuvers up to 0.4 g lateral acceleration.

The effect of torsional stiffness was also studied for the trailer portion of the existing model. By again simulating the vehicle response using varying values of torsional stiffness and comparing these responses with the original rigid model, it was found that the overall effect on vehicle response was minimal for both static and dynamic maneuvers up to 0.5 g lateral acceleration.

INTRODUCTION

Despite an increase in travel on America's roadways, advancements in vehicle safety have reduced the number of

fatalities due to crashes involving heavy trucks from 5,282 in 2000 to 4,822 in 2007 [1]. This improvement represents a decrease in the number of trucks involved in fatal crashes per 100 million miles traveled from 2.43 in 2000 to 2.04 in 2007. Even though a significant improvement in heavy truck safety has already been achieved, further safety advancements are possible. Of the total fatal crashes involving heavy trucks, tractor-trailer jackknives were attributed to 6.4% of these in 2007, down from 8.5% in 2000. However, the percentage of fatal crashes involving rollover showed a slight increase from 13.1% in 2000 to 13.9% in 2007 [2].

One area of advancement in heavy truck handling stability is the incorporation of electronic stability control (ESC) systems. A computer model has been developed [3,4,5,6] to simulate the partial workings of a commercial ESC system for a heavy truck. Two commercial software packages were used for this research: MATLAB Simulink [7] and Mechanical Simulation's TruckSim [8]. TruckSim can be interfaced with Simulink in order to develop more complex vehicle models. TruckSim is used to model the physical vehicle characteristics while Simulink is used to develop additional models such as the antilock brake systems (ABS) and ESC systems. The overall co-simulation model was used to give a better understanding of the dynamics of heavy trucks for a wide range of vehicle maneuvers. A shortcoming



of the current model, however, is that the vehicle is assumed to be torsionally rigid. This means that the vehicle does not deflect along its longitudinal axis as a moment is applied to its frame. It is known from experimental testing that this is not the case. Further improvement of this model will lead to a better assessment of heavy truck dynamics, as well as an increased understanding of the effectiveness of ESC systems.

This research was sponsored by the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VRTC) in East Liberty, Ohio. VRTC is located on the grounds of the Transportation Research Center, Inc. (TRC). Ultimately, this model may aid in the study of the effectiveness of heavy truck ESC systems as it provides the ability to understand truck dynamics at speeds higher than can be safely obtained in experimental testing and can reduce the amount of time and money spent on the physical test track.

STEERING MANEUVERS

Two different steering maneuvers were used for the evaluation of the torsional stiffness model. Each is outlined in more detail below.

SLOWLY INCREASING STEER (SIS)

For this maneuver, the steering handwheel angle is increased at a constant rate (VRTC uses 13.5 deg/sec) for a certain length of time as the vehicle travels at constant speed. The SIS maneuver is useful for evaluating the steady-state, or static, steering gains of the vehicle. These gains are then determined according to a first-order polynomial regression within the linear range and provide useful insight into vehicle response and performances. Typical gains of interest are as follows:

- Roll Angle versus Lateral Acceleration
- Roll Angle versus Yaw Rate
- Roll Angle versus Steer Angle
- Lateral Acceleration versus Steer Angle

RAMP STEER MANEUVER (RSM)

For this maneuver, the steering wheel angle is increased at a steady rate (VRTC uses 175 deg/sec) to a maximum angle, held constant for a certain length of time, and then decreased at the same rate back to zero degrees. The severity of the maneuver can be adjusted by the rate of increase, the maximum steering wheel angle, and the length of the hold. Using the lateral acceleration versus steer angle gain from the SIS maneuvers, the steady-state data is extrapolated to estimate the steering angle which causes the vehicle (bobtail tractor) to reach 0.5 g lateral acceleration. This steering angle is then chosen as the maximum steering wheel angle for VRTC's RSM maneuvers. Once the steering maneuver

commences, the throttle is dropped so that the vehicle coasts through the remainder of the maneuver. Unlike the SIS maneuver, the RSM gives an indication of the dynamic response of the vehicle. Vehicle rollover propensity is analyzed by increasing the initial speed of the maneuver in successive tests until the vehicle rolls over. Experimentally, rollover is deemed as the point where outrigger contact occurs.

MODEL DEVELOPMENT

The implementation of a torsional stiffness model was completed in two stages - first for the tractor and then for the tractor-trailer combination. The current tractor model is for a 2006 6×4 Volvo and the current trailer model is for a 1992 Fruehauf box trailer. A model for a 28-foot Great Dane flatbed trailer was also developed.

VOLVO TRACTOR MODEL

Within TruckSim, a simulation box can be activated from the *Vehicle: Lead Unit Sprung Mass* screen, shown in [Figure 1](#), in order to use the torsional stiffness model for the tractor and trailer. If this box is unchecked, TruckSim assumes that the selected vehicles are torsionally rigid. The torsional model is implemented by two masses connected with a torsional spring and damper.

☒ **Frame Torsional Flexibility and Suspended Cab**
 Check this box to use optional, more detailed math models. The optional models include the effects of torsional flexibility of the chassis (frame) of the lead unit and all trailers, and a further option to define a suspended cab.

 The extended models require a separate license feature.

Frame torsional properties:
 Distance between points used to measure stiffness:
 Longitudinal: 5000 mm
 Lateral: 1000 mm

 X coordinate of torsional node: 3000 mm
 X coord. of effective engine mounting: 0 mm
 Stiffness about longitudinal axis: 1e6 Nm/deg
 Damping about longitudinal axis: 1000 Nm/deg/sec

Figure 1. TruckSim Tractor Torsional Stiffness Interface

At this point in the research, emphasis was placed on the effect of trailer torsional stiffness on the overall system response. As a result, a great deal of time was not spent in developing the torsional stiffness model for the tractor alone. For the tractor, the torsional stiffness was modeled as $1.0(10^6)$ N-m/deg. This value is discussed in more detail in the trailer model section. In order to achieve critical damping

and maintain numerical stability, the damping for the torsional model was set to a large value. Setting this value too large did cause the simulation to become unstable, so the value of 1000 N-m/(deg/sec) was chosen. This resulted in an adequate amount of damping, but did not cause numerical instability. It is also noted in the TruckSim user's manual that the damping value is not highly influential to the model response, but is merely used for numerical stability. With the tractor stiffness set to a large value, the vehicle was nearly rigid, and so the remaining setup parameters pertaining to the distance between points used for measurement and the location of the torsional node were not critical. Determination of these parameters will be discussed in more detail with the trailer model. Simulations were conducted to ensure that any changes to these parameters had a minimal effect on the overall torsional response of the tractor. Further validation for the torsional stiffness model was performed for the tractor-trailer combination. The tractor torsional model was set up because the torsional flexibility box had to be checked for the lead unit in order to use the torsional model for the trailer.

VOLVO-FRUEHAUF COMBINATION MODEL

This section discusses the experimental method used to measure the parameters for the trailer torsional stiffness model. Secondly, the implementation of these parameters into TruckSim is discussed.

Fruehauf Trailer Measurements

After attaching a beam near the front of the trailer, a moment was applied to the beam by hanging known weights on one end and pulling upward using a pulley system on the other end. In addition to knowing the forces applied, the trailer wheels were placed on load scales to provide a secondary measurement for the applied moment. By measuring the angle at the beam and plotting this against the applied moment, the overall trailer torsional stiffness was determined as the best fit line across the loading range. While the overall trailer torsional stiffness was known, this value represented the parallel combination of the trailer torsional stiffness and the stiffness of the suspension. Since the TruckSim model was only interested in the trailer torsional stiffness by itself, further work was performed to determine this parameter. The trailer torsional stiffness was determined by performing a linear fit of the applied moment against the trailer twist angle. The trailer twist angle was defined as the difference between the twist angle of the beam and the average of the angles measured directly above each trailer axle. The result of these measurements is shown in [Figure 2](#).

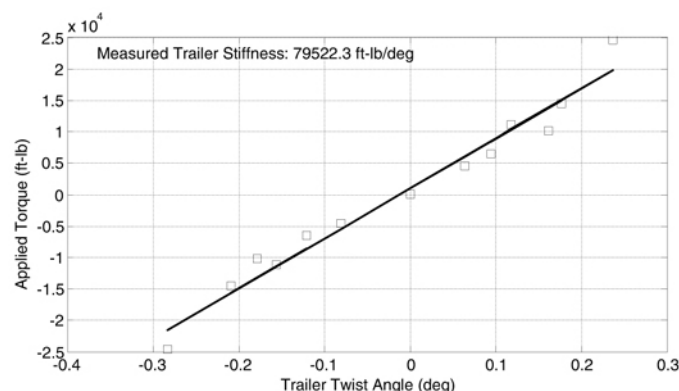


Figure 2. Measured Torsional Stiffness for Fruehauf Trailer with Outriggers

Volvo-Fruehauf Stiffness Model

Similar to the tractor torsional stiffness model, the stiffness parameters for the Fruehauf trailer were entered on the *Vehicle: Trailer Sprung Mass* screen. Based on tests conducted at VRTC for the Fruehauf trailer, the torsional stiffness was measured to be 79,500 ft-lb/deg or 108,000 N-m/deg [9]. Recall that the tractor stiffness was set to $1.0(10^6)$ N-m/deg, or about 10 times that of the trailer stiffness. The torsional damping of the trailer was again set to 1000 N-m/(deg/sec) for the same reasons discussed for the tractor torsional stiffness model. The distance between points used to measure stiffness refers to the setup of the method used to determine the torsional stiffness. The longitudinal distance represents the distance from the application of the weights used to twist the trailer to where the trailer is held stationary. For the Fruehauf trailer, the longitudinal distance was taken as the length of the trailer between the kingpin and the midpoint of the two trailer axles, or 11,722 mm. The lateral distance used was 1,219 mm, or half the width of the trailer. The location of the torsional node represents the location on the trailer where no twist occurs. For this trailer, this node occurred at the midpoint of the trailer length, or 5,861 mm behind the kingpin. A pictorial representation of the torsional stiffness model can be seen in [Figure 3](#). Additional information about the truck-trailer model can be found in [\[10\]](#).

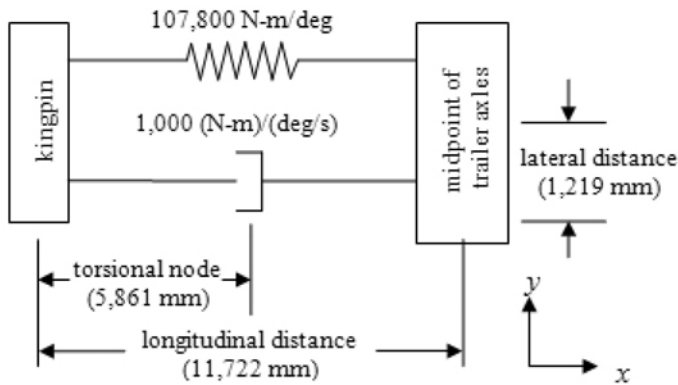


Figure 3. Overhead View of Trailer Torsional Model

GREAT DANE TRAILER MEASUREMENTS

Measurements for the Great Dane flatbed trailer were performed according to the same basic procedure as for the Fruehauf box trailer. The only difference between the two was that since the Great Dane trailer had only a single axle, the trailer twist angle was defined as the difference between the beam angle and the angle measured directly above the lone trailer axle. The resulting trailer stiffness measurements are shown below in [Figure 4](#).

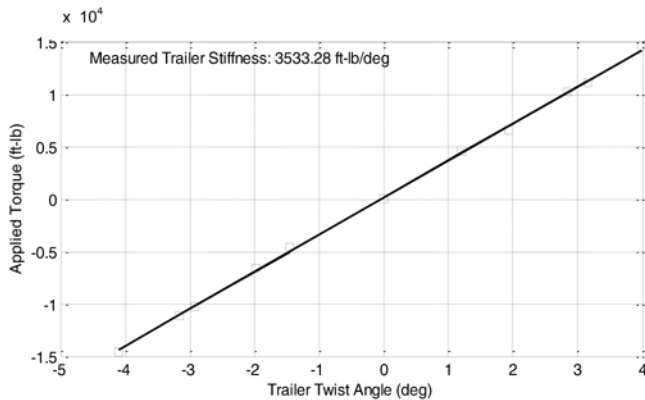


Figure 4. Measured Torsional Stiffness for Great Dane Trailer with Outriggers

The torsional node was again set equal to half the length of the trailer. The damping was set to achieve critical damping and maintain numerical stability. The parameters entered into TruckSim are shown below in [Table 1](#).

Table 1. Great Dane Trailer Torsional Stiffness Parameters

Longitudinal distance between points used to measure stiffness	6794.5 mm
Lateral distance between points used to measure stiffness	1219 mm
X coordinate of torsional node	3397.3 mm
Stiffness about longitudinal axis	4790 N-m/deg
Damping about longitudinal axis	1000 N-m/(deg/sec)

SIMULATIONS

VOLVO TRACTOR MODEL

Simulations were run comparing the $1.0(10^6)$ N-m/deg torsional stiffness tractor to a tractor with half this torsional stiffness and the original (rigid) tractor for a slowly increasing steer (SIS) maneuver at 30 mph with a steering rate of 13.5 deg/sec. At the conclusion of these simulations, it was shown that the amount of chassis twist was proportional to the chassis stiffness. Note that due to the large value of torsional stiffness, the torsional deflection of the tractor was minimal. Continuing the discussion to the steady-state gains of the vehicle, the current implementation of torsional stiffness in TruckSim showed essentially no difference (less than one percent) on the overall vehicle response among any of the three cases. The model also showed essentially no difference in vehicle path or vertical wheel forces among the three cases.

VOLVO-FRUEHAUF MODEL

Two loading conditions were used by the tractor-trailer simulation. The lightly-loaded trailer (LLVW) was the trailer with no additional load. The overall trailer center of gravity (CG) was 1000 mm above the ground. The gross vehicle weight rating (GVWR) configuration consisted of front and rear ballasts whose characteristics are shown in [Table 2](#). The overall trailer CG was 2099 mm above the ground.

Table 2. High CG Height GVWR Loading Configuration

	Load Mass (kg)	CG Distance Behind Kingpin (mm)	CG Height Above Ground (mm)
Front Ballast	10464	822	2296
Rear Ballast	8650	11833	2617

In order to test the effect of the trailer torsional stiffness model, TruckSim simulations were run comparing different trailer torsional stiffness values with the rigid tractor-trailer model using a SIS maneuver. Configurations for both a lightly-loaded low vertical CG height and a gross vehicle