

Semitrailer Torsional Stiffness Data for Improved Modeling Fidelity

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ABSTRACT

Vehicle dynamics models employed in heavy truck simulation often treat the semitrailer as a torsionally rigid member, assuming zero deflection along its longitudinal axis as a moment is applied to its frame. Experimental testing, however, reveals that semitrailers do twist, sometimes enough to precipitate rollover when a rigid trailer may have remained upright. Improving the model by incorporating realistic trailer roll stiffness values can improve assessment of heavy truck dynamics, as well as an increased understanding of the effectiveness of stability control systems in limit handling maneuvers.

Torsional stiffness measurements were conducted by the National Highway Traffic Safety Administration (NHTSA) for eight semitrailers of different types, including different length box vans, traditional and spread axle flat beds, and a tanker. Known moments were applied to the front of each trailer while the trailer twist angle was measured at various locations along the length of the trailer. Suspension stiffness, trailer body stiffness, and overall stiffness results were tabulated for all types.

INTRODUCTION

Though heavy truck safety has substantially improved over the past decade through the implementation of anti-lock braking systems (ABS), electronic stability control (ESC), and other innovations, further safety advancements are

possible. Due to the exceptionally wide variety of semitrailer types and loading conditions, it is very challenging, for instance, to develop a stability control strategy for optimal safety in every case. It is even more challenging, however, if the models used to evaluate stability do not reflect the vehicles' true behavior.

Heavy truck dynamic simulation is often performed with mathematical models which treat the trailer as a rigid body. While sufficient for many types of maneuvers, this type of model is insufficient for rollover studies. Consider the test shown in [Figure 1](#). This flatbed trailer was loaded front and rear with a fairly high center of gravity load. The roll moment over the trailer's rear axles was countered chiefly by the rear suspension, since the flatbed has relatively low torsional stiffness. During this 35mph ramp steer maneuver the rear deck twisted a full 90° before the tractor wheels left the ground.

Were this same load on a rigid trailer, it is possible that enough of the roll moment would have been shared by the tractor to have prevented rollover. More importantly, should this same dynamic loading condition be repeated, an ESC-equipped truck would ideally recognize the danger and intervene more aggressively. A similar situation with a box van can be found in real crash video available in the public domain [1].

Mechanical Simulation's TruckSim [2] has an optional "Frame Twist Module" which enables this degree of freedom

in either tractor or trailer. The user must specify a node location where the stiffness element is applied as well as a torsional stiffness value. The data available in this paper will enable intelligent selection of trailer stiffness values for the desired vehicle type.



Figure 1. Rollover in 35mph ramp steer maneuver.

A computer model developed to simulate the partial workings of a commercial heavy truck ESC system [3,4,5,6] was expanded by McNaull et al.[7] to include a torsional stiffness model. The latter study employed a vehicle dynamics model in TruckSim integrated with ABS and ESC control modules in MATLAB Simulink [8]. Simulating slowly-increasing steer and ramp steer maneuvers on several tractor-trailer combinations with different loading schemes, McNaull concluded that the overall effect of varying torsional stiffness on vehicle response was minimal for both static and dynamic maneuvers up to 0.5g.

However, the smallest trailer stiffness reported for these tests was 26,956 N-m/deg (19,880 ft-lb/deg), which is at least twenty times higher than the stiffness of a 48-foot flatbed such as that shown in Figure 1. The authors also acknowledge that the effects of trailer loading configuration were not studied. Though this paper did not conclusively demonstrate the need for including the trailer twist degree of freedom, the model may yet aid in the study of the effectiveness of heavy truck stability control systems. 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 experimental testing.

In order to compile trailer torsional stiffness data for heavy truck dynamic simulation, the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VRTC) tested eight different trailers [9]. The methods employed and results are summarized below.

METHODS

The trailer torsional stiffness measurements were made by applying known moments (torques) to the front of the trailer and measuring the trailer twist angles at various locations along the length of the trailer. The moments were applied through a beam attached near the front of the trailer. On one side of the beam, a downward force was applied by hanging known weights at a known distance from the centerline of the trailer. On the other side of the beam, an upward force was applied at the same distance from the trailer centerline by hanging known weights on a pulley with one cable end attached to the beam. These static downward and upward forces produced static force couples, the static applied moments.

The trailers' rear axle(s) were placed on load scales during these tests. The scales provided an independent measure of the applied moments, and in general the load transfer moments measured by the scales during the tests were in very good agreement with the applied moments. A portion of the test apparatus showing the beam and scales can be seen in Figure 2.



Figure 2. Torsional stiffness test apparatus.

All stiffness values reported are linear curve fits of the graphs of applied torque versus measured angle. The curve fits employed all measured data points. The sense of direction is in accordance with the SAE coordinate system; i.e., positive angles are those with the driver side of the trailer up and the passenger side of the trailer down (left-hand drive). Similarly, positive torques are those which generate positive angles of twist, so that the calculated stiffness values are positive.

The testing involved loading and unloading of heavy weights - in some cases more than 1000 lbs. - at various locations along the beam. This somewhat cumbersome nature of applying the torsional moments was not conducive to

generating smooth loading and unloading characteristic curves. As a result, it was not possible to differentiate the loading and unloading curves to evaluate the hysteresis in the stiffness measurements. Nonetheless, all of the measurement data collected was used in the graphs contained in this report.

Two different “zero” angles were used for the graphs. All positive angle direction measurements were referenced from the first zero angle, the first data point taken with no torque applied through the beam just prior to the positive direction tests. All negative angle direction measurements were referenced from the second zero angle, the data point taken with no torque applied through the beam just prior to the negative direction tests.

Six of the semitrailers were tested with and without outriggers, with the other two trailers tested only without outriggers. Outriggers are used in dynamic testing when a danger of rollover is present. The 1500-lb. outriggers were folded back along the body for the tests which included them.

Three separate trailer stiffness metrics were recorded. The overall stiffness, $K_{overall}$, is the trailer torsional stiffness ($K_{trailer}$) acting in series with the trailer suspension roll stiffness ($K_{suspension}$). This relationship is pictured in [Figure 3](#). The theoretical relationship among these three metrics is shown in [Equation \(1\)](#). Though each of these three was independently determined from measured values, this relationship was used as a check; measured $K_{overall}$ was compared with the $K_{overall}$ calculated by [Equation \(1\)](#). The measured and calculated overall stiffness values compared very well; the average percent difference between them was 0.6%.

$$K_{overall} = \frac{K_{trailer} \times K_{suspension}}{K_{trailer} + K_{suspension}} \tag{1}$$

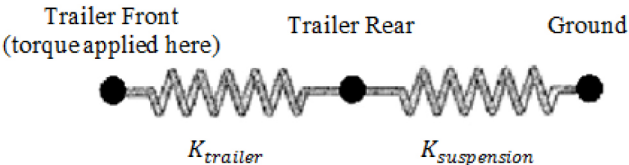


Figure 3. Semitrailer torsional stiffness schematic.

TRAILER BODY TWIST ($K_{trailer}$)

Trailer body twist was the measured difference between the tilt angles at the front and rear of each semitrailer. The angle measurements were made with precision digital inclinometers at several locations. One angle measurement on all trailers was made at the front beam location. Other measurements were made as shown in [Table 1](#). For those trailers with two rear measurement points, the overall twist angle was the

angular difference between the front beam to the *average* of the rear two points.

$K_{trailer}$ was determined from the slope of the linear curve fit on the graph of applied torque versus trailer twist angle. Values for these calculations are listed under the “Measured trailer stiffness” column in [Table 2](#).

Table 1. Angle measurement locations by trailer type, in addition to the front beam.

Semitrailer type	Rear angle measmt. location
Box vans	On top of trailer deck directly above leading and rear axles
Flatbeds with 2 axles	On top of trailer deck directly above leading and rear axles
Tanker (2 axles)	On lower tank cross members 14.0 inches in front of the leading axle and 6.0 inches behind the rear axle
Single axle (28 ft) trailers	On top of the trailer deck directly above the axle

SUSPENSION DEFLECTION ($K_{suspension}$)

The suspension deflection angle was simply the rear deck angle (or average of the two shown in [Table 1](#)), the amount the trailer suspension deflected under the applied torque. $K_{suspension}$ values were determined from the slope of the linear curve fit on the graph of applied torque versus suspension deflection angle.

OVERALL STIFFNESS ($K_{overall}$)

The measured overall stiffness, reflecting the combined effect of body twist and suspension deflection, was the slope of the linear curve fit of applied torque versus front beam angle.

RESULTS

Test results for the eight semitrailers are displayed in [Table 2](#). For the six trailers tested with and without outriggers attached, two numbers are shown in each cell. The cell's top number is stiffness without outriggers, and the bottom number is stiffness with them.

Attaching the outriggers acts to stiffen the semitrailer frames. With the exception of the Heil tanker, all of the overall stiffnesses and trailer stiffnesses increased when the outriggers were installed. Because the tanker trailer stiffness is much greater than the other trailers, reflecting extremely small measured trailer twist angles; the fact that no outrigger-related increase was observed likely reflects a limitation of the measurement accuracy.

The suspension stiffness for a given semitrailer should be the same whether or not the outriggers are attached to the trailer. With one exception, the suspension stiffnesses with and without outriggers differed by less than 2.5%.

Table 2. Semitrailer stiffness data. Bottom (red) values are for measurements with outriggers installed.

	Overall stiffness (ft-lb/deg)	Suspension stiffness (ft-lb/deg)	Trailer stiffness (ft-lb/deg)
2008 Fontaine 48-ft spread axle flatbed	741 1,030	NA ¹	833 1,190
1999 Fruehauf 48-ft flatbed	543 862	NA ¹	564 922
2004 Great Dane 28-ft flatbed	1,980 2,730	13,500 12,000	2,320 3,530
1975 Great Dane 28-ft flatbed	991	7,420	1,140
Ravens ² 28-ft flatbed	2,110	24,800	2,300
2001 Fruehauf 53-ft box van	16,200 18,100	22,800 23,000	51,300 79,500
2008 Strickland 53-ft box van	13,100 13,400	14,700 14,600	115,000 139,000³
2008 Heil 9200-gal tanker	12,300 12,000	12,700 12,400	396,000 365,000

¹The suspension stiffness on these two trailers could not be determined by the test method. This is discussed further below.

²The Ravens flatbed is an older trailer but the model year was not available.

³For the test of the 2008 Strickland with outriggers, the data used to determine trailer stiffness is not as consistent as that obtained for other trailers. It appears as though one of the angles for the last three measurements was shifted.

The trailer frames on the Fruehauf Flatbed Trailer and the Fontaine Spread Axle Trailer twisted in such a way as to cause the rear axles to develop a torque in the opposite direction as the torque in front axles. For instance, when a negative torque was applied, which caused the passenger's side of the front of the trailer to lift up and the driver's side of the front of the trailer to squat down; the left side tires on front trailer axle increased in vertical load while the left side tires on the rear trailer axle decreased in vertical load. As a result of this phenomenon, no suspension stiffnesses were computed for these two trailers. For these two trailers, trailer stiffness was determined from the linear curve fit of the graph of applied torque versus trailer twist angle, where trailer twist

angle was taken as the difference between the beam angle and the angle measured above the front axle.

It should be noted that all semitrailers in Table 2 were of steel construction. Aluminum-framed trailers would typically display lower stiffnesses, depending on construction style. Reconsidering Figure 1, for instance: a welded steel flatbed may not twist as dramatically as the aluminum trailer shown.

Figures 4,5,6,7,8,9,10,11,12,13,14,15,16,17 in the appendix display the measurements from which Table 2 was created.

CONCLUSIONS

Motivated by the desire to make data available to increase the fidelity of heavy truck vehicle models, torsional stiffness measurements were taken for the frame and suspension of eight trailers. These trailers were representative models of short and long flatbeds, two box vans, and one tanker.

The suspension stiffnesses for the eight trailers ranged from 7,400 to 24,800 ft-lb/deg, with an average of 16,000 ft-lb/deg. No suspension trends were apparent for trailer styles; both the lowest and highest values were measured on 28-ft flatbeds. Inclusion of outriggers had only a minor effect on suspension stiffness.

The trailer body stiffnesses were more predictable. Not surprisingly, the body type had an substantial effect on stiffness: the Heil tanker body was over 700 times stiffer than the Fruehauf flatbed. The 48-ft flatbeds averaged 700 ft-lb/deg, and the 28-ft flatbeds averaged 1,920 ft-lb/deg. The two 53-ft box vans were much stiffer, at 51,000 and 115,000 ft-lb/deg. The tanker body measured nearly 400,000 ft-lb/deg.

The trailer bodies for which reliable measurements were made averaged 53% stiffer when the outriggers were attached. This disparity should be taken into consideration when conducting experimental tests to validate simulation-based results. Outrigger-equipped measurements for the Strickland box van and Heil tanker were not trustworthy.

Overall stiffness measurements did not have so wide a spread as the trailer body stiffnesses, because the series spring effect (Equation 1) was dominated by the weakest of the suspension and body stiffness values. Thus the overall stiffness of the flatbeds was generally determined by the trailer frame, whereas the overall stiffness of the other semitrailer types is determined by the suspension. The semitrailers with lowest overall stiffness were still the long flatbeds, but the two box vans demonstrated higher overall stiffness than the tanker.

Another noticeable trend is the lower trailer stiffness evident in the older semitrailers, suggesting that trailer stiffness declines with age or usage. This is true for the 48-ft flatbeds (32% different, 9 year age gap), 28-ft flatbeds (51% different,