A rationale for regulating roll stability of combination vehicles

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This paper presents the technical basis for a scheme intended to insure a minimum static roll-stability of combination vehicles through regulation of the individual units making up those vehicles.

In the United States, consideration has been given to raising the ultimate limits on weight and length of commercial vehicles allowed to operate on the federal highway system. Vehicles heavier than the current limit of 36,400 kg (80,000 lb) would be allowed. Combination vehicles exceeding the length of the currently allowed 8.5-meter (28-foot) double (most importantly, 8.5-meter triples) might also be allowed. Authorization to use such oversized vehicles would be granted only through the issuance of special operating permits. To obtain such a permit, the operator would be required to demonstrate that the vehicle met minimum requirements in certain safety-related performance areas.

One of the performance qualities of interest is static-roll stability. Most large commercial vehicles are combination vehicles made up of separate units such as tractors, semitrailers, dollies, etc. Technically, the roll stability of these vehicles is best examined when they are in their combined state. Administratively, it is more attractive to regulate the individual units of combination vehicles.

Methods for separately evaluating the stability qualities of semitrailers and their support units using the tilt-table approach are described. The rationale behind these methods, as well as the means for appropriately matching separate units to form combinations meeting the minimum performance standard, are presented.

1.0 INTRODUCTION

Several researchers have used the tilt-table method to measure the static-roll-stability limit of tractor-semitrailers and other combinations of vehicle units that form a single rolling unit [1-9].[1] Because of the fundamentally nonlinear quality of the mechanics of the quasi-static rollover process, the static stability limit of such combinations is determined by a complex, highly synergistic relationship between the roll plane properties of the individual units. To date, the complexities of the process have not been unraveled sufficiently to provide a rational approach to the independent measurement of the stability quality of the individual units that make up a combination. This paper describes both a rationale and tilt-table-test procedures for the separate characterization of the roll-stability quality of support units (i.e., tractors, dollies, or other units providing fifth-wheel support) and payload units (i.e., payload bearing units requiring fifth-wheel support from another unit).

The research project leading to this paper was undertaken by UMTRI for the National Highway Traffic Safety Administration of the US DOT [10]. At the time of this study, new legislation that might allow the nationwide introduction of vehicle combinations heavier than 36,400 kg (80,000 lb) and longer than twin, 8.5-meter (28-foot) doubles was under consideration. The underlying purpose of the work was to develop means of assuring that the safety-related performance of such new vehicles would be as good as or better than the vehicles that they would replace. Two regulatory scenarios pertaining, respectively, to the basic resistance to rollover and the obstacle avoidance maneuvering capability of longer and heavier commercial vehicles were developed. This paper presents test methods developed for use in the roll-stability regulation. The test method for obstacle avoidance-maneuvering capability is given in a companion paper [11]. A full description of both regulatory scenarios is given in [10].

The primary goal of the scenario developed for regulating roll stability was to provide a reasonable assurance that all complete vehicles operating under the system would have a static-rollover threshold exceeding a specified minimum value. But commercial vehicle traffic in the USA is dominated by the tractor-semitrailer combination. The continuous mixing and matching of tractors and trailers is essential to maintaining the high level of productivity typical of the daily operation of the industry. Therefore, a means of qualifying individual support and payload units so that they could be appropriately matched in the field was essential to the development of a viable regulatory scenario.

The regulatory scheme developed suggested using a minimum static-stability limit of 0.35 g of lateral

1. Bracketed numbers refer to bibliographic references given at the end of this report.

acceleration. Screening procedures were developed to provide a simple means for qualifying units that would clearly meet this stability criterion. Under the regulatory scheme, only vehicles that are "too close to call" by the screening procedures would be required to undergo the tilt-table-test methods to be described here. The rationale for choosing 0.35 g as the performance requirement and details of the screening procedures are given in [10] and [12].

2.0 BACKGROUND RATIONALE FOR SEPARATE TESTING OF INDIVIDUAL UNITS

The static-roll stability of any highway vehicle depends on a number of vehicle parameters involving height, width, suspension geometry, and compliances of the body, suspension, and tires. The mechanics of the quasi-static rollover process of commercial vehicles are rather complex and virtually always highly nonlinear. Extensive discussion of quasi-static rollover mechanics can be found in the literature [13-16].

Figure 1 is a rear view of a commercial vehicle as it proceeds through a steady turn. Centrifugal force at the center of gravity (cg) causes the vehicle to roll outwardly in the turn. The destabilizing moments that can cause rollover come (i) from the centrifugal force itself, and (ii) from the outboard translation of the cg relative to the wheel track (Δy). The stabilizing moment that keeps the vehicle upright comes from the side-to-side transfer of vertical load on the tires. When the destabilizing moments combine to exceed the maximum stabilizing moment available from complete side-to-side load transfer, the vehicle rolls over.

The roll moment equilibrium equation for the system of figure 1 is:

$$\sum_{i=1}^{n}\left[(F_{Ri}-F_{Li})\frac{T_i}{2}\right]=WA_yH-\Delta yW \qquad (1)$$

where:

- A_y is lateral acceleration in g's.
- F_{Li}, F_{Ri} are the vertical loads on the left and right tires, respectively, of the i^{th} axle.
- H is the height of the vehicle cg.
- n is the number of axles on the vehicle.
- T_i is the effective track width of the i^{th} axle.
- W is the weight of the vehicle.
- Δy is the lateral position of the cg relative to the center of track.

Equation (1) has been arranged so that the stabilizing moments developed at the axles are represented on the left side of the equation and the destabilizing moments are on the right side. Interpretation of the left side of the equation indicates that the maximum stabilizing moment that can be generated by any axle is proportional to the load carried by that axle. For example, in a left turn, the

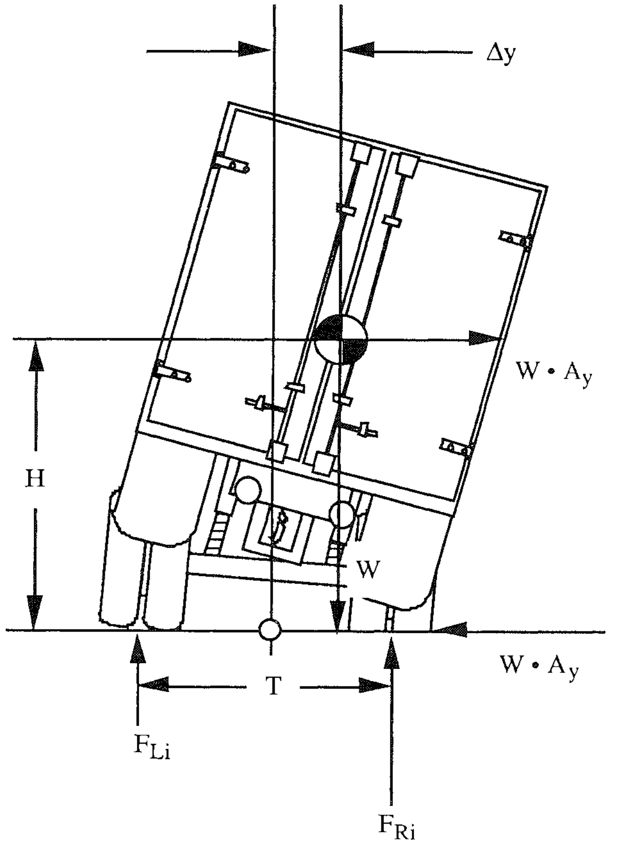

Figure 1. A heavy truck in a steady turn

maximum stabilizing moment of the i^{th} axle, carrying a total load of W_i, is ($W_i\ T_i/2$). This moment is developed when $F_{Ri} = W_i$ and $F_{Li} = 0$.

This view suggests that each axle's "fair share" of the total stabilizing moment available to the vehicle is proportional to the weight carried by that axle. Moreover, for combination vehicles, each unit's fair share of the roll-stabilization task is in proportion to the load carried by that unit's axles.

In the makeup of combination vehicles, different units of the vehicle play fundamentally different roles in the context of roll mechanics. Specifically, semitrailers typically bear the payload but require vertical support at the fifth-wheel coupling point. Other units (typically tractors and dollies) provide the needed support for payload units. Some special units (B-train semitrailers and cargo-bearing tractors) play both payload-unit and support-unit roles simultaneously. In order to deal rationally with both of these types of units individually, tilt-table-test procedures have been developed for payload units requiring fifth-wheel support and for support units.

3.0 THE TILT-TABLE-TEST PROCEDURES

The underlying premise of the testing procedures is that each individual unit of the vehicle system must be able to stabilize its fair share of the total mass it supports (where fair shares are apportioned according to axle loading). If each unit is roll stable to a minimum level of

0.35 g when subject to its share of vertical and roll moment loading, the rollover threshold of the combined vehicle will meet or exceed this same standard.

In the discussion that follows, the term "roll angle" refers to the roll angle of an element relative to the surface of the tilt table, and the term "tilt angle" refers to the inclination angle of the tilt table surface relative to horizontal.

3.1 Testing Payload Units

The test of payload units which require fifth-wheel support is the more complex of the test procedures and requires some explanation.

The purpose of the test is to determine whether or not a payload unit is capable of providing its fair share of roll stabilization as needed for a complete combination to meet or exceed the minimum roll-stability level of 0.35 g. The test would be conducted with a specified loading condition characterized by payload weight and cg height. The operating permit issued as a result of a successful test would declare these to be maximum allowable values.

The philosophy of the test is somewhat indirect. The test determines the roll moment required at the fifth wheel in order for the payload unit to remain stable in roll at 0.35 g. If the required moment at the fifth wheel does not exceed a fair share based on fifth-wheel vertical load, the payload unit qualifies. The point is, of course, that if the required moment at the fifth wheel is less than or equal to the support unit's fair share, the payload unit's own suspensions must be providing at least their fair share toward stability.

During the tilt-table test, fifth-wheel vertical support and stabilizing roll moment are provided to the payload unit by a simple fixture called a "virtual tractor." The virtual tractor is articulated in roll with a roll-center height representative of typical suspension/tire behavior. The virtual tractor is instrumented to measure both roll displacement and roll moment. A full description of the defining properties of the virtual tractor is given in [10] along with the details of the virtual tractor fabricated by UMTRI.

A sketch showing a payload unit (semitrailer) mounted on a tilt table with a virtual tractor is shown in figure 2. In the test, the table is first tilted to 19.29 degrees (0.35 g simulated) and stopped. During the tilt motion, the virtual tractor is forcibly restrained to prevent roll motion of the test unit. With the table at 19.29 degrees, the test unit is then allowed to roll by allowing roll motion of the virtual tractor to take place very slowly. The virtual-tractor restraining moment is recorded as a function of the roll angle of the virtual tractor. The minimum restraining moment recorded is used to determine the pass/fail result.

A simplified explanation of the mechanics of this test process and the pass/fail criterion can be presented with the aid of figure 3. This figure is a presentation of the roll behavior of the system of figure 2, with the simplifying assumptions that (i) the sprung mass of the test unit is rigid, (ii) the roll angle of the virtual tractor and the sprung

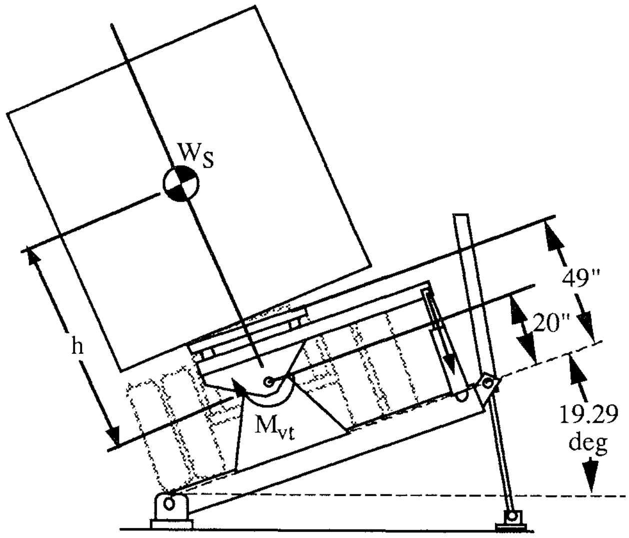

Figure 2. A tilt test using the virtual trailer

mass are equal (i.e., there is no fifth-wheel lash), (iii) the suspension roll-center height is equal to the virtual-tractor roll-center height, and (iv) the suspension roll stiffness is linear. The analysis also assumes small roll angles. (Later, the influence of more realistic test-unit properties will be discussed.) The nomenclature of the figure is as follows:

A_y	is the simulated lateral acceleration (0.35g).
h	is the height of the sprung mass cg above the roll center.
M_{susp}	is the stabilizing roll moment provided by the unit's suspension(s).
M_{vt}	is the stabilizing moment provided by the virtual tractor.
W_S	is the weight of the sprung mass.
W_{susp}	is the portion of W_S supported by the suspension of the test unit.

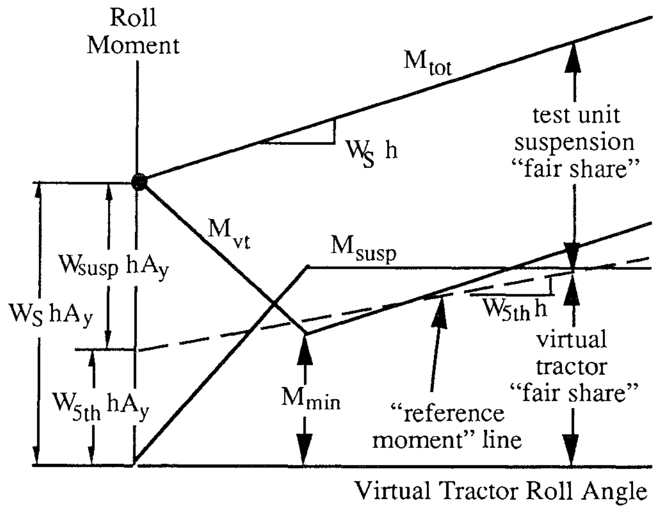

Figure 3. Mechanics of the payload unit tilt table test

W_{5th} is the portion of W_S supported by the fifth wheel of the virtual tractor.

ϕ is the roll angle of the virtual tractor (that is, the angle between the surface of the virtual tractor's fifth wheel and the surface of the tilt table).

Figure 3 presents plots of the virtual-tractor roll moment, the suspension roll moment, and the total roll moment (sum of the two) as they might occur during the test just described (that is, in the portion of the procedure with the table angle at a tilt angle of 19.29 degrees). At the beginning of the test, the body-roll angle is zero and the three plots start at points on the moment axis. As the test proceeds, body-roll angle increases and the three individual plots progress to the right. An explanation of these plots follows.

The roll equilibrium equation for sprung mass of the test unit during this test can be written as:

$$W_S A_y h = M_{susp} + M_{vt} - W_S h \phi \qquad (2)$$

Equation (2) is very much analogous to equation (1), but with (i) an additional "fifth-wheel moment," (ii) the load transfer term represented more simply as the "suspension moment," and (iii) the lateral motion of the cg expressed as a function of roll.

For this explanation, it is useful to rearrange (2) and define M_{tot} as:

$$M_{tot} \equiv M_{susp} + M_{vt} = W_S A_y h + W_S h \phi \qquad (3)$$

At the beginning of the test, the unit is constrained to a zero body-roll angle. The term, $W_S h\phi$, is therefore zero, and since the suspensions are undeflected, M_{susp} is also zero. Thus $M_{vt} = W_S A_y h$. These facts are reflected in the figure by the values of M_{vt}, M_{susp}, and M_{tot} at the moment axis. As the unit is allowed to roll, the sprung mass cg moves laterally (similar to the outward motion of the cg in a turn) and the total stabilizing moment required increases at a rate of $W_S h$ per radian of body roll. At the same time, however, the suspensions are rolling and providing stabilizing moment. As a result, the required moment at the fifth wheel falls as body roll increases.[2] The sum of M_{vt} and M_{susp}, however, continues to equal M_{tot}. This situation continues until the roll deflection of the suspension is so great as to cause wheel lift. (For simplicity, this explanation and the plot of figure 3 ignore all the possible complications associated with such things as suspension lash and multiple suspensions.) At this point, all available moment from the suspension has been delivered. M_{susp} saturates and remains constant for increasing roll angle. After all of the high-side tires lift off the table surface, the test can be stopped. (If it were continued, M_{susp} and M_{tot} would continue to increase as the vehicle was set down onto its side.)

An additional dotted line is plotted on the graph of figure 3. This reference moment line shows the proportion of the total moment which is the fair share of the virtual tractor. The proportioning is established according to the proportion of total weight to fifth-wheel weight (W_{5th}). The difference between the total moment and the reference moment is the fair share of moment to be provided by the test unit's own suspensions.

At tire liftoff, the test unit's suspensions will be providing at least their fair share of the required moment if the fifth wheel is providing its fair share *or less*. Therefore, if the M_{vt} line penetrates below the reference line during the test, the suspensions of the payload unit are adequate for providing their fair share of roll support at least to the simulated acceleration level of 0.35g. Further, the minimum value of M_{vt} can be used to calculate the minimum required track of the support unit (assuming support unit mass is insignificant). Using M_{min} as defined in the figure:

$$T_{min} = 2\left[\frac{M_{min}}{W_{5th}} + h_{RC} A_y\right] \qquad (4)$$

where the previously undefined terms are:

T_{min} is the minimum track required for the support unit.

h_{RC} is the height of the roll center of the virtual tractor.

As noted above, figure 3 and the subsequent discussion were based on a number of simplifying assumptions. We will now examine the influence of real-world violations of these assumptions on the procedure.

First, consider the influence of fifth-wheel lash. Figure 4 illustrates that the introduction of fifth-wheel lash simply shifts behavior of the system relative to the roll-angle axis by the value of the lash. That is, the test-unit

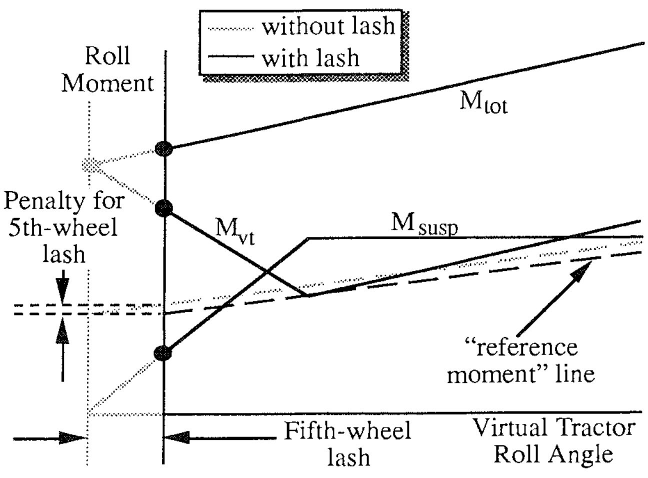

Figure 4. The influence of fifth-wheel lash

2. That is, fifth-wheel moment will fall if the unit's suspensions are of adequate stiffness. It is conceptually possible for the suspensions to be so compliant as to require fifth-wheel moment to increase immediately, but such a vehicle would not be practical, and certainly would not pass the regulatory test.

sprung mass has rolled through the lash angle while the virtual tractor roll remains at zero. Since the reference-moment line remains fixed relative to virtual-tractor angle, the test unit is automatically penalized appropriately for the loss of roll stability resulting from its fifth-wheel lash.

Next, consider figure 5, which indicates the influence of a test-unit suspension with a roll center higher than the roll center of the virtual tractor. The basic effect is a change in the real value of the parameter h. Since the roll axis of the test unit will now slope up toward the rear, the value of h is reduced, and the value of the total moment, M_{tot}, is effected as shown. Because the total moment declines, the demand on the virtual tractor also declines and the test unit reaps a benefit. The actual benefit is somewhat greater than what is "proper" since the slope of the reference line has not been decreased in accordance with the decrease in h.

Figure 6 illustrates the influence of torsional and lateral compliances of the sprung mass. These compliances will result in a greater lateral displacement of the cg of the vehicle at the beginning of the test as well as throughout the later portions of the test. This, of course, will put a greater demand on the virtual tractor. However, chassis compliance also means there will be some additional suspension deflection at the start of the test. This will relieve some of the extra burden on the virtual tractor. Chassis compliance will also influence apparent suspension stiffness throughout the test. The sum of the influences represents an additional burden on the virtual tractor, and, therefore, a penalty in the context of the test.

Finally, figure 7 illustrates the influence of nonlinear suspension properties. The suspension-moment plot has been altered to reflect the influence of lash as is often found in leaf-spring suspensions. Because of the lash, additional suspension deflection is required to achieve the maximum roll moment available from the suspension, and a greater demand is placed on the virtual tractor. In the particular case shown, the lash makes the difference between passing and failing the test. Depending on the particulars of all of the properties of the system, it is possible for a similar unit to meet the criterion because the virtual-tractor moment penetrates below the reference-moment line either before or after the suspension passes through its lash.

Samples of actual tilt-table data are presented in figure 8. These data were gathered in tests of a single-axle semitrailer and virtual tractor. The trailer was equipped with a leaf-spring suspension with a fair amount of spring lash. The trailer was loaded to a gross weight of 17,582 kg (38,760 lb). The sprung-mass weight was 16,785 kg (37,005 lb) and the fifth-wheel weight was 7878 kg (17,368 lb). The vertical position of the sprung mass cg could be altered easily using an adjustable-height load rack. Starting from the bottom of the figure, the three data sets were gathered with the vehicle configured to have sprung-mass cg heights of 1910, 2123, and 2350 mm (75.2, 83.6, and 92.5 in), respectively.

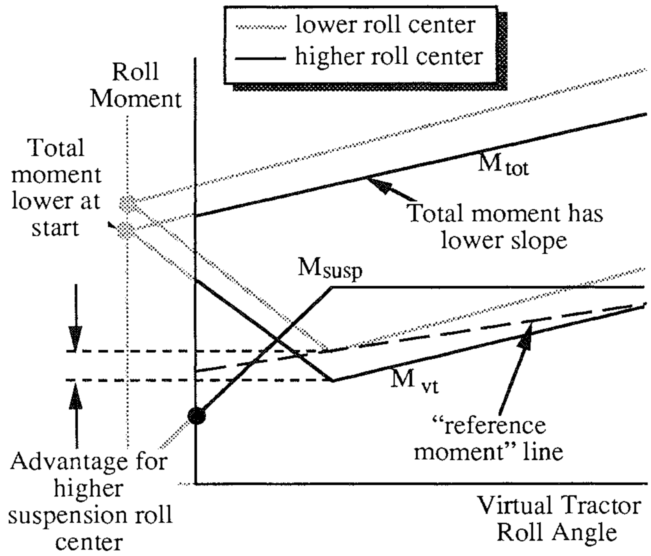

Figure 5. The influence of a higher roll center

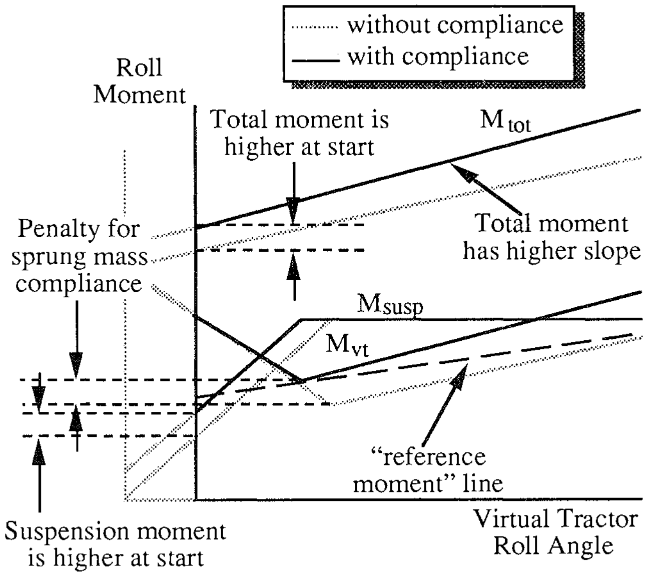

Figure 6. The influence of a sprung mass compliance

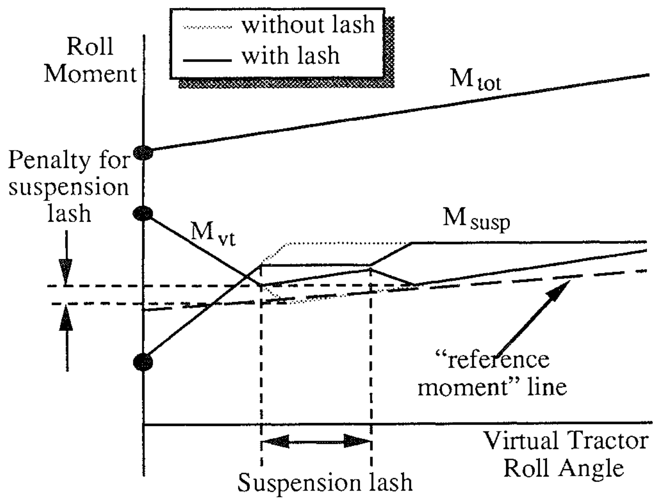

Figure 7. The influence of suspension nonlinearities

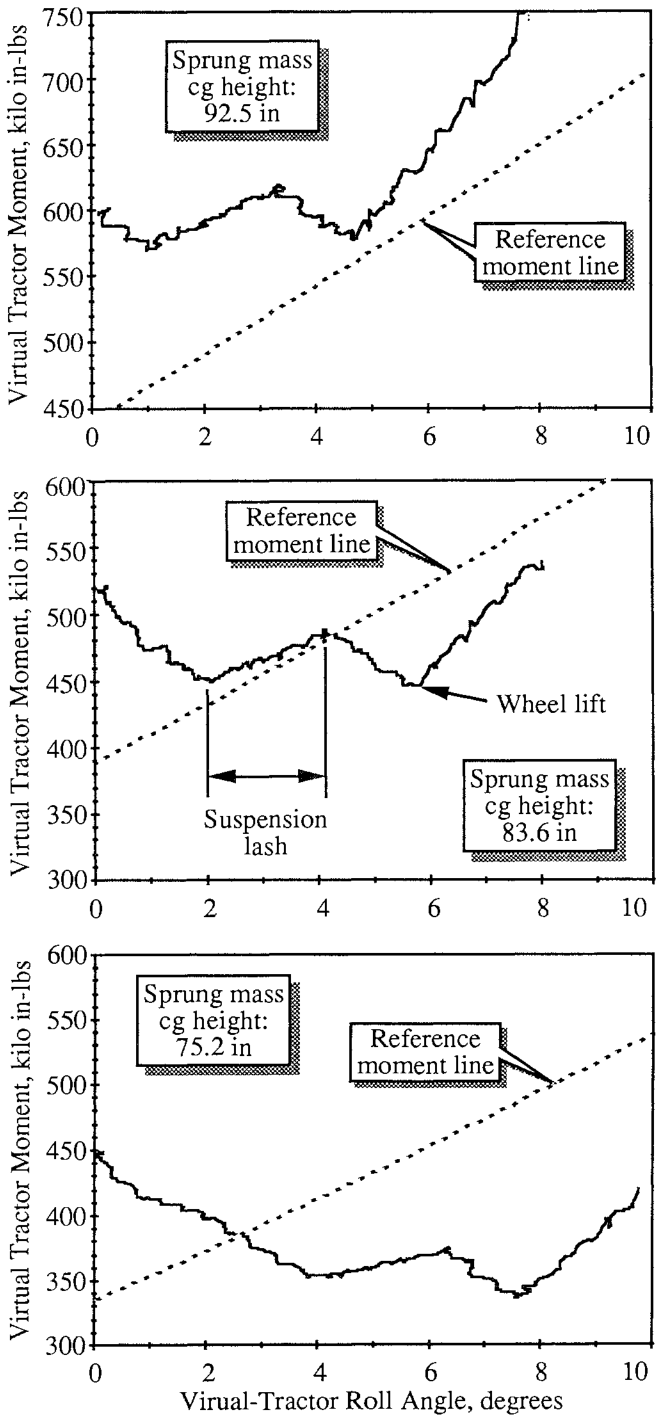

Figure 8. Tilt-table data from tests of a semitrailer with three different cg heights

Regarding general form, these data clearly behave as the previous discussion would predict. As the virtual-tractor roll angle increases from zero degrees, the virtual-tractor roll moment decreases. When the test-unit suspension enters its lash, the moment demand on the virtual tractor increases with roll angle. After the lash, tractor moment again declines until tire lift off occurs, when once again, tractor moment increases with roll.

These graphs also include the reference moment line. Where the preceding tutorial had assumed small angles for clarity, the reference-moment lines in figure 8 are not based on that assumption. These lines are plotted according to the more accurate equation:

$$\mathbf{M_{ref} = W_S\, h \tan(19.29/57.3 + \phi)} \qquad (5)$$

where M_{ref} is the reference moment.

These data plots indicate that this vehicle meets the stability requirement with the two lower cg-height loads, but fails with the highest load.

3.2 Testing Support Units

In comparison to the test for payload units, the method for tilt-table testing of support units is very straightforward.

The purpose of this procedure is to determine whether or not a fifth-wheel support unit is capable of providing its fair share of roll stabilization as needed for a complete combination to meet or exceed the minimum roll-stability level of 0.35 g. The test would be conducted with a specified loading condition characterized by the load supported at the fifth-wheel and the cg height of that load. The operating permit issued as a result of a successful test would declare these to be maximum allowable values.

The philosophy of the test is simply to subject the support unit to the fifth-wheel loading that it would experience if it were loaded by a "worst-case" payload unit. Worst case, here, implies a payload unit that just meets the 0.35 g stability requirements described previously. The implication is, of course, that if the payload unit just meets the criterion, then at 0.35 g the payload unit's suspensions are just providing the stabilizing moment required for the portion of the load that they support. Therefore, all of the moment required to stabilize the load carried by the fifth wheel (but no more) must come from the fifth wheel. To subject the support unit to this condition requires simply that the fifth wheel be loaded with a mass of similar (fifth-wheel) weight and cg height.

The fifth-wheel loading device used in the support unit test is called the "virtual trailer." This device is simply an adjustable-height, ballast-weight rack designed to be installed directly onto a conventional fifth wheel and to provide realistic loading to the fifth wheel of the supporting unit during tilt-table testing. The virtual trailer attaches to the fifth wheel of the supporting unit in a conventional manner using a standard kingpin. The center of gravity of the virtual trailer is directly over the center of the pitch pivot of the fifth wheel of the supporting unit so that virtually all the load is borne by the fifth wheel. Special additional restraints stabilize the load in pitch and yaw without significantly altering either the relative roll motion (fifth-wheel lash) or the loading patterns which influence roll behavior. A full description of the virtual tractor fabricated by UMTRI is given in [10].

With the virtual trailer loaded to a prescribed weight and cg height and installed on the support unit, the loads transferred to the support unit fifth wheel *when the tilt table is inclined to 19.29 degrees* (0.35 g simulated) will be substantially the same as those created by a worst-case payload unit with the same fifth-wheel weight and sprung-mass cg height.

The tilt-table test of the loaded support unit is conducted in the manner of a normal tilt-table test of a complete vehicle. If the unit remains stable at 0.35 g (i.e., 19.59 degrees), it qualifies for a permit. The permit would include notice of the weight and cg height parameters of the fifth-wheel test load. Payload units that exceeded either of these parameters would not be acceptable for use with this support unit.

4.0 SUMMARY

Tilt-table-test procedures for separately evaluating the stability qualities of payload units (e.g., semitrailers) and their support units (e.g., tractors and dollies) have been described. These test procedures were developed as part of a regulatory scheme intended to provide a reasonable assurance that combination vehicles composed of complying units would meet or exceed a specified minimum static-rollover threshold. The ability to test individual units separately was seen as an important element of a viable regulatory system in the context of the US commercial-trucking industry.

The test methods are meant to determine whether or not the suspensions of a particular unit are capable of providing their fair share of roll stabilization as required for the complete combination vehicle to achieve the specified, minimum stability level. A unit's fair share of the roll stabilization task is assumed to be in proportion to its total axle loading. This approach derives from the observation that the maximum stabilizing moment available from an axle is, indeed, proportional to the load carried by the axle.

The method for testing payload units involves the use of a virtual tractor. This device provides fifth-wheel support and fifth-wheel roll moment to the test unit. The approach in this test is to determine the roll moment required from the virtual tractor to stabilize the unit at the required threshold acceleration. If this fifth-wheel moment is equal to or less than the fair share indicated by fifth-wheel load, the test unit's own suspensions must be accomplishing their fair share, or more, of the stabilizing task. During the test, the payload unit is loaded to a specified weight and cg height. In the event of a successful test, these parameters would be indicated as maximum allowable load conditions on the payload unit's operating permit.

The method for support units involves the use of a virtual trailer. This device is simply an adjustable load rack, which mounts on a fifth wheel using a conventional kingpin. Additional yaw and pitch stabilization is provided for the virtual trailer in a manner that allows realistic loading of the test unit's fifth wheel, including relative roll motion as allowed by fifth-wheel lash. During the test, the virtual trailer is loaded to a specified weight and cg height. In the event of a successful test, these parameters would be indicated as maximum allowable fifth-wheel load conditions on the support unit's operating permit.

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