SCENERIOS FOR REGULATION OF COMMERCIAL VEHICLE STABILITY IN THE US

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ABSTRACT

This paper describes two regulatory scenarios pertaining, respectively, to the basic resistance to rollover and the obstacle avoidance maneuvering capability of longer and heavier commercial vehicles. These scenarios were developed in a recent project undertaken by UMTRI for the National Highway Traffic Safety Administration of the US DOT. At the time of the study, new legislation which could allow the nationwide introduction of vehicle combinations heavier than 36,400 kg (80,000 lbs) 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 or better than the vehicles that they would replace.

The primary goal of the scenario develop for regulating roll stability was to provide a reasonable assurance that all vehicles operating under the system would have a static rollover threshold exceeding 0.35g. Secondary goals of the system were to minimize the burden placed on a truck operator in providing that proof, and to allow for qualifying vehicles on a unit-by-unit basis. Simple screening calculations, based largely on the well-known T/2H stability parameter, were developed by which vehicle units which would easily meet the stability criterion could qualify. Tilt table test procedures were developed for vehicles "too close to call" by the screening methods.

The primary goal of the scenario developed to regulate obstacle avoidance capability was to provide a reasonable assurance that all vehicles operating under the system would exhibit rearward amplification less than or equal to 2.0. The test procedure develop solves many of the difficult problems associated with deriving a representative measure of rearward amplification from test data, and insuring adequate repeatability of test results. Screening procedures based on tabulated rearward amplification values derived from detailed simulations were also developed.

INTRODUCTION

This paper describes two regulatory scenarios pertaining, respectively, to the basic resistance to rollover and the obstacle avoidance maneuvering capability of longer and heavier commercial vehicles. These scenarios were developed in a recent project undertaken by UMTRI for the National Highway Traffic Safety Administration of the US DOT [1].[1] At the time of this study, new legislation which could allow the nationwide introduction of vehicle combinations heavier than 36,400 kg (80,000 lbs) and longer than twin, 8.5-meter (28-foot) doubles was under consideration. The underlying purpose of the work was to develop

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[1] Bracketed numbers refer to, bibliographic references given at the end of this paper.

means of assuring that the safety-related performance of such new vehicles would be as good or better than the vehicles that they would replace.

The work of the project involved setting performance targets (minimum levels of performance), developing screening procedures for identifying vehicles that would easily meet the performance standards, and developing test procedures for measuring the performance of vehicles that would be "too close to call" using the screening procedures. The resulting procedures have been documented in a video report that contains segments on tilt-table testing, obstacle avoidance test procedures, operational characteristics of longer combination vehicles with and without innovative dollies, and the experiences of operators, drivers, and regulatory officials that have been involved with the use of C-trains.

THE SCENARIO FOR REGULATING MINIMUM STATIC ROLL STABILITY

The primary goal of the scenario develop for regulating roll stability is to provide a reasonable assurance that all vehicles operating under the system will have a static rollover threshold exceeding a specified minimum value. The system would apply only to "overweight" and "over-length" vehicles and would require that they operate only under special permit. "Proof" of adequate stability would be required to obtain a permit, but a secondary goal of the system is to minimizes the burden placed on a truck operator in providing that proof.

Common operating procedure in the US trucking industry often involves the continuous "mixing and matching" of tractors and semitrailers as well as trucks and full-trailers. It is therefore, also a goal of this system to allow for permitting of vehicles on a unit-by-unit basis.

To accommodate these goals, a regulatory scenario has been evolved in which a vehicle can qualify as sufficiently roll stable by passing either one of two screening calculation procedures or by demonstrating adequate stability in a tilt table test. In either case, the procedures allow for the qualification of individual vehicle units by assuming "minimally acceptable" qualities for their mating units. Since the properties of the payload mass are so dominant in determining the actual roll stability of an operating commercial vehicle, screening and test procedures were developed which account for the intended loading conditions.

The permit document for any unit which bears a payload includes statements as to its allowable loading. The permit for a payload unit also describes the significant properties of any other supporting unit to which it can be mated, so that acceptable combinations can be readily identified in the field. Examples of how permit documents for payload and supporting units might appear are given in Figure 1.

The Specified Minimum Roll Stability

The level of lateral acceleration chosen to represent the minimum desired rollover threshold in the development of this procedure was 0.35g. Of course, the choice of this, or any other specific required performance would be critical in determining both the cost and the benefit derived from the implementation of such a regulatory scenario. The importance of *the* selected level can hardly be understated. However, a rigorous approach to establishing this level was beyond the scope of this project. Certainly, no formal cost/benefit analysis which could support this figure has been performed. The level of 0.35g chosen here is simply an "educated guess" ventured by the authors. Canadian regulators have adopted a requirement of 0.4g (and several other performance requirements) in developing the type-specification for an inter-provincial "B-train." New Zealand has adopted regulations similar to the Canadian rules. Our instinct is that this figure may be unduly conservative for the US highway system (but certainly not very much so). On the other hand, our instinct is also that 0.35 may be near the low end of the generally useful range of such a requirement.

All of this aside, 0.35g was chosen for this "example" exercise, and it probably serves as well as any value for the purpose of "demonstrating" the scenario.

Fundamentals of Static Roll Stability

The static roll stability of any highway vehicle is dependent on a number of vehicle parameters involving height, width, suspension geometry, and compliances of the body, suspension, and tires. The actual mechanics of the quasi-static rollover process (the "slow" progress of the vehicle from a condition of zero lateral acceleration up to and through a level of lateral acceleration causing rollover) are rather complex and usually highly nonlinear. The more important nonlinearites are typically step-changes in system compliance which occur as various "events" (such as tire liftoff at a given axle) take place. The discussion which follows is a minimal treatment of the subject, ignoring most such complexities. Substantive discussion of the rollover process can be found in the literature [2,3,4].

Figure 2 illustrates a commercial vehicle as it proceeds through a steady turn. Centrifugal force at the center of gravity (cg) causes the vehicle to roll outward in the turn. The destabilizing moments that can cause rollover come from (i) the centrifugal force itself, and (ii) from the outboard translation of the cg relative to the wheel track (Δy). The opposing, 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 2 is:

$$W A_y H = (F_2 - F_1)\frac{T}{2} - \Delta y\, W \qquad (1)$$

where:

W	is the weight of the unit.
A_y	is the lateral acceleration in g's.
H	is the height of the unit cg.
F_1, F_2	are the vertical loads on the left and right tires, respectively.
T	is the effective track width.
Δy	is the lateral position of the cg relative to the center of track.

This equation can be solved for A_y and written in the following form:

$$A_y = \frac{(F_2 - F_1)T}{2WH} - \frac{\Delta y}{H} \qquad (2)$$

where A_y is lateral acceleration in g's.

If we assume for the moment that the vehicle, including its tires and suspension, is rigid, (that is $\Delta y \equiv 0$), and recognizing that, at the threshold of rollover, $F_1 = 0$ and $F_2 = W$, then equation (1) simplifies to:

$$A_y = \frac{T}{2H} \qquad (3)$$

Thus, T/2H — the ratio of the half-track to the cg height — is broadly recognized as being the most fundamental vehicle property determining static roll stability. This property is often referred to as the so-called static stability factor.

In the context of a roll stability regulation, it is of importance to note that T/2H is a function of both the inherent design quality of the vehicle and its loading condition. While track width is a property established by design, cg height is dominated by in-use loading. Typically, the mass of the payload may far exceed the tare mass of the vehicle. Thus, the recognition that T/2H is the fundamental vehicle property establishing roll stability implies that a regulation seeking to control roll stability must account for loading.

Of course, real vehicles are not rigid. Tire, suspension, and body compliances cause the actual roll stability to be less than T/2H. By allowing outboard motion of the cg (Δy), compliant deflections reduce the rollover threshold by $\Delta y/H$. The resulting reduction of roll stability is usually significant for commercial vehicles. An actual rollover threshold of 30 to 50% less than T/2H is not at all unusual.

The nonlinear quality of the rollover process mentioned above is embodied in the relationship between A_y and Δy. One can think about the outboard motion of the cg resulting from the experience of lateral acceleration as a "spring" deflection process where the spring compliance is in units of lateral motion per g of lateral acceleration. This system compliance is a function of weight, cg height, suspension geometry and all of the many individual compliances of the vehicle. And this system compliance changes each time one of these individual compliances changes — for example, when a tire lifts off the surface or when a spring or a fifth wheel coupling passes through lash.

Overview and Rationale of the Roll Stability Regulation

The regulatory system developed recognizes three classes of vehicles, namely, Class I, II, and III, defined as vehicles passing the Class I screening calculation, the Class II screening calculation, or a tilt table test requirement. In addition to being classified as I, II, or III, individual units are also identified as "payload" and/or "support" units.

Payload and support units.

In the makeup of combination vehicles, different units of the vehicle play fundamentally different roles in the context of roll mechanics. Specifically, some units, — those that carry payload such as trucks, semitrailers and full trailers — dominate in determining the vehicle mass properties (weight and cg height). Payload units always provided some, but not necessarily all of their own support. Other units (typically tractors and dollies) provide some of the 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, the roll stability regulation system defines both "payload" and "support" units and has different rules for permitting each. The rules are based on the assumption that the mass properties (weight and cg height) of the combination are dominated by the payload unit. Units which serve both payload and support roles must meet *both* rules. Some payload and support units are shown in Figure 3.

The Screening Procedures.

The screening procedures are intended to provide easy methods by which vehicles which clearly have a high level of roll stability can acquire operating permits. The calculations involved are rather crude, but their inaccuracies are accommodated by a high level of conservatism in setting the requirements.

Both of the screening procedures set a requirement on T/2H of payload units, but not support units. Since the total mass of a combined vehicle is dominated by the payload units, and since these methods are only approximate, the influence of support unit mass on T/2H is ignored. This approach accommodates the desire to treat all units independently. The Class II screening procedure adds certain requirements for the tire and suspension properties of both support and payload units.

Class I Screening. The requirement for a Class I vehicle is a screening process intended to pass any vehicle which is so inherently stable, by virtue of a high value of T/2H, that it would achieve at least an 0.35 g rollover threshold, with virtually any realistic set of tire and suspension properties.

We have seen above that T/2H is the most fundamental vehicle property relating to roll stability. Further, in practice, T/2H varies considerably, largely due to the variations in H. Thus, it is both necessary, and, at the screening level, sufficient to regulate T/2H in order to regulate roll stability. (One could argue that track does not vary much across all commercial vehicles and could therefore be considered constant for purposes of a screening process. However, T is so very easy to measure compared to H that excluding it provides very little benefit in reduced burden. Further, including T in the system encourages the use of wide track axle arrangements.)

The value of T/2H required by the Class I screening is 0.58. (The methods for determining T and H will be explained below.) Since this screening depends only on cg height and track width, Class I screening is applied only to payload units. Any support unit automatically meets Class I requirements "regardless of its tire and suspension properties."

Class II Screening. This level of screening is intended to pass vehicles whose T/2H value is not as high as 0.58, but high enough to be clearly satisfactory, given some minimal quality of suspension and tire properties. In this case the required value of T/2H is lowered to 0.46.

Tires and suspensions at each axle are required, in effect, to have minimal values of stiffness which are dependent on the rated load of the axle. The values required represent relatively "good" stability qualities. In practice, OEM tire and suspension manufactures could "certify" particular models as qualifying as "Class II components."

In determining T/2H for payload units, the value of T assumed for any "missing" support unit axle would be "declared" by the applicant, but the payload unit permit would then require use of Class II support units with at least that effective track. Support unit permits would, of course, include a track width rating.

Choosing the Screening Requirements

Two approaches were used to establish the Class I and Class II qualifying values of T/2H, namely 0.58 and 0.46g, respectively. The first was to calculate the required value of T/2H to achieve the desired 0.35g rollover threshold, given a "worst case" selection of the appropriate vehicle compliance properties. The second was to examine all of the available rollover threshold data available in the literature. This second method served more as a check, or validation of the calculations, rather than as a primary selection means.

Figure 4 illustrates the results of the stability calculations. The model for this calculation is a full trailer composed of a single axle dolly and single axle semitrailer. Both suspensions are the same, and are loaded identically. The value of "H" used to determine T/2H is the total cg height number of similar models composed of tractors, dollies and/or semitrailers of various axle configurations could be used. The marginal difference in results is of little concern given the "round number" quality of the other parameters used in the calculation. These values are shown in the figure key.

The figure is a column graph showing the minimum value of T/2H required to achieve a rollover threshold of 0.35g. The darker columns show results for calculations relating to the Class I hypothesis, that is, "worst case" parameters.[2,3] The lighter columns show the results for calculations when the tire and suspension stiffness (but not other parameters) are improved to the minimum Class II requirements.[4] In each case, results are shown for the effective track widths which result from the four combinations of 244 or 259 mm (96 or 102 inch) axles and wide base single or dual tires.

The graph clearly shows that the required T/2H depends on the tire/axle combination. At first, this may seem odd, but it is due to the fact that the relative importance of the rigid body mechanism (T/2H) and the compliance mechanism ($\Delta y/H$) changes when the absolute value of track and the absolute value of tire stiffnesses change. Stated more simply, the rigid body approximation is not the whole story. As a result, the selection of a single T/2H implies some "error," even at these simple screening levels. The values of 0.58 and 0.46 were selected to fall within the error band, being conservative with respect to three of the four axle/tire combinations.

Figure 5 shows the typical values of the height of the cg of the *payload* which would be allowed under the Class I and Class II regulations. The figure is based on the assumption of "typical" van trailer values for the tare mass qualities of the trailer and 9090 kg (20,000 lbs) axle loads. This graph shows that (i) only vehicles with rather dense, low cargoes are likely to qualify for Class I permits, (ii) vehicles with moderate to relatively high loads can qualify for Class II permits, and (iii) the use of wide track axle/tire arrangements is rewarded by allowing higher loads.

An "empirical" check on the validity of the choices of 0.58 and 0.46g as the Class I and Class II requirements for assuring a minimum 0.35 g stability was attempted by evaluating data available in the literature. A number of researchers have examined commercial vehicle roll stability and published results [5-15]. It would be ideal for our purposes here, if all had used the same measurement procedure and all had reported test vehicle parameters in detail, but, of course, they did not. Testing methods vary from tilt table to track testing, and a variety of surrogate measures are sometimes used to define the roll stability limit. The reporting of test vehicle parameters is rather limited. In some instances, one or another cg height (payload, sprung mass, etc.) is reported. Nevertheless, the available information was used to develop the presentation of Figure 6, which compares rollover threshold with T/2H of the payload unit (usually a semitrailer). It should be stressed, however, that for many of the plotted points, a good deal of liberal interpretation of the reported data was required on the part of the authors to determine one or the other or both of the measures (threshold and T/2H). In general, this plot should be considered as only a rather crude representation of actuality.

With these shortcomings declared, the data of Figure 6 tend to confirm the choices of 0.58 and 0.46g. The figure plots rollover threshold on the ordinate and T/2H on the abscissa. As a reference, the plot includes a "45 degree" line showing the set of points where rollover threshold equals T/2H. Two vertical reference

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[2] The choice of the "worst case" values used is based on UMTRI parameter measurement experience. Unfortunately, that experience derives from a rather haphazard selection of samples. Rigorous establishment of worst case values might require a large parameter measurement and market survey study.

[3] Roll stiffness and roll center height numbers come from the single "worst case" suspension, a specific air suspension of rather low roll stiffness. Lower (worse) roll center heights are found on other stiffer (better) suspensions.

[4] These values also derive largely from the authors' judgment and measurement experience. To first order, requiring that tire and suspension stiffness be proportional to load maintains the influence of these compliances constant relative to roll stability. The vertical stiffness of radial truck tires is more-or-less proportional to rated load of the tire; the tire stiffness specification might require "over tiring" relative to rated load. Finally, the specification for suspension roll stiffness insures that heavily loaded axles will necessarily use one of the more stable suspensions available in the market.

threshold equals T/2H. Two vertical reference lines, one each at T/2H values of 0.46 and 0.58, are shown, as is one horizontal reference line at the rollover threshold of 0.35. The fact that none of the data points fall in the "Class I" shaded portion of the plot bounded by the 0.35 and 0.58 reference lines tends to confirm that all vehicles whose T/2H parameter exceeds 0.58, also exceed 0.35 in rollover threshold. Similarly, only a few vehicles (mostly partially filled tankers) fall in the Class II region bounded by the 0.35 and 0.46 references. At the same time, none of the reference boundaries are grossly removed from the body of data. (However, the plot also highlights the shortcomings of the data, or rather the shortcomings of the authors' interpretation of the data. Two points actually fall above the 45 degree reference—a physical impossibility. The close proximity of a number of other points to this reference, especially those of relatively low stability, is also suspect.)

Determining T/2H.

In calculating the value of T/2H for the screening procedures, the track of the unit is determined by weighted average of the tracks of its individual axles. For payload units which require a mating support unit, the track of the support unit is included in the calculation, weighted by the fifth wheel load rating. The track of an axle with two single tires is the distance between the tire centerlines. The track of axles with two sets of dual tires is the distance between the centerlines of the dual sets. For Class I calculations, all support unit axles are assumed to be a "worst case" valve of 1829 mm (72 inches).

The more difficult portion of calculating T/2H is determining H, while keeping the methodology simple. Indeed, a workable scheme to calculate a representative value of H for payload units is the key to establishing a workable and worthwhile system.

The basic equation for determining H is:

$$H = \frac{H_E W_E + H_P W_P}{W_E + W_P} \qquad (4)$$

where:

W_E	is the certified weight of the empty unit.
W_P	is the maximum weight of the payload specified by the applicant.
H_E	is the cg height of the empty vehicle, determined by approved calculation or test, or assumed to be 1905 mm (75 inches).
H_P	is the cg height of the payload estimated with the prescribed procedure.

The key parameter in this calculation is, of course, the height of the payload cg. The procedures for determining this value depends on the type of vehicle and/or the type of freight. Tank vehicles are the easiest case. Assuming that the payload cg lies at the centroid of the tank volume is the obvious choice. But for more general purpose vehicles, such a simple choice is not practical. The choice of the centroid of the load space volume would be a severe, and unjustifiable penalty for users hauling high density freight siting low in the available load space.

The scheme developed determines H_P based on the height and area of the load floor and the assumed or declared density of the freight (except for the case of tankers, where the centroid is used). By this scheme, applicants could seek a permit for use with (i) uniform density freight of a *specified* minimum density, (ii) LTL package freight, or (iii) general (unspecified) freight. A fourth category of permit would apply to tankers.

For general freight: H_P = the height of the midpoint between the load floor and the top of the load space. That is:
$H_P = H_F + 0.5(H_T - H_F)$

For LTL packaged freight: H_P = the 40% point between the load floor and the top of the load space. That is:
$H_P = H_F + 0.4(H_T - H_F)$

For uniform density freight: H_P = the midpoint of the load as calculated using the declared minimum density and the load floor area and height. That is:

$$H_P = H_F + 0.5\left(\frac{W_P}{A_F * D}\right)$$

For wet or dry bulk tankers: H_P = the height of the centroid of the tank volume.

Where:

H_F	is the height of the floor of the load space (weighted average by area if the floor is not level).
H_T	is the top of the load space (ceiling height if applicable, or legal limit).
A_F	is the area of the load floor.
D	is the payload density (including packaging efficiency).
W_P	is the maximum payload weight.

The general freight formula is meant to apply a "worst case" assumption to the calculations for cases where the permit is to cover all uses of the unit.

The LTL freight procedure is based on "typical" LTL loading practice as described by Ervin in his studies conducted for RTAC [16]. It reflects the tendency of LTL shippers to place heavier packages low in the load space.

The specified uniform density freight scenario provides a means to "fit" specific uses quite closely, allowing those moving high density freight to appreciate the benefit of low profile loads. This scenario would depend on published values of cargo density. For example, the American Trucking Association publishes an extensive list of typical densities for various types of freight.

Issued payload permits would include a notation describing the maximum allowable payload weight and the class and/or minimum density of freight.

The Class III Tilt Table Test Procedure

Vehicles whose calculated value of T/2H is less than 0.46g are considered "too close to call" relative to the 0.35g roll stability requirement. A tilt table test procedure is required to qualify these vehicles. Test procedures, which will be explained below, allow for individual testing of payload and support units and determining that each provides their "fair share" of stability to the system. Similar to the Class II screening, these tests require that relevant properties of the "missing" units be declared by the applicant. If the unit passes the test, the resulting permit is qualified by the requirement that the unit be mated only with Class III units of "at least" similar properties. Finally, the rationale for the individual test procedures is dependent on "conventional" design practice. In order to accommodate improvements which might result from unconventional designs, any complete combination vehicle could be qualified by a straightforward tilt table demonstration that its roll stability exceeded 0.35g.

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 proportioned according to axle loading). If each unit is roll stable to a minimum level of 0.35g when subject to its share of vertical and roll moment loading, then the rollover threshold of the combined vehicle will meet or exceed this same standard.

Testing Complete Roll Units. The most straightforward tilt table test procedure is for complete roll units. A complete roll unit is a single unit or combination of units which is not roll coupled to any other units. For example, a unit truck is a complete roll unit; a tractor-semitrailer combination is a complete roll unit; both the truck and the full trailer of a truck-trailer combination are complete roll units if the trailer dolly is an A-dolly.

Any complete roll unit can be tested in a straight forward manner on a tilt table to establish its rollover threshold. In this regulatory system, vehicle loading would be specified by the applicant. The specification would include weight and payload cg height. Longitudinal distribution of the load would be "water-level" across the load floor. If the vehicle remained stable at a simulated 0.35g (19.29 degrees) it would qualify for a permit. Test weight, cg height and floor area would be used to determine the allowable cargo parameters to be indicated on the permit. If the tested roll unit were composed of separable sub-units, then the permit would include notations limiting use to the specific combination tested.

Testing Payload Units. The test of payload units, which require fifth wheel support from a support unit, is the most complex of the test procedures and requires some explanation.

The philosophy of the test is somewhat indirect. The test is run to determine what level of stabilizing moment is required at the fifth wheel in order for the payload unit to remain roll stable at 0.35g. If the required moment at the fifth wheel does not exceed a "fair share," based on fifth wheel load and support unit track, then 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," then 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." A sketch showing a payload unit (semitrailer) mounted on a tilt table with a virtual tractor is shown in Figure 7. As the figure shows, the virtual tractor has a "roll center" located 508 mm (20 inches) above the ground and a conventional fifth wheel whose support surface is 1245 mm (49 inches) above the ground. This roll center height is representative of the effective, combined roll center height derived from roll motions due to tire deflection and the roll motions of "typical" suspensions about their own roll center. The fifth wheel height is representative of US practice.

In the test, the table is first tilted to 19.29 degrees (0.35g 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 slowly allowed to roll by allowing roll motion at the roll center of the virtual tractor. The virtual tractor restraining moment is recorder as a function of the body roll angle of the test unit. ("Body roll angle" in this discussion refers to the roll angle of the payload unit body relative to the surface of the tilt table.) 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 8. This is a plot of roll moment versus test unit body roll angle. Shown on these axes are plots of virtual trailer roll moment, suspension roll moment, and total roll moment (sum of the two) as they might occur during the test just described (that is, 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.

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

$$W_S A_y h = M_{susp} + M_{vt} - W_S h\phi \quad (4)$$

where:

W_S	is the sprung mass weight.
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.
ϕ	is the body roll angle.

(The equation assumes small angles and a rigid sprung mass.)

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

For this explanation, it is useful to rewrite (4) and define M_{tot} as:

$$M_{tot} \equiv M_{susp} + M_{vt} = W_S A_y h + Wh\phi \quad (5)$$

At the beginning of the test, the unit is constrained to a zero body roll angle. The term $Wh\phi$ is therefore zero, and since the suspensions are undeflected, M_{susp} is also zero. Thus $M_{vt} = WA_y h$. 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 Wh 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.[5] 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 8 ignores 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 tire liftoff occurs, the test can be stopped. (If it were continued, the test unit would slowly be "set down" onto its side. The reason for the subsequent increase of fifth wheel moment is readily apparent when this is visualized.)

An additional dotted line is plotted on the graph of Figure 8. This reference 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 unit's

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[5] 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.

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). As shown in the figure, the equation is:

$$T_{min} = 2\left[\frac{M_{vt}}{W_{5th}} + h_{RC} A_y\right] \qquad (6)$$

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.

Testing Support Units. The method for tilt table testing of support units is rather straight forward. Fifth wheel loading of the support unit is specified by the applicant. The specification includes both the fifth wheel weight and the cg height. The specified load is mounted on the fifth wheel using a "virtual trailer." This device is simply a specialized load rack which mounts on a fifth wheel and provides realistic loading, including the influence of fifth wheel lash.

The tilt table test of the loaded support unit is conducted in a normal manner. If the unit remains stable at 0.35g, it qualifies for a permit. The permit would include notice of the test weight and cg height parameters. Payload units which exceeded either of these parameters would not be acceptable for use with this support unit.

Summary of the Roll Stability Regulation

A regulatory means for providing reasonable assurance that complying vehicles have a minimum static rollover threshold of 0.35g has been presented. To accommodate the common mixing of individual units in combination vehicles, the system is structured to allow for compliance on a unit-by-unit basis. The method includes two levels of screening for allowing vehicles which clearly meet the stability criterion to easily demonstrates compliance. Vehicle units which are "too close to call" can be tested for stability on a tilt table. Tilt table procedures for testing individual units are also defined.

THE SCENARIO FOR REGULATING OBSTACLE AVOIDANCE CAPABILITY

The primary goal of the scenario developed to regulate obstacle avoidance capability is to provide a reasonable assurance that all vehicles operating under the system will exhibit rearward amplification less than or equal to a specified minimum. As was the case for roll stability, proof of adequate performance needed to acquire an operating permit can be provided through actual vehicle testing or a simple screening procedure.

The test procedure developed addresses and, we believe, solves many of the difficult problems associated with (i) deriving a representative measure of rearward amplification from test data which typically varies significantly from sinusoidal form, and (ii) insuring adequate repeatability of test results. These problems have appeared repeatedly in previous investigations of rearward amplification.

While it was hoped that simple formulations for calculating rearward amplification at the screening level could be developed, it still appears that the real physical complexity of the system precludes that. However, rearward amplification tables which can serve as the screening mechanism have been developed for popular vehicle configurations. This tables can readily be expanded if desired.

Background on the Concept of Rearward Amplification

Multi-trailer vehicles may have special performance problems when the driver makes a quick steering maneuver to avoid an unexpected obstacle in the road ahead. These problems are manifested in a tendency for the rear trailer to have a much larger lateral response than that of the tractor. The ratio of the lateral acceleration of the center of gravity of the last payload unit divided by the level of lateral acceleration occurring at the front of the vehicle is called "rearward amplification" (RA). See Figure 9 for an idealized representation of this phenomenon.

Rearward amplification has been used for more than ten years to describe the tendency of the last trailer to either swing out of line or rollover over in obstacle avoidance maneuvers. However, before this study various ad hoc procedures had been used for measuring rearward amplification [16,17,18]. Furthermore, simplified procedures for predicting rearward amplification [19,20], although they are good in providing a qualitative understanding of the phenomenon, have proven to be inaccurate for vehicles with large payloads having high centers of gravity [21]. Based upon these considerations, a new type of test procedure was developed in this study and, since no simple screening analysis was found to be satisfactory, a screening method based upon simulation results has been adopted. Since the new test procedure was found to be quite repeatable, the test results could be used to confirm the results of simulations. Hence, in addition to a test procedure, there are now screening tables available for use in certifying the rearward amplification performance levels of common types of longer combination vehicles (LCVs). (Similar tables can be constructed for other types of combination vehicles if there exists sufficient interest to warrant the effort.)

In order to have a basis for comparison, the performance of the twin 8.5-meter (28-foot) double (the so-called "Western double") has been selected as a baseline. Although there is not much data on the safety record of doubles combinations, there have been analyses of accident and exposure data that show that the accident involvement rate of doubles with trailers that are approximately 8.5 meters in length may be several times less than that of doubles with trailers that are 7.3 meter (24 feet) or less in length. For example, the longer vehicles appear to be 3.8 times less involved in single vehicle accidents on high-speed roads [21].

This difference in safety record has been associated with a difference in rearward amplification. The shorter vehicles have a predicted rearward amplification level of around 2.6. On the other hand, given that the Western double in currently legal nationwide, tests and analyses of this twin 8.5-meter (28-foot) double imply that the currently accepted vehicle in the USA has a rearward amplification of approximately 2.0. This level of rearward amplification (i.e., RA = 2.0) has therefore been chosen as the performance target for use in judging the acceptability of LCVs in this study.

Description of a new test procedure for rearward amplification

The difference between this procedure and those used in the past is that the new procedure involves a prescribed path that the front axle of the tractor is to follow in performing a test. Now as in the past, the goal has been to obtain a waveform of lateral acceleration of the tractor that is close to one cycle of a sine wave. The reason for this is that this form of lateral acceleration will result in an obstacle avoidance maneuver in which the vehicle translates sideways and ends up heading in the original direction of travel.

Experience has shown that one cycle of a sine wave of steering usually leads to an asymmetric form of lateral acceleration of the tractor, thereby making comparisons between different types of vehicles very difficult. In that case, the method for quantifying rearward amplification necessarily involves arbitrary choices in defining the numeric for rating rearward amplification. A major reason for deciding to develop a prescribed path approach has been to provide a common basis for comparing vehicles. This has not always been possible using a specified input at the steering wheel because the tractors performed different maneuvers (sometimes just due to idiosyncrasies of the tractor's steering system).

The path chosen for use in the new test procedure is designed to correspond to one cycle of a sine wave of lateral acceleration. That is, the following relationships apply to the dynamic maneuvering section of the test course shown in Figure 10.

$$A_y = A \sin (2\pi t/T) \qquad (7)$$

$$V_y = [A/(2\pi/T)]\, [1 - \cos(2\pi t/T)] \qquad (8)$$

$$y(t) = [A/(2\pi/T)]\, [t - (\sin(2\pi t/T) / (2\pi/T))] \qquad (9)$$

Where:

t	is time.
T	is the period.
A	is the amplitude in feet per second squared.
V_y	is the time rate of change of y, and
y	is the lateral position of the path along the ground.

Equations 7, 8, and 9 pertain to a situation in which the longitudinal distance, x, is traversed at a constant forward velocity, V, such that:

$$x(t) = Vt \qquad (10)$$

Let X be the longitudinal coordinate at the end of the maneuvering section of the obstacle avoidance path, that is, the longitudinal coordinate of the path at t = T. For a forward velocity, V, X = VT. Using these relationships yields the following important simple relationship:

$$y(X) = AT^2/2\pi$$
$$(\text{or } y(X) = AX^2/2\pi V^2) \qquad (11)$$

This means that the displacement at the end of the avoidance maneuver depends upon the period and the level of lateral acceleration. For example, if A = 0.15 g, that is, 1.469 m/sec^2 (4.824 ft/sec^2) and T = 2.5 seconds; y(X) = 1.44 m (4.80 ft) (see Fig. 10).

The simple relationships for the path (equations 7 to 11) make it easy to specify courses of different amplitudes and periods. However, an amplitude of 0.15 g was found to be a reasonable level for investigating vehicles with RA =2.0 and greater. (For RA = 2.0 and A_y = 0.15g, the lateral acceleration of the last trailer will be 0.3g which is approaching the rollover threshold of many heavy trucks. Hence outriggers for preventing rollovers are necessary.) If amplitudes lower than 0.15g are used, rearward amplification tends to increase because the phenomenon is nonlinear. Using 0.15g provides a test that challenges the safety qualities of heavy truck combinations (particularly those qualities related to rolling over) and allows those qualities to be compared to those of the Western double.

Rearward amplification is known to depend upon the period of the maneuver [22] and previous procedures [16,18] had involved tests at various periods. In this study, paths with periods of 2.0, 2.5, and 3.0 seconds were laid out and investigated at a speed of 88 kph (55 mph). The results of experimenting with these different paths indicated that the end of each path could be superimposed on the others with little difference between them. In practice, the course with a 2.5 second period tended to evoked the most rearward amplification and to be the easiest to perform satisfactorily. Based upon this experience, only the 2.5 second period has been recommended in specifying the procedure. (Of course, it is a simple matter to use other periods—it is just that the 2.5 second period appears to be sufficient for evaluating rearward amplification. And besides, if this path is driven at different speeds, the period and lateral acceleration will be different anyhow.)

To insure that the test is performed accurately, it is stipulated that the driver must pass over each plate in the test course shown in Figure 10. A system for marking the pavement with the actual path of a point on the front axle was developed for checking that the driver stayed within 152 mm (± 6 inches) of the prescribed path. It was found that with the aid of a sighting strip on the hood the driver could follow the path within these limits on almost every test run.

Nevertheless, the *peak* measured values of the lateral accelerations corresponding to the path that the driver actually followed did not always provide a good indication of the magnitude of the maneuver for the purpose of calculating rearward amplification. After investigating several possibilities for quantifying the input motion, it was found that the root-mean-square (rms) value of the lateral acceleration of the front axle of the tractor was a good indicator of the magnitude of the input. The rms value times 1.414 is now used to describe the magnitude of the input (that is, the magnitude of an equivalent cycle of a sine wave of lateral acceleration). This procedure provides repeatable results in evaluating the denominator of the rearward amplification ratio.

The numerator of the rearward amplification ratio depends upon the lateral acceleration of the center of gravity of the last trailer. For this quantity the peak reading of the lateral acceleration transducer (mounted upon a stable platform) proved to be satisfactory. The wave form is "clean" and passes through relatively smooth peaks because the trailer's dynamic qualities tend to filter out any higher frequency irregularities. Simple digital filtering techniques have been used to provide repeatable readings of the peak values obtained in vehicle tests. This is fortunate because the response of the last trailer is asymmetric and there is nothing (that we know of) to warrant using an assumed shape or an rms reading or another method for averaging over time.

The pertinent requirements for performing the new test procedure are summarized in Table 1. This table highlights the essential features of the transducers, data processing, performance evaluation, and quality checks. These features form the foundation of the steps involved in performing the tests (see Figure 11). A key idea portrayed in Table 1 and Figure 11 is to check the quality of each test run to see that the test was performed properly.

The results from five good runs are processed to provide the measure of rearward amplification performance obtained by the vehicle in this obstacle avoidance maneuver. If the tests are done properly, the standard deviation of a sample of five runs should be less than ten percent of the mean of the five runs. Sensitivity analyses, using UMTRI's Yaw/Roll simulation [24] and considering changes in vehicle parameters, test velocity, and amplitude and period of input (while still requiring the reference front axle point to pass over the plates), showed that it is reasonable to expect this quality of results for vehicles with acceptable dynamic properties. The full scale tests done in this study support this conclusion.

The results are to be presented as follows:

$$\mathbf{RA = m \pm 0.953\ S} \qquad (12)$$

where:

m is the sample mean (the average of 5 runs), and

S is the sample standard deviation where $S^2 = (\Sigma\,(RA_i - m)^2) / 4$.

(Note: S, as used here, is a numerical property of the data which fits the needs of the method. Further, the value of 0.953 is appropriate only with a procedure constrained to 5 repeats.)

The requirement for "passing" the test is:

$$\mathbf{m + 0.953\ S \leq 2.0} \qquad (13)$$

The idea behind this requirement is that m±0.953 S are the 90 percent confidence limits on the mean result of a large number of tests. Or, in other words, satisfying equation 13 implies a 95 percent confidence that the mean rearward amplification does not lie above 2.0.

Detailed formal descriptions of the test procedure are given in proposed SAE Recommended Practice J2179 and in reference [23].

The new procedure has been used to quantify the performance of a Western double and a triple trailer combination. Both of these vehicles were evaluated in A-train and in C-train configurations. Figure 12 illustrates the dollies used in the A-train and C-train configurations. The results of this initial test program (see Figure 13) show that the confidence bands are small. They also show that the C-dolly provides an improvement factor of 1.35 when the performances of the C-trains are compared to those of the A-trains. This same level of improvement factor has been predicted by simulation [24], not only for these combinations, but also for a variety of different doubles combinations. It is interesting to observe that the rearward amplification for the A-train triple went from 2.5 to 1.8 for the C-train triple when C-dollies were used in place of the A-dollies in the same vehicle. In addition, the 2.0 level found for the Western double corresponds to the results predicted by simulations. These results indicate that the rationale behind the new procedure is sound and that one can expect to obtain repeatable and predictable results.

Screening Procedures for Specifying Acceptable Combinations

A goal of this work is to provide screening procedures for identifying vehicles with acceptable rearward amplification performance. Given a screening approach, there would be two paths to certification (see Figure 14).

In the beginning it was hoped that a simplified model could be developed for screening purposes. This did not materialize. It was found that the roll characteristics of the vehicle had a significant influence on rearward amplification. The computed results given in Figure 15 illustrate this point. In this case the center of gravity of the payload was artificially lowered to show the effect. Examination of the computed time histories of lateral acceleration show much higher peaks for the vehicle that rolls more. The yaw rate time histories indicate greater yaw motion also for the vehicle with the higher cg. These results indicate that roll characteristics need to be included in the analysis. A complicate calculation procedure would be needed to include roll effects. Instead results from a comprehensive simulation program [24] have been used to provide tables for use in screening types of longer combination vehicles (LCVs) currently popular in the US.

Since rollover of the last trailer is a concern in obstacle avoidance maneuvers and since the roll properties of the vehicle have an important influence on rearward amplification, it is specified that vehicles must meet the rollover threshold requirements (i.e., a minimum threshold of 0.35g) to pass the requirements for obstacle evasion.

In addition, the cornering stiffnesses of the tires have a large influence on rearward amplification. A further stipulation is that the vehicle must be equipped with tires that have stiffnesses comparable to those corresponding to modern radial truck tires — specifically, at least 3110 N/deg (700 lbs/deg) at a load of 2270 kg (5000 lbs).

Given these stipulations, screening tables have been constructed for 5, 7, and 9 axle doubles and 7 axle triples. (See Tables 2 and 3.) Table 2 gives restrictions on the minimum lengths of the trailers when conventional A-dollies are used in joining doubles combinations together. Table 3 is for combinations using C-dollies. When C-dollies are used, the vehicles may be shorter and triples are allowed. The C-dolly was found to provide an improvement factor of approximately 1.35 in rearward amplification for all of the LCVs studied. (Hence a triple, which has an RA of 2.5 with conventional dollies, would have an RA substantially less than 2.0, approximately 1.8, if C-dollies are used.)

Tables 2 and 3 are for specific maximum weights for each vehicle combination. The lengths allowed are for these weight restrictions. The allowable lengths were determined by making simulations over a range of lengths and reading the results to find the lengths that correspond to a RA of 2.0.

Findings and Conclusions Concerning Obstacle Evasion Performance

The following list of findings and conclusions summarize this part of the study:

- ☐ Rearward amplification (as defined in the test procedure) is a useful performance measure for quantifying obstacle avoidance capability.
- ☐ A performance target of RA ≤ 2.0 for vehicles weighing over 36,400 kg (80,000 lbs) will mean that their rearward amplification values will be comparable to that of the current Western 8.5-meter (28-foot) doubles.
- ☐ Vehicle roll characteristics have an important influence on obstacle avoidance capability.
- ☐ Screening procedures have been developed for LCVs. These procedures provide weight limits based upon vehicle dimensions and hitching arrangements.
- ☐ A new, objective test procedure for assessing the obstacle avoidance capabilities of heavy trucks has been developed.

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Transducers

- Lateral acceleration of the front axle, AyX
- Lateral acceleration of the cg of the sprung mass of the last trailer, AyT (stabilized platform)
- Time period between the start point and the end point of the maneuvering section of the test course.
- Laser system or water jets for measuring tractor and trailer paths

Data processing

- Smoothing (0.2 second moving average, applied twice)
- Peak reading for AyT
- rms calculation for AyX
- RA = peak AyT / 1.4 rms AyX

Performance evaluation

- Compute mean (RAM) and sample standard deviation (S) for 5 repeats of the test
- RA = RAM ± 0.953 S
- Example targets: RAM + 0.953 S < 2.0; dynamic offtracking < 2 ft (0.6 m)

Quality

- Driver follows path within ±6 inches (0.15 m)
- S is approximately 10% of RAM
- Velocity held within ±1 mph (±0.4 m/sec)

Table 1. Test procedure requirements

Screening Summary Table Based on A-Train Configurations
— Length Compensation —

Standard double configuration	*5 Axles*	*7 Axles*	*9 Axles*
Max. GCW (lbs)	90,000	108,000	120,000
Min. box length of leading trailer (ft)	27	45	26
Min. box length of second trailer (ft)	27	20	26
Max. overhang of leading trailer (ft)	4	3	4

Table 2. Screening for A-trains doubles

Screening Summary Table Based on A-Train Configurations
— Length Compensation —

Standard double configuration	*5 Axles*	*7 Axles*	*9 Axles*
Max. GCW (lbs)	90,000	108,000	120,000
Min. box length of leading trailer (ft)	36	45	36
Min. box length of second trailer (ft)	36	27	36
Max. overhang of leading trailer (ft)	4	3	4
Projected RA	1.8	1.8	1.8

Standard triple configuration: Three 28 foot trailers,
3 foot overhang,
3 foot king-pin offset,
Max. GCW (lbs) 117,000

RA correction factor: 1.35
Expected Rearward-Amplification: 1.8

Table 3. Screening for C-trains (doubles and triples)

This vehicle is permitted to operate as a ☐ Class I ☐ Class II ☐ Class III payload unit with any of the following payload configurations.

	Type of Payload	Maximum Payload Weight
☐	General Freight	
☐	LTL Package freight	
☐	Uniform density cargo Density equal or exceeding ________ lbs per cu. ft	

If this payload is a semi-trailer, it must be supported by:

☐	Class I	Any tractor, dolly or B-type semitrailer.
☐	Class II	A Class II tractor, dolly or B-semi with a track width rating of ________ inches or greater.
☐	Class III	A Class III tractor, dolly or B-semi qualified for ________ lbs fifth wheel load at ________ inch c. of g. height, and with a minimum track rating of ________ inches. Or with the specific support vehicle:________

ROLL STABILITY QUALIFICATION PERMIT—SUPPORT UNIT

This vehicle is permitted to operate as a ☐ Class II ☐ Class III support unit in combination with appropriate, permitted payload units. Ratings for this support unit are:

	UNIT CLASS	UNIT RATINGS
☐	Class II	Track width rating: ________ inches.
☐	Class III	Fifth wheel load rating: ________ pounds C.G. height rating: ________ inches Track width rating: ________ inches

Figure 1. Example permit document for the roll stability regulation

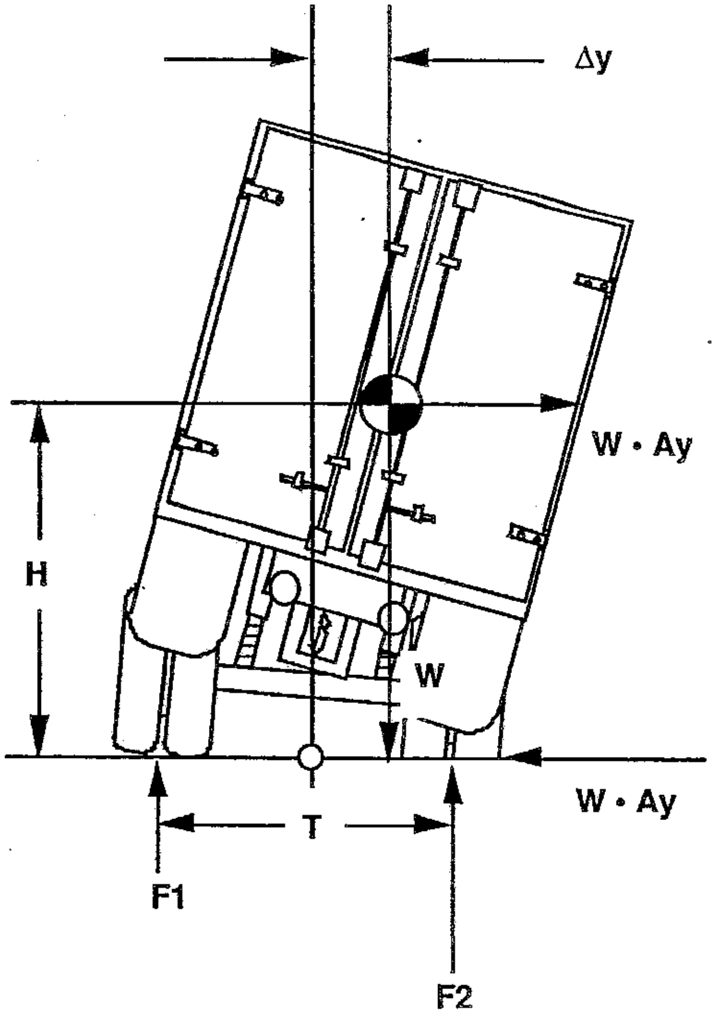


Figure 2. Schematic diagram of a heavy truck in a steady turn

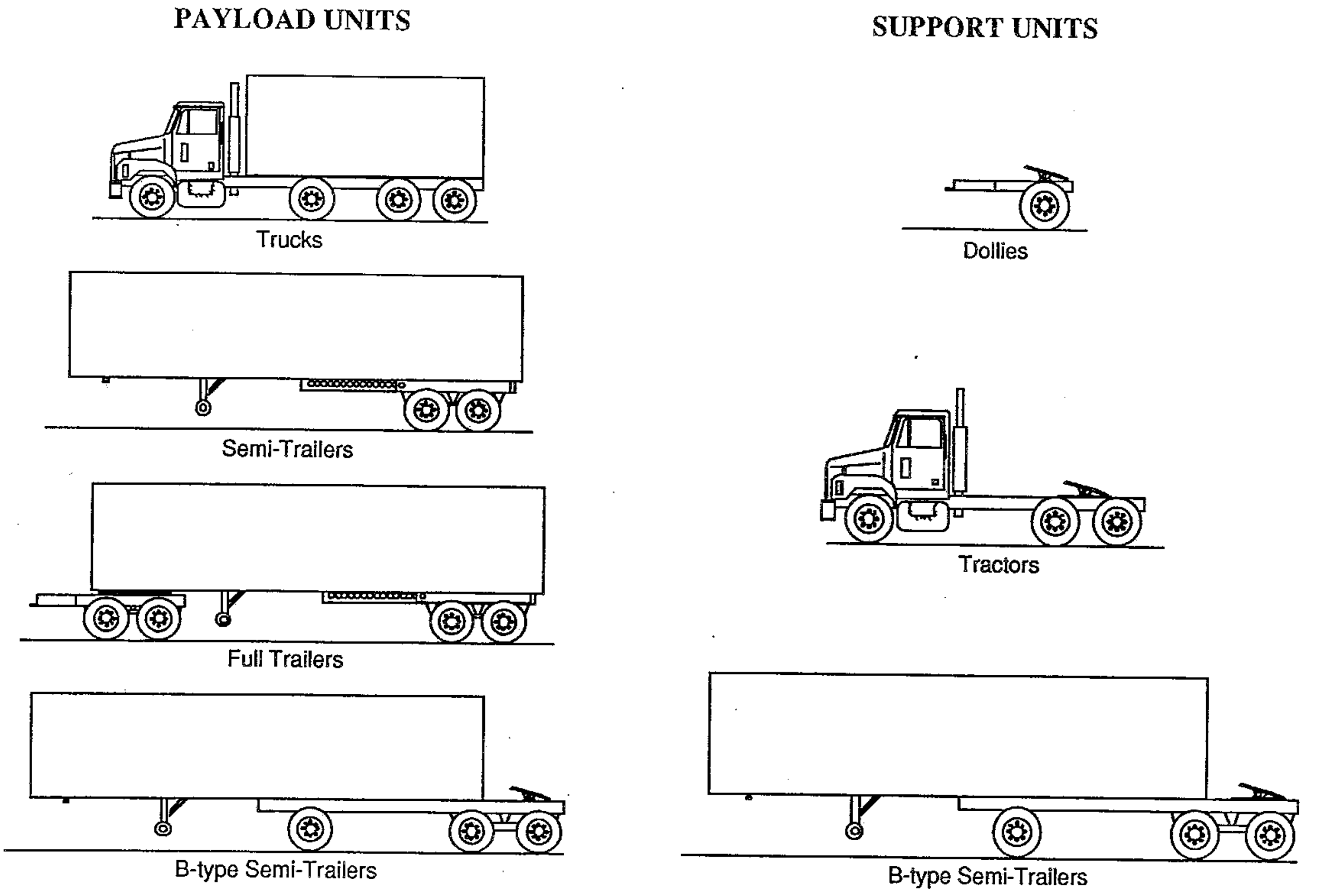


Figure 3. Support and payload units

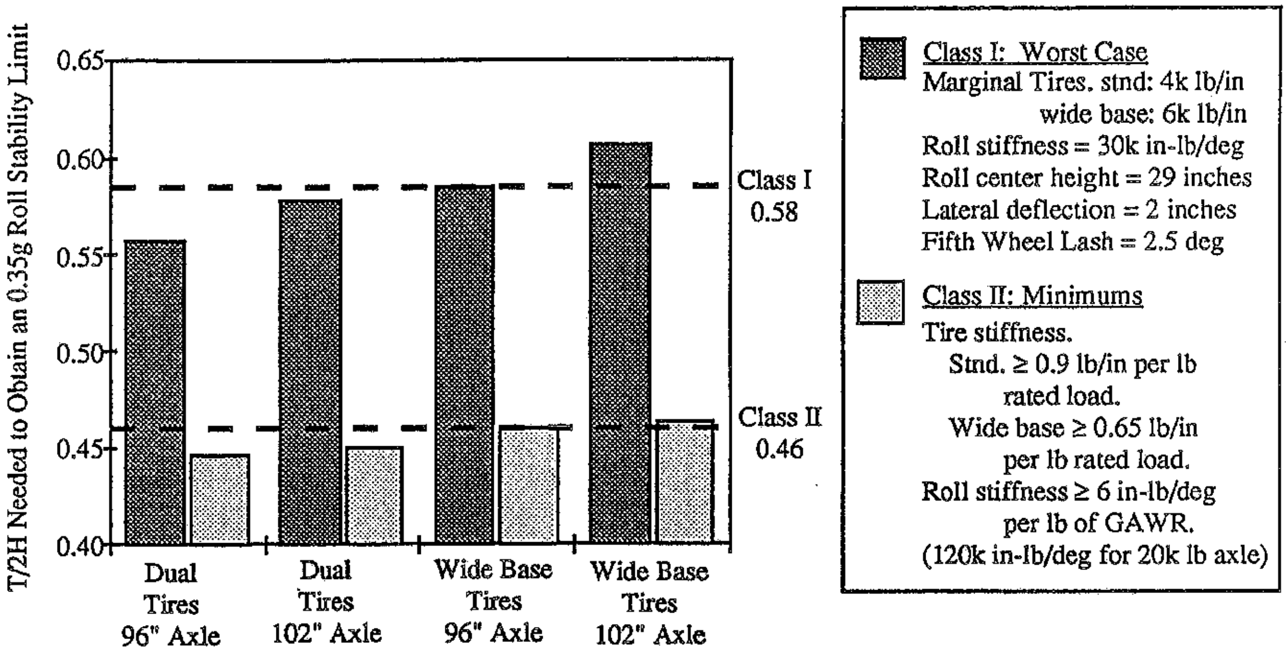


Figure 4. Calculation results supporting 0.58 and 0.46 for Class I and Class II requirement for T/2H

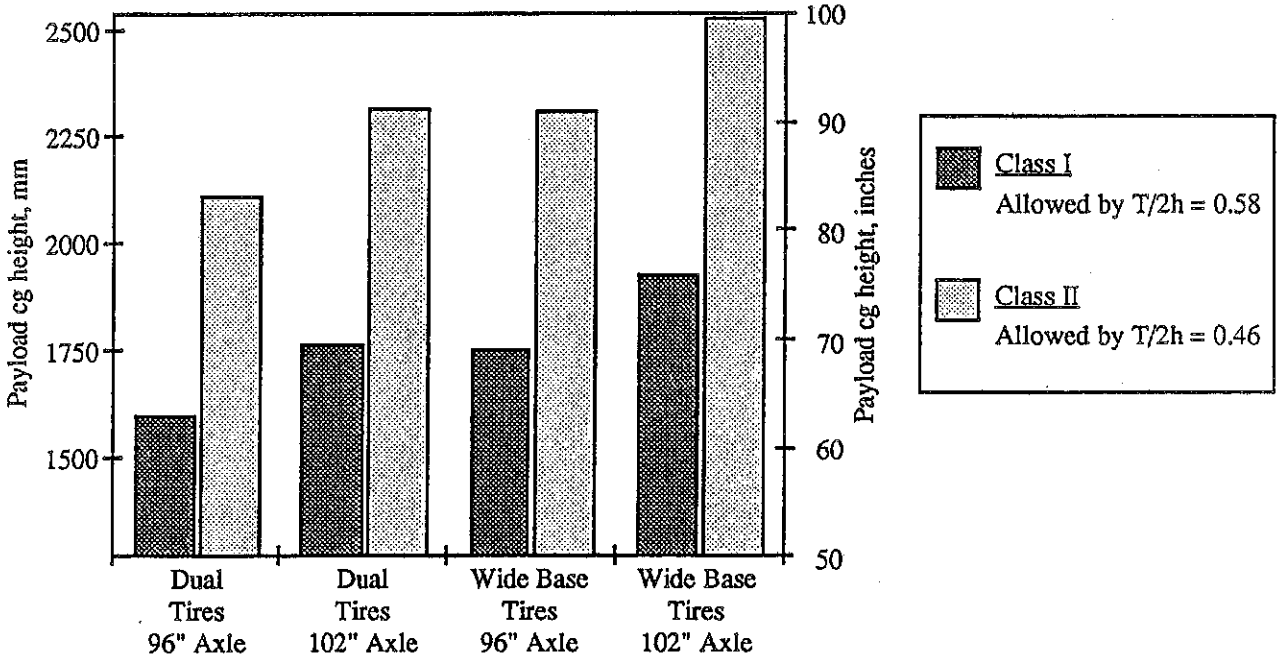


Figure 5. Typical payload center of gravity heights allowed by Class I and Class II requirements

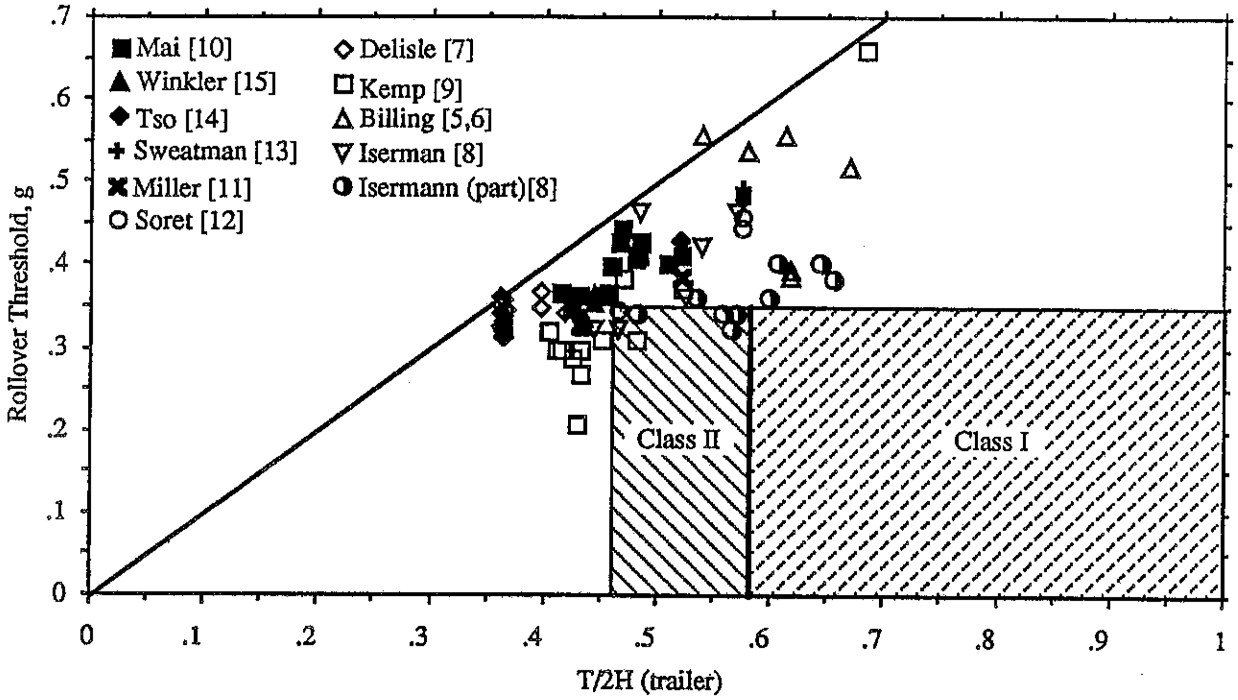


Figure 6. Measured rollover threshold as function of T/2H from the literature.

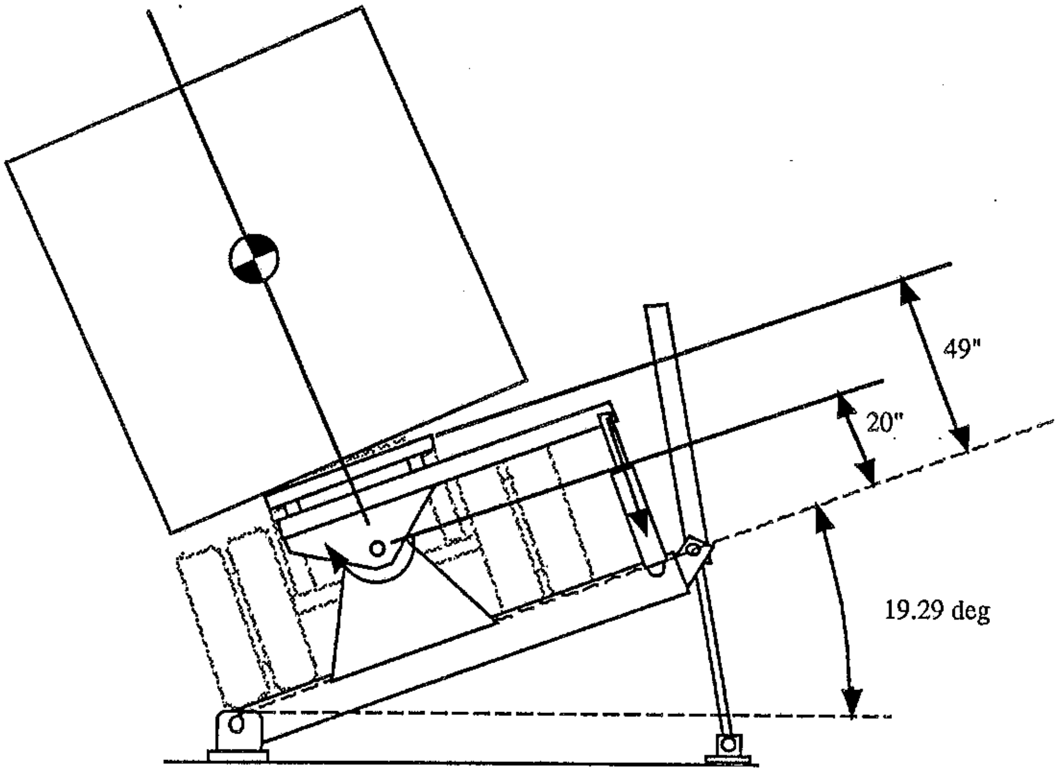


Figure 7. A payload unit tilt test using the virtual tractor

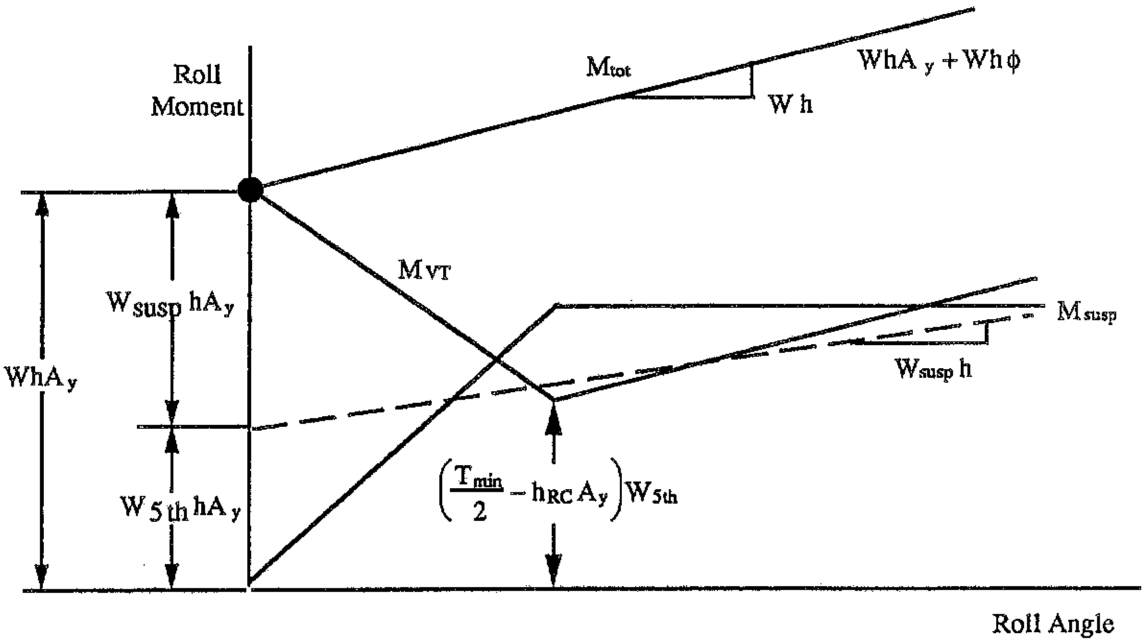


Figure 8. Mechanics of the payload unit tilt table test

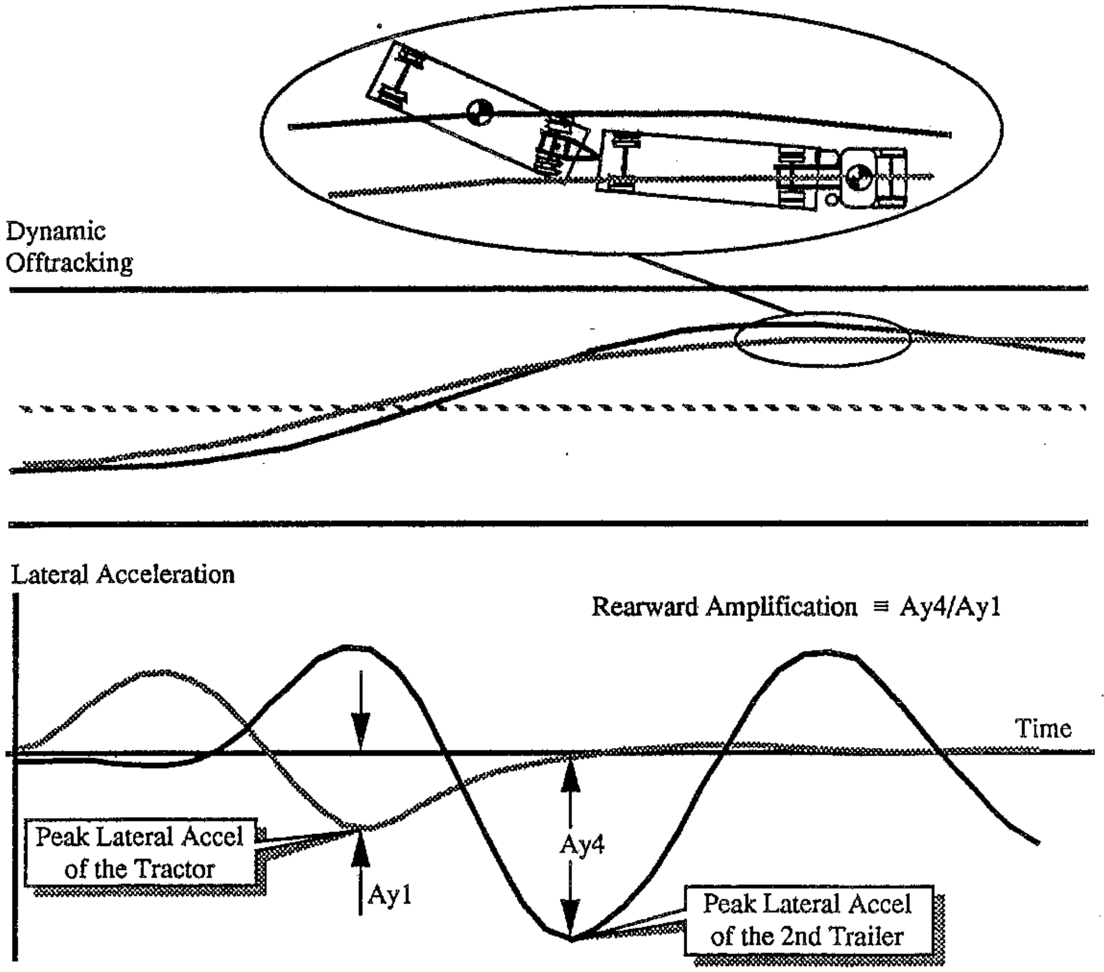


Figure 9. In a rapid obstacle avoidance maneuver, rearward amplification produces dramatic motion of the rear trailer, sometimes resulting in rollover.

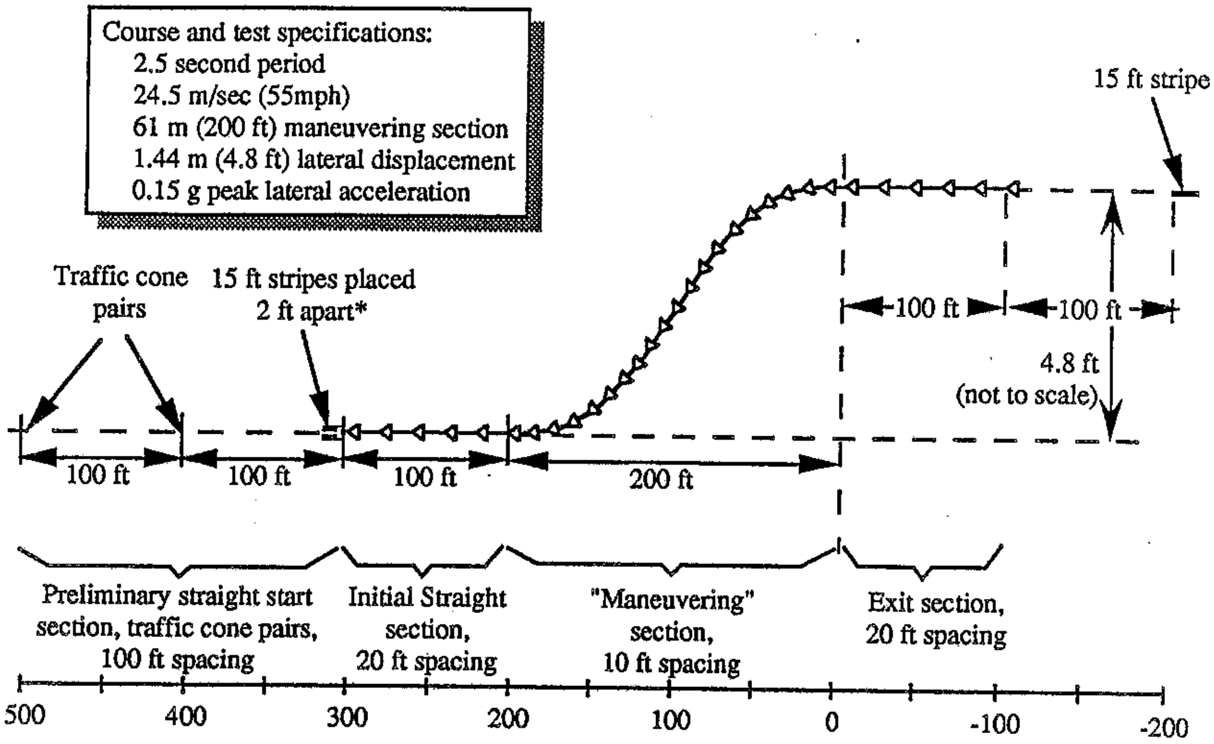


Figure 10. The test course for rearward amplification testing

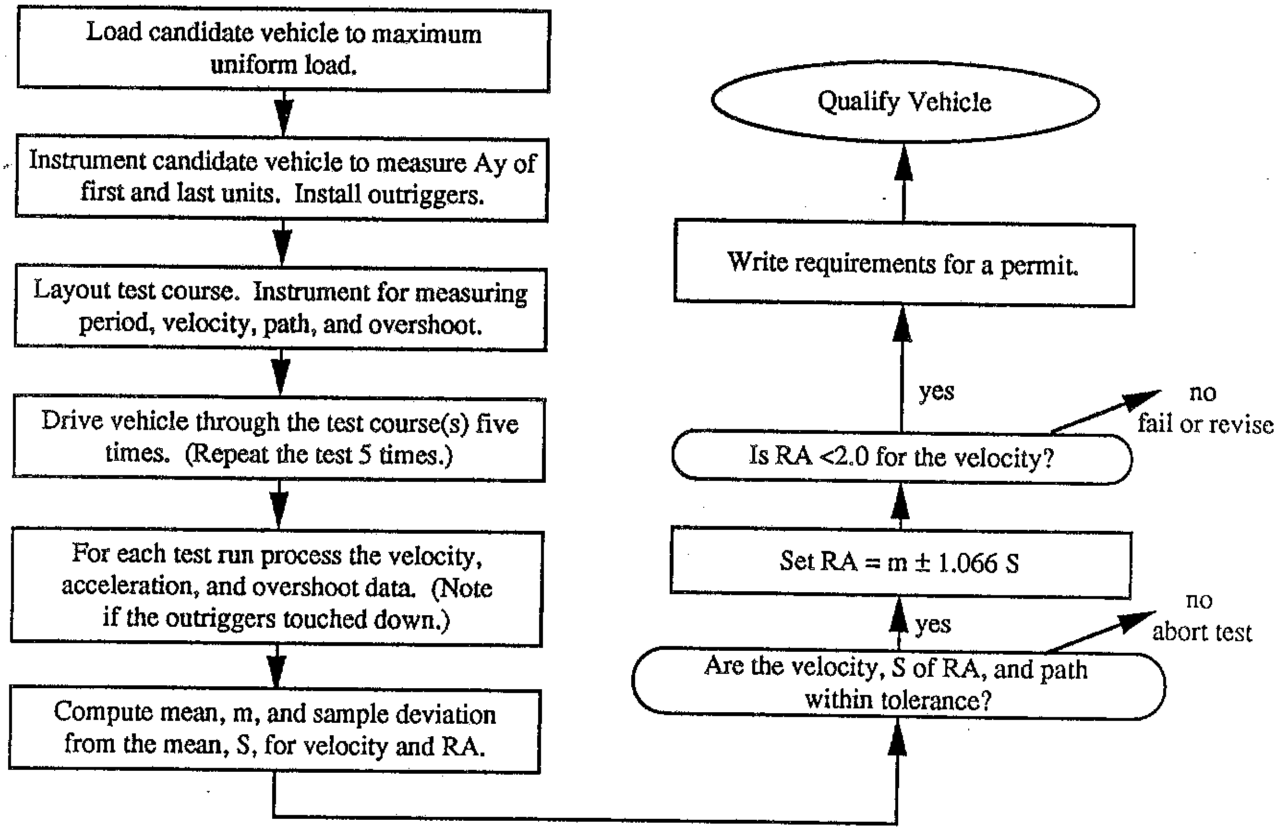
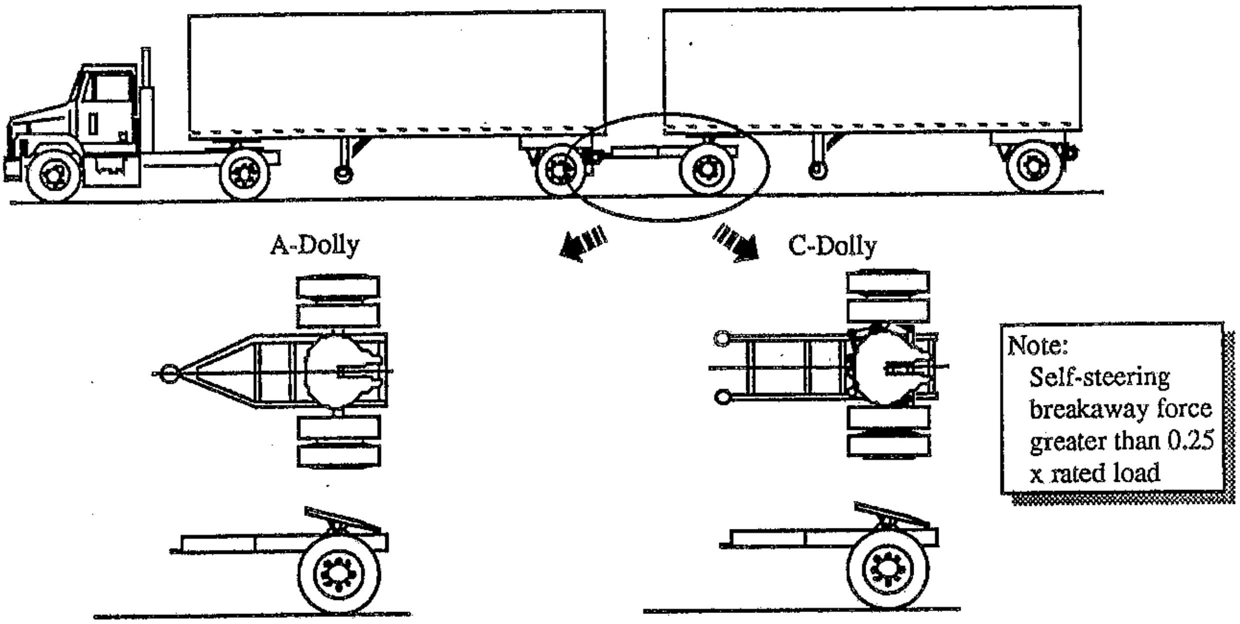


Figure 11. Block diagram of testing for obstacle avoidance capability



Note:
Self-steering
breakaway force
greater than 0.25
x rated load

Figure 12. The single draw-bar A-dolly and the double draw-bar C-dolly

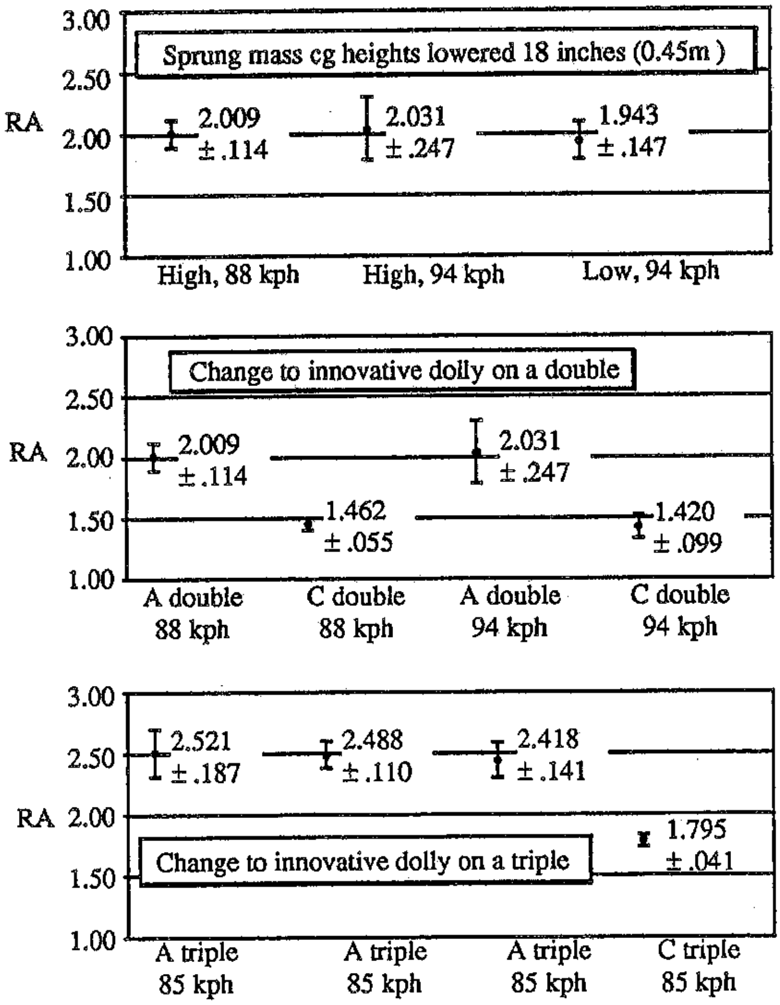


Figure 13. Test results indicating influences of changing sprung mass cg height and changing dolly types

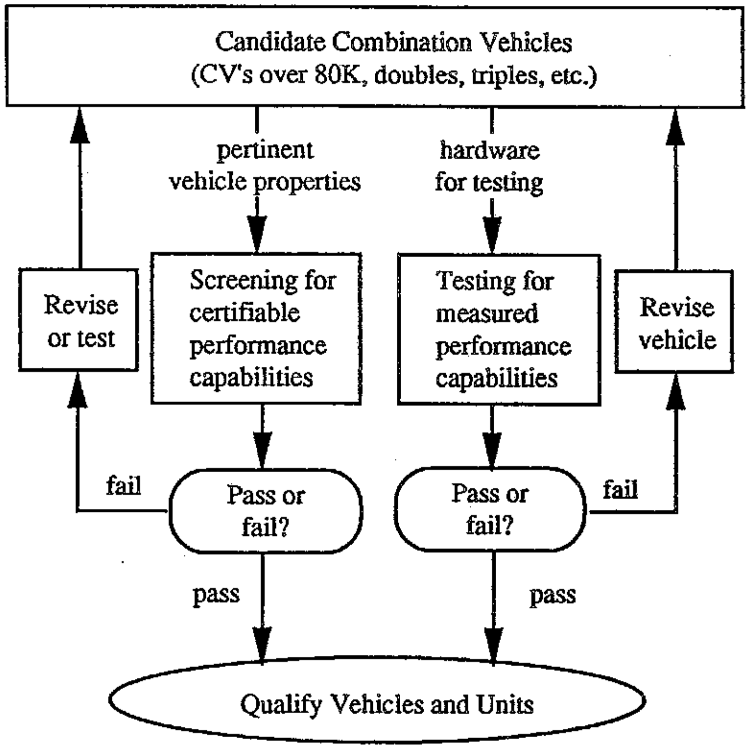


Figure 14. Overview of the certification process showing two paths (screening and testing) to certification

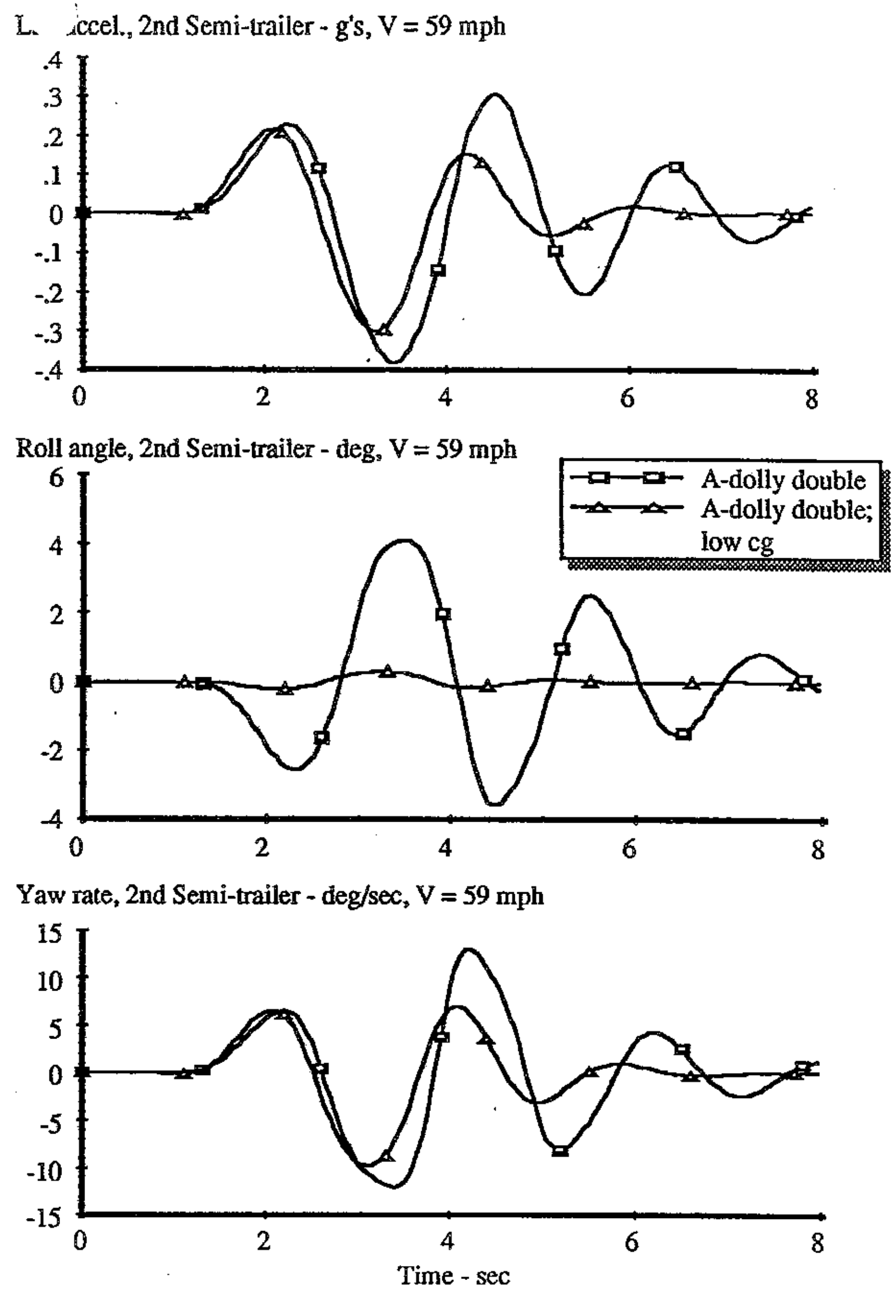


Figure 15. The influence of cg height on lateral and roll motions