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16. Abstract

This report describes two regulatory scenarios pertaining, respectively, to the basic resistance to rollover and the obstacle avoidance maneuvering capability of longer and heavier commercial vehicles. At the time of the study, new legislation that 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 primary goal of the scenario developed 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. Another goal was to allow for qualifying vehicles on a unit-by-unit basis. Simple screening calculations were developed by which vehicle units that 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 developed 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.

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—Heavy Vehicle Size and Weight— Test Procedures for Minimum Safety Performance

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EXECUTIVE SUMMARY

In this study, UMTRI investigated methods for ensuring that the safety-related performance of longer and heavier trucks would be as good as or better than the vehicles that they would replace. Specifically, the study addressed performance standards pertaining to basic resistance to rollover and obstacle avoidance maneuvering capability. The skeletal format of a regulatory system by which these performance standards could be applied to new oversized vehicles that might weigh more than 80,000 lb. and/or be longer than twin 28-foot (Western) doubles was developed. The regulatory scenario would require that such vehicles demonstrate minimum performance capabilities in order to obtain a special operating permit.

The work of the project involved setting performance targets (minimum levels of performance), developing screening procedures for qualifying 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 results of this study have been documented in this *Final Technical Report* and in the video presentation, *Tomorrow's Trucking—Safety/Productivity*. The video 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 who have been involved with the use of C-trains.

Resistance to Rollover: Procedures, Findings, and Conclusions

As a result of this study, there now exist screening and testing procedures for ensuring that heavy vehicle combinations or the individual units making up these combinations will have rollover thresholds greater than 0.35 g as measured by a tilt table test. (A tilt table test is the recommended means for gauging the level of lateral acceleration at which a roll unit of the vehicle would be expected to rollover in a steady turn. Tilt table tests are simpler, less expensive, better controlled, and more precise than proving grounds tests.)

The screening procedures for rollover resistance are based upon a calculation of the ratio of half the track width (T/2) divided by the center of gravity (CG) height of the vehicle (H). T is determined from tape measurements and simple procedures for "averaging" the influences of different track widths at various axles. H depends upon cargo weight, cargo type, load space dimensions, and the tare (empty) weight of the vehicle or roll unit involved. Analyses of published results for rollover thresholds from numerous sources indicate that if $T/2H \geq 0.58$, the rollover threshold will be greater than 0.35 g, regardless of the other properties of the vehicle. Given information that the suspensions and tires meet minimum stiffness requirements, the level of T/2H may be reduced such that if T/2H ≥ 0.48, then the rollover threshold will be greater than 0.35 g. In this way two classes of screening can be used—one that is very conservative but does not allow many vehicles to pass (only those with exceptionally low payload heights) and another that is more discriminating but applies to more vehicles.

Since tractors and trailers are manufactured and sold separately, they are often interchanged in large trucking operations. Hence their roll stability properties need to be evaluated unit by unit. The procedures provided by this study take this matter into account. Methods for treating "payload" units (e.g. trucks, semitrailers, and full trailers) and "support" units (e.g. tractors and dollies) have been developed. The key to this is simply to use the properties of a minimally satisfactory support or payload unit when evaluating the other type of unit. The combination of any two satisfactory units would then result in a satisfactory combination.

For vehicles or units that do not pass a screening test, tilt table procedures have been developed. Individual payload or support units may be tested on the tilt table using special devices developed for this purpose in this study. These devices are called the "virtual tractor" and the "virtual trailer." In the tilt table test, they simulate the functions of supporting and loading, which real tractors and trailers perform. This approach is much the same as used in the screening procedures except that these are mechanical devices that have appropriate mechanical properties to simulate the rollover resistance of minimally satisfactory units. Of course, a whole roll unit can be tested on the tilt table if the situation warrants it.

An underlying notion with regard to the application of these procedures is that they will be used in a "certification" operation. A total vehicle or a vehicle made up of certified units would be authorized for specific applications depending upon characteristics of the load allowed. This is necessary because the weight and center of gravity height of the load are very critical in determining the roll stability of commercial vehicles. If operators of vehicles with low loads are not to be unduly restricted, the regulatory system needs to be responsive to the type of cargo to be carried. Operators, who want complete generality in the types of loads that they are allowed to carry, would have to meet the worst case (toughest) requirements concerning weight and center of gravity height.

Obstacle Avoidance Maneuvers: Findings, Procedures, and Conclusions

Multitrailer vehicles may have special performance problems when the driver must make a quick maneuver to avoid an unexpected obstacle in the road ahead. This problem is manifested in a tendency for the rear trailer to have a much larger lateral response than that of the tractor. The ratio of the level of lateral acceleration of the center of gravity of the last payload unit divided by the lateral acceleration occurring at the front of the vehicle is called "rearward amplification".

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 roll over in obstacle avoidance maneuvers. However, before this study no standardized procedures for measuring rearward amplification had been developed. Furthermore, simplified procedures for predicting rearward amplification, although they were good in providing a qualitative understanding of the phenomenon, proved to be inaccurate for vehicles with high payloads. These early findings changed the nature of the work performed in this study. A new type of test procedure was developed, and since no simple screening analysis was found to be satisfactory, a screening method based upon simulation results was adopted. Since the new test procedure was found to be repeatable, the 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).

Tests and analyses of the twin, 28-foot (Western) double indicate that this vehicle, (which is currently allowed on the entire Interstate highway system,) has a rearward amplification of 2.0. This level of rearward amplification has been chosen as the performance target for use in judging the acceptability of LCVs.

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., 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 cornering stiffnesses comparable to those corresponding to modern radial truck tires (specifically, at least 700 lbs/deg at a load of 5000 lbs). Given these stipulations, screening tables have been constructed for 5-, 7-, and 9-axle doubles and 7-axle triples. One set of tables gives restrictions on the minimum lengths of the trailers when conventional A-dollies are used in joining doubles combinations together. The other set of tables 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 a rearward amplification of 2.5 with conventional dollies, would have a rearward amplification substantially less than 2.0, approximately 1.85, if C-dollies are used.)

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 rearward amplification ≤ 2.0 for vehicles weighing over 80,000 lbs will mean that their rearward amplification will be comparable to that of current Western (STAA) 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.

Concluding Remarks

The procedures for tilt table testing of complete roll units and the obstacle evasion procedure for rearward amplification have been drafted for use as SAE Recommended Practices. Hence, these procedures are now receiving the attention of the vehicle testing and manufacturing community. This activity should result in statements of the procedures that are understood by, and acceptable to, industry.

Formal charts outlining the screening procedures have been prepared and they were presented to NHTSA at a final briefing on this project.

1.0 INTRODUCTION

This report 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 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 that 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 as 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 who have been involved with the use of C-trains.[2]

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

2 The executive summary, which precedes this introduction, provides a comprehensive overview of the work completed in this project.

2.0 THE SCENARIO FOR REGULATING MINIMUM STATIC ROLL STABILITY

The primary goal of the scenario developed 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 that account for the intended loading conditions.

The permit document for any unit that 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.

2.1 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 that could support this figure has been performed. The level of 0.35g chosen here is simply an educated guess ventured by the authors. Canadian

ROLL STABILITY QUALIFICATION PERMIT —PAYLOAD UNIT

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 unit 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: C.G. height rating: Track width rating:	________________ ________________ ________________	pounds inches inches

Figure 1. Example permit document for the roll stability regulation

regulators have adopted a requirement of 0.4g (and several other performance requirements) in developing the type specification for an interprovincial "B-train." New Zealand has adopted a system similar to the Canadian rules but with a static rollover threshold of 0.35g. Our instinct is that 0.4g 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.

2.2 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 nonlinearities are typically step changes in system compliance which occur as various events (such as tire liftoff at a given axle) take place. The discussion that 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:

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

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.

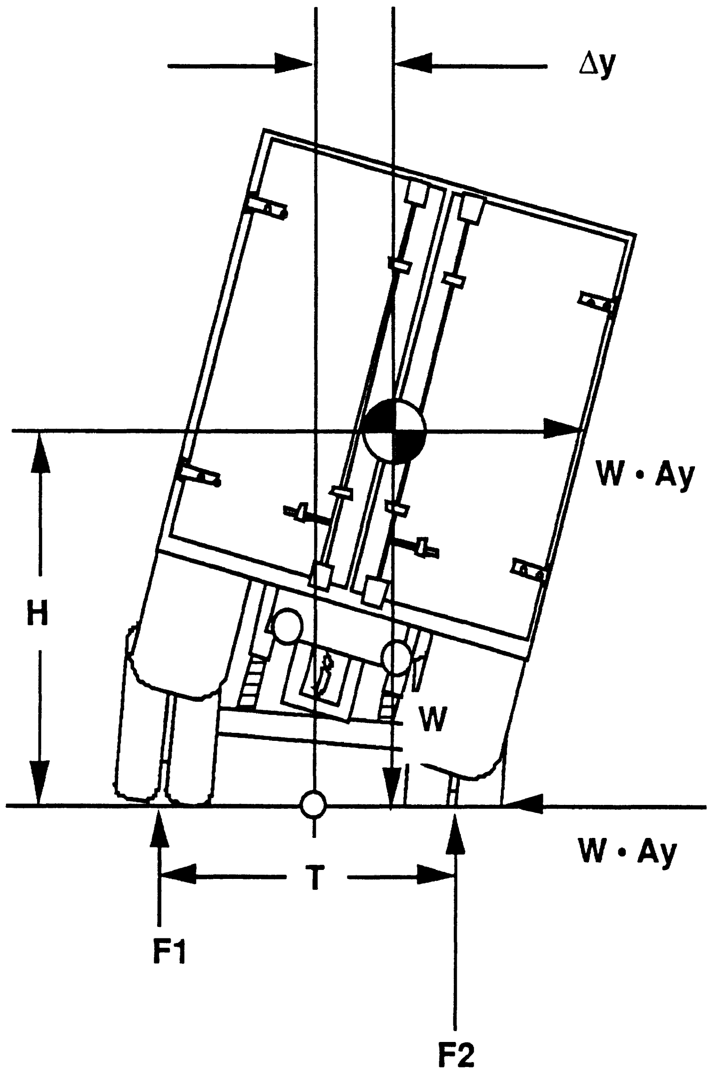

Figure 2. Schematic diagram of a heavy truck in a steady turn

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 important 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.

2.3 Overview and Rationale of the Roll Stability Regulation

The regulatory system developed recognizes three classes of vehicles. Class I vehicles are those which pass a first-level screening calculation; Class II vehicles are those which pass a second screening calculation; Class III vehicles are those which pass 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.

2.3.1 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 that serve both payload and support roles must meet *both* rules. Some payload and support units are shown in figure 3.

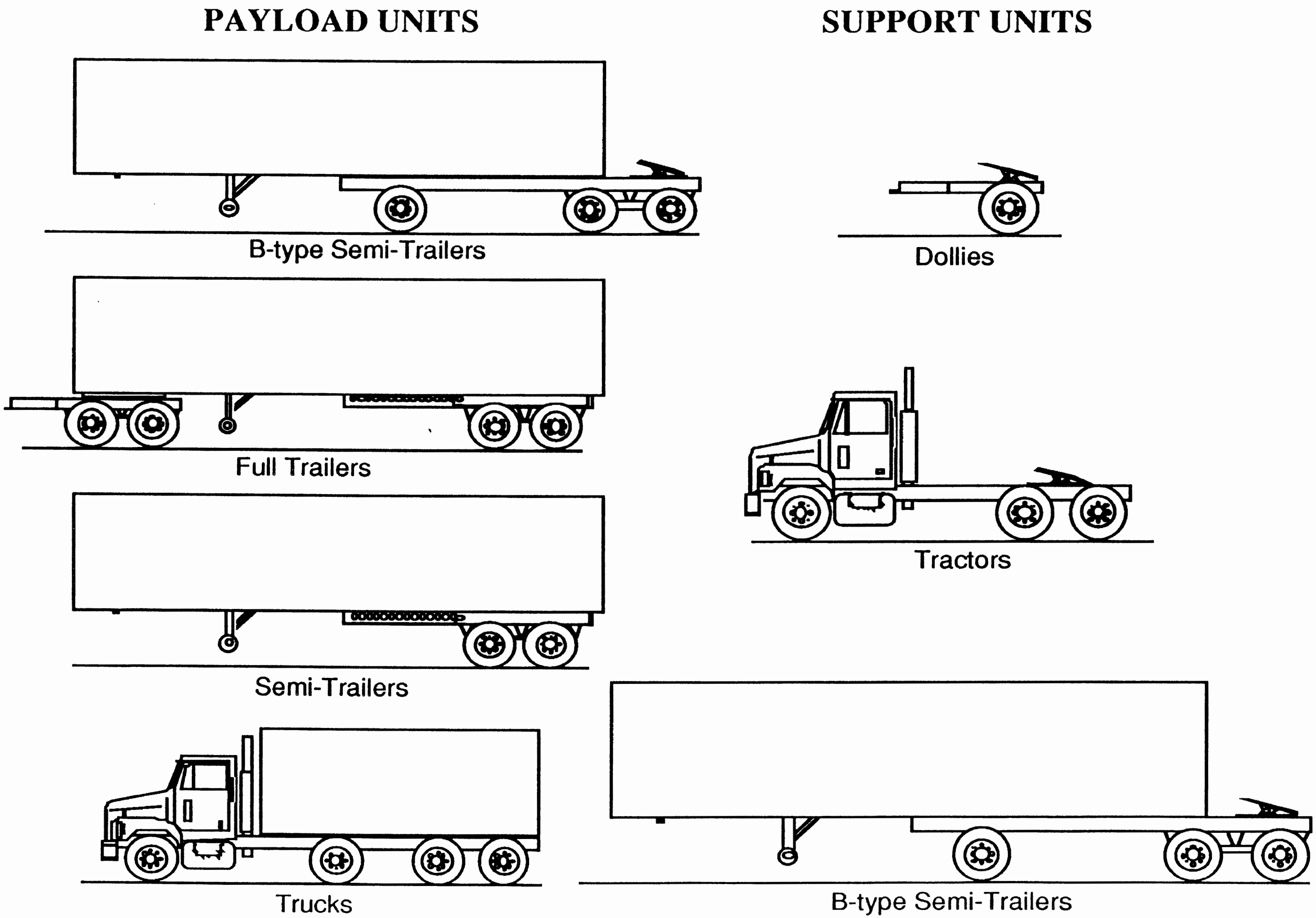

Figure 3. Support and payload units

2.3.2 The Screening Procedures.

The screening procedures are intended to provide easy methods by which vehicles that 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 Class I screening process is 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 calculation 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.

2.3.3 Choosing the Screening Requirements

Two steps were used to establish the Class I and Class II qualifying values of T/2H (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 in the literature. This second step served more as a check, or validation of the calculations, 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 of the semitrailer (the payload unit) alone. Any 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.

Figure 4 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.[3,4] 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.[5] In each case, results are shown for the

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3 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.

4 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.

5 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.

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.

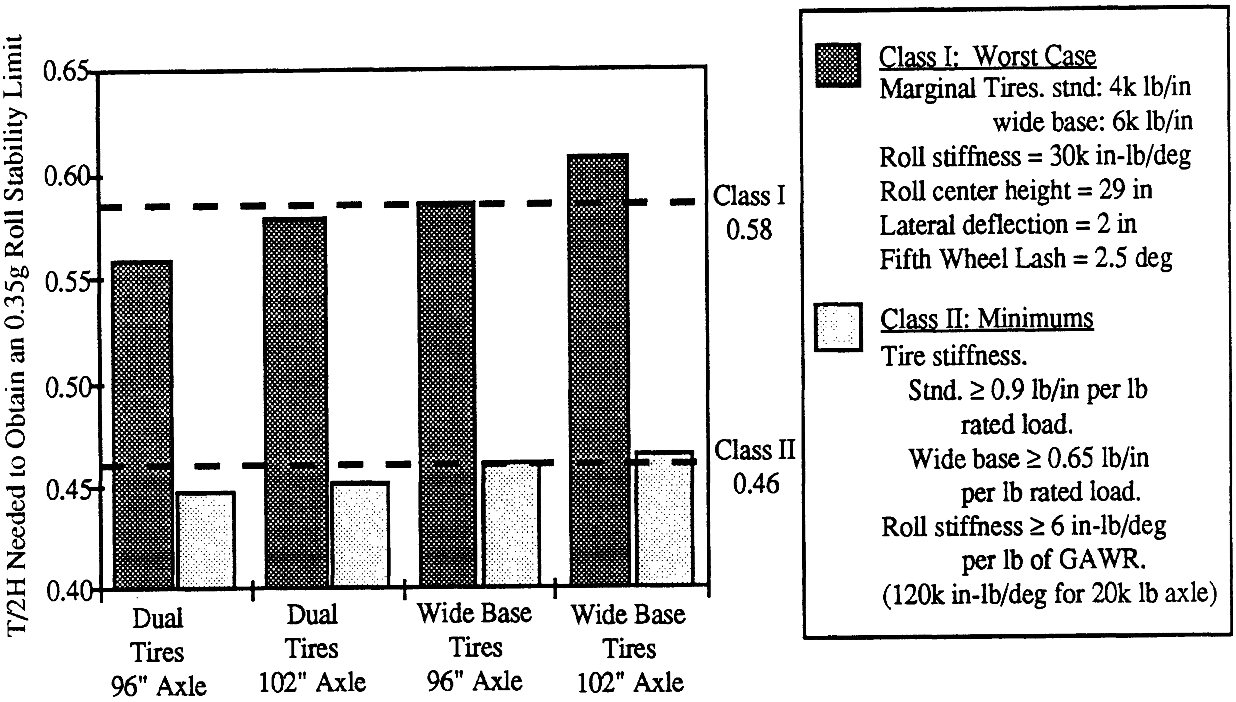

Figure 4. Calculation results supporting 0.58 and 0.46 for Class I and Class II requirement for T/2H

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 (a) only vehicles with rather dense, low cg cargoes are likely to qualify for Class I permits, (b) vehicles with moderate to relatively high cg loads can qualify for Class II permits, and (c) the use of wide track axle/tire arrangements is rewarded by allowing higher loads.

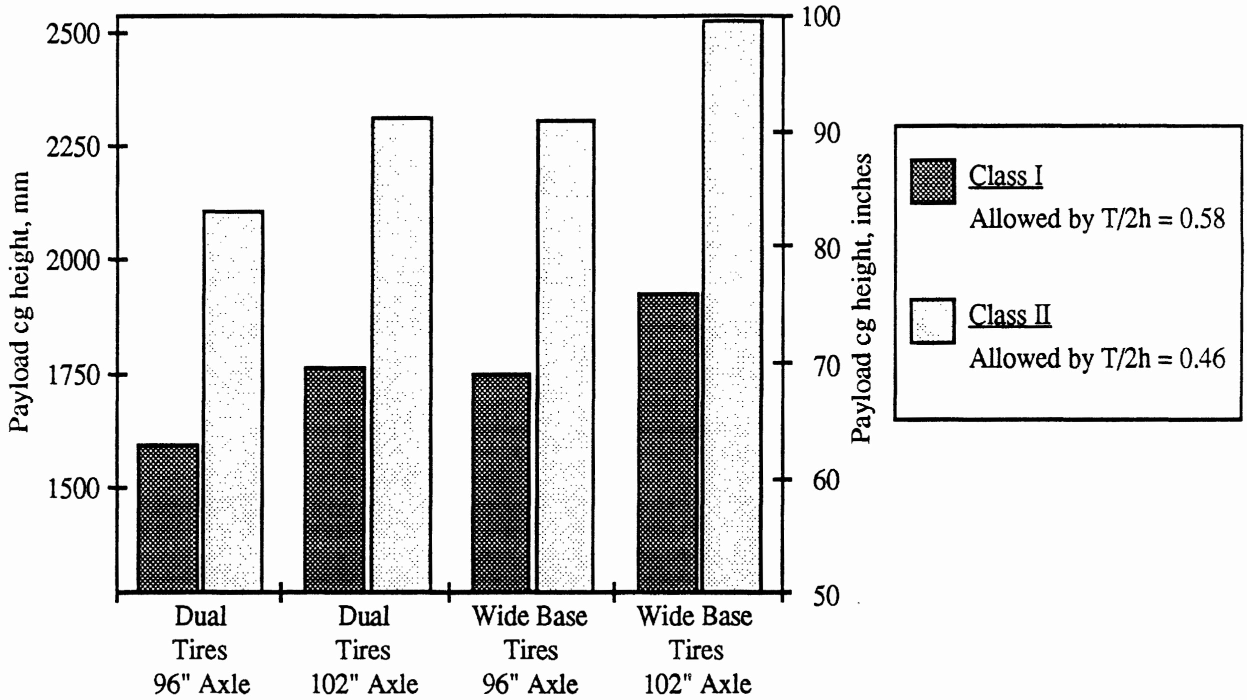

Figure 5. Typical payload center of gravity heights allowed by Class I and Class II requirements

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 lines, one each at T/2H values of 0.46 and 0.58, are shown, as is one horizontal reference line at the rollover

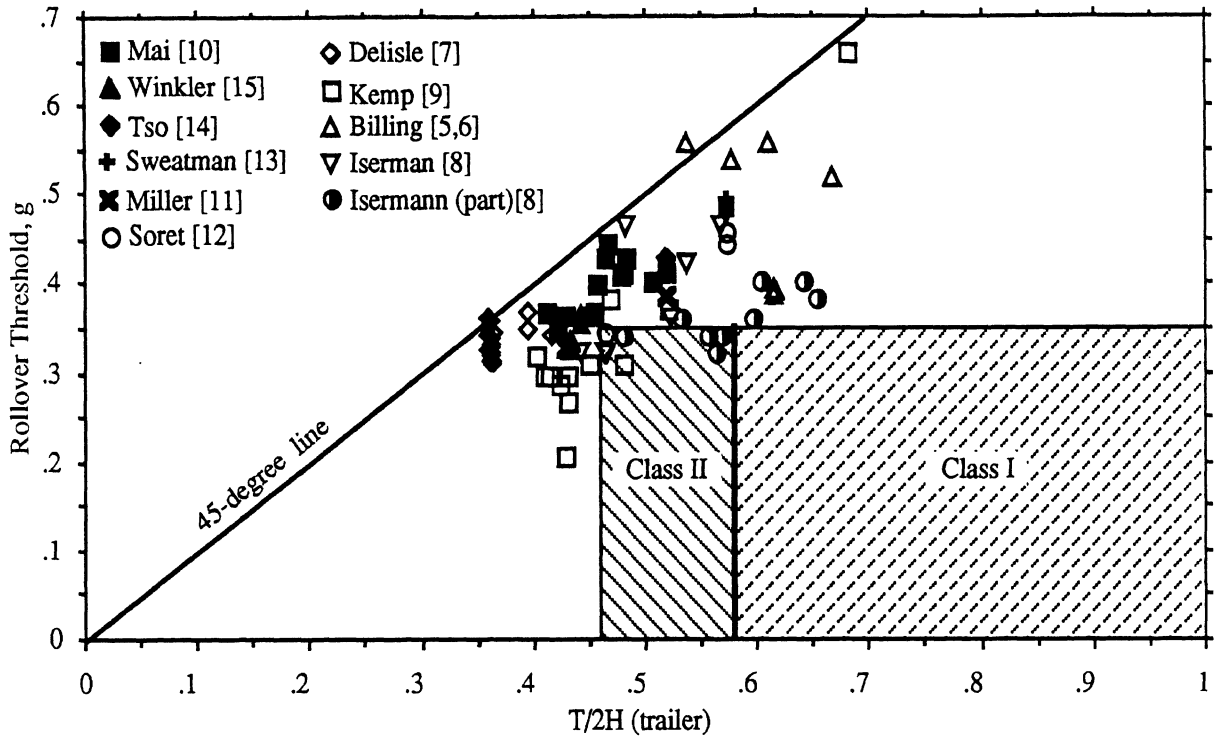

Figure 6. Measured rollover threshold as function of T/2H from the literature.

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.)

2.3.4 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 that require a mating support unit, the track of the support unit is included in the calculation, weighted by the fifth-wheel load rating entered in the qualifying permit (see figure 1). 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 value 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:

$$\mathbf{H} = \frac{\mathbf{H_E W_E + H_P W_P}}{\mathbf{W_E + W_P}} \tag{4}$$

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 depend 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 sitting 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 (see Appendix D), (ii) less-than-truck-load (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:

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

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.

2.3.5 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 its 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 that 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.

In the discussion which 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.

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 that 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 . (Strictly speaking, the full trailer is an independent roll unit if it uses an A-dolly, but not if it uses a double draw-bar C-dolly. However, this procedure assumes that no roll support is provided through the C-dolly tow bar, and, therefore, treats A-dollies and C-dollies similarly).

Any complete roll unit can be tested in a straightforward 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 degree tilt angle) 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." (Details of one design of a virtual tractor are presented in Appendix A.) 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 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.

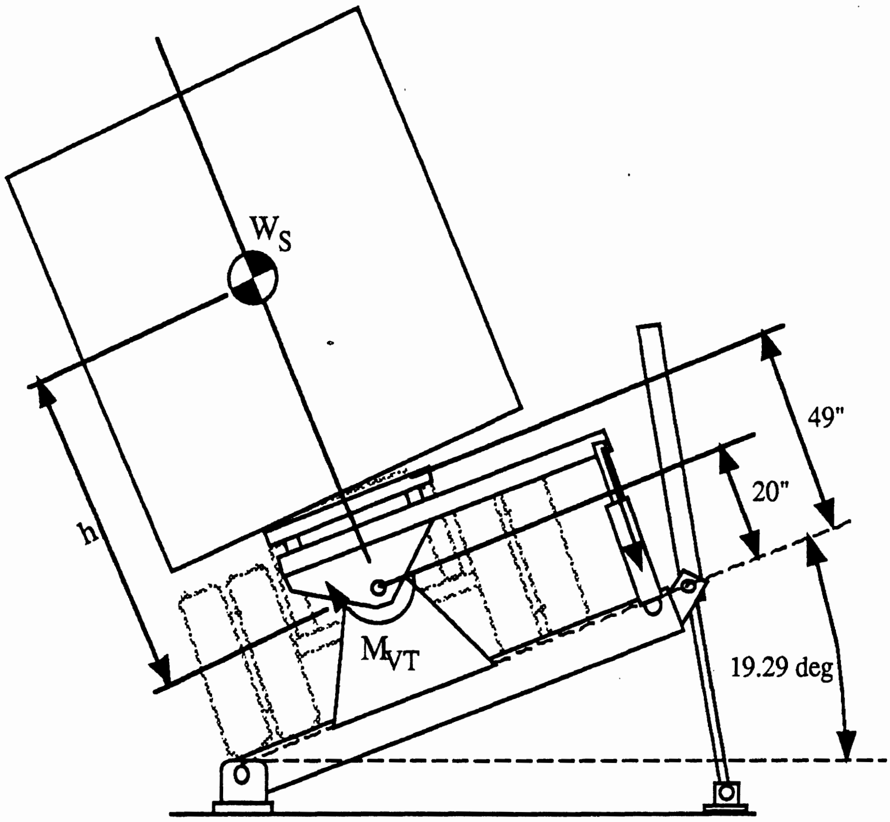

Figure 7. A payload unit tilt test using the virtual trailer

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 figure is a presentation of the roll behavior of the system of figure 7, with the simplifying assumptions that (a) the sprung mass of the test unit is rigid, (b) the roll angle of the virtual tractor and the sprung mass are equal (i.e., there is no fifth-wheel lash), (c) the suspension roll-center height is equal to the virtual-tractor roll-center height, and (d) the suspension roll stiffness is linear. The analysis also assumes small roll angles. (Later in the discussion, 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.
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.)

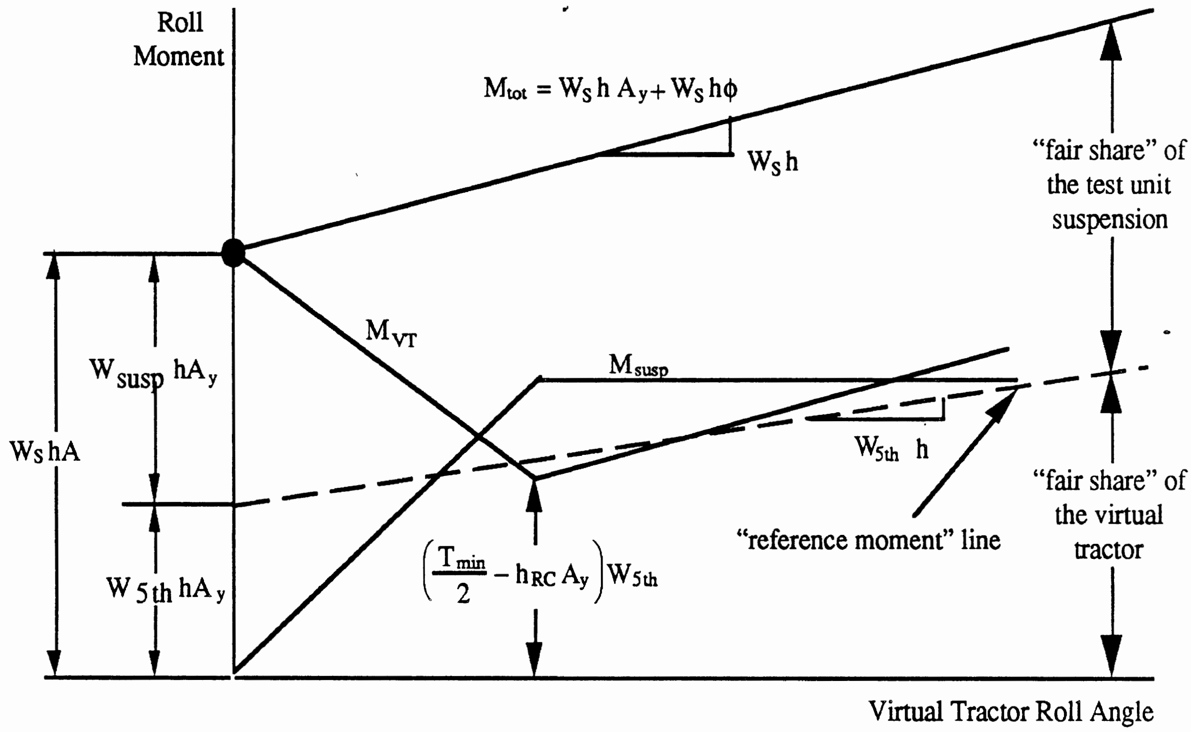

Figure 8. Mechanics of the payload unit tilt table test

Shown in figure 8 are 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, 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:

$$W_S A_y h = M_{susp} + M_{vt} - W_S h\phi \tag{5}$$

Equation (5) is very much analogous to equation (1), but with (a) an additional "fifth wheel moment," (b) the load transfer term represented more simply as the "suspension moment," and (c) the lateral motion of the cg expressed as a function of roll.

For this explanation, it is useful to rewrite (5) and define M_{tot} as:

$$\mathbf{M_{tot} \equiv M_{susp} + M_{vt} = W_S A_y h + W_S h\phi} \tag{6}$$

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.[6] 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 all of the high-side tires lift off the table surface, 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 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). As shown in the figure, the equation is:

---

6 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.

$$T_{min} = 2\left[\frac{M_{vt}}{W_{5th}} + h_{RC} A_y\right] \quad (7)$$

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 8 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 9 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 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 10, 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

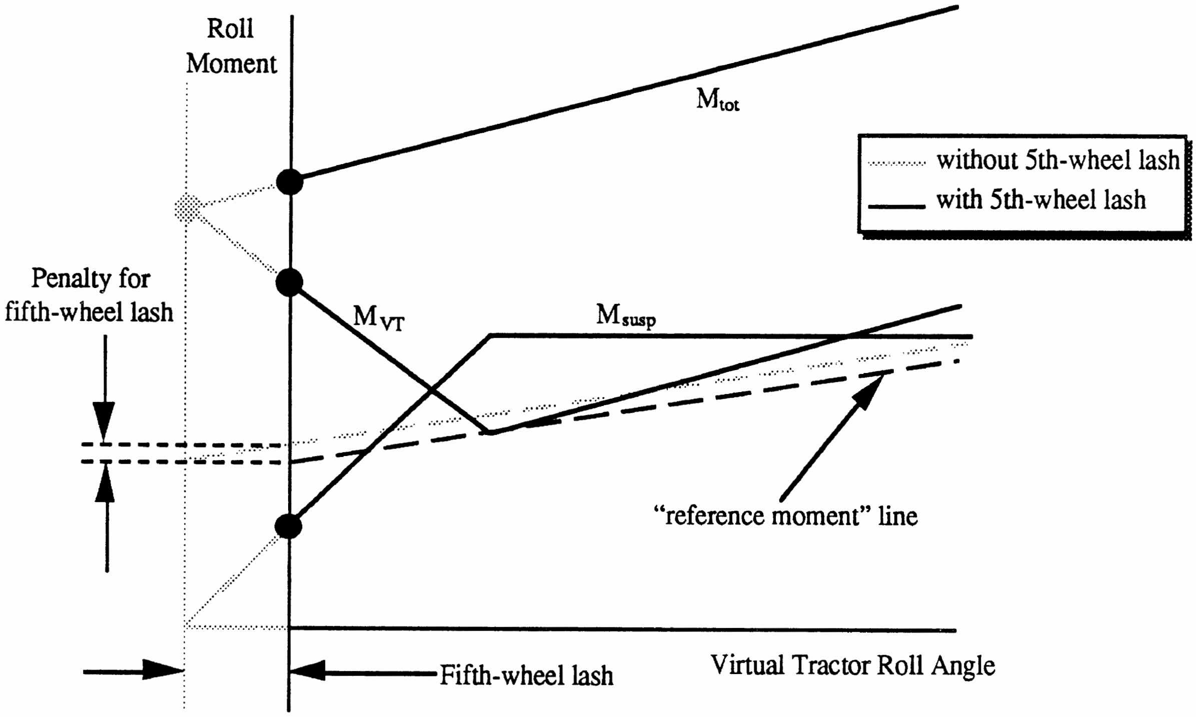

Figure 9. The influence of fifth-wheel lash

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.

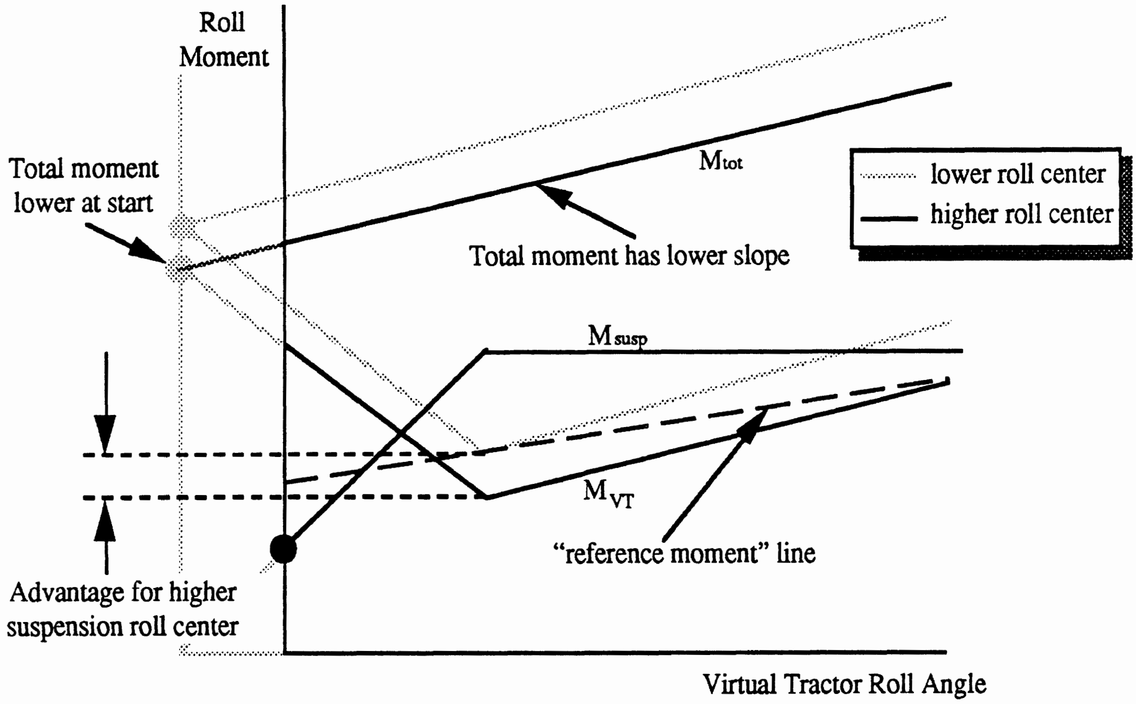

Figure 10. The influence of a higher test-unit roll center

Figure 11 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.

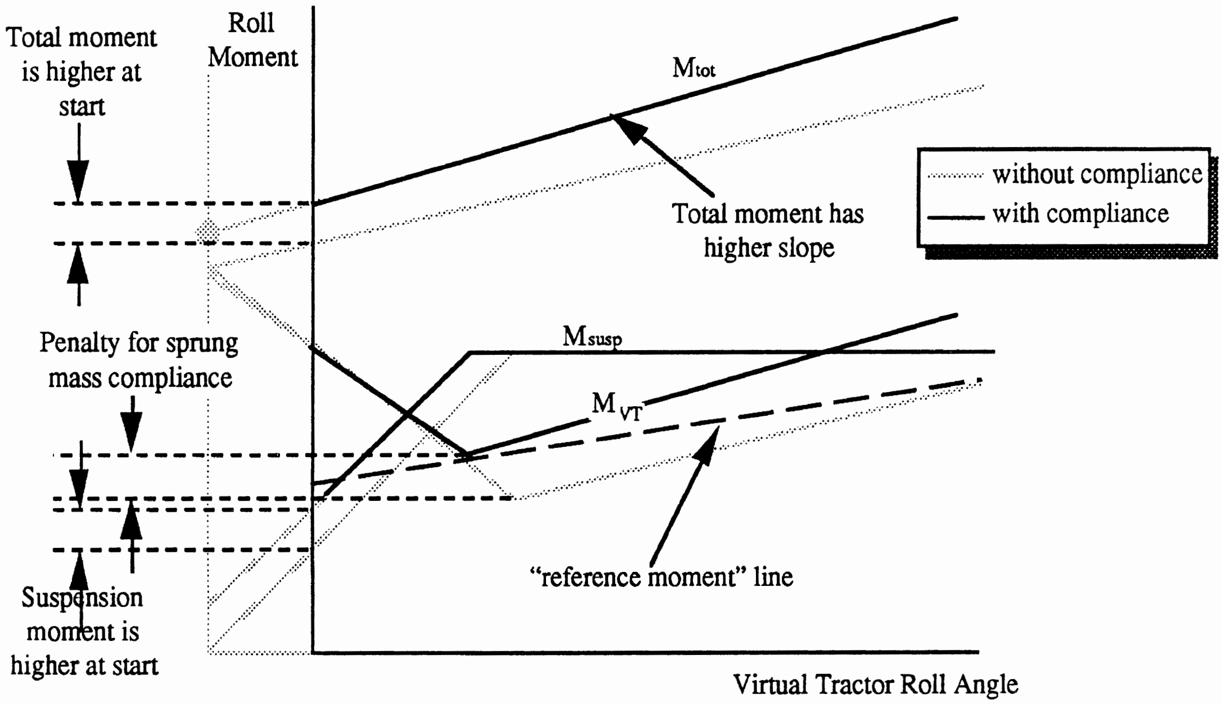

Figure 11. The influence of a sprung mass compliance

Finally, figure 12 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.

A sample of actual tilt-table data is presented in figure 13. These data were gathered in tests of the single-axle semitrailer shown on the tilt table with the virtual tractor in figure 14. The trailer was equipped with a leaf-spring suspension with a fair amount of spring lash. The plot clearly shows the form predicted by the previous discussion. As the virtual-tractor roll angle increases from zero degrees, the virtual-tractor roll moment decreases. This continues until the test unit suspension enters its lash. Then the moment demand on

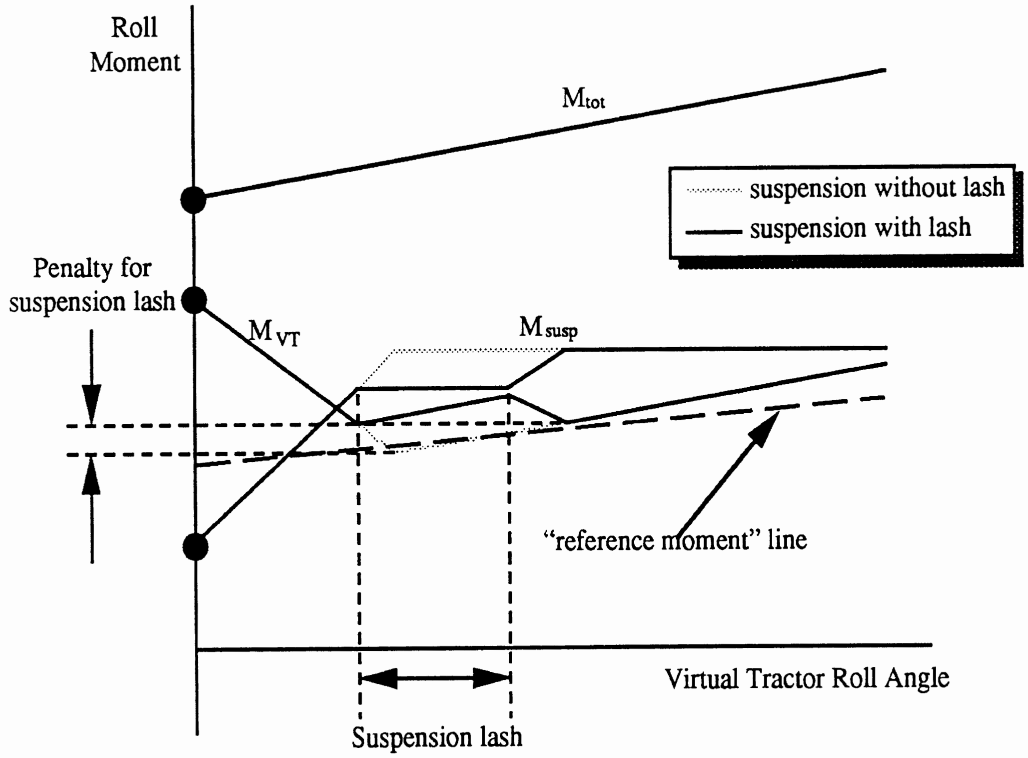

Figure 12. The influence of a suspension nonlinearities

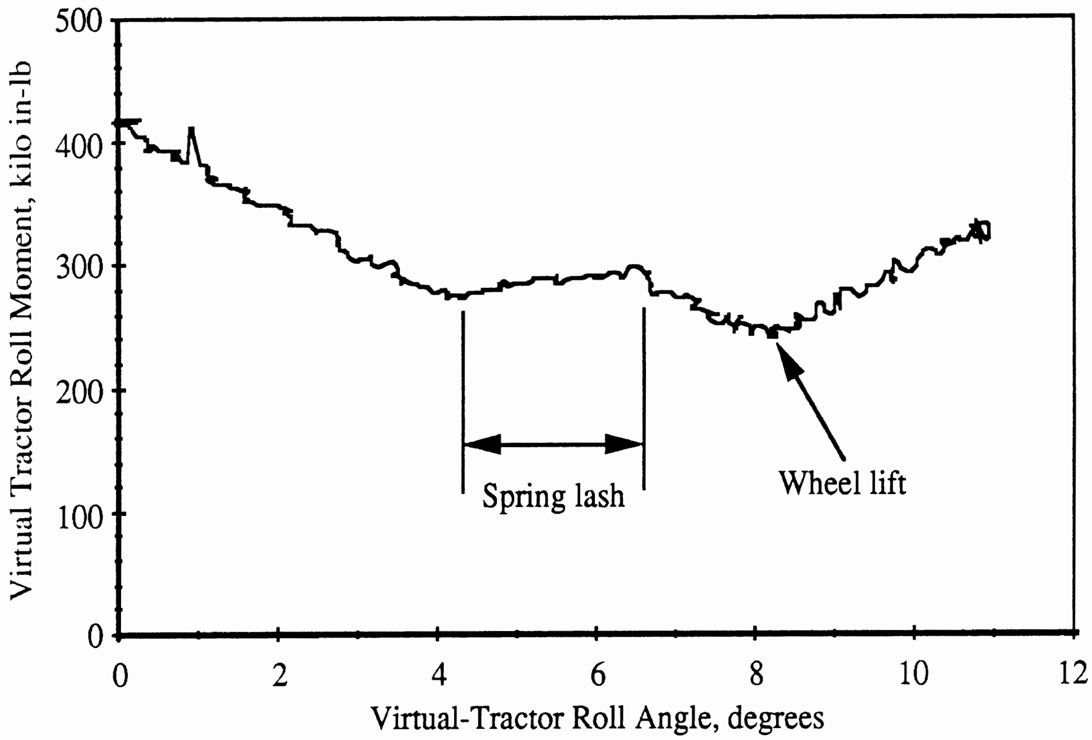

Figure 13. Example data from a tilt-table test of a semitrailer

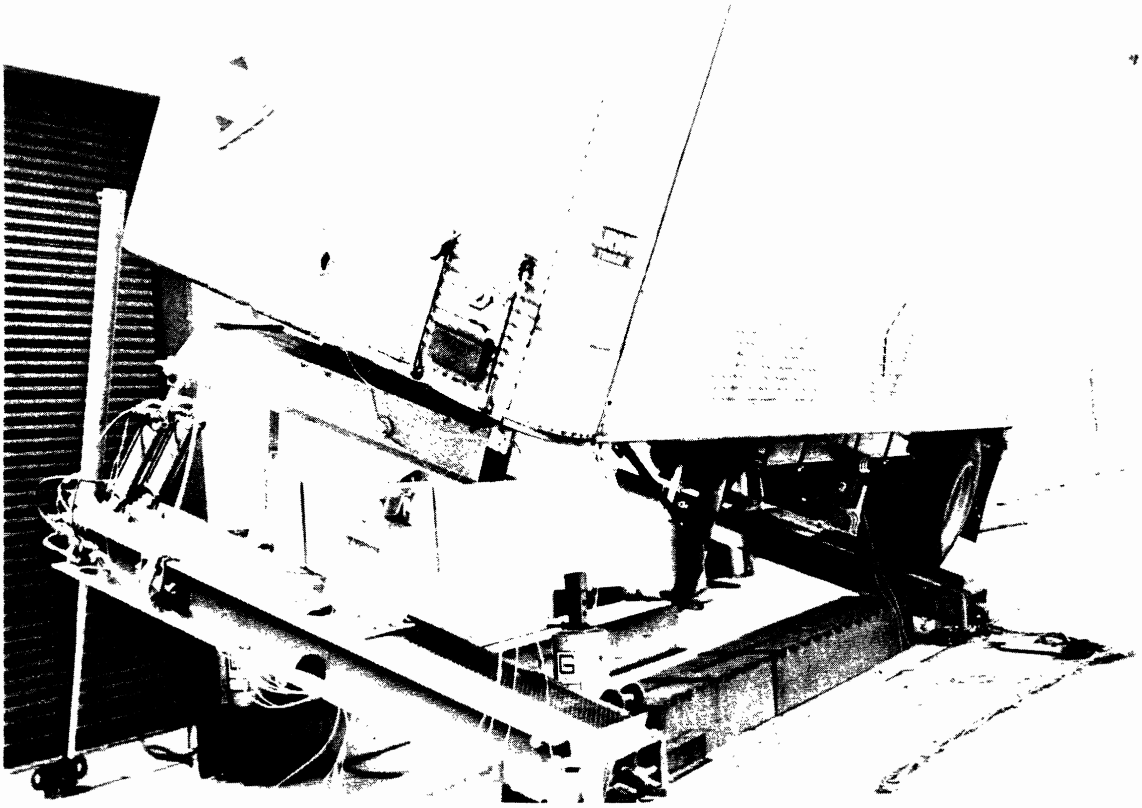

Figure 14. A single-axle semitrailer and the virtual tractor on the tilt table

the virtual tractor increases with roll angle until the suspension lash is passed. After the lash, tractor moment again declines until tire lift off occurs.

Figure 15 presents additional data gathered on this semitrailer. The trailer was loaded to a gross weight of 38,760 lb. The sprung mass weight was 37,005 lb and the fifth-wheel weight was 17,368 lb. The vertical position of the sprung mass cg could be altered easily using the adjustable height load rack, which can be seen in figure 16. Starting from the bottom of figure 15, the three data plots were gathered with the vehicle configured to have sprung mass cg heights of 75.2, 83.6, and 92.5 inches, respectively.

These plots also include the reference moment line. Where the preceding tutorial had assumed small angles for clarity, the reference moment lines in figure 15 are not based on that assumption. These lines are plotted according to the more accurate equation:

$$\mathbf{M_{ref} = W_s \; h \; tan(19.29 + \phi/57.3)} \tag{8}$$

where M_{ref} is the reference moment (in-lb).

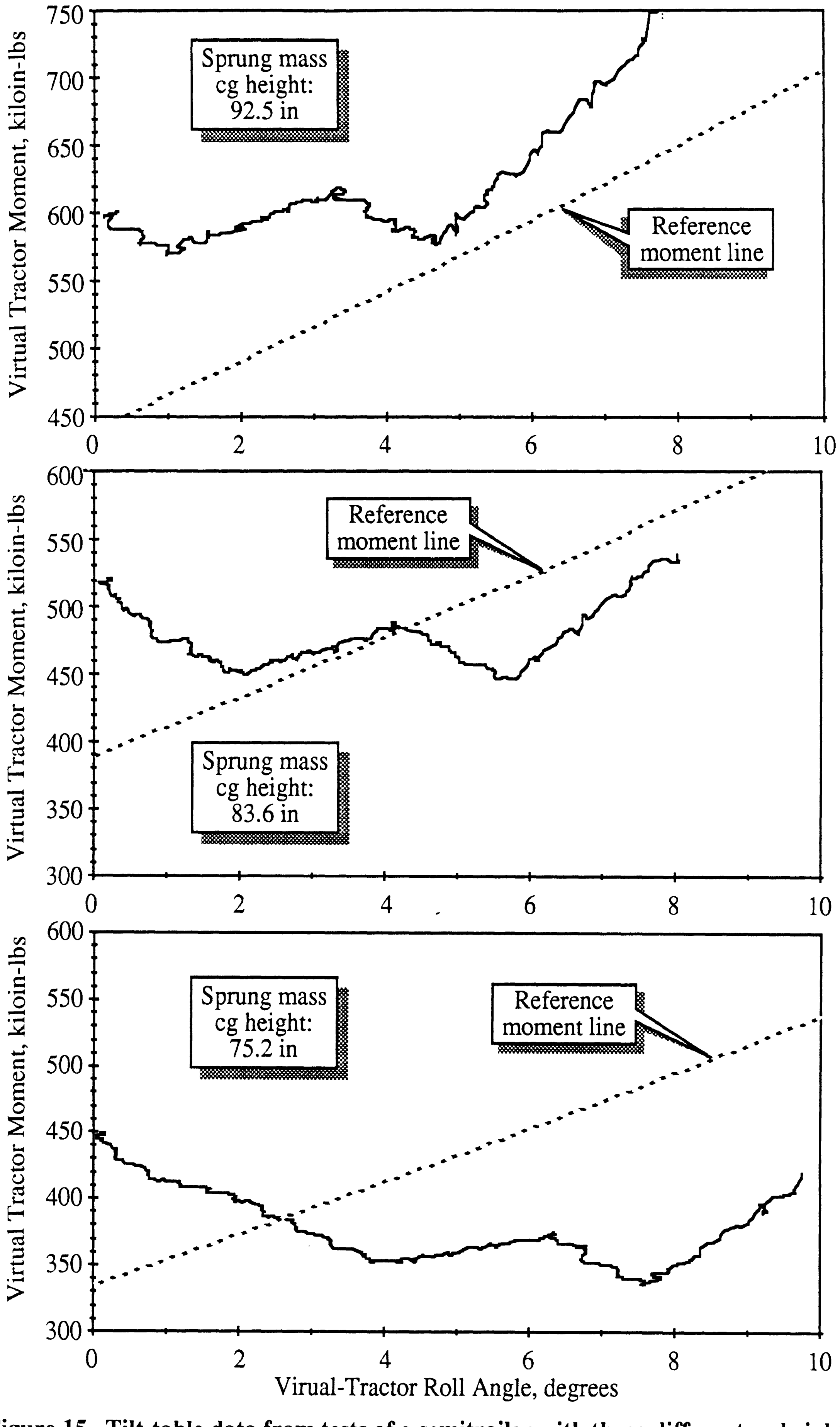

Figure 15. Tilt-table data from tests of a semitrailer with three different cg heights

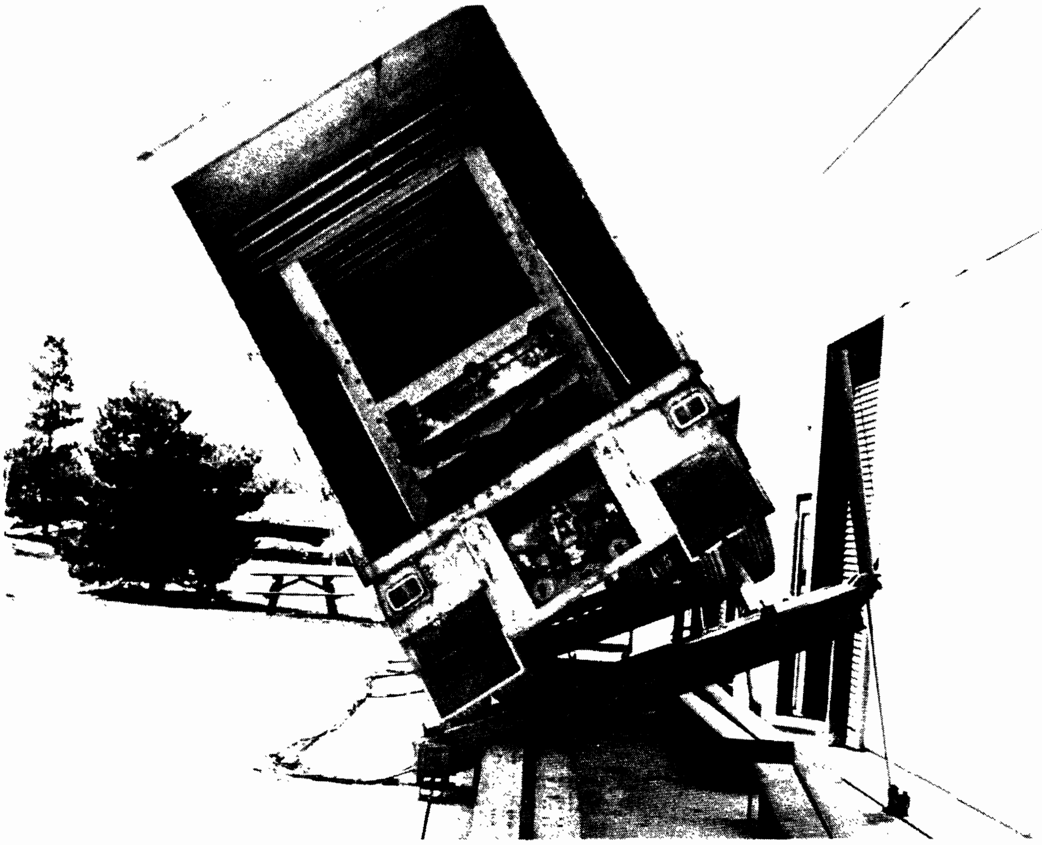

Figure 16. Adjustable height load rack

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

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. (See appendix B for details of an example.)

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 that exceeded either of these parameters would not be acceptable for use with this support unit.

3.0 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 solves many of the difficult problems associated with (a) deriving a representative measure of rearward amplification from test data that typically varies significantly from sinusoidal form, and (b) 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 that can serve as the screening mechanism have been developed for popular vehicle configurations. These tables can readily be expanded if desired.

3.1 The Concept of Rearward Amplification

Multitrailer 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 17 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 roll 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 RA [19, 20], although they are good in providing a qualitative understanding of the phenomenon, have proven to be inaccurate for vehicles

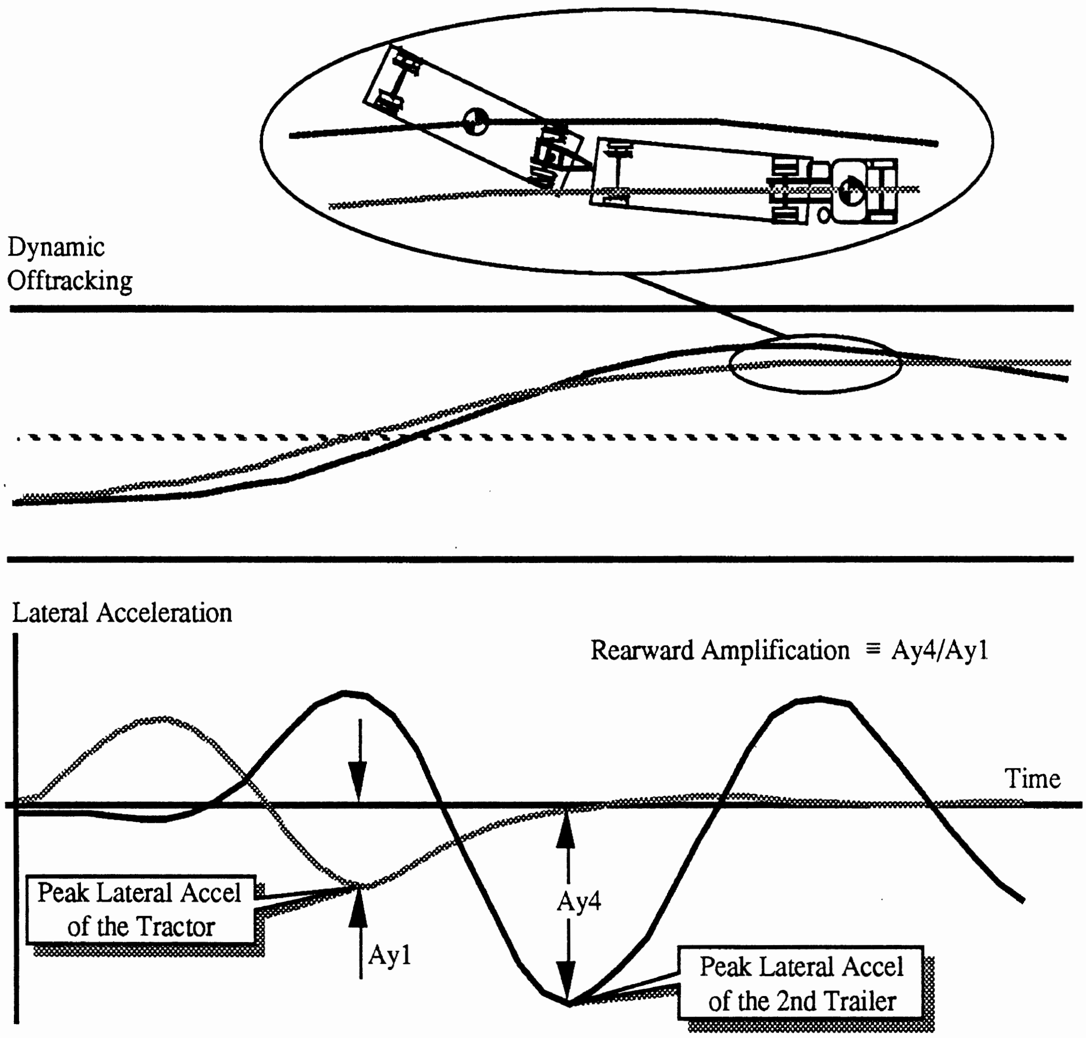

Figure 17. In a rapid obstacle avoidance maneuver, rearward amplification produces dramatic motion of the rear trailer, sometimes resulting in rollover.

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 RA 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.)

3.2 Choosing the Performance Requirements

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 meters (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 RA. The shorter vehicles have a predicted RA level of around 2.6. On the other hand, given that the Western double is currently legal nationwide, tests and analyses of this twin 8.5-meter (28-foot) double imply that this vehicle, (which is currently allowed on the entire Interstate highway system,) has an RA of approximately 2.0. This level of RA (i.e., RA = 2.0) has therefore been chosen as the performance target for use in judging the acceptability of LCVs in this study.

3.3 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 18.

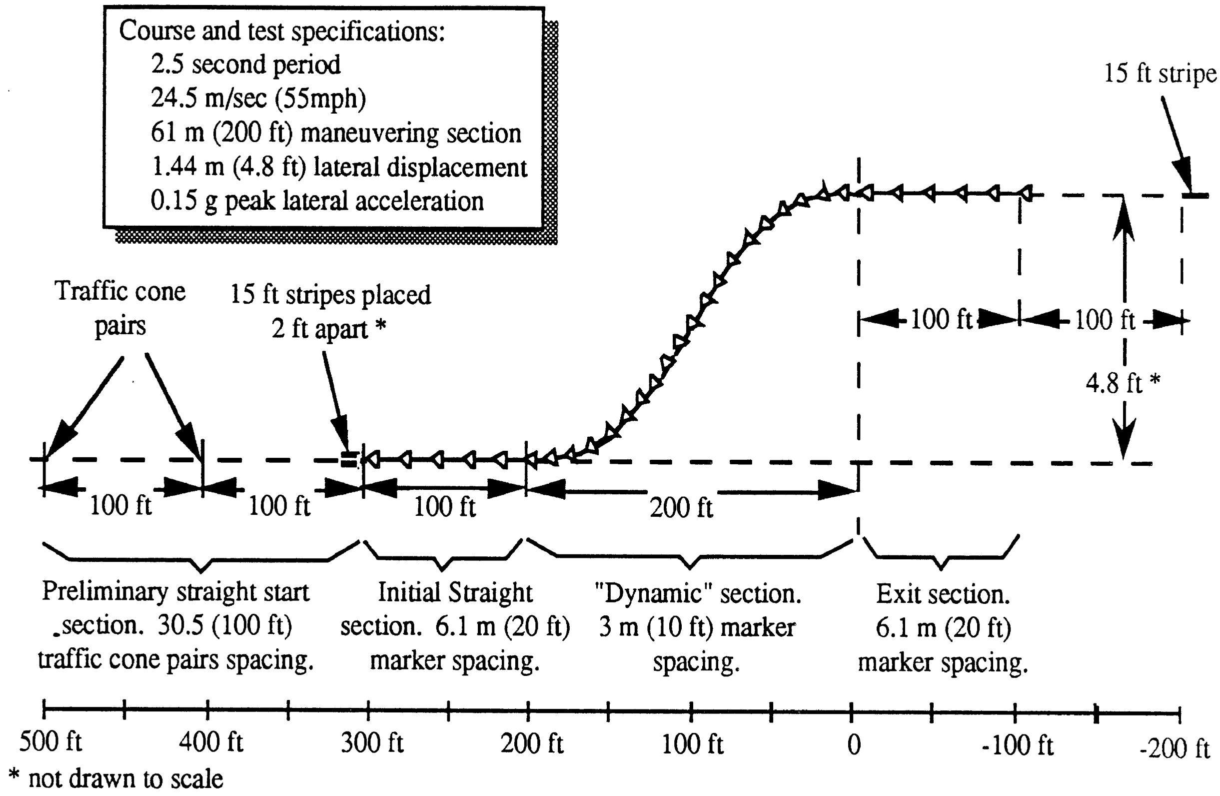

Figure 18. The test course for rearward amplification testing

$$A_y = A \sin(2\pi t/T) \tag{9}$$

$$V_y = [A/(2\pi/T)]\,[1 - \cos(2\pi t/T)] \tag{10}$$

$$y(t) = [A/(2\pi/T)]\,[t - (\sin(2\pi t/T)\,/\,(2\pi/T))] \tag{11}$$

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 9,10, and 11 pertain to a situation in which the longitudinal distance, x, is traversed at a constant forward velocity, V, such that:

$$x(t) = Vt \tag{12}$$

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:

$$y(X) = AT^2/2\pi$$

$$(\text{or } y(X) = AX^2/2\pi V^2) \tag{13}$$

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, then y(X) = 1.44 m (4.80 ft) (see fig. 18).

The simple relationships for the path (equations 9 to 13) 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.)

(A formal statement of the test procedure is given in Section 4. The following material provides discussion and a general description of the test procedure.)

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 18. 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 19). A key idea portrayed in table 1 and figure 19 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.

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 (see Appendix C) or water jets for measuring tractor and trailer paths
Data processing
• Minimum sampling rate 80 samples/second. • 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

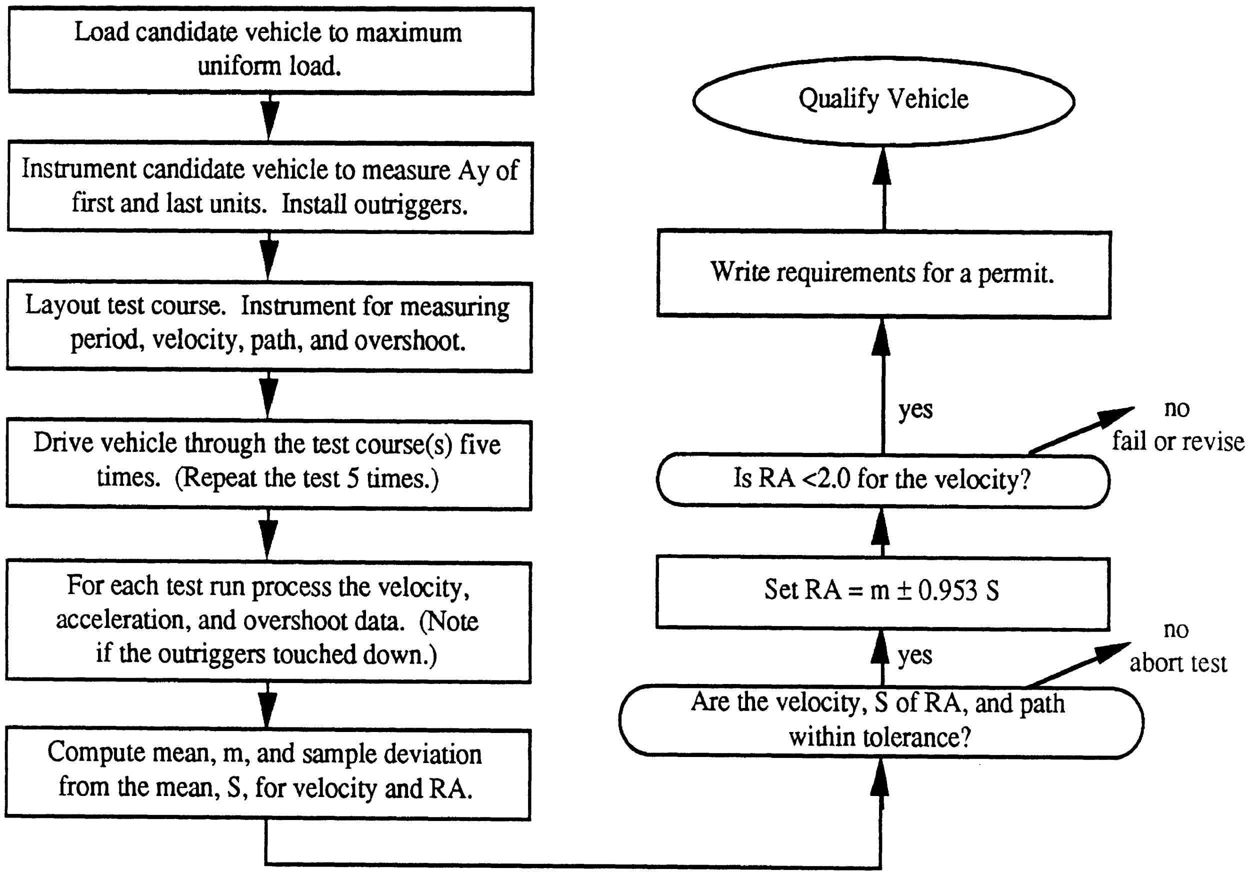

Figure 19. Block diagram of testing for obstacle avoidance capability

The results are to be presented as follows:

$$\mathbf{RA = m \pm 0.953\ S} \tag{14}$$

where:

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

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

(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:

$$\mathbf{m + 0.953\ S \leq\ 2.0} \tag{15}$$

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 15 implies a 95 percent confidence that the mean rearward amplification does not lie above 2.0.

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 20 illustrates the dollies used in the A-train and C-train configurations. The results of this initial test program (see figure 21) show that the

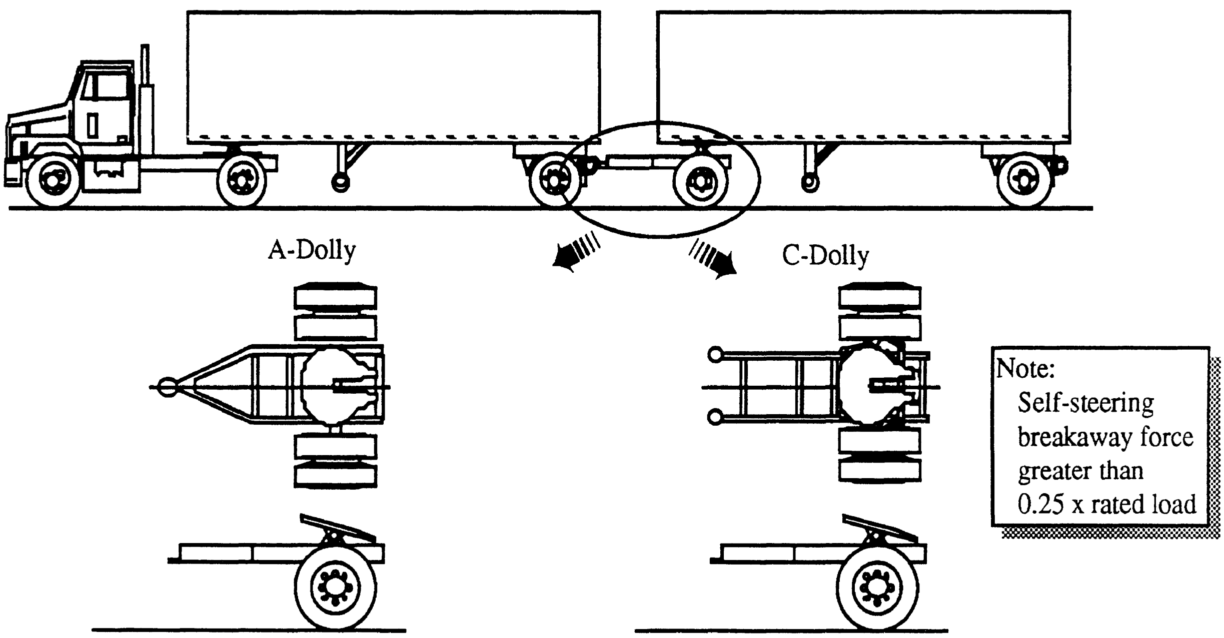

Figure 20. The single draw-bar A-dolly and the double draw-bar C-dolly

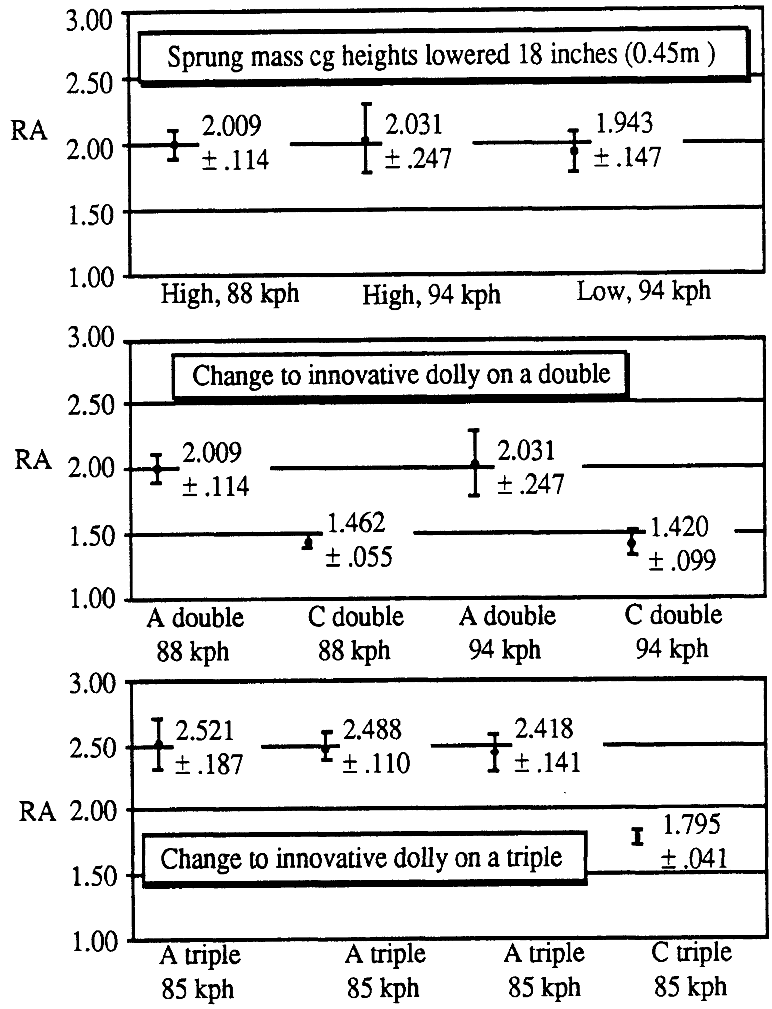

Figure 21. Test results indicating influences of changing sprung mass cg height and changing dolly types

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 [23], 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.

3.4 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 22).

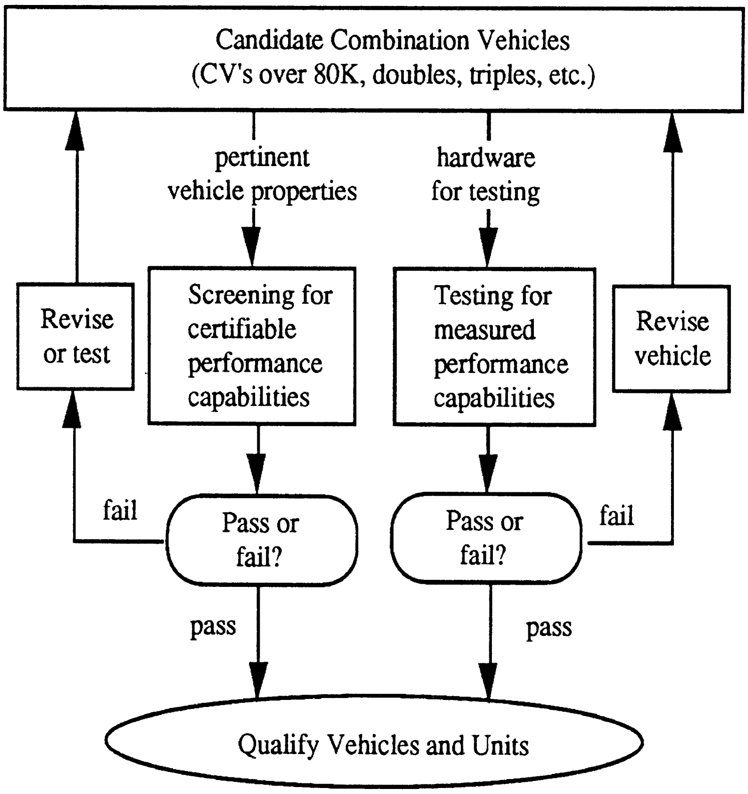

Figure 22. Overview of the certification process showing two paths (screening and testing) to certification

In the beginning it was hoped that a simplified model could be developed for screening. 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 23 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 complicated 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.

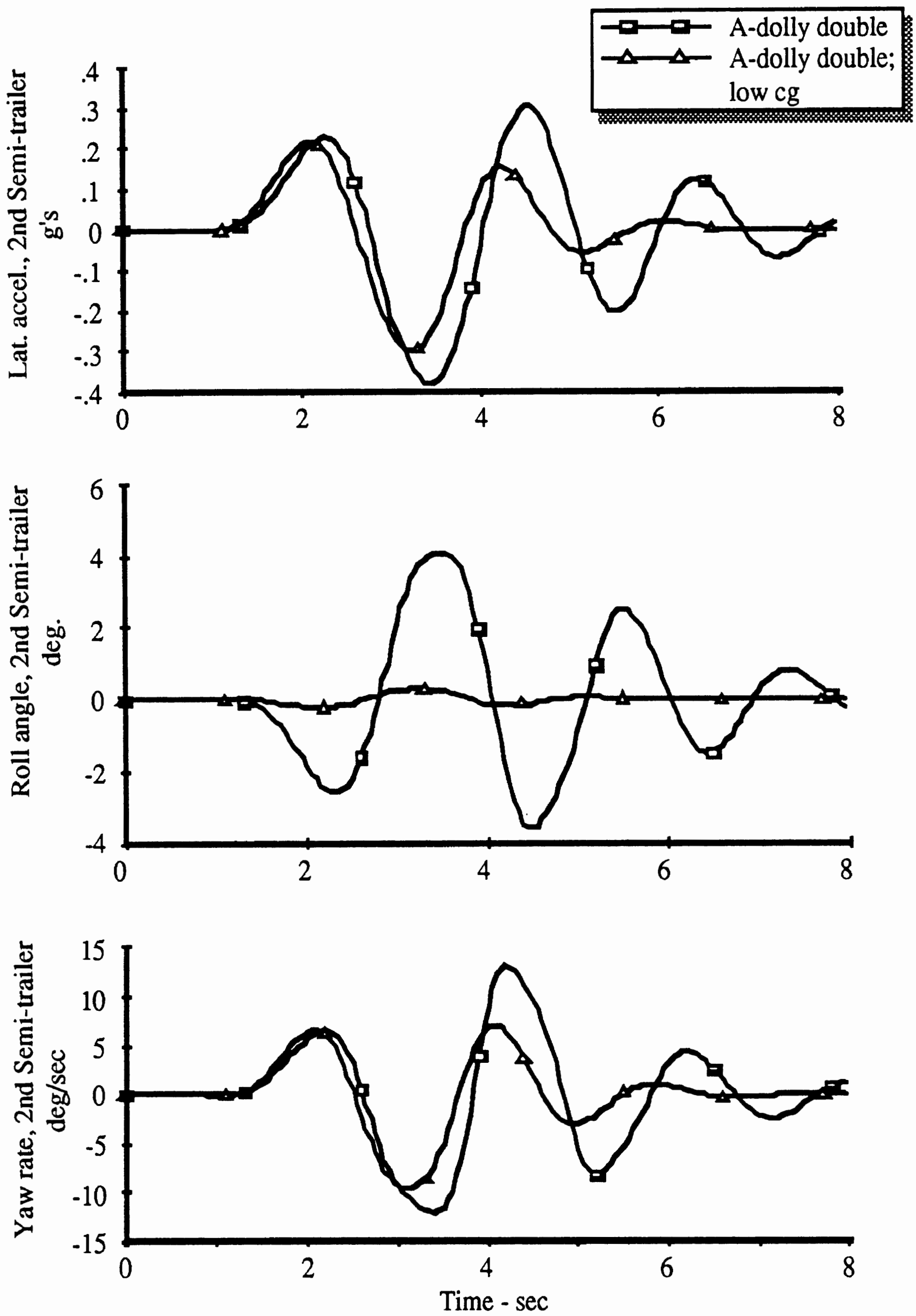

Figure 23. The influence of cg height on lateral and roll motions

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 a 7-axle triple. (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.)

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

Table 2. Screening for A-trains doubles

Screening Summary Table—Hitch Compensations — Based on C-Dolly or B-Train Configurations—

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
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)

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 an RA of 2.0.

4.0 TEST PROCEDURES

This section contains detailed statements describing the rollover and rearward amplification test procedures.

4.1 Statement of the Tilt Table Test Procedures

4.1.1 Introduction

The procedures presented herein are intended to provide an experimental means for determining whether or not the static roll stability of a vehicle test unit exceeds 0.35 g and therefore meets one requirement for an oversized vehicle operating permit.

The procedures can deal with either (1) complete roll units (straight trucks, tractor-semitrailer combinations, or full trailers), or with (2) payload units (vehicle units requiring fifth-wheel support), or (3) support units (vehicle units providing fifth-wheel support). In testing a complete unit, the procedures determine whether or not the vehicle stability threshold does or does not exceed 0.35 g. In testing support or payload units, the procedures address whether or not the unit's own suspensions can perform their fair share of the task of stabilizing the complete roll unit.

In all cases, permit application is for a specific range of loading conditions defined by maximum payload weight and maximum payload center-of-gravity height. Testing is conducted at a loading condition defined by these two properties and the permit would be for any loading condition not exceeding either of these maximums. For tank vehicles, test payload weight is specified by the permit applicant, and center-of-gravity height is determined by the geometry of the tank. For all other vehicles, test-payload weight and center-of-gravity height are to be specified by the permit applicant.

The procedures are based on the use of conventional commercial vehicle tilt tables plus two specialized pieces of equipment—a "virtual trailer" and a "virtual tractor."

The term "tilt table" refers to a device that rolls (rotates) the surface ("table") supporting a vehicle about a longitudinal axis. Such a device may be composed of one table that is longer than the vehicle's wheelbase [24] or a number of smaller tables, each large enough to support the wheels on an axle [15]. In the case of multiple tables, the pivot axes are aligned on a common line and the tilting action of the tables is coordinated. Required specifications of the tilt table will be given in the following sub section.

The virtual tractor is a specialized device, which provides fifth-wheel support to a payload unit under test. In addition to vertical support, the virtual tractor allows for roll motion and provides restraining roll moment at the fifth wheel. Details of the virtual tractor are provided in Appendix A.

The virtual trailer is a device intended to provide realistic fifth-wheel loads to a support vehicle under test. The virtual trailer is little more than an adjustable load rack intended to be mounted to a conventional fifth wheel and to provide representative loading to the fifth wheel. Details of the virtual trailer are provided in Appendix B.

4.1.2 General Tilt-Table Requirements

General specifications for a tilt table and its use as required for these procedures are given in table 4. These requirements are similar to those being considered for SAE

General Tilt Table Requirements	
Minimum tilt-angle range	0 to at least 19.3 degrees
Overall accuracy of tilt-angle measurement	±0.1 degrees
Pivot-axis alignment Overall: Multiple-axle tables:	 Horizontal ± 0.25 deg Co-linear ±2.5 mm
Tilt-angle alignment at each test vehicle axle and/or the virtual tractor*	±0.1 deg
Tilt rate	≤ 0.25 deg/sec above 15 degrees
Pretest suspension setting (hysteretic effects)	Nominally centered
Tire lateral restraint	Table surface-to-tire friction in excess of 0.35 with no other lateral restraint.
Vehicle-to-pivot-axis alignment	Centerline of each axle and of the virtual tractor within ±12 mm of a line parallel to the pivot axis.
Wind disturbance acceleration	≤ 0.003g influence (nominally ≤ 4.5 kph wind speed)

* Reflects on required table-surface planar quality, stiffness, and/or the alignment of individual axle tables.

Table 4. General tilt-table requirements

Recommended Practice J2180. Review of that Recommended Practice is advised.

These specifications are generally intended to establish a procedure whose overall accuracy is equivalent to approximately 0.01 g.

The purpose of these procedures is to determine whether or not the test vehicle static-roll stability does or does not exceed 0.35 g. Therefore, the maximum required tilt angle is only 19.3 degrees. For the same reason, table surface finish providing at least 0.35 effective tire-to-surface friction is adequate to restrain the vehicle. Medium grit 3M SafetyWalk applied to a clean hard surface should generally be more than adequate.

In addition to the specified properties of table 4, the tilt-table facility should provide safety items to restrain the vehicle in the event that its static roll stability or the surface friction limit is exceeded during testing. Straps, chains, or similar devices attached to the high-side wheels or chassis can be used to catch the vehicle once rollover has started (see figure 24). Restraints that can be adjusted under load are particularly desirable. The total weight of all restraints supported by the test vehicle should not exceed 0.1% of the

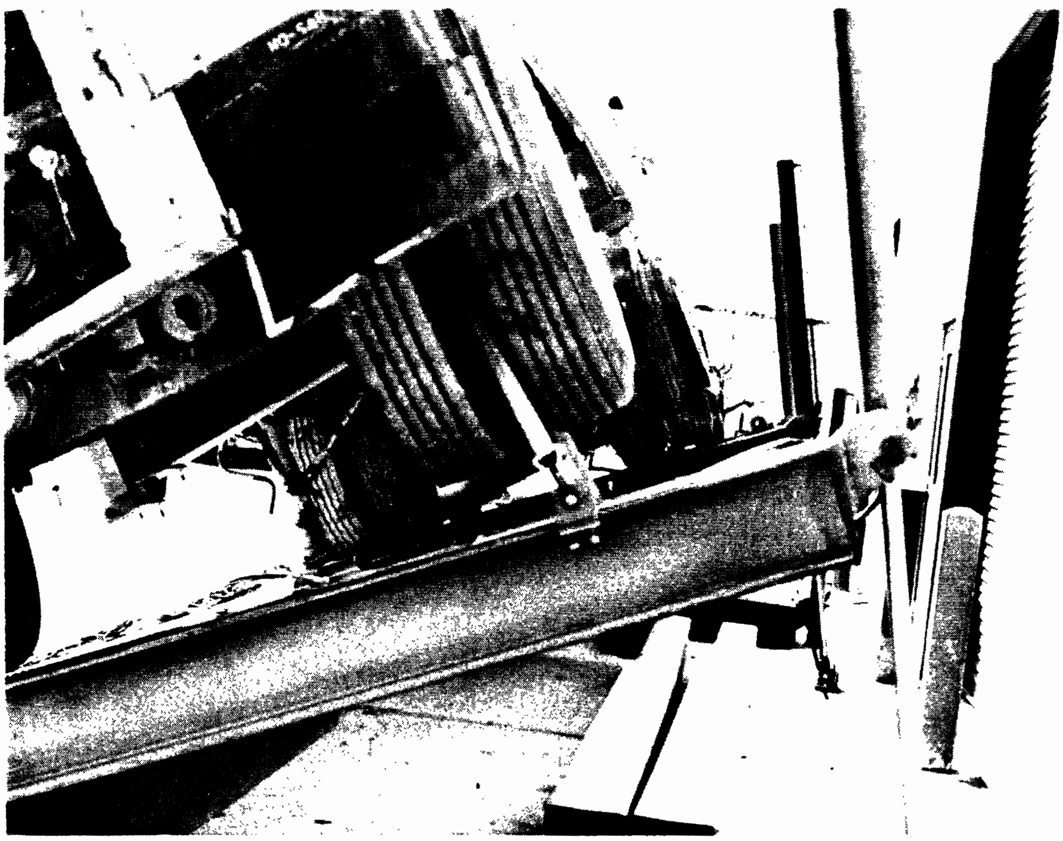

Figure 24. Anti-rollover restraining straps on the high-side wheels

weight of the test vehicle. Also, even though the tire should not contact a vertical surface during normal testing, it is good safety practice to have a restraining curb in place to hold the wheel in case it does slide sideways. An initial clearance of 75 to 100 mm (3 to 4 inches) between the side walls of the low-side tires and a restraining curb is generally adequate to prevent contact in the normal conduct of a test.

Although not strictly required by any of the procedures, a practice tilt for the purpose of adjusting the high-side restraints is most advisable. For many large vehicles, the high-side tires of different axles will lift off the table surface at different tilt angles. As the test proceeds, axles that lift early may clear the table surface by distances exceeding 0.3 meters prior to the vehicle becoming unstable. It is desirable for all constraints to come taut simultaneously, shortly after the occurrence of instability. However, the difference between axle heights at the point of instability is difficult to predict.

To establish proper adjustment of constraints, start the initial tilt with all constraints adjusted to allow only a few centimeters of wheel lift. As the tilt proceeds and individual constraints become taut, stop the table and adjust constraints to provide freedom to roll as required. Continue this procedure up 19.3 degrees or to the tilt angle at which the vehicle becomes unstable, whichever is less. In the case of individual payload units, continue through the tilt action of the virtual tractor. Adjust all restraints (1) to allow only the minimum unconstrained roll motion needed to clearly identify the occurrence of instability, or (2) to provide a small amount of slack in each restraint at the end of the procedure if the vehicle remains stable.

In conducting all tilt-table tests, it is important to recognize that many commercial vehicles will become unstable in roll with the tires of one or more axles remaining on the table surface. For example, for straight trucks and tractor semitrailers with up to five axles, the most typical situation is for the vehicle to become unstable when the high-side tires of all axles *other than the power unit steering axle* have lifted off. Tensile loads in the safety constraints are small when they come taut close to the instability point, but they grow rapidly if the vehicle is allowed to roll significantly past instability. In practice tests, care should be taken to carefully evaluate the stability or instability of the vehicle at each point of tire liftoff.

4.1.3 Test Vehicle Identification

The test vehicle is to be identified not only as a particular unit or units (i.e. VINs) but according to the condition of a number of vehicle factors that play an important role in determining static roll stability. These factors are:

1) Payload—weight and center of gravity location. (Details of loading procedures are given with individual test procedures.)

2) Tires—size, model, construction type, and pressure setting (nomenclature and DOT identification number). All tires should be new.

3) Suspensions—model, size, type, and characteristics such as air-spring height. Height regulation valves should be deactivated (held at static values) during the actual tilt to avoid inflation/deflation of the air bag during the tilt.

4.1.4 Test Procedure for Complete Roll Units

Purpose

The purpose of this procedure is to determine whether or not the static roll stability of a complete roll unit meets or exceeds the minimum stability level of 0.35 g under the test load conditions, as required for an oversize-vehicle operating permit. The maximum weight and center-of-gravity height of the test payload are to be declared by the applicant, and the resulting permit would be limited to use with payloads compatible with those limits.

Scope

The test procedure applies to all vehicles or combinations that are complete roll units. These include straight trucks, tractor semitrailer combinations, full trailers, and complete B-trains. Full trailers include converter dolly-semitrailer combinations. The procedure assumes that roll coupling provided by double draw-bar dollies is insignificant in typical *static-roll* scenarios. Therefore, full trailers using double draw-bar dollies are considered as complete roll units.

The test procedure is intended to determine only whether or not the static roll stability of the test unit is equal to or exceeds 0.35 g, not to determine the actual value of static roll stability of the test unit.

Vehicle Loading and Configuration

The permit applicant is to specify the test payload weight.

The test vehicle is to be loaded with payload equal to or exceeding the specified test payload weight. (Payload includes ballast weights and any framework or other support members added for ballast support, adjustment, or securing purposes.) In all cases, any payload and/or payload support frames should not add substantially to the structural rigidity of the test vehicle.

For testing tank vehicles, the test payload center of gravity is to be located at the volumetric centroid of the tank. (Tank vehicles may be loaded with a liquid, powder or granulated product that provides the required weight with no less than 5% tank outage.)

For all other vehicles, the test payload center-of-gravity height is to be specified by the permit applicant. The actual height of the center of gravity of the test load should equal or exceed the center-of-gravity height specified by the applicant. The longitudinal position of the payload center of gravity is to be as close to the position that would result from an even distribution of payload over the load-floor area of the vehicle as is compatible with the gross-axle-weight ratings of the vehicle, and/or other applicable axle-weight regulations. The lateral position of the payload center of gravity is to be the position that would result from an even distribution of payload over the load-floor area.

For tractors equipped with sliding fifth wheels, fifth-wheel position should be as far forward as is compatible with vehicle geometry, the gross-axle-weight ratings of the vehicle, and/or other applicable axle-weight regulations.

Test Procedure

With the tilt-table surface in the horizontal position, the loaded test unit should be mounted on the table such that its left side will be toward the lower side of the table when tilted.

The vehicle should be located on the tilt table such that the side-to-side centerline of each axle is within ±12 mm of a reference line on the table surface which is parallel to the pivot axis of the table. For testing full trailers, the dolly should be aligned such that the side-to-side centerline of the tow bar is also within ± 12 mm of the reference line.

The vehicle's suspensions should be nominally in the center of their hysteretic range (i.e., not severely tilted as can occur immediately after recovering from a tilt test). All air suspensions should be inflated normally as established by the standard control system, and then all inflation and exhaust functions should be disabled for the duration of the test. At the conclusion of the test, the condition of each air suspension should be checked to insure that no air was lost during testing.

When testing full trailers with draw bars articulated in pitch (typical of turntable dollies and some tandem axle dollies), the draw bar should be supported from the vehicle in a position parallel to the ground. When testing full trailers with draw bars not articulated in pitch (typical of single-axle converter dollies) the frame of the dolly should initially be parallel to the ground and trailer and dolly brakes set to maintain that condition. In cases where the longitudinal offset of kingpin and dolly suspension is unusually large, restraint chains or straps should be considered to prevent dolly yaw during testing.

Although not strictly required, a practice tilt for the purpose of adjusting the high-side restraints is most advisable. If a practice tilt is performed, the proper suspension conditions should be reestablished prior to conducting the actual test.

With all safety restraints installed and properly adjusted, the angle of the table should be gradually tilted up to a position with its surface 19.3 degrees or less from the horizontal. At angles above 15 degrees, tilt rate should not exceed 0.25 degrees per second. A fixed angle of 19.3 degrees should be held for at least 15 seconds. If the vehicle remains stable with all restraining straps slack, the vehicle passes. If the vehicle becomes unstable it fails. If the vehicle clearly becomes unstable at any tilt angle less than 19.3 degrees, the test should be stopped without proceeding to any higher tilt angle.

The entire test procedure should be repeated with the loaded test vehicle mounted on the table such that its right side is toward the lower side of the table when tilted.

4.1.5 Test Procedure for Individual Support Units

Purpose

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 roll unit, of which the support unit is a member, to meet or exceed the minimum roll-stability level of 0.35 g, under the test-load conditions, as required for an oversize-vehicle operating permit. The maximum fifth-wheel load and center-of-gravity height are to be declared by the applicant, and the resulting permit would be limited to use with payloads compatible with those limits.

Scope

The test procedure applies to units that provide fifth-wheel support to payload bearing units, that is, tractors and converter dollies. (Lead trailers of B-trains, which are payload-bearing units and also provide fifth-wheel support to another payload unit, are to be tested according to the *Test Procedure for Payload Units*, but with the additional virtual-trailer loading, described in this procedure, applied to their fifth wheels.) The procedure assumes that roll coupling provided by double draw-bar dollies is insignificant in typical *static-roll* scenarios. Therefore, double draw-bar dollies are treated in the same manner as single draw-bar dollies.

The test procedure is intended to determine only whether or not the unit provides adequate roll stabilization at 0.35 g. It is not meant to determine the maximum lateral acceleration at which the unit could stabilize its fair share of matching payload unit.

Vehicle Loading and Configuration

The permit applicant is to specify the fifth-wheel loading for testing. Fifth-wheel loading is to be specified in terms of fifth-wheel weight and payload center-of-gravity height.

A virtual trailer (see Appendix B) should be installed on the test-unit fifth wheel. The virtual trailer should be ballasted and adjusted such that its total weight matches or exceeds the specified payload weight and so its center-of-gravity height matches or exceeds the specified payload center-of-gravity height. The fore/aft position of the virtual trailer center of gravity should be within ± 12 mm of directly above the fifth-wheel pitch pivot. The side-to-side position of the center of gravity should be within ± 12 mm of directly above the longitudinal centerline of the fifth wheel.

For tractors equipped with sliding fifth wheels, fifth-wheel position should be as far forward as is compatible with vehicle geometry, the gross-axle-weight ratings of the vehicle, and/or other applicable axle-weight regulations.

Test Procedure

With the tilt-table surface in the horizontal position, the loaded test unit should be mounted on the table such that its left side will be toward the lower side of the table when tilted.

The unit should be located on the tilt table such that the side-to-side centerline of each axle is within ±12 mm of a reference line on the table surface which is parallel to the pivot axis of the table.

The vehicle's suspensions should be nominally in the center of their hysteretic range (i.e., not severely tilted as can occur immediately after recovering from a tilt test). All air suspensions should be inflated normally as established by the standard control system, and then all inflation and exhaust functions should be disabled for the duration of the test. At the conclusion of the test, the condition of each air suspension should be checked to insure that no air was lost during testing.

Although not strictly required, a practice tilt for the purpose of adjusting the high-side restraints is most advisable. If a practice tilt is performed, the proper suspension conditions should be reestablished prior to conducting the actual test.

With all safety restraints installed and properly adjusted, the angle of the table should be gradually tilted up to a position with its surface 19.3 degrees or less from the horizontal. At angles above 15 degrees, tilt rate should not exceed 0.25 degrees per second. A fixed angle of 19.3 degrees should be held for at least 15 seconds. If the test unit remains stable with all restraining straps slack, the unit passes. If the test unit becomes unstable it fails.

If the unit clearly becomes unstable at any tilt angle less than 19.3 degrees, the test should be stopped without proceeding to any higher tilt angle.

The entire test procedure should be repeated with the loaded test unit mounted on the table such that its right side is toward the lower side of the table when tilted.

4.1.6 Test Procedure for Individual Payload Units

Purpose

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 roll unit, of which the payload unit is a member, to meet or exceed the minimum roll-stability level of 0.35 g, under the test load conditions, as required for an oversize-vehicle operating permit. The maximum weight and center of gravity height of the test payload is to be declared by the applicant, and the resulting permit would be limited to use with payloads compatible with those limits.

In the case of a payload unit that also serves simultaneously as a support unit, the purpose is expanded to also determine whether or not the unit is simultaneously capable of providing its fair share of roll stabilization as needed for a complete roll unit, of which the payload unit is a member, to meet or exceed the minimum roll-stability level of 0.35 g, under the test load conditions, as required for an oversize vehicle operating permit. The maximum fifth-wheel load and center-of-gravity height are to be declared by the applicant, and the resulting permit would be limited to use with payloads compatible with those limits.

Scope

This test procedure applies to all units intended to bare payload but requiring fifth-wheel support from other units (e.g., conventional semitrailers). It also applies to payload units which simultaneously serve as support units (e.g., lead B-train semitrailers).

The test procedure is intended to determine only whether or not the unit provides adequate roll stabilization at 0.35 g. It is not meant to determine the maximum lateral acceleration at which the unit could stabilize its fair share of its own load and, when appropriate, the load of a mating payload unit.

Vehicle Loading and Configuration

The permit applicant is to specify the test payload weight for the payload unit.

The tests unit is to be loaded with payload equal to or exceeding the specified test payload weight. (Payload includes ballast weights and any framework or other support members added for ballast support, adjustment, or securing purposes.) In all cases, any payload and/or payload-support frames should not add substantially to the structural rigidity of the test vehicle.

For testing tank units, the test payload center of gravity is to be located at the volumetric centroid of the tank. (Tank vehicles may be loaded with liquid, powers or granulated products that provide the required weight with no less than 5% tank outage.)

For all other types of payload units, the test payload center-of-gravity height is to be specified by the permit applicant. The actual height of the center of gravity of the test load should equal or exceed the center-of-gravity height specified by the applicant. The longitudinal position of the payload center of gravity is to be as close to the position that would result from an even distribution of payload over the load-floor area of the unit as is compatible with the gross-axle-weight ratings of the unit, and/or other applicable axle-weight regulations. The lateral position of the payload center of gravity is to be the position that would result from an even distribution of payload over the load-floor area.

When the payload unit is the type of unit that also serves simultaneously as a support unit, the permit applicant is to also specify the rear[7] fifth-wheel loading for testing. Rear fifth-wheel loading is to be specified in terms of fifth-wheel weight and payload center-of-gravity height.

To apply rear fifth-wheel loads, a virtual trailer (see Appendix B) should be installed on the test-unit rear fifth wheel. The virtual trailer should be ballasted and adjusted such that its total weight matches or exceeds the specified payload weight and so its center of gravity height matches or exceeds the specified payload center of gravity height. The fore/aft position of the virtual trailer center of gravity should be within ± 12 mm of directly above the fifth-wheel pitch pivot. The side-to-side position of the center of gravity should be within ± 12 mm of directly above the longitudinal centerline of the fifth wheel.

For units equipped with sliding rear fifth wheels, rear-fifth wheel position should be as nearly centered in the adjustment range as is compatible with vehicle geometry, the gross-axle-weight ratings of the vehicle, and/or other applicable axle-weight regulations.

When the payload unit is installed on the tilt table, it should be coupled to a virtual tractor, which supplies vertical support at (the forward) fifth-wheel coupling as well as the means to apply stabilizing roll moment to this coupling. The virtual tractor includes the ability to measure this moment and to measure the roll angle of the virtual tractor. (See Appendix A.)

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7 Most typically, such units support another payload unit at a rear-mounted fifth-wheel coupling while they are, themselves, supported at a front-mounted fifth-wheel coupling. The two couplings are distinguished herein by the words "rear" and "forward."

Test Procedure

With the test vehicle loaded, the vertical load on the (forward) fifth wheel should be measured and recorded for use during data reduction. The measurement should be taken with the (forward) fifth wheel at an equivalent height to its height when coupled to the virtual tractor.

With the tilt-table surface in the horizontal position, the loaded test unit should be mounted on the table such that its left side will be toward the lower side of the table when tilted. The (forward) fifth wheel of the payload unit should be coupled to the fifth wheel of the virtual tractor which is also to be mounted on the tilt table.

The unit should be located on the tilt table such that the side-to-side centerline of each axle and the side-to-side centerline of the fifth wheel connection with the virtual tractor are all within ±12 mm of a reference line on the table surface, which is parallel to the pivot axis of the table.

The vehicle's suspensions should be nominally in the center of their hysteretic range (i.e., not severely tilted as can occur immediately after recovering from a tilt test). All air suspensions should be inflated normally as established by the standard control system, and then all inflation and exhaust functions should be disabled for the duration of the test. At the conclusion of the test, the condition of each air suspension should be check to insure that no air was lost during testing.

Although not strictly required, a practice tilt for the purpose of adjusting the high-side restraints is most advisable. If a practice tilt is performed, the proper suspension conditions should be reestablished prior to conducting the actual test.

With all safety restraints installed and properly adjusted, the roll angle of the virtual tractor should be forcibly restrained to zero degrees, and the table should be tilted to a position with its surface 19.3 degrees from the horizontal. With the tilt table held at a fixed angle of 19.3 degrees, the roll angle of the virtual tractor should be allowed to increase (in the same direction as tilt angle of the table) at a rate not to exceed 0.25 deg/sec. While rolling, the roll angle and roll moment about the roll center of the virtual tractor should be measured and recorded continuously. Roll motion of the virtual tractor should proceed until all high-side tires of the unit have lifted off the ground. Alternatively, if the instrumentation system allows for on-line observation, roll motion of the virtual trailer can be halted when (a) measured data clearly indicates the payload unit passes the test, or (b) measured data clearly indicates a minimum roll moment has been achieved. (The latter is more likely to occur with some high-side tires still on the ground if the unit has a large number of axles.)

The entire test procedure should be repeated with the loaded test unit mounted on the table such that its right side is toward the lower side of the table when tilted.

Data Analysis

The recorded data should be plotted in the form of an x-y graph with virtual-trailer roll angle as the abscissa and virtual-trailer roll moment as the ordinate. A reference moment line, described by the following formula, should be plotted on the same axes.

$$\mathbf{M_{ref} = W_{5th}\ h\ tan(19.3 + \phi)} \qquad (16)$$

where:

- h is the height of the sprung mass cg (exclusive of the virtual trailer mass if present) above the roll center, in inches.
- M_{ref} is the reference moment, in in-lb.
- W_{5th} is the measured load supported by the fifth wheel of the virtual tractor, in pounds.
- ϕ is the roll angle of the virtual tractor (relative to the surface of the tilt table), in degrees.

An example of the data analysis graph is shown in figure 25. If the test data plot penetrates below the reference moment line at any point (exclusive of the influence of measurement "noise"), the test unit qualifies for an oversized operating permit. For example, the data and reference line of figure 25 indicate a successful test.

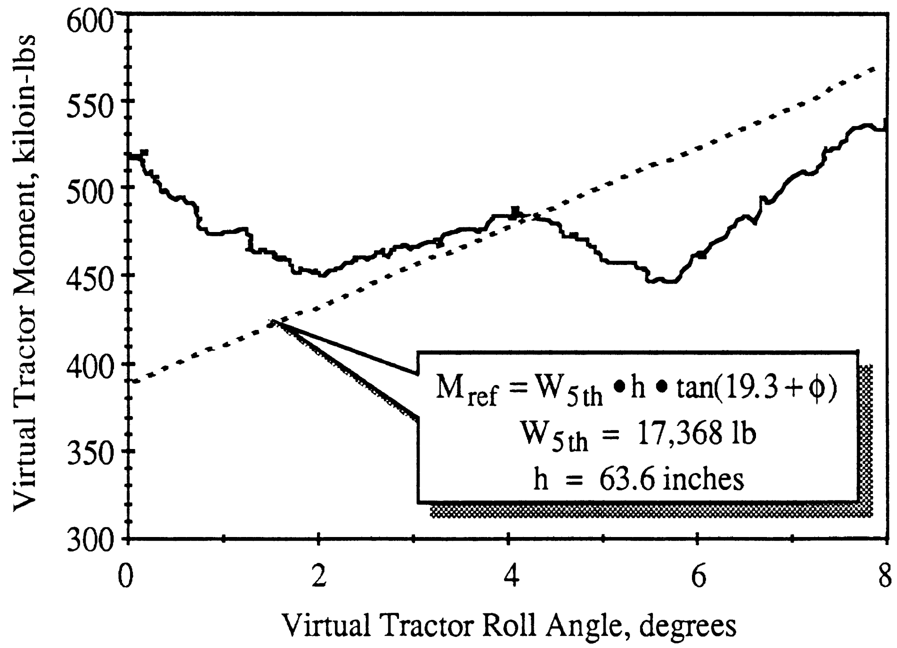

Figure 25. An example data plot from a successful test of a payload unit.

4.2 Statement of the Test Procedure for Quantifying Vehicle Performance in an Obstacle Avoidance Maneuver

Procedures very similar to this are being considered as SAE recommended practice J2179. Nevertheless, the following procedure was developed as the basis for regulations. The procedure is given in a form that allows it to be lifted directly from this document.

4.2.1 Introduction

This procedure involves a test course especially laid out to excite the rearward amplification tendencies of multiarticulated heavy trucks. The form of the course is illustrated in figure 26. The test driver follows this course in performing the test.

The vehicle is instrumented to measure lateral accelerations at the tractor's front axle and at the center of gravity of the sprung mass of the last trailer. The lateral acceleration of the tractor is the input that excites the vehicle motion. This input is quantified by computing its root-mean-square (rms) value over the lateral maneuvering section of the test course.[8] The value of the input is obtained by multiplying the rms value of the input by the square root of 2 to provide an estimate of the amplitude of an equivalent sinusoid of lateral acceleration. The output is quantified by measuring the maximum absolute value of the lateral acceleration of the last trailer. The rearward amplification is the ratio of (a) the value of the output divided by (b) the value of the input.

Studies of various methods of processing the data have led to a technique that can be used to measure rearward amplification to within approximately 10 percent of the average value with a confidence of 90 percent that the true value lies within this band. This level of confidence can be obtained using the results from five repeats of the test. The following statement of this test procedure for evaluating obstacle evasion capability contains sections entitled:

(1) Purpose.

(2) Scope.

(3) Test Course.

(4) Vehicle Condition and Preparations.

(5) Instrumentation Requirements.

(6) Needed Data Gathering and Processing Capabilities.

---

8 After investigating several possibilities for quantifying the input motion (including peak measured values of lateral acceleration, for example), it was found that the rms value of the lateral acceleration of the front axle of the tractor was a good indicator of the magnitude of the input, and when this rms value is used, the variability of the test results is less than that obtained using other possibilities.

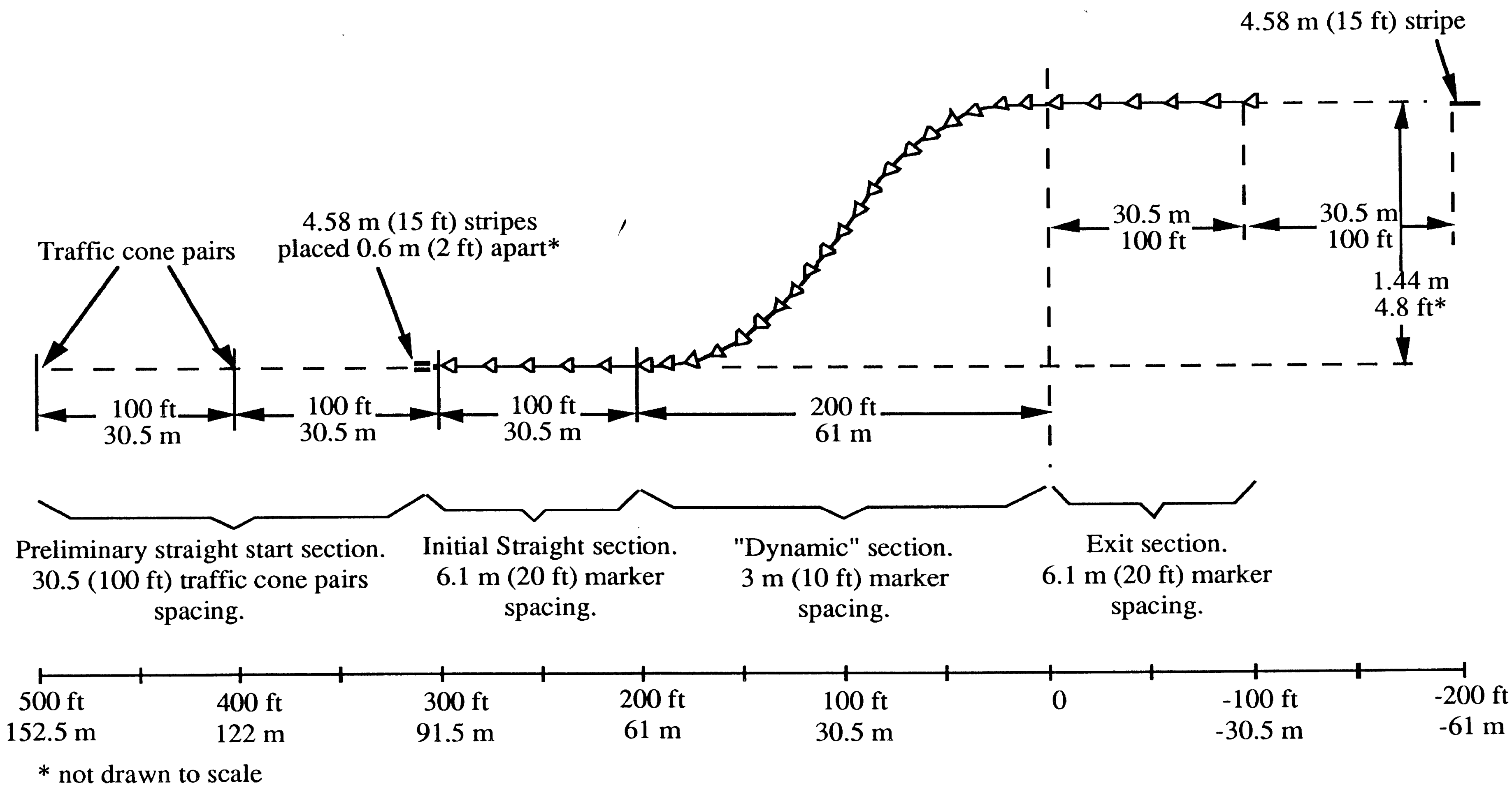

Figure 26. Layout of the test course.

(7) Requirements for Proper Execution of the Test Maneuver.

(8) Analysis of the Test Data.

(9) Interpretation of the Results.

The procedure, which is presented next, is intended to meet the following general requirements:

- To be able to distinguish reliably between vehicles with different levels of performance in obstacle avoidance maneuvers.
- To have reasonable instrumentation and data processing requirements.
- To have repeatable results.
- To be easy to perform correctly.

4.2.2 Formal Statement of the Test Procedure

Purpose

This test procedure is intended to be used for determining the rearward amplification and dynamic offtracking qualities of multitrailer commercial vehicles (heavy trucks and buses).

Scope

The procedure applies to heavy vehicles weighing more than 11,800 kilograms (26,000 pounds) and particularly to those vehicles having two or more articulation joints that allow rotation in a horizontal plane. The procedure pertains to the lateral directional response of multiarticulated vehicles in avoidance maneuvers performed at highway speeds without braking.

Test Course

The test involves the course illustrated in figure 26. (Also see section 4.2.3.) The test driver is to follow this course in a manner that meets the requirements of the section "Requirements for Proper Execution of the Test Maneuver" below. As shown in figure 26, there is a straight section 91.5 meters (300 feet long) leading up to a maneuvering section that attains a 1.44 meter (4.8 foot) lateral displacement in a longitudinal distance of 61 meters (200 feet). After the "dynamic" maneuvering section, the course remains parallel to the original direction of travel for an additional 61 meters (200 feet).

The lateral displacement of the course in the maneuvering section represents the motion of a point that is travelling at 88 kph (55 mph) for 2.5 seconds with a lateral acceleration of the form A $\sin(2\pi t/2.5)$ where t is time in seconds ($t = 0$ at the beginning of the maneuvering section) and $A = 0.15$ g.

The test course should be laid out on a proving grounds or other facility with adequate room to allow a heavy truck to reach 88 kph (55 mph) — or its maximum speed on level ground if that speed is less than 88 kph.

The facility needs to have space to allow the driver to recover control of the vehicle in case control is lost during the prescribed obstacle-avoidance maneuver occurring on the maneuvering section. Also, the driver needs space to steer and/or brake to exit from the maneuver.

The test course should be nearly level (planar with a uniform grade) in all directions with a maximum slope that is less than 1 percent in any direction.

Ambient wind conditions should be less than 24 kph (15 mph). Surface and wind conditions should be entered into the data sheets for each test.

The skid number of the dry test surface shall exceed 50 when measured at 88 kph (55 mph).[9] If available, the skid number of the surface should be recorded.

Vehicle Condition and Preparation

The results of this test are known to be sensitive to how the vehicle is loaded and the condition of its tires. Also there is a danger that unrestrained vehicles may rollover in this test.

The condition of the vehicle's tires needs to be controlled. If the vehicle is to be operated with bias ply tires, it should be tested with new (broken in) bias ply tires installed on the vehicle. Otherwise, the vehicle is to be tested with new radial ply tires.

The tires should be broken in with at least 50 miles of running. Also the tires should be exercised by driving through the test course at least five times before taking any data. (The test driver will probably need at least this many practice runs to become used to the vehicle and the test course.)

Tire wear should be less than 2 mm (3/32 of an inch). That is, the tread depth should be no less than the new tire tread depth minus 2 mm. If the vehicle is tested at other states of tire wear, those tread depths shall be reported.

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9 For directions on measuring dry surface skid numbers see Federal Motor Vehicle Safety Standard MVSS 105 or 121. These measurements follow ASTM procedures for measuring skid number except that the pavement is not wetted.

The tire inflation pressures shall be set at the manufacturers recommendations or the Tire and Rim Association specifications for the tire loads involved. Tire condition and inflation pressure shall be recorded on the data sheets. The tires shall be identified on the data sheets. Ideally, the cornering stiffnesses for the tires will have been measured, and these values will be recorded to aid in identifying the vehicle. Identification of the tires is very important because the shear force capabilities of the tires (particularly cornering stiffness) may have a large influence upon the results of these tests.

Unless special test loads are specified, the vehicle should be uniformly loaded to the maximum weight that it is expected to carry. Ordinarily (unless otherwise specified) this will be at the GCWR with axle loads close to their GAWR. The height of the center of gravity of the test load should be set to a height specifically chosen for the test. (If practical, a tilt table test (J2180) may be used to identify the rollover threshold of vehicles that are to be tested for rearward amplification.) The cg height and rollover threshold, if available, for the vehicle in the condition used in testing for rearward amplification shall be recorded on the data sheets. The axle loads and the payload's cg height shall also be recorded on the data sheets identifying the vehicle.

Since load distribution is important , the load used in the test needs to be described carefully. Ideally, this description will either give the dimensions and location of the load or the moments of inertia of the load about horizontal, lateral, and vertical axes through the center of gravity of the load plus the location of the center of gravity of the payload. To the extent feasible, the moments of inertia of the load used in testing should be representative of the intended load to be carried in service.

(In summary, and to aid in defining and identifying the vehicle being tested, Section 4.2.4 provides a list of pertinent vehicle properties that should be described and included with the test results.)

Since an unconstrained vehicle may roll over in this maneuver, the test vehicle shall be equipped with outriggers. (Information on outriggers is presented in section 4.2.5.)

Instrumentation Requirements

Transducers. Transducers shall be provided for measuring:

- Forward Velocity (V) with an accuracy of ±0.5 mph over a range from 80 to 100 kph (50 to 60 mph).
- The time period of the maneuver (T) from the moment the front axle reaches the first plate of the maneuvering section until it reaches the last plate of the maneuvering section with an accuracy of ±0.03 seconds over a range from 2.0 to 3.0 seconds. (The idea here is to provide an event recorder that can determine the start and the end of the maneuvering section.)

- Lateral Acceleration of the center of the front axle (AYX) with an accuracy of ±0.01g over a range from 0.0 to 0.2g. (This accelerometer may be attached to the axle and need not be mounted on a stabilized platform.)
- Lateral acceleration of the center of mass of the sprung mass of the last semitrailer (AYT) with an accuracy of ±0.01g over a range from 0.0 to 0.5g. This accelerometer may be mounted upon a stable platform to eliminate the influence of vehicle roll upon the measurement of lateral acceleration, or trailer roll angle may also be measured to compensate for gravitational effects of a rigidly mounted accelerometer.

Measurements from the transducers listed above are sufficient to determine rearward amplification. The following instrumentation is needed to determine the quality of the driver's steering and to evaluate the level of transient high-speed (dynamic) offtracking.

The test course is marked by "plates" that have five sides and a point as illustrated in figure 27. The point is placed on the test course. A water-jet attached at a selected point on the front axle may be used to mark the vehicle's path. (See section 4.2.6.) Alternatively, a laser system or some other system may be used to measure the distance from the vehicle's path to the desired path (the test course). The test driver shall be capable of following the desired path within 15.2 centimeters (±6 inches). Any test run that does not meet this requirement is unsatisfactory and must be rejected.

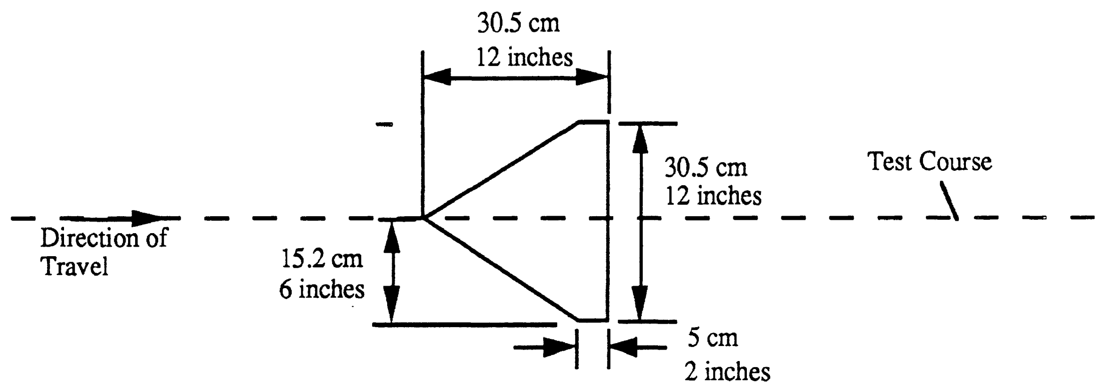

Figure 27. "Home plates" used to mark the test course.

Data Gathering and Processing Capabilities Needed

The data from the transducers described in section 2.5 shall be gathered as the test vehicle traverses the test course. The data should be recorded at a rate of 80 samples per second (or faster). At approximately 88 kph (55 mph) there will be approximately 10 seconds of data for each channel. The data channels that need to be recorded are as follows:

- Time, t.
- Time of the start of the maneuvering section and time of the end of the maneuvering section, with the difference being the period, T.
- Velocity, V.
- Lateral acceleration of the front axle, AYX.
- Lateral Acceleration of the last trailer, AYT.

These signals need to have zero and full-scale calibration levels recorded and they need proper anti-aliasing filters. Low pass filters with cutoffs at 15 hz are suitable.

The data processing system shall be capable of smoothing these signals using a 0.2-second moving average. (A 0.2-second moving average means replacing each data point with the average of all data points within a band of ± 0.1 seconds about the original data point.)

The root-mean-square (rms) value of AYX from the start to the end time of the maneuvering section will need to be computed. The maximum absolute value of AYT will need to be found.

The data processing system shall be capable of computing means, standard deviations, and confidence intervals for sets of runs.

Requirements for Proper Execution of the Test Maneuver

For a test run to be properly executed, the driver shall follow the test course so that a selected point on the front axle of the vehicle does not deviate more than ± 15 centimeters (±6 inches) from the desired path defined by the test course. (The selected point may be located to aid the driver in following the course. A marker over the hood on the truck may aid the driver in sighting along the course. See section 4.2.7 for more detail.)

The vehicle's average velocity shall be within 1.6 kph (±1 mph) of the selected speed over the maneuvering section. Nominally, the selected test speed will be 88 kph (55 mph), however, lower speeds may be selected if the vehicle is not capable of traveling at 88 kph (55 mph) on the test course. (For example, if the vehicle is only capable of traveling at approximately 85 kph (53 mph), a set of five runs at 85 ± 1.6 kph (53 ±1 mph) are needed to have a valid test sequence.) Higher speeds may also be run but the course is intended for use at 88 kph (55 mph).

The vehicle's velocity should be as constant as possible throughout the entire test course but a 3 kph (±2 mph) deviation from the selected speed is permissible on the initial and exit sections of the course if this helps the driver in executing the maneuver.

The period of time, T, taken from the start to the end of the maneuvering section shall be used to determine the average velocity over the maneuvering section. The average velocity is given by the following formula:

$$V = 61/T \ \text{(m/sec.) or } (3.6)\, 61/T \text{ (kph)}$$

A set of five acceptable runs is required to establish vehicle performance. In addition to the velocity (that is, period) requirements prescribed above, the consistency of AYX should not be excessively erratic. The effective value of AYX (that is, the rms value times 1.414) should not have a sample standard deviation greater than 0.02 g in a set of five runs. Ideally, the average value of AYX will be 0.15 g at 88 kph (55 mph). At speeds other than 88 kph (55 mph), the ideal level of AYX is given by the following formula:

$$AYX = 0.15\,(2.5 / T)^2.$$

The effective value of AYX should be greater than 0.1 g for a run to be acceptable.

Analysis of the Test Data

The test data is analyzed as follows.

First, the checks for each test run as described in the preceding section, "Requirements for Proper Execution of the Test Maneuver," are applied and bad runs are screened out.

For each test run that passes the checks, the average value of AYX is computed over the entire test course and this average is subtracted from AYX to remove any bias. Then the resulting signal is filtered twice using a moving average smoothing filter with a time width of 0.2 seconds. Then the rms value of this signal is computed from the time at the start of the maneuvering section to the time at the end of the maneuvering section. The effective value of AYX is 1.414 times the rms value. This effective value is saved to be used in the denominator of the calculation of rearward amplification.

The signal AYT is filtered twice using a moving average with a width of 0.2 seconds. (The zero value of AYT needs to be carefully calibrated at the time of testing since there is no easy way to remove any bias in the recording.) Then the peak value of this signal in the vicinity of the time of the end of the maneuvering section is read. This value is used as the numerator of the calculation of rearward amplification.

The value of rearward amplification is computed and stored for each run that has been found to be acceptable per the requirements of the preceding section, "Requirements for

Proper Execution of the Test Maneuver". (That is, the checks on V and AYX as specified in that section are applied.) Once a set of five acceptable runs is obtained, the mean value (RAM) and the standard deviation (S) of the sample are computed. The result for the five acceptable runs is stated in the following form:

$$RA = RAM \pm 0.953\ S$$

where:

$RAM = \Sigma\, RAi / 5$

$S^2 = \Sigma\, (RAi - RAM)^2 / 4$

RAi represents the individual values of rearward amplification measured in each of the five acceptable test runs.[10]

These values are to be used to determine whether the vehicle meets the following requirement:

$$RAM + 0.953\ S < 2.0$$

Interpretation of the Results

The value of RAM + 0.953 S represents an upper bound on the level of rearward amplification. From a statistical point of view and based upon the test results, there is a five percent chance that the mean rearward amplification for five runs is greater than RAM + 0.953 S.

Results obtained by applying this test procedure to a heavily laden 36,000 kilograms (80,000 pounds) Western double with a rollover threshold of 0.35g and equipped with modern radial truck tires indicate that its mean rearward amplification is approximately 2.0. For a vehicle to have a mean rearward amplification that is no higher than 2.0 the following inequality is based upon 95 percent confidence:

$$RAM + 0.953\ S < 2.0$$

In summary, if the above inequality is satisfied, one can say with 95 percent confidence that RA is less than 2.0.[11]

This ends the specification of this test procedure.

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[10] 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 five repeats.

[11] See, for example, Paul G. Hoel, "Introduction to Mathematical Statistics" John Wiley & sons, New York, 1984, pp. 146-149 for a discussion of "A Confidence Interval for a Normal Mean".

4.2.3 *Placing the Test Course*

The test course for measuring rearward amplification consists of a "lane-change-like" maneuver in which the vehicle is required to move laterally 1.44 m (4.8 feet) as it moves forward 61 m (200 feet) at 88 kph (55 mph). (Figure 26 diagrams the course.) Table 5 details the specific distances for marking the initial straight, "dynamic", and exit sections of the course. The plate orientation is such that the course always passes through the tip of the plate and the center of the edge opposite the tip. (Plate geometry is detailed in figure 27.)

Below is a list of the materials used to mark the test course:

1. Thin Sheet Metal - used to cut out the plates that marked the path.
2. Putty - used to secure the plates to the road surface. This has proved to be a very convenient way of temporarily securing the plates.
3. Heavy String - used as a reference marker for the off-tracking measurement.
4. Paint - used to permanently mark the plate, traffic cone, stripe, and string locations.
5. Bright Durable Material - used to mark the entry and exit of the path. These help the driver align the vehicle with the path.
6. Traffic Cones - used to mark the course entry and exit.

4.2.4 *Pertinent Vehicle Properties*

This section provides a list of items pertaining to vehicle properties that have an important influence on rearward amplification. These properties should be described carefully so that persons examining the data from this test will be able to identify the vehicle being tested and know its pertinent mechanical properties.

Items to be described and transmitted with the data include the following:

- General identification of the tractor or truck towing the combination. Include items such as year, make, model, mileage,VIN, style, engine, powertrain, and other items that will serve to identify the power unit and its components.
- General identification of all semitrailers, full trailers, dollies, and innovative dollies. Including year, make, model, etc. much like above with the exception of power related items.
- Major dimensions including the locations (vertical, horizontal, and lateral) of all axles, tires, hitches etc. (A side-view drawing is a good way to show the vertical and horizontal dimensions.) Also the locations and sizes of all of the cargo containers and load beds should be specified.

X in meters	Y in centimeters	X in feet	Y in inches
-30.48	0.0	-100	0.0
-24.38	0.0	-80	0.0
-18.29	0.0	-60	0.0
-12.19	0.0	-40	0.0
-6.10	0.0	-20	0.0
0	0.0	0	0.0
3.05	0.3	10	0.1
6.10	1.3	20	0.5
9.14	3.3	30	1.3
12.19	7.1	40	2.8
15.24	12.7	50	5.0
18.29	20.3	60	8.0
21.34	30.0	70	11.8
24.38	42.2	80	16.6
27.43	55.9	90	22.0
30.48	70.6	100	27.8
33.53	84.8	110	33.4
36.58	100.3	120	39.4
39.62	112.8	130	44.4
42.67	123.4	140	48.6
45.72	132.3	150	52.1
48.77	138.7	160	54.6
51.82	143.0	170	56.3
54.86	145.3	180	57.2
57.91	146.3	190	57.6
60.96	146.3	200	57.6
67.06	146.3	220	57.6
73.15	146.3	240	57.6
79.25	146.3	260	57.6
85.34	146.3	280	57.6
91.44	146.3	300	57.6

Table 5. X,Y coordinates of the course

- A description of the load. Its dimensions and weight and/or density. The distribution of loads on the tires. (The axle loads, as determined from scale readings, perhaps, is a good way to show the distribution of load on the various wheels.) If available, measured values for center of gravity heights of the loads and their moments of inertia should be provided.
- Dimensions and specifications of pertinent major components such as suspensions, springs, axles, wheels, and tires. There should be sufficient information so that the same (that is, a very similar) vehicle could be assembled and tested again.
- Tire condition and state of use. The make, model, size and load range, tread depth, and hot or cold inflation pressure should be recorded for each tire. Tread depths before and after testing are desirable.
- Any unique or unusual factor that would make the test vehicle behave differently from traditional highway trucks should be described.
- If available, results of tilt-table tests for rollover threshold are useful information to include with the results of this test.

A very complete form for use in describing the units of combination vehicles is being developed for SAE Recommended Practice J1574. If practical, a filled-in copy of that form would serve the purpose of providing a detailed definition of the vehicle tested.

4.2.5 The Outrigger Concept

Outriggers are lateral extensions added to both sides of a unit to prevent it from rolling completely over. They are usually adjusted to allow the unit to roll beyond its recoverable roll angle before touching the ground and supplying a righting moment to prevent rollover. Figure 28 offers some detail of the outriggers used by UMTRI to measure rearward amplification and high-speed transient offtracking of double and triple truck combinations.

A set of mechanical design drawings for the outriggers that UMTRI designed and fabricated for this project is supplied to NHTSA with this report.

4.2.6 Technique and Verification for Path Following

This section describes one very simple method, including "instrumentation," which has been used for (a) aiding the driver in following the precise path required for this test method and (b) verifying that actual front-axle path was within the requirements of the method. The system also allows for measuring the maximum offtracking of the rear axle of the vehicle with respect to the path of the front axle. A more sophisticated instrument system for determining front-axle path which was developed and used in this project is described in Appendix C.

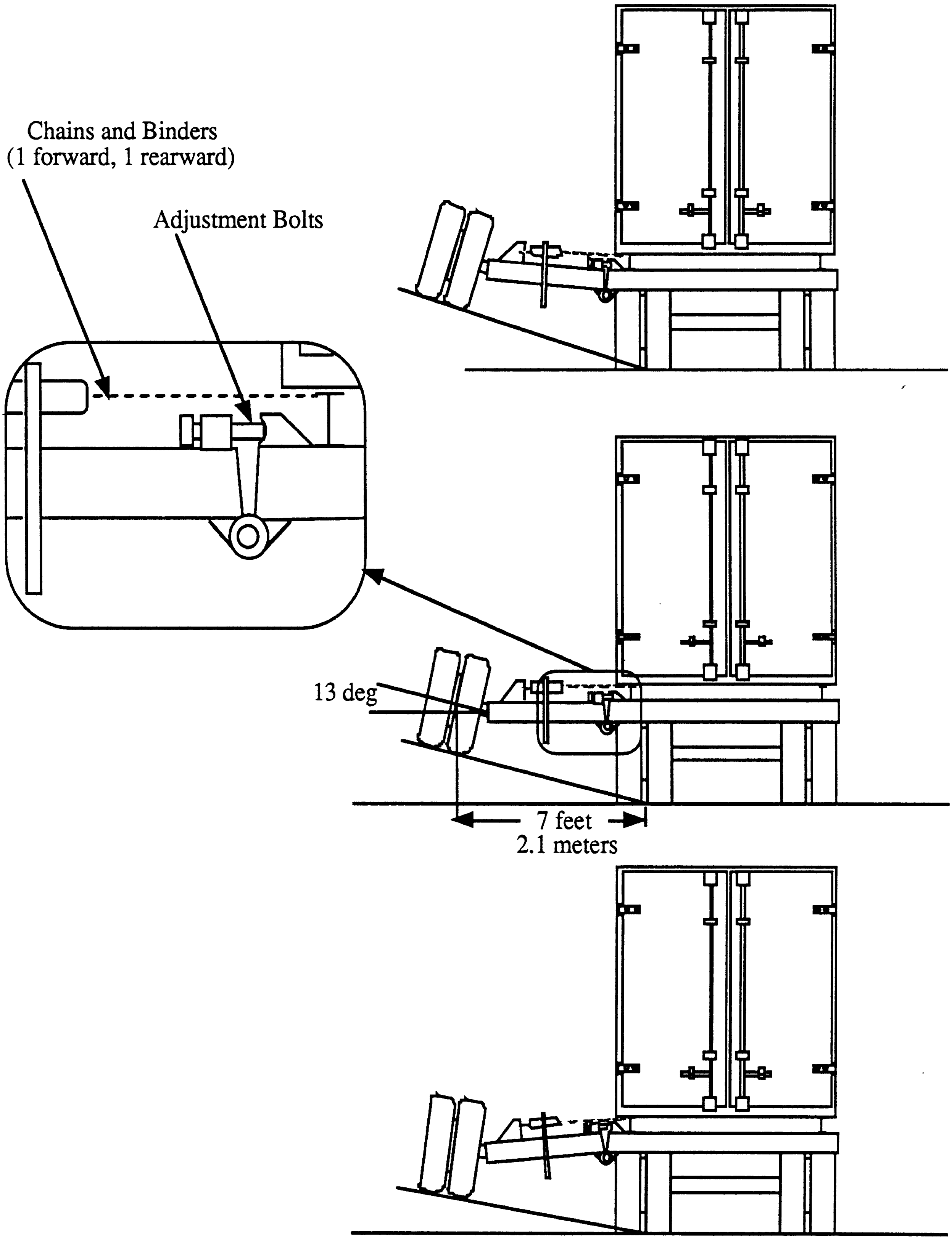

Figure 28. Adjustable outrigger at three diffrent heights

Driving Technique

The definition of the test course was given in Section 4.2.2. This definition included the description of "home plate" shaped path markers.[12] The pointed shape of these markers was seen as an aid to the driver in his task of driving the course within the required lateral-displacement limits. The lateral dimension of the marker is equal to the allowable lateral position of the first axle of the test vehicle.

The basic instruction given to the test driver was simply to follow this course in a manner such that the path markers would pass directly beneath his seat. (This, of course, was found to be easier for the driver than aligning the marks with, for example, the centerline of the vehicle.) To aid in this task, the driver was allowed to place visual markers (e.g., tape) on the windshield, and/or hood of the tractor to help him consistently align the vehicle with the course. The driver was allowed all the practice he desired to become proficient at following the path. With this simple system, it was found that the driver could learn to follow the path within the required accuracy on the majority of test runs.

Verification

A very simple water spray system was used to mark the path of the first and last axles during the conduct of the rearward-amplification test procedure. The system used hardware from conventional garden spraying equipment, adapted to provide a stream of water directed onto the pavement from a nozzle mounted on the axle. The system leaves a well defined water mark on the pavement indicating the path of the axle. With nozzles mounted on the first and last axles, the path of the first axle and the relative displacement (offtracking) of the last axle can be determined. When used in the summer months, it was found that the amount of water sprayed could be adjusted such that the marking lasted long enough to take the necessary measurements, but evaporated soon enough to allow repeated use of the same course without confusion from earlier markings.

System Hardware

A schematic diagram of the system used for one axle is shown in figure 29. The system was based on conventional hand-pump garden sprayer hardware.

The tank of the garden sprayer was modified to provide an air pressure inlet above the waterline. This inlet was fed with regulated pressure, and was also equipped with a safety

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[12] The very specific "home plate" design described in section 4.2.2 was chosen to coordinate with an optical tracking system. That system is described in Appendix C. For purposes of the simpler system described here, a laterally symmetric triangle, or similar marker, of 305 mm total width would serve just as well.

relief valve to prevent over pressurizing the tank. The relief valve used was set to approximately 240 kpa. Regulated pressures were set to approximately 200 kpa.

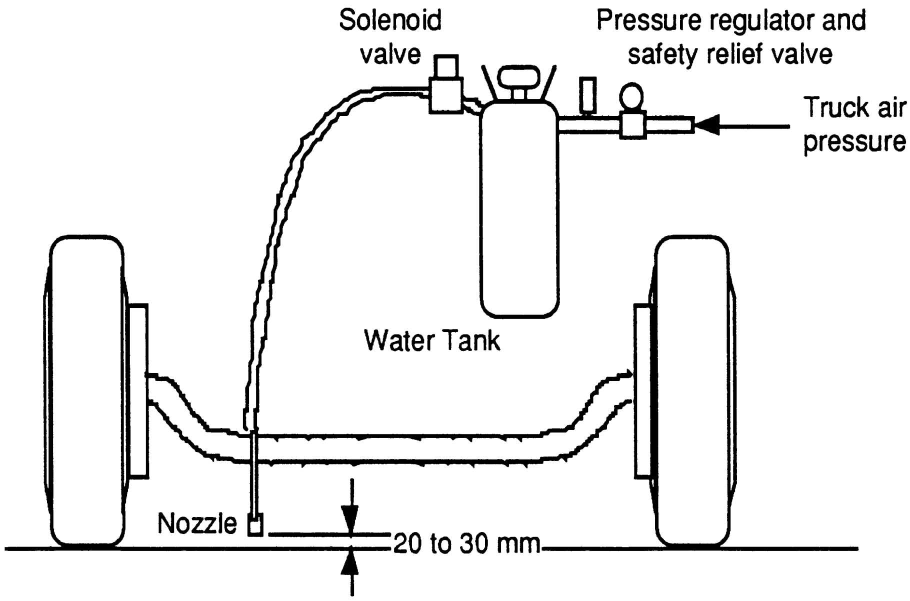


Figure 29. Axle path marker system.

The outlet path was modified by removing the hand-operated valve and functionally replacing it with an inexpensive electric-solenoid valve (the kind commonly used in automatic dishwashers and/or washing machines). A push button for controlling both front and rear axle solenoids was mounted in the tractor cab.

For the front-axle installation, the water tank was mounted on the tractor chassis behind the cab and a length of hose used to route the pressurized water to the front-axle area. In the rear-axle installation, the water tank was mounted inside the trailer above the rear axle, and, again, a length of hose was used to route water to the axle.

In both cases, the original garden sprayer nozzle was mounted to the axle using a simple hose clamp arrangement. The nozzle was oriented to spray water straight down toward the road surface from a height of only about 20 to 30 mm above the surface. A solid-stream type nozzle was used, and the rate of water discharge was adjusted with the nozzle adjustment feature of the garden equipment.

Front Axle System Alignment

Alignment of the nozzle used on the front axle was accomplished as follows. In general, the philosophy of the approach was to align the marker system to the driver's preference in aligning the vehicle on the course, that is, not to burden the driver with any concern about alignment of the marker.

A set of path markers was laid out on the pavement in a straight line. This was done on the area in which testing would eventually be conducted in order that any influence of surface cross slope would be properly included. The driver was instructed to drive the vehicle in a straight line over the markers at low speed until he was satisfied that the vehicle was well aligned over the markers. He was then asked to stop the vehicle directly over a marker, and the water nozzle was adjusted laterally to align with the center of the marker.

Next, the driver was ask to drive the vehicle over the same straight line set of markers at test speed and to apply the water-mark system in the process. Although, of course, the driver's performance was somewhat variable, the "average" lateral position of the water mark relative to the course markers was noted over several runs. The lateral position of the nozzle was then adjusted as necessary to obtain a condition wherein the water mark position was centered on the markers.

With this alignment accomplished, a test run could be considered valid if the front-axle water mark passed over some portion of each of the course path markers. However, if the water mark missed any marker, the run was not considered valid.

Rear Axle System Alignment

The use of the term "alignment" here is not exactly correct; "zero calibration" would be more precise. That is, the approach used to determine offtracking from the first and last axle water marks was not to attempt to perfectly align the two markers, but rather to determine the offset of the two markers when the vehicle was traveling in a straight line, and to use this dimension as a reference zero condition to correct offset measurements made in dynamic conditions. The procedure used was as follows.

After alignment of the front-axle nozzle, the lateral position of the rear-axle nozzle was adjusted to be approximately the same as the lateral position of the front-axle nozzle. The driver was then ask to drive the vehicle over the straight line course at test speed and to apply both water markers while doing so. This was done several times, and after each pass of the vehicle the lateral displacement of the rear-axle mark relative to the front-axle mark was measured with a tape measure at several places along the straight line course. Largely because of the lightly damped behavior of multitrailer vehicles (this procedure was used with both double- and triple-trailer vehicles), the measurement varied appreciably during each run. Nevertheless, an average value over several runs was determined and was used as the reference "zero offset" of the markers.

During subsequent dynamic testing, the peak lateral displacement of the two water marks was measured using a tape measure immediately after each pass of the vehicle. The oscillatory response of the last trailer made it very easy to determine which mark came from which axle. Further, the peak displacement could quickly be determined with a few iterative measurements. Once the position of peak lateral displacement was determined, a longitudinal measurement was also made from that point to a course reference point (the exit gate at the end of the dynamic section of the course) in order to locate the point of maximum offtracking along the course.

5.0 CONCLUDING STATEMENTS

5.1 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 that clearly meet the stability criterion to easily demonstrate compliance. Vehicle units that are "too close to call" can be tested for stability on a tilt table. Tilt table procedures for testing individual units are also defined.

5.2 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.

6.0 REFERENCES

1. "Heavy vehicle size and weights—development of test procedures for minimum safety performance standards." A task order under Contract DTNH22-87-D-17174. "Crash avoidance research technology support/vehicle stability and control." NHTSA, US DOT.

2. Winkler, C.B., Fancher, P.S., and MacAdam, C.C., "Parametric Analysis of Heavy Duty Truck Dynamic Stability. Volume I." University of Michigan Transportation Research Institute. UMTRI-83-13-1, DOT/HS 806 411, DTNH-22-80-C-07344, 1983, 170 p.

3. Ervin, R., et al., "Influence of Truck Size and Weight Variables on the Stability and Control Properties of Heavy Trucks." Presented at the Society of Automotive Engineers, West Coast International Meeting, Vancouver, British Columbia, Canada. SAE Paper No. 881163, 1983, 28p.

4. Ervin, R.D., "Mechanics of the Rollover Process." *The Mechanics of Heavy Duty Trucks and Truck Combinations*, Chapter 19, The University of Michigan Engineering Conferences. Ann Arbor, 1991.

5. Billing, J.R., "Vehicle Weights and Dimensions Study, Volume 4. Demonstration Test Program: Five, Six, and Seven Axle Tractor Semitrailers." Canroad Transportation Research Corporation, 1986.

6. Billing, J.R., "Summary of tests of Baseline Vehicle Performance." Canroad Transportation Research Corporation, CV-86-12, 1986.

7. Delisle, G., and Pearson, J.R., "Vehicle Weights and Dimensions Study. Volume 7 - Investigating Articulated Vehicle Stability Using a Tilt-Table Device." Roads and Transportation Association of Canada, 1986.

8. Isermann, H., "Overturning Limits of Articulated Vehicles with Solid and Liquid Load." The Motor Industry Research Association, 1970.

9. Kemp, R.N., Chinn, B.P., and Brock, G., "Articulated Vehicle Roll Stability: Methods of Assessment and Effects of Vehicle Characteristics." Transport and Road Research Laboratory, 1978.

10. Mai, L., and Sweatman, P., "Articulated Vehicle Stability - Phase II. Tilt Tests and Computer Model." Australian Road Research Board, 1984.

11. Miller, D.W.G., and Barter, N.F., "Roll-Over of Articulated Vehicles. in Vehicle Safety Legislation - Its Engineering and Social Implications." Cranfield Institute of Technology. Mechanical Engineering Publications Limited, 1973.

12. Soret, P., "Handling and Road Holding of Tractor Semi-Trailer Units: Improvement of Rollover Threshold." The Motor Industry Research Association,1984.

13. Sweatman, P.F., "Stability of THOMAS Tanker." Road User Research, 1991.

14. Tso, Y., "Interim Report on Articulated Vehicle Stability - Phase III Full-Scale Dynamic Tests." Australian Road Research Board, 1987.

15. Winkler, C.B., "Experimental Determination of the Rollover Threshold of Four Tractor-Semitrailer Combination Vehicles." University of Michigan Transportation Research Institute, 1987.

16. Ervin, R.D., and Guy, Y., "Influence of Weights and Dimensions on the Stability and Control of Heavy-Duty Trucks in Canada." Final Report, Sponsored by Canroad Transportation Research Corporation. University of Michigan Transportation Research Institute, Report No. UMTRI-86-35, July 1986.

17. Ervin, R.D., et al., "Ad Hoc Study of Certain Safety-Related Aspects of Double-Bottom Tankers." Final Report, Sponsored by Michigan State Office of Highway Safety Planning, Contract No. MPA-78-002A. Highway Safety Research Institute, University of Michigan, Report No. UM-HSRI-78-18, May 7, 1978.

18. Winkler, C.B., et al., "Improving the Dynamic Performance of Multitrailer Vehicles: A Study of Innovative Dollies." Final Report, Contract No. DTFH61-84-C-00026, University of Michigan Transportation Research Institute, Report No. UMTRI-86-26, July 1986.

19. Fancher, P.S., and Mathew, A., "A Vehicle Dynamics Handbook for Single-Unit and Articulated Heavy Trucks." University of Michigan Transportation Research Institute, Report No. UMTRI-87-27, DTNH-22-83-C-07187, 1987, 367 p.

20. Fancher, P.S., Ervin, R.D., Winkler, C.B., and Gillespie, T.D., "A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks. Phase I. Final report." University of Michigan Transportation Research Institute, Report No. UMTRI-86-12, DTNH-22-83-C-07187, 1986, 190 p.

21. Fancher, P.S., Mathew, A., Campbell, K.L., Blower, D., and Winkler, C. B., "Turner truck handling and stability properties affecting safety, Volume I - technical report." Final report. University of Michigan Transportation Research Institute, Report No. UMTRI-89-11-1, 1989, 206 p.

22. Fancher, P.S., "The Transient Directional Response of Full Trailers." SAE Paper No. 821259, November 1982.

23. Gillespie, T.D., and MacAdam, C.C., "Constant Velocity Yaw/Roll Program: User's Manual." UMTRI-82-39, 1982, 179p.

24 Laird, L., "Measurement of Heavy Vehicle Suspension Roll-Stability Properties, and a Method to Evaluate Overall Stability Performance." SAE Paper No. 881869.

APPENDIX A
THE VIRTUAL TRACTOR

The virtual tractor is a device that provides fifth-wheel support to a payload unit during tilt-table testing of that unit. In addition to vertical support, the virtual tractor also provides stabilizing roll moment to the test unit at the fifth-wheel coupling. The virtual tractor is articulated in roll such that the relationship between fifth-wheel roll and lateral motion is representative of heavy-vehicle-suspension/tire-roll compliance behavior. The virtual tractor is instrumented to measure both roll displacement and roll moment.

The virtual tractor that was designed and fabricated by UMTRI for this project is shown in the sketch of figure A.1. A photograph of the device in use during a tilt-table test of a semitrailer is shown in figure A.2. A set of the mechanical design drawings produced by UMTRI in the development of this virtual tractor is supplied to NHTSA with this report.

The defining properties of the virtual tractor are:

- the use of representative fifth-wheel hardware for immediate support of the test unit
- the location of the supporting surface of the fifth wheel at a height of 48 inches above the tilt table surface
- the location of the roll pivot at a height of 20 inches above the tilt table surface and on a common centerline with the fifth wheel
- sufficient roll angle articulation to allow all high-side tires of the test unit to lift off the table surface during tilt-table testing
- continuous measurement of the roll displacement of the virtual tractor with an overall accuracy of 0.1 degrees (with sufficient structural rigidity to complement this level of accuracy)
- the ability to apply the necessary levels of stabilizing roll moment about the roll pivot
- continuous measurement of roll moment about the roll pivot with an overall accuracy of 2 percent of reading.

This particular design of virtual tractor shown in this appendix uses hydraulic cylinders to provide the necessary stabilizing roll moment. The geometry of the device insures that the effective moment arm of these cylinders with respect to the roll pivot remains constant to within 0.35 percent over the full stroke of the cylinders. Tensile load cells in the cylinder rods are used to transduce cylinder force, which is multiplied by the moment arm length to obtain roll moment about the pivot. In this application, an active servo system acting on virtual-tractor roll angle was used to control the action of the cylinders.

These particular design details are not required, as long as the all of the defining properties listed above are fulfilled. For example, the function of the hydraulic cylinders used in this design could be replaced by a cable and winch arrangement, or, in the extreme, something as simple as a high-load turnbuckle.

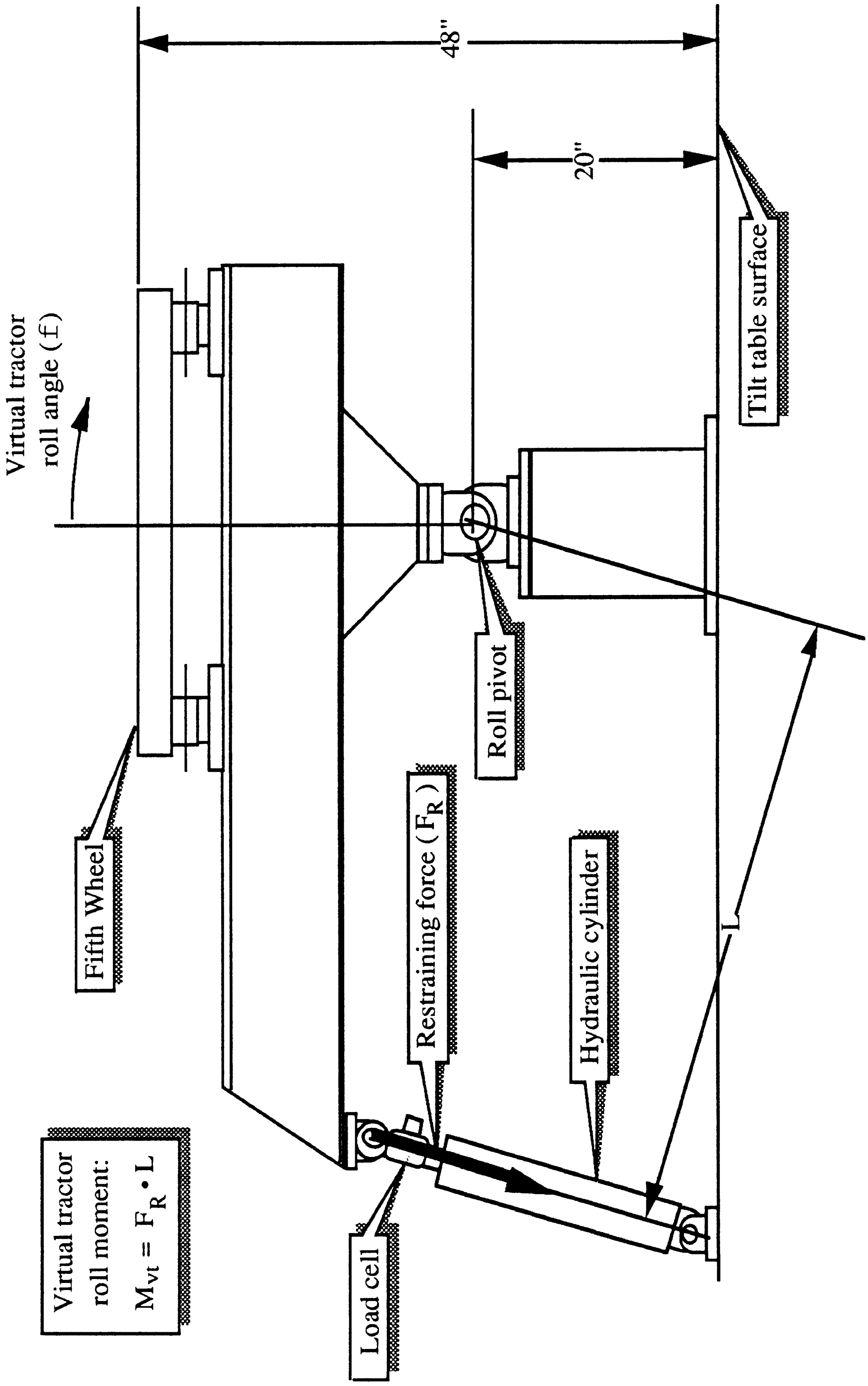


Figure A.1. Sketch of a virtual tractor.

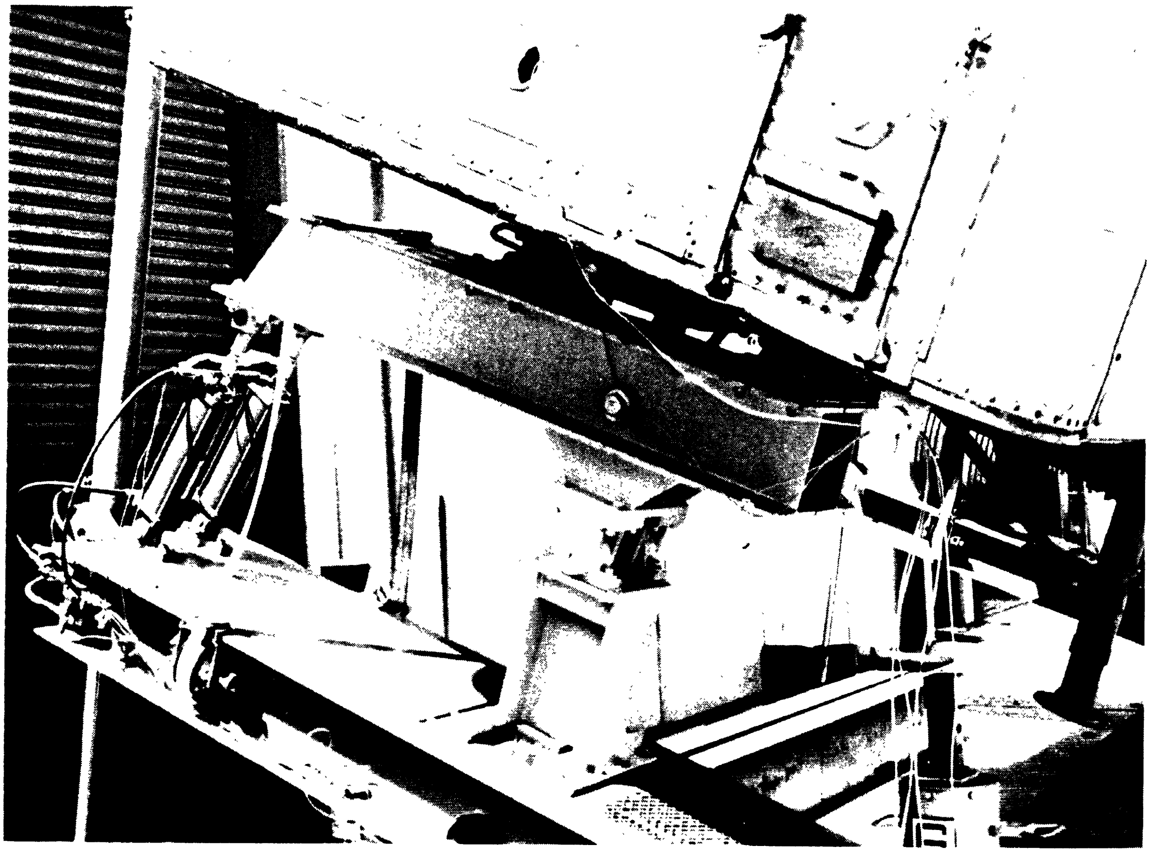


Figure A.2. The virtual tractor in use with a semitrailer

APPENDIX B
THE VIRTUAL TRAILER

The virtual trailer is essentially 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 the loading patterns.

A sketch of the virtual trailer constructed by UMTRI for this project is shown in figure B.1. Two photographs of the device in use appear in figure B.2. A set of the mechanical design drawings produced by UMTRI in the development of this virtual trailer is supplied to NHTSA with this report.

This particular virtual trailer is designed to take advantage of a set of iron ballast weights on hand at UMTRI prior to the project. Accordingly, details of this device meant to accommodate the geometry of those weights are probably not applicable to other designs.

This virtual tractor consists of:

1) A fixed frame, which mounts on a conventional fifth wheel via a standard kingpin coupling.
2) A load rack, which (a) rides within the fixed frame, (b) carries iron ballast weights, and (c) allows vertical adjustment of the load.
3) Pitch and yaw stabilizer hardware, which mounts to the frame of the test unit.

The fixed frame is symmetrically constructed about a vertical centerline which is collinear with the vertical axis of its kingpin. The four corner posts of this frame form a track, within which rides the adjustable load rack.

The adjustable load rack hangs from four chains supported from the top of the four corner posts. The fidelity of adjustment of the vertical position of the rack is therefore equal to the length of one chain link. The corners of the adjustable frame are equipped with clamping bolts to lock the frame securely with respect to yaw, lateral, and longitudinal motion after the proper vertical position is established.

The adjustable rack provides for two tiers of ballast weights, each with two rows. This arrangement allows for use of up to sixty-eight, 500-pound weights. Any even number of weights can be symmetrically located about the vertical axis of the kingpin. The tare weights of the fixed and adjustable racks are 1489 and 1529 pounds, respectively. When constructed, the center of gravity position of each was carefully measured. Thus, the vertical center of gravity position of the complete, loaded structure can easily be determined by calculation.

The pitch and yaw stabilizers are mounted on two, small I-beams, which mount laterally on the vehicle frame.

The pitch stabilizers are a set of four knife-blade supports located, respectively, near the four corners (plain view) of the fixed frame. The blades are arranged so that their bearing edges point upward, are aligned in the longitudinal direction, and are in line with the outboard edges supporting the fifth wheel. The pad on the underside of the fixed frame where the blades bear on the frame are in the same plane as the upper fifth-wheel plate of the fixed frame.

The vertical position of the blades (relative to the frame of the test vehicle) is adjustable. Prior to testing, the vertical positions of the blades are adjusted so that total center of gravity of the load frame is virtually balanced over the fifth-wheel pitch pivot, but a small (less than 2 mm) clearance is left between one pair (fore or aft pair) of blades and the under side of the rack when the rack is resting on the other pair. With this arrangement, it is assured that (a) virtually the full load (weight and roll moment) of the virtual trailer is carried by the fifth wheel, (b) the virtual trailer is free to roll through kingpin lash in a realistic manner, and (c) the virtual trailer is stabilized in pitch.

The yaw stabilizers are simply adjustable vertical plates also located near the four corners of the fixed frame. Prior to testing the yaw position of the virtual trailer is carefully adjusted so that the frame is square on the test vehicle. Then the restraining plates are located such that each has approximately 6 mm clearance with respect to the frame. (Since there may be some lateral lash in the fifth-wheel connection, this clearance should be checked after an initial practice tilt.) Thus, if for any reason the virtual trailer would begin to yaw on the fifth wheel during testing, that motion would be arrested.

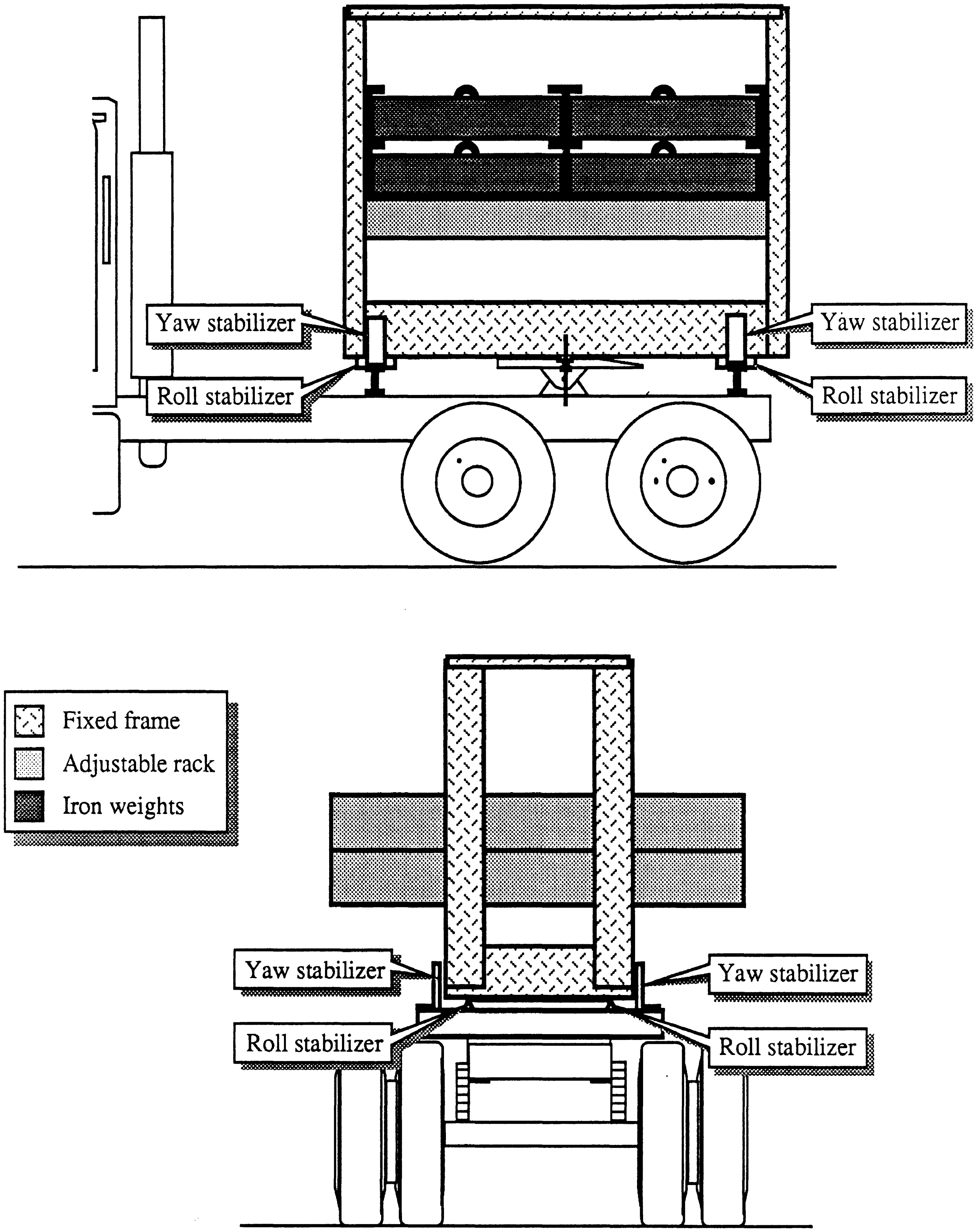


Figure B.1. A sketch of the virtual trailer.

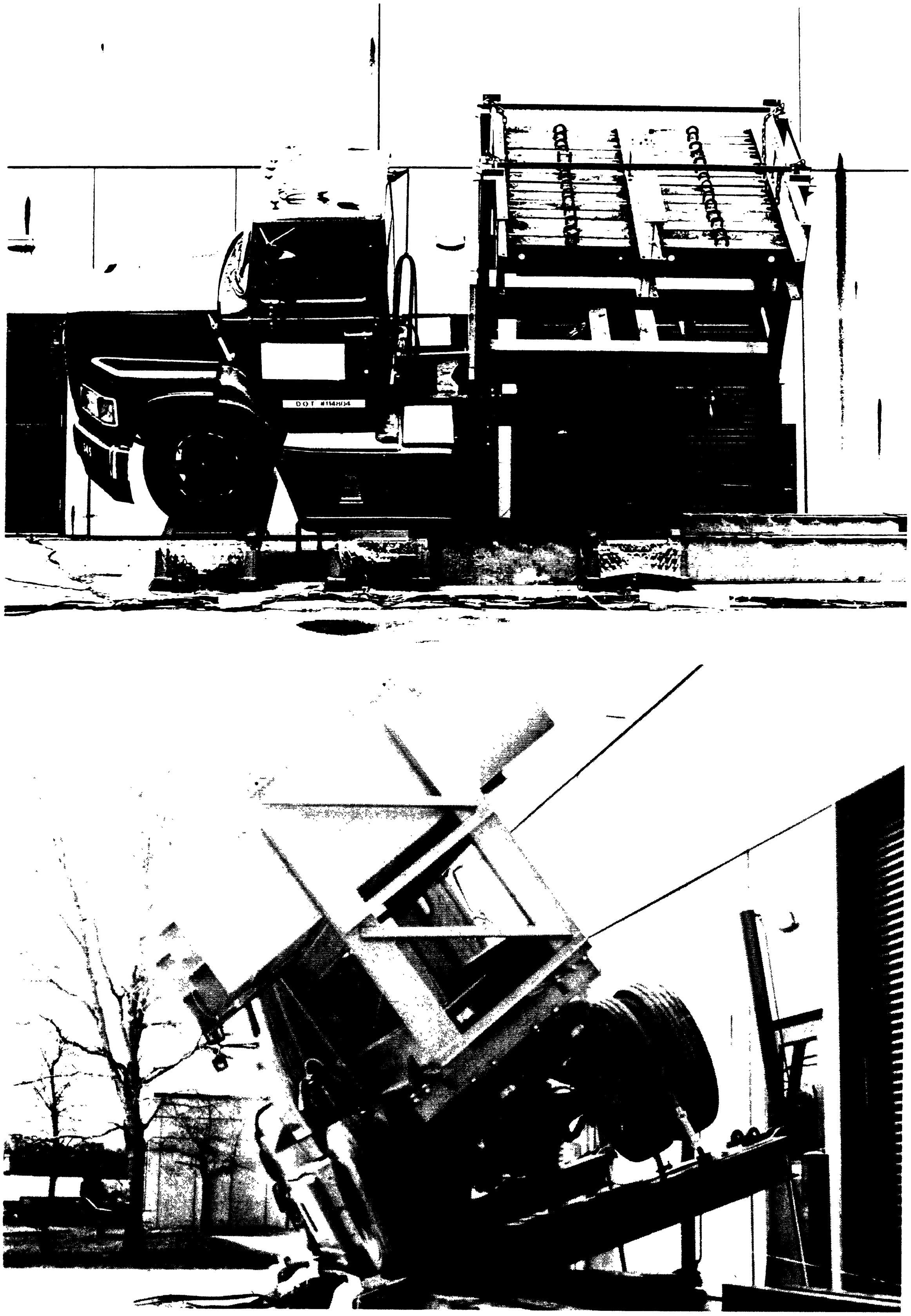
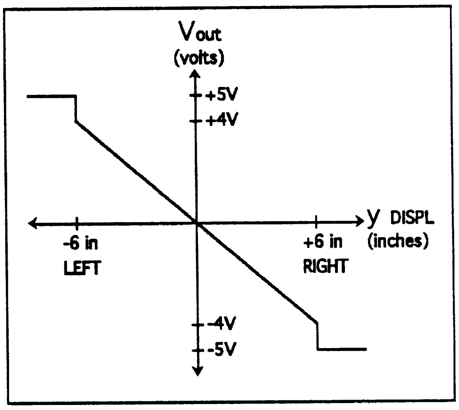


Figure B.2. The virtual trailer in use with a tractor

APPENDIX C
LASER PATH-FINDING SYSTEM

System Overview

The path-finding system was designed to measure the lateral position of a vehicle with respect to a series of path markers on the road surface. The system produces an output voltage (Vout) which is a function of the lateral displacement of the vehicle-mounted sensor with respect to the center of the last marker observed. The output function is shown at right. When the sensor is to the left of centerline, the output is positive, and is negative when the sensor is to the right of center. V_{out} is proportional to displacement over the range of ± 6 inches. The output is either ± 5 volts whenever the absolute value of displacement falls in the range of 6 to 12 inches.



The system is composed of two basic components: the marker-sensor system, and an analysis system. In the marker-sensor system, each of three individual sensors emits laser light, senses its reflection off the road or marker surface, and indicates whether the sensor is positioned above a marker or not. The analysis system analyzes these three signals to produce the lateral displacement measurement, Vout.

Sensor System

Concept

Each sensor in the system is responsible for providing modulated power to a laser diode, power to a detector, and for the demodulation of the detector signal. The final output voltage will be logically inverse, so a low voltage (0V) indicates the laser is over a reflective surface, and a high voltage (15V) indicates that the laser is over a nonreflective surface. The modulated light source and demodulation circuitry provided effective band-pass filtering of unwanted signals and allowed the three lasers to function together without interference.

Main Components

Each laser sensor has three main components: modulated laser light, the receiver or photo-detector, and the demodulation circuitry.

Laser Emitter

Solid state diode lasers are particularly well suited for this application. Their small size, low cost, and ease of use make them ideal for mounting in confined or hazardous areas with simple control systems and power supplies. The diode lasers used in this project were the CQL30 collimator pens manufactured by Phillips Components, based in the Netherlands. The CQL30 is a low-power, compact-disc diode laser complete with collimating optics, and is specified to output a maximum of 2.5mW at a wavelength of 790nm. The laser functions at a nominal voltage of 1.8V, however we typically ran them at 2.1 - 2.4V. The emitted light was modulated by turning the laser on and off at the modulation frequency.

Photo Detector

The detector was a photo-transistor device which functioned as an NPN transistor with a fixed positive collector-emitter voltage and with the base producing a positive voltage when struck by light. The detector used for this application was the NTE3037 NPN photo-transistor distributed by New-Tone Electronics (NTE) of New Jersey. The signal from this detector was amplified, demodulated, and filtered to produce the final sensor output.

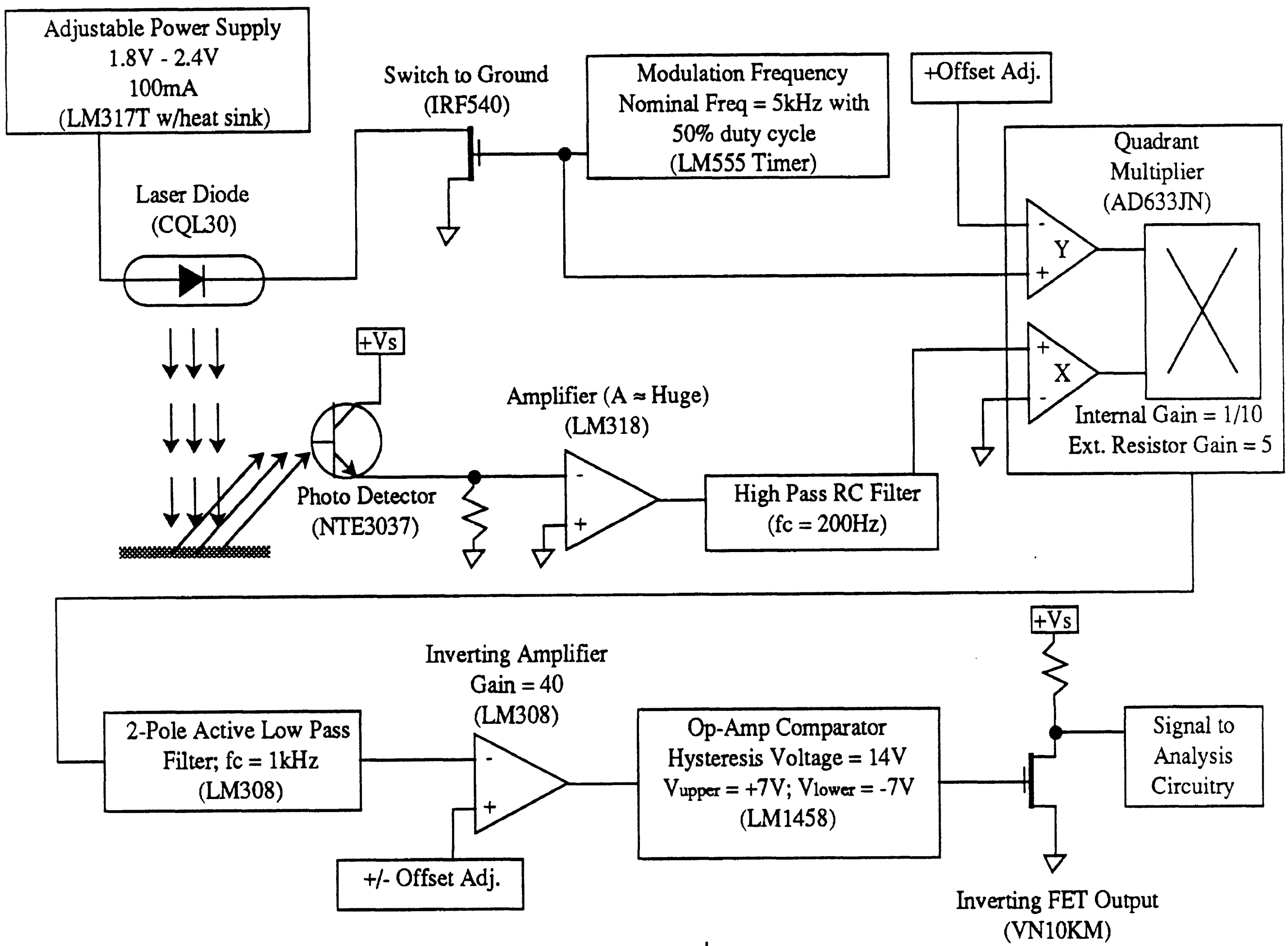
Demodulation Circuitry

The modulation / demodulation scheme of the sensor allowed band-pass filtering of extraneous light and noise from the system, and kept the detector locked on the modulated reflected laser light. The circuitry consisted of an analog multiplier, filters, and amplifiers. The final stage of demodulation was a comparator and an FET used for logic inversion and for transmission of the signal to the analysis circuitry.

Circuit Description (see figure C-1)

The laser power supply was typically adjusted to produce a DC voltage between 2.1 and 2.4 Volts. The voltage was slightly different for each laser diode due to variations in the relationship of laser output power to supply voltage. The amount of power required was determined by the reflective properties of the two surfaces. Enough power was needed for reflection off the white plates, but too much power produced reflection off the darker pavement.

LASER DRIVER & DETECTOR SYSTEM



TIMING DIAGRAMS & WAVEFORMS

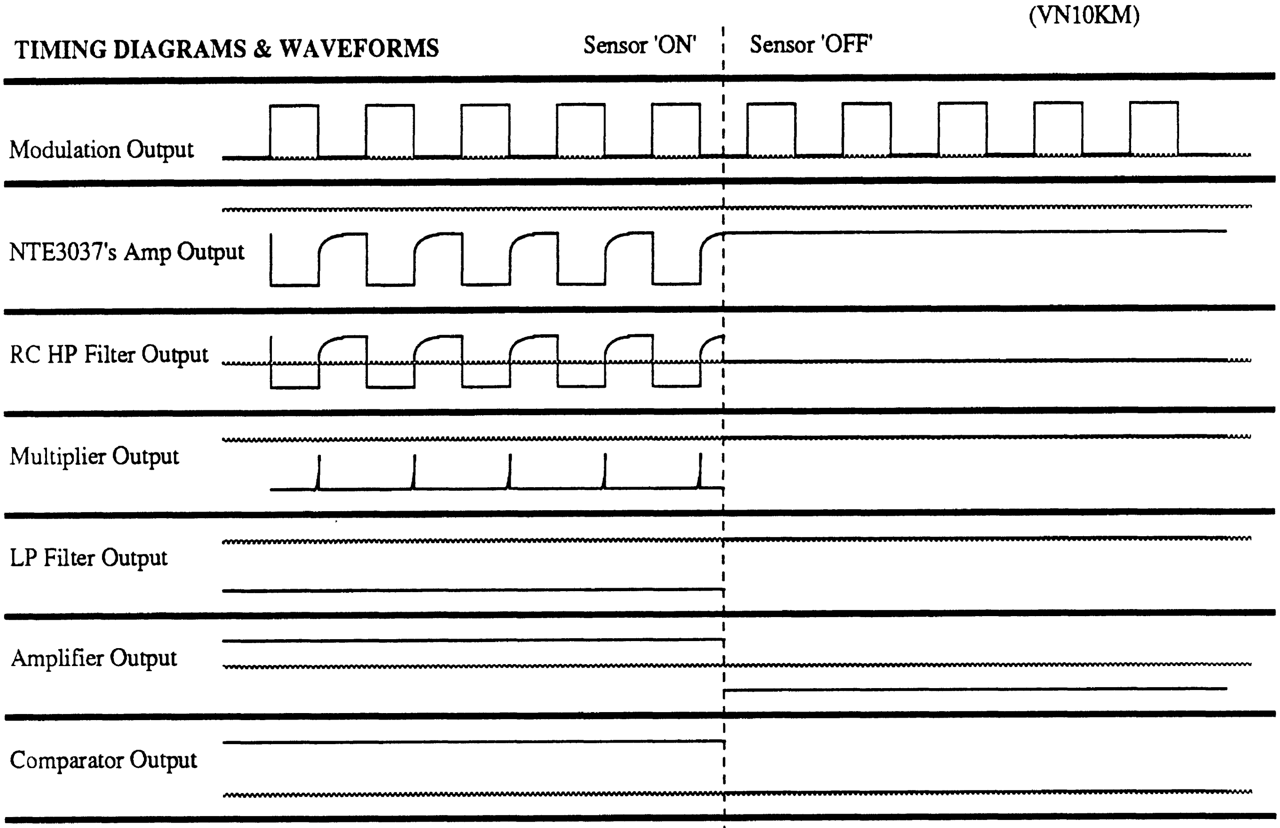


Figure C-1. Driver circuit and timing diagram

The light was modulated to 5kHz at a 50 percent duty cycle through modulation of its supply. Modulation timing was achieved by an LM555 timer circuit. The same modulation signal that drove the laser was fed into the multiplier for demodulation of the detector signal.

The signal from the photo transistor was amplified, high-pass filtered to remove the strong DC bias, and then multiplied by the modulation signal. This produces a signal which is essentially a DC signal with a bit of phase-related noise if the detector is receiving the reflected laser light, or zero volts if the detector is not receiving any modulated light.

Low-pass filtering removed extraneous noise from the output of the multiplier. The negative signal was then inverted and amplified and given a negative offset, producing a large positive signal ($\approx +Vs$) for a solid 'on' condition and a large negative signal ($\approx -Vs$) for a solid 'off' condition. An op-amp comparator with a large amount of hysteresis was employed to eliminate spurious output transitions caused by drift, light spots (stones) in the pavement, and dark or dirty spots on the baseball plates. The output was then inverted by the FET to produce a low voltage (0V) representing an on condition, and a high voltage (15V) representing an off condition. Note that this inversion was only necessary due to the input requirements of the ramp switching and trigger ICs in the analysis system.

Analysis System

Concept

The analysis system uses the on - off signals generated by the sensors, produces a time-on voltage ($V_t = fn(t)$) and computes the lateral position as a function of the two time-on signals. The system can be derived as follows:

The baseball plate, axes, and signal orientation are as shown in figure C-2. The times t_1, t_2, and t_3 represent the time that the sensor produces an on signal.

The system can be described in two distinct states. One in which $t_1=0$, $t_2\neq0$, $t_3\neq0$, or $t_1\neq0$, $t_2\neq0$, and $t_3=0$. In either case we can define the distance x_i for each transducer as the length of the plate minus the distance the sensor was on the plate, and relate each x_i to plate geometry, time, and velocity as:

$$\text{if } t_1 \neq 0 \text{ then } x_1 = [a+W/\Delta] - t_1 v$$

$$\text{if } t_2 \neq 0 \text{ then } x_2 = [a+W/\Delta] - t_2 v$$

$$\text{if } t_3 \neq 0 \text{ then } x_3 = [a+W/\Delta] - t_3 v$$

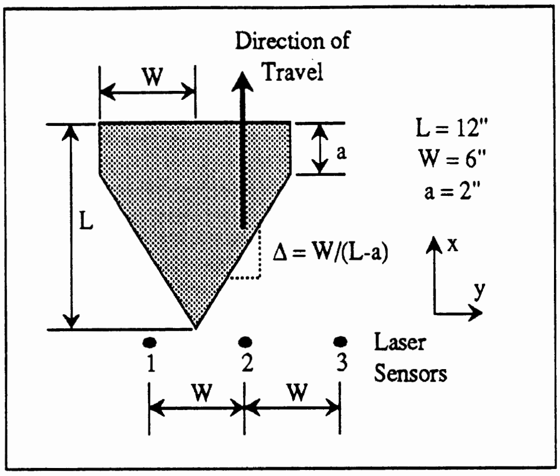


Figure C-2. Baseball plate, axes, and signal orientation

For each case in these equations m and n represent the two sensors which are used with m being the left-most sensor and n is the right-most sensor, and can be defined as:

$$\text{if } t_1 = 0 \quad \text{then} \quad m = 2, \; n = 3$$

$$\text{if } t_3 = 0 \quad \text{then} \quad m = 1, \; n = 2$$

If y_m and y_n are the lateral positions of the sensors m and n, respectively, we can define the relationship

$$y_n - y_m = W$$

and we can also define y_{ref} as the midpoint between the two active sensors, m and n, as

$$y_{ref} = \frac{y_m + y_n}{2}$$

The equations for y_m and y_n are linearly related to x_m and x_n, respectively, by using the slope of the plate's leading edges and the equations:

$$y_m = -\Delta x_m$$

$$y_n = \Delta x_n$$

Substituting the equations for x_i into each equation, one obtains:

$$y_m = -\Delta x_m = -\Delta\left[a + \frac{W}{\Delta} - t_m v \right]$$

$$y_n = \Delta x_n = \Delta\left[a + \frac{W}{\Delta} - t_n v \right]$$

Substituting for y_{ref} and simplifying,

$$y_{ref} = \frac{y_m + y_n}{2} = \frac{\Delta\,(t_m - t_n)\,v}{2}$$

The velocity variable is the only variable left to remove, and while the vehicle's velocity is available as a calibrated analog signal (and could thus simply be sampled and put into the equation) it is a source of noise and potential error. The velocity component can be removed, however, by using the geometry of the baseball plate and the time signals.

The velocity variable can be derived from the above equations for y_m and y_n :

$$y_m = -\,\Delta\left[\,a + \frac{W}{\Delta} - t_m v\,\right]$$

and

$$(y_m + W) \;= y_n = \Delta\left[\,a + \frac{W}{\Delta} - t_n v\,\right]$$

so

$$\frac{W}{\Delta} = 2a + \frac{2W}{\Delta} - v\,(t_m - t_n)$$

and solving for v,

$$v = \frac{2a + W/\Delta}{t_m + t_n}$$

Now, replacing v and solving for y_{ref}

$$y_{ref} = \frac{t_m - t_n}{t_m + t_n}\left[a\Delta + \frac{W}{2}\right]$$

Finally, by definition,

$$\text{if } t_1 = 0\text{, then } \; y_2 = y_{ref} - W/2$$

$$\text{if } t_3 = 0\text{, then } \; y_2 = y_{ref} + W/2$$

In order to simplify the circuit design, one can show that the two states are the negative of each other. If we define a constant $C_s = a\Delta + W/2$, then

$$\text{if } t_1 = 0,\ i=3; \quad y_2 = \frac{t_2 - t_i}{t_2 + t_i}\,C_s - \frac{W}{2}$$

and

$$\text{if } t_3 = 0,\ i=1; \quad y_2 = \frac{t_i - t_2}{t_2 + t_i}\,C_s + \frac{W}{2}$$

or

$$y_2 = -\frac{t_2 - t_i}{t_2 + t_i} C_s + \frac{W}{2}$$

so

$$y_2 = -\left[\frac{t_2 - t_i}{t_2 + t_i} C_s - \frac{W}{2}\right]$$

Therefore, the final system equations are the negative of each other with the sign dependent on the active sensor pair:

$$\text{when } t_1 = 0,\ i = 3;\quad y_2 = +\left[\frac{t_2 - t_i}{t_2 + t_i} C_s - \frac{W}{2}\right]$$

$$\text{when } t_3 = 0,\ i = 1;\quad y_2 = -\left[\frac{t_2 - t_i}{t_2 + t_i} C_s - \frac{W}{2}\right]$$

Main Components

The analysis system consists of 4 main components (see figure C-3): The signal timers, the off-path error timer, the function execution (summation, division, amplification and offsets), and the sign logic ("which side am I on?") components.

Signal Timer Circuits

The signal timers consisted of timing circuitry which generated a linear ramp function as

$$V_t\,(1 \text{ or } 3) = \text{fn (time sensor 1 or 3 is on)}$$

$$V_t\,(2) = \text{fn (time sensor 2 is on)}$$

The ramp voltage increased as a linear function of time as long as the sensor was in an on position. At the point where the sensor ceased to be on, the output voltage of the ramp was sampled and stored for use through the function circuitry. The output of the ramp then dropped to zero where it remained until the sensor provided another on signal.

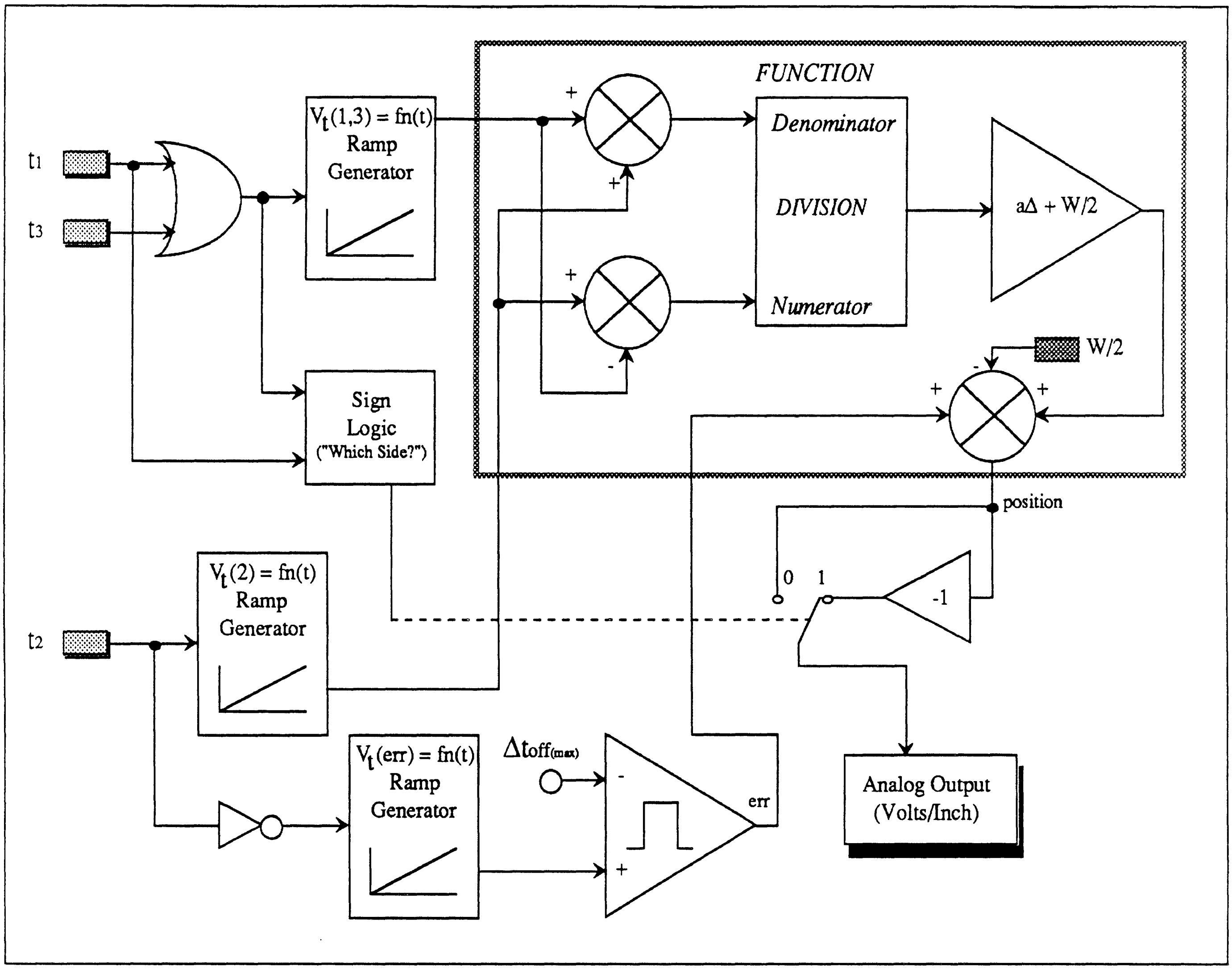


Figure C-3. Main components of the system

Off-Path Error Timer Circuit

The signal timer here consisted of timing circuitry, which generated a linear ramp function as

$$V_t(err) = \text{fn (time sensor 2 is off)}$$

The ramp voltage increased as a linear function of time as long as sensor 2 was in an off position. At the point where the sensor ceased to be off, the output of the ramp simply dropped to zero where it remained until the sensor provided another 'off' signal. If the voltage of the ramp were to increase to a value above a predetermined threshold, an error would be generated and added into the final position value. The threshold voltage was set such that if sensor 2 did not get a positive signal within a set time (in our case nominally within 25 feet @ 55 mph) the error signal would occur and would remain on until the sensor produced an 'on' signal.

Function Circuits

The functional circuitry executed the system's non-linear y_{ref} function of

$$y_{ref} = \frac{t_m - t_n}{t_m + t_n}\left[a\Delta + \frac{W}{2}\right] .$$

and combined with the logic circuits to produce the output

$$\text{when } t_1 = 0,\ i = 3;\ \ y_2 = +\left[\frac{t_2 - t_i}{t_2 + t_i} C_s - \frac{W}{2}\right]$$

$$\text{when } t_3 = 0,\ i = 1;\ \ y_2 = -\left[\frac{t_2 - t_i}{t_2 + t_i} C_s - \frac{W}{2}\right]$$

This component consisted of two summing junctions, a divider for division of the summed values, a gain amplifier to multiply the quotient by the constant in the velocity factor, and then the subtraction of an offset to complete the y_2 factor.

Sign Logic Circuits

The sign logic circuitry determined what sign the output of the function should be with each different state the sensors can be in. If sensor one was on, indicating the vehicle was to the right of center, the logic would provide an overall gain of +1 on the output of the system. If sensor three was on, indicating the vehicle was left of center, the logic would provide an overall gain of -1 to the output of the system. Note that this is opposite of the equations in order to provide a more intuitive polarity relationship.

Circuit Description (see Figures C-4 and C-5)

The first section of the analog circuitry performs the timing of the on and off signals from the sensors and generates a voltage corresponding to the length of this time. The ramp generation is performed by an op-amp connected with a capacitor as the feedback element and a shorting switch acting as the start and stop control. The on ramps generated a nominal linear output of Vout = 0.40 V/ms, and the off error ramp generated a nominal linear output of Vout = 0.021 V/ms. The peak ramp voltage (i.e. the voltage at the point where the signal went off) was sampled when the sensor signal went off, after which the ramp function was allowed to go to zero. The sampled voltage was held until the next patch was seen by the sensors, and new ramp voltages could be generated. Note that a new sample was taken only after the sensor signal returned to an off position, thus preserving the previous sample while the ramp was being generated. The one-shot circuitry provided the trigger for the sample-and-hold amplifier, and when combined with

ANALYSIS SYSTEM CIRCUIT

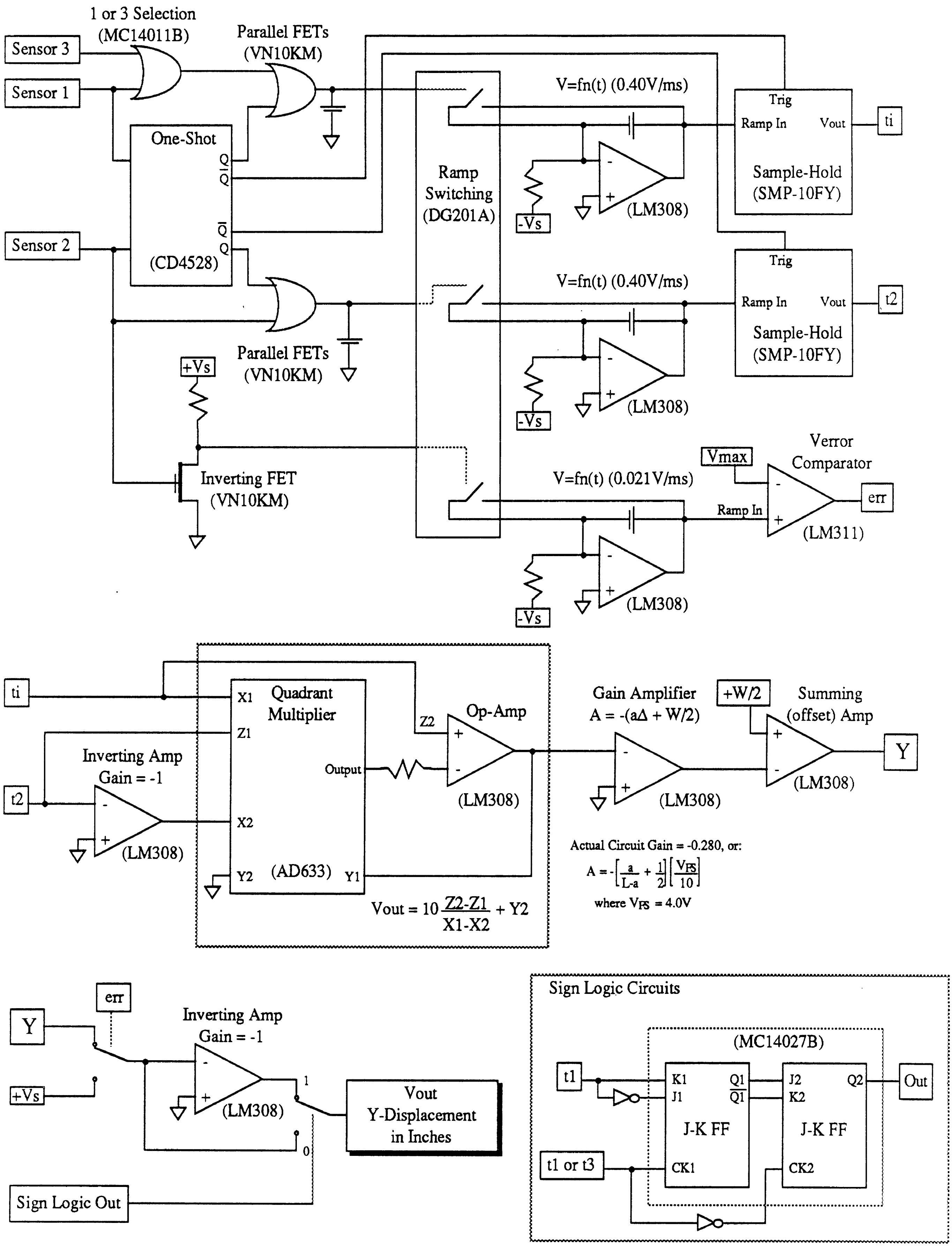


Figure C-4. Analysis system circuit

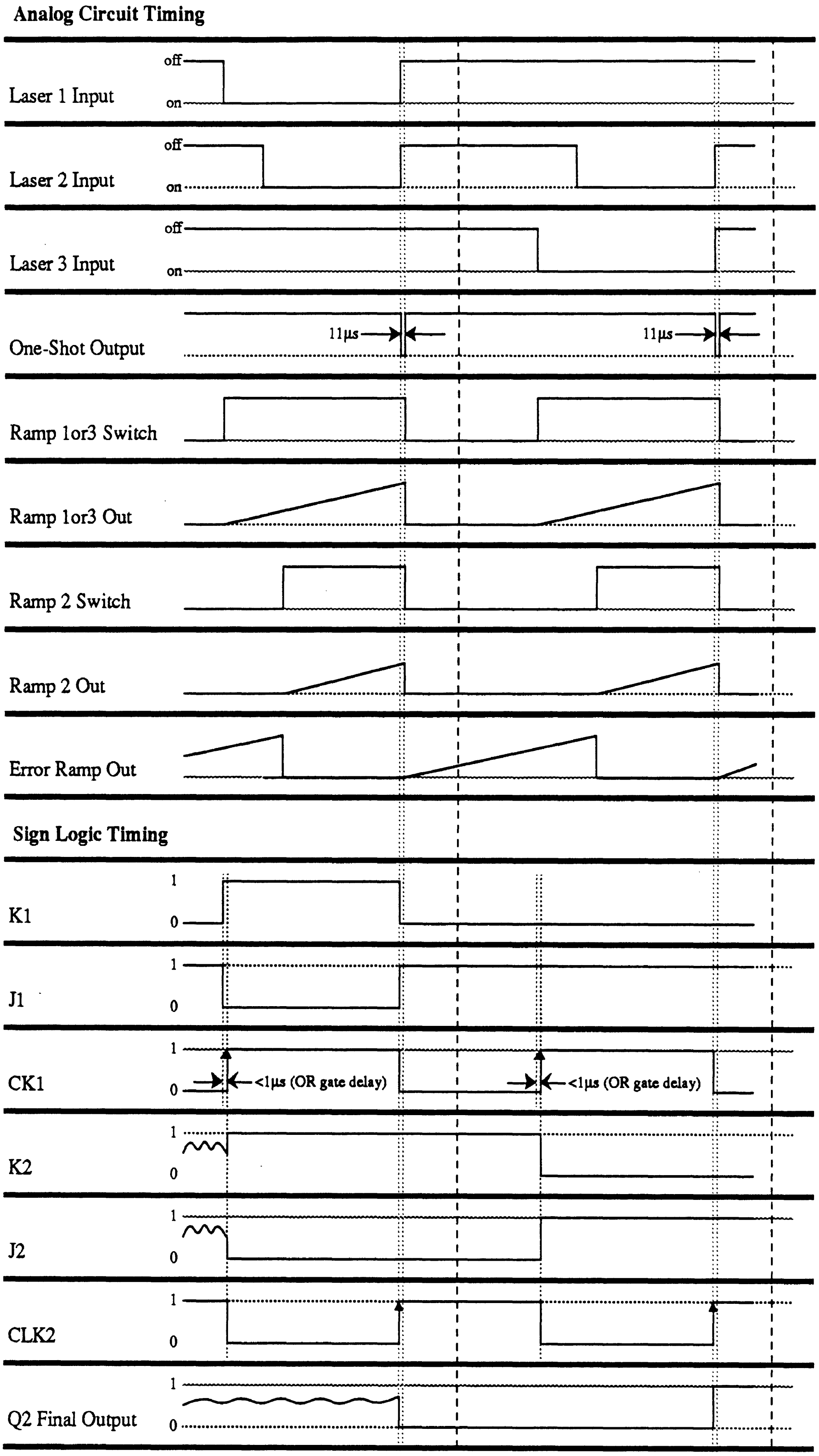


Figure C-5. Example timing diagram and wavewform

the or-gates (parallel FETs), provided the delay necessary to hold the ramp on while the sampling took place.

The voltage from the sample-hold amplifiers is the input to the function circuitry, which computes the displacement according to the system formulae. The multiplier has input amplifiers capable of performing the subtraction and addition functions of the system, and the division is accomplished by placing the multiplier in the feedback loop of an op-amp. The components used produced a gain of 10, which was taken into account in the next amplifier stage along with the scaling for Vfs (Volts - Full Scale) and the ($a\Delta+W/2$) multiplier factor. In this case, the Vfs was to be 4 volts (our system had the capability of digitizing 5 volts, but Vout > 4V was to represent an error signal). Finally the offset W/2 could be subtracted.

The final stage of the computation was the determination of the sign of the output signal, or the side of the path the vehicle was on. The sign logic circuitry consisted of two JK flip-flops with one acting as a decision maker and the other acting as a lock of that decision. The first flip-flop was set according to whether laser one was on or not, and was set at the onset of a path marker. The second flip-flop was set at the end of the same path marker and held the value determined by the first flip-flop. This value was thus present and available to the analog circuitry until updated at the end of the next path marker. This dual flip-flop configuration held the sign of the last computed value while new signals were being generated, and didn't allow the new sign to propagate through the circuitry until the sample-hold amplifiers had locked onto their respective new values.

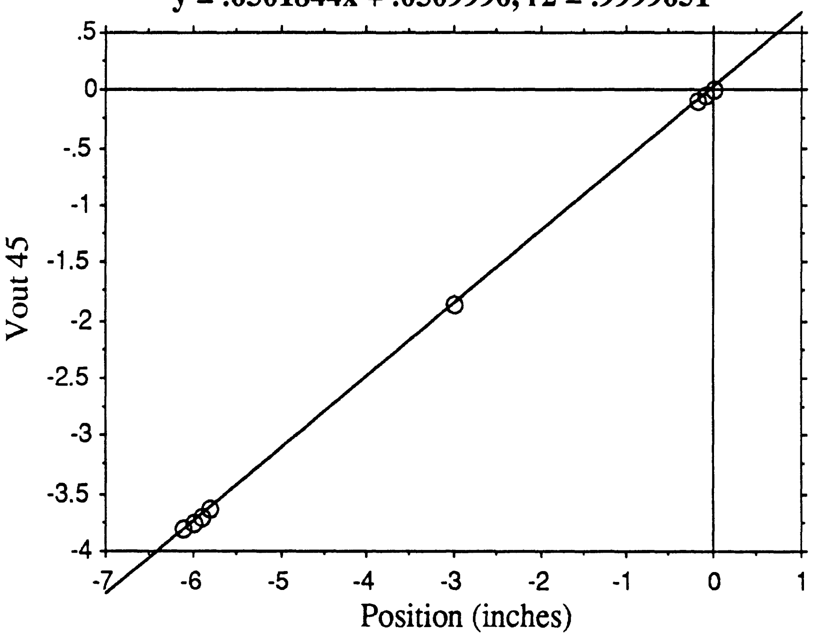
Calibrations

The components and values in the system were chosen to achieve a nominal calibration of ±4 Volts = ±6 inches. The surface of the wheel was painted black and baseball plates were painted on it on opposite sides of the wheel, with the circumferential distance between each plate being approximately 8 feet. The sensors were installed in their mounting bracket and this was suspended by a large calliper, which allowed accurate lateral positioning to be achieved.

Calibrations were performed at 45 mph and 55 mph, and also at ±2° of yaw rotation at 55 mph. The rotational aspect was to investigate what happened to the calibration if the sensors went over the plates at an angle (i.e. didn't exit at the same time), with +2° representing the right sensor (#3) exiting first, and -2° representing the left sensor (#1) exiting first.

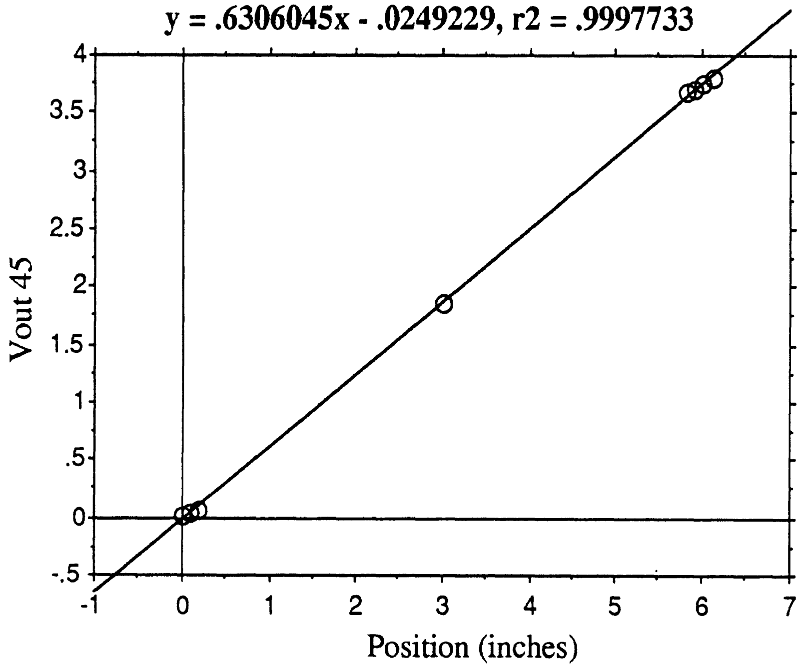
The design-intent gain value was 1.500 in/V, and the values from the calibrations vary from 1.53 in/V to 1.59 in/V. When the analysis circuit alone was calibrated with simulated timing signals, the gain was found to be 1.515 in/V. Plots of the calibration data follow.

Velocity = 45mph; Negative (left of center) position.



Residuals-V
.0131
.0001
-.0129
.0041
-.0104
.0150
.0020
-.0110

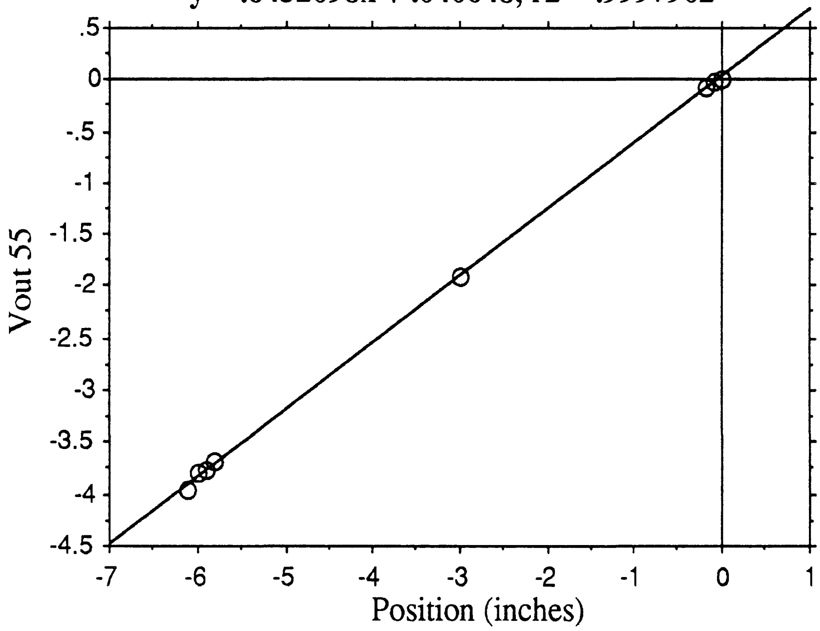
Velocity = 45mph; Positive (right of center) position.



Residuals-V
.0449
-.0081
-.0312
-.0169
.0374
.0044
-.0087
-.0218

Velocity = 55mph; Negative (left of center) position.

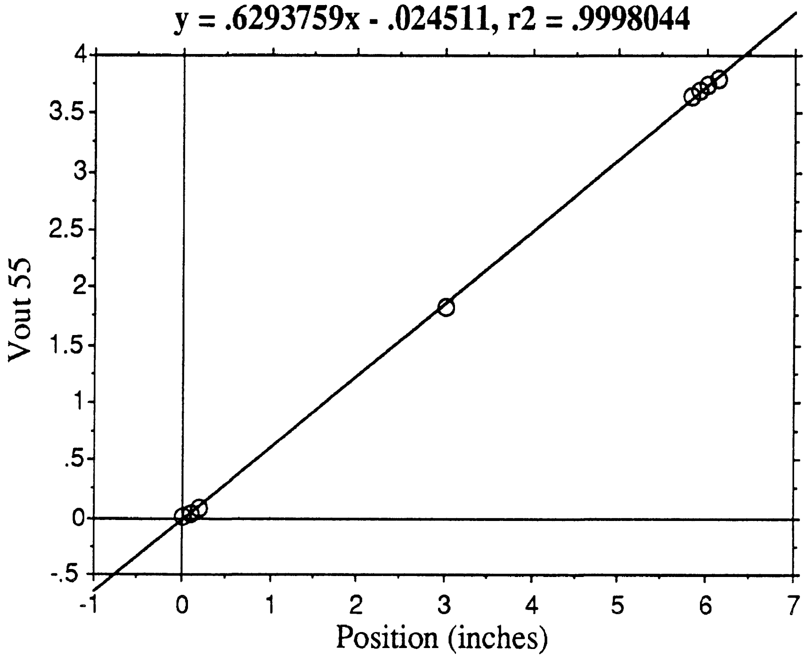
y = .6452098x + .040648, r2 = .9997902



Residuals-V
-.0549
.0306
.0161
.0116
-.0050
.0184
.0039
-.0206

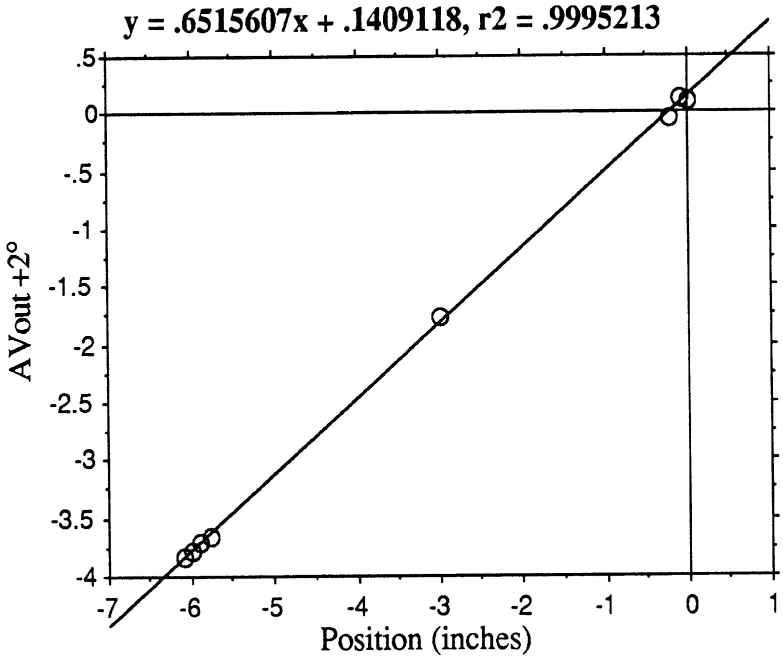
Velocity = 55mph; Positive (right of center) position.

y = .6293759x - .024511, r2 = .9998044



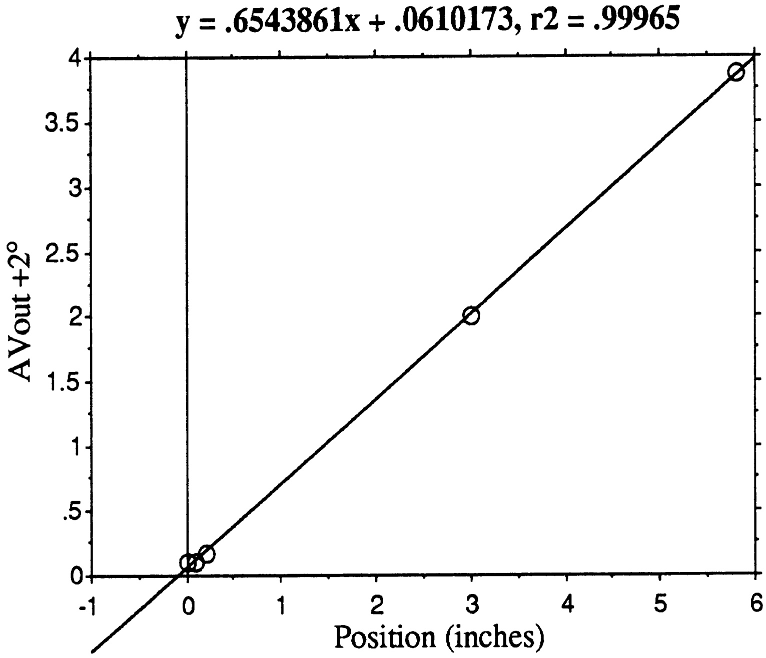
Residuals-V
.0445
-.0084
-.0214
-.0336
.0241
.0112
-.0017
-.0147

Velocity = 55mph, Angle=+2°; Negative (left of center) position.



Residuals-V
.0036
-.0115
-.0067
-.0119
.0538
-.0606
.0642
-.0309

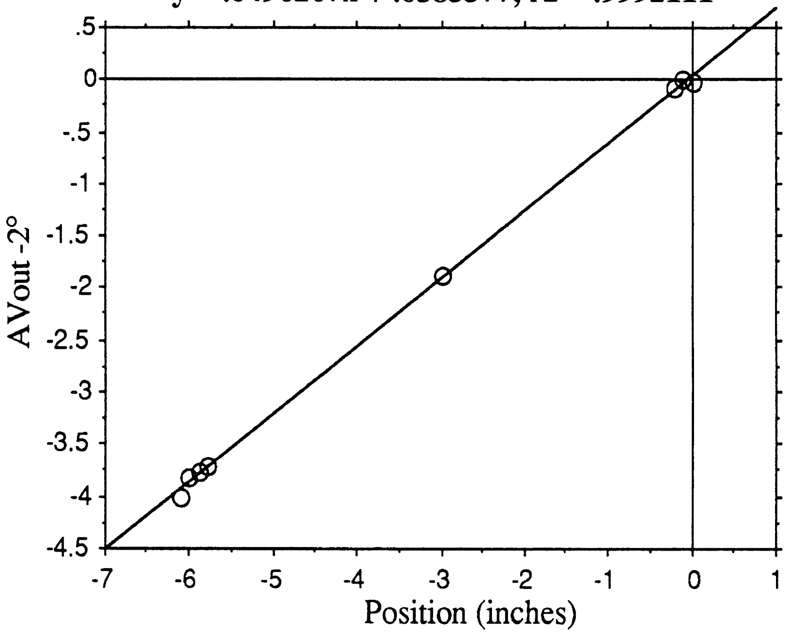
Velocity = 55mph, Angle=+2°; Positive (right of center) position.



Residuals-V
.0490
-.0165
-.0219
-.0242
.0135

Velocity = 55mph, Angle=-2°; Negative (left of center) position.

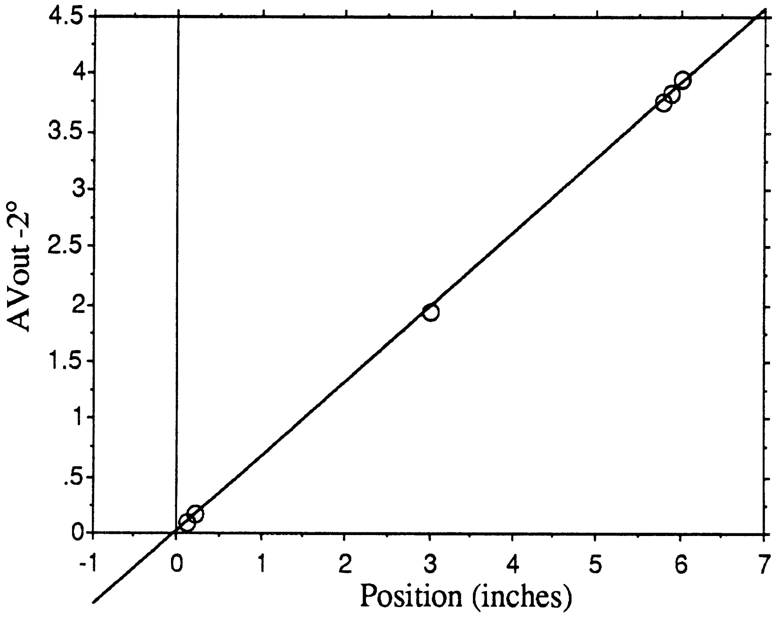
y = .6490207x + .0385577, r2 = .9992111



Residuals-V
-.0995
.0356
.0207
.0258
.0385
.0212
.0263
-.0686

Velocity = 55mph, Angle=-2°; Positive (right of center) position.

y = .64715x + .0316417, r2 = .9998682



Residuals-V
.0036
.0089
-.0231
-.0151
-.0098
.0355

Errors & Problems

Four distinct problems arose with the system during its short service, all of which became apparent during the latter parts of testing. One of the problems was related to the sensors, and the other three to the analysis system.

Sensor Problems

The choice of laser diodes presented two unique problems. The first problem was that the wavelength of light emitted was in the infrared region, making visual examination of the unit's health and alignment difficult. Secondly, UMTRI has no way of measuring or quantifying laser light, so power measurements were virtually impossible, making system diagnosis somewhat difficult.

The lasers in the sensor system were controlled by an adjustable voltage source. As stated earlier, the amount of voltage provided by the source required adjustment depending on the road surface, the ball plate conditions, and the particular laser diode being powered. Also, the mounting of the unit on the vehicle frame next to the engine caused high temperatures (sometimes too hot to touch) to affect the circuit's behavior, thus requiring frequent maintenance.

The two factors of the diode power control and the circuit's high maintenance made the output of the sensors a questionable factor. A laser diode that operates in the visible spectrum (such as Phillip's CQL90) was not available at the time of this project, however such a device would greatly enhance the visual inspection of a sensor's health and its functionality. Also, a better power control of the laser would be an improvement. The laser diodes, while specified to produce 2.5mW, actually can produce several times this much power. The design of the system in the early stages was done with a CQL30 laser which happened to have a relatively high power output capability. When later diodes, which produced less power (but still within manufacturing specs), were purchased and installed, they functioned in seemingly erratic ways. A current source rather than a voltage source may have provided better control, but ultimately a power-measuring device such as a photometer would have been ideal.

Analog Problems

During testing, the analog circuit also developed problems, two of which can be classified as environmental design flaws and one of which was a logic design flaw.

The first problem encountered was that of inaccurate data and a changing (increasing) gain. This was traced to the sample-hold amplifier circuits, which displayed radical dependencies on the humidity of the environment they were operating in. Heat itself did not seem to bother the circuitry, but the high humidity did. It is not known which component exactly was the problem as it could be the IC itself or the hold capacitor.

Potting this section of the circuit on both sides of the board may have helped, but this was not attempted due to time and material constraints.

The second problem developed within the last few days of testing. We had recently installed a monitoring device, which consisted of a cable to bring the transducer signals going into the analysis circuits out to a box containing LEDs, which could be put outside the vehicle for use in adjusting the response of the sensor units. The long cable (approximately 20 feet) connecting this box to the circuits acted as an antenna, creating noise in the error-detection signals and triggering the error voltage each time the sensors went off the path marker. The antenna properties stem from the location of the driver FETs for the LEDs, and the cable length.

The third problem, and perhaps the most preventable, was a flaw in the logic of the sign circuitry. While the sign produced is dependent on which sensors (1 or 3) are on, the actual dependence is on which of the two are on *first*. When the vehicle struck the timing marks, one of which was a rectangle, it would produce a positive or a negative sign, depending on the angle of attack. While this angle is nominally zero, it never was exactly zero, and alternating signs on the start and stop marks caused confusion in the subsequent data analysis. While the logic functions perfectly well and doesn't necessarily need to be changed, if the phenomenon had been known prior to the start of testing, timing marks other than rectangles could easily have been used.

APPENDIX D
APPROXIMATE DENSITIES OF VARIOUS TRUCK CARGO TYPES

The tabular presentations of cargo densities on the following pages were derived primarily from material presented in the *1973 Ford Truck Data Book* (Ford Marketing Corporation in Dearborn, Michigan). UMTRI's contribution has been to fill in many blanks in the density columns headed by "Lb. Per Cu. Ft." and "Per," and to add the additional "With Packing Factor" column. This latter column presents an estimate of the effective density of the named cargo, given that it is expected to be contained in packages whose density is different than the cargo itself or which necessarily leave empty space between packages (e.g. barrels).

No claims are made for the accuracy of the data presented. These data are presented simply as a demonstration that such figures are, or can be made, available. These data should not be used for any other purposes without further verification.

Product	Size Container	Lb. Per Cu. Ft.	No. of Lb.	Per	With Packing Factor
Acetone		50	6.6	gal.	-
Alabaster, gypseous		160	4320	cu. yd.	-
Alcohol, commercial		51	6.8	gal.	-
proof spirits		57	7.6	gal.	-
Alfalfa seed	bushel	48.2	60	bu.	37.9
Aluminum - pure (cast)		165	4450	cu. yd.	-
Andesita stone		180	4860	cu. yd.	-
Antimony		420	11350	cu. yd.	-
Apple (lumber)*		44	3670	M. Bd. ft.	-
Apples, fresh	basket-bushel	38.6	48	bu.	30.3
Western, box	11-1/2" x 12" x 20"	31.3	50	box	-
New England, box	11-1/4" x 14-1/2" x 17-1/2"	33.9	56	box	-
Standard barrel	17" hd., 28-1/2" stave	43.5	160	bbl.	34.2
Dried	bushel	19.3	24	bu.	15.2
Apricots, fresh	bushel	38.6	48	bu.	30.3
Western, box	5-1/2" x 12" x 20"	30.1	23	box	-
Artichokes, box	10" x 11-1/2" x 22"	30.1	44	box	-
Asbestos		153	4130	cu.yd.	-
Ash - black or red*		40	3330	M.Bd.ft.	-
white*		46	3830	M.Bd.ft.	-
Ashes, coal (packed)		45	1215	cu. yd.	-
Asparagus, crate					
Loose	11-1/2" high x9-3/4" top	28.4	38	crt.	-
Bunches	11" bottom x 19-3/8" long	23.2	31	crt.	-
Asphalt - brick		125	3375	cu. yd.	-
lump		85	2300	cu. yd.	-
paving		100	2700	cu. yd.	-
Asphalt - hot oil		71	9.5	gal.	-
Avocados - box	5-3/4" x 11-1/4" x 17-1/2"	24.4	16	box	-
Babbitt		440	11900	cu. yd.	-
Bamboo*		22	-	-	-
Bananas, single stem	bunch	-	45-65	bunch	-
Barley	bushel	38.6	48	bu.	30.3
Barytes, mineral		280	7560	cu. yd.	-
Basalt, rock		185	5000	cu. yd.	-
Basswood*		30	2500	M.Bd.ft.	-
Bauxite		160	4320	cu. yd.	-
Beans, dry - lima	bushel	45.0	56	bu.	35.3
white	bushel	48.2	60	bu.	37.9
castor	bushel	37.0	46	bu.	29.0
fresh - lima	bushel	31.3	39	bu.	24.6
string	bushel	28.9	36	bu.	22.7
	hamper, 5-peck	-	45	hamper	-
Beech*		30	2500	M.Bd.ft.	-
Beef, slack barrel	21" x 30" stave (200 lb. net)	42.2	254	barrel	33.2

*Kiln dried lumber averages 10% to 15% lighter and green lumber 40% to 50% heavier than air dried. All weights in the table are for air dried lumber.

Product	Size Container	Lb. Per Cu. Ft.	No. of Lb.	Per	With Packing Factor
Beer, wood barrel	1/2 barrel (16 gal.)	95.8	205	barrel	75.3
	1/4 barrel (8 gal.)	98.2	105	barrel	77.1
steel barrel	1/2 barrel (16 gal.)	88.8	190	barrel	69.8
	1/4 barrel (8 gal.)	88.8	95	barrel	69.8
Dutchman	1/8 barrel (4 gal.)	95.4	51	barrel	74.9
case carton - 24, 12-oz.					
regular bottles	17-1/4" x 11-1/2" x 9-7/8"	39.7	45	case	-
steinie bottles	18-3/8" x 12-1/8" x 7-3/8"	42.1	40	case	-
tin cans	16-1/4" x 11" x 5-1/8"	52.8	28	case	-
wooden case - 24,12-oz.					
regular bottles	21" x 13-1/2" x 10"	32.3	53	case	-
steinie bottles	22" x 13-3/4" x 7-1/2"	35.0	46	case	-
Beets	bushel	40.2-	50-60	bu.	31.6-
small crate	9-3/4" x 13-3/4" x 24"	48.2	50	crate	37.9
Western crate	14" x 19" x 24-1/2"	26.9	95	crate	-
		25.2			-
Berries - crate 24 pt	9-3/4" x 9-3/4" x 20"	22.7	25	crate	-
24 qt	11-3/4" x 11-3/4" x 24"	25.0	48	crate	-
32 qt	15-1/2" x 11-3/4" x 24"	24.9	63	crate	-
Birch*		48	4000	M.Bd.ft.	-
Bluegrass seed	bushel	35.4	44	bu.	27.8
Bluestone		120	3240	cu. yd.	-
Bone		115	3110	cu. yd.	-
Borax		110	2970	cu. yd.	-
Bran	bushel	16.1	20	bu.	12.6
Brass - cast		525	14175	cu. yd	-
rolled		534	14420	cu. yd.	-
drawn		542	14635	cu. yd	-
Brick -					
soft, 2-1/4" x 4" x 8-1/4"		100.5	4320	M	-
common, 2-1/4 x 4" x 8-1/4"		125.6	5400	M	-
hard, 2-1/4" x 4-1/4" x 8-1/2"		137.8	6480	M	-
pressed, 2-3/8 x 4" x 8-3/8"		162.9	7500	M	-
paving, 2-1/4" x 4" x 8-1/2"		152.5	6750	M	-
paving block, 3-1/2" x 4" x 8-1/2"		127.1	8750	M	-
fire, 2-1/2" x 4-1/2" x 9"		119.5	7000	M	-
Broccoli - bushel crate	12-3/4" x 12-3/4" x 17"	18.8	30	bu.	-
Bronze		550	14850	cu. yd.	-
Brussels sprouts, crate	7-3/4" x 10-1/2" x 21-3/8"	25.8	26	crate	-
Buckwheat	bushel	39.4	49	bu.	30.9
Butter-tub, small	15" dia x 5-1/4"	46.6	25	tub	36.6
standard	15" dia. x 15"	45.6	70	tub	35.8
case, 30-1-lb. bricks	10-1/4" x 8-3/4" x 10-1/2"	58.7	32	case	-
9-lb. pail	pail (assume small tub)	~46	10	pail	~36
Butternut (lumber)*		30	2500	M.Bd.ft.	-
Cabbage	bushel	30.5	38	bu.	24.0
hamper	1-1/2 bushel	31.1	58	hamper	24.4
crate	12-3/4" x 18-1/2" x 19"	23.1	60	crate	-
Western crate	14" x 19" x 24-1/2"	22.5	85	crate	-
bbl. crate	12-3/4" x 18-3/4" x 37-3/8"	21.3	110	crate	-
Calf, live (average)	per head	-	140-160	head	-
Cantaloupe, crate -					
Pony	11-3/4" x 11-3/4" x 23-1/2"	30.9	58	crate	-
Standard	12-3/4" x 12-3/4" x 23-1/2"	30.8	68	crate	-
Jumbo	13-3/4" x 13-3/4" x 23-1/2"	30.3	78	crate	-
Pony flat	4-3/4" x 12-3/4" x 23-1/2"	31.6	26	crate	-
Standard flat	5-1/4" x 14-1/4" x 23-1/2"	27.5	28	crate	-
Jumbo flat	5-3/4" x 15-1/4" x 23-1/2"	26.8	32	crate	-
Honeydew (Casaba)	6-3/8" x 15-1/8" x 23-1/2"	26.7	35	crate	-
Carbolic acid		60	8.0	gal.	-

NOTE: Beer cases vary as to size and shape. Suggest checking with local source.

Product	Size Container	Lb. per Cu. Ft	No. of Lb.	Per	With Packing Factor
Carrots - topped	bushel	44.2	55	bu.	34.7
with tops	bushel	32.1	40	bu.	25.2
crate	11-3/4" x 14-1/8" x 24"	26.0	60	crate	-
Castor oil		61	8.1	gal.	-
Cauliflower	bushel	24.1	30	bu.	18.9
crate	9-3/8" x 19" x 24"	20.2	50	crate	-
Cedar*		30	2500	M.Bd.ft.	-
Celery - Standard crate	11-5/8" x 22" x 22-5/8"	20.9	70	crate	-
one-half crate	10-3/4" x 13" x 20-3/8"	21.2	35	crate	-
Northern crate	16-1/2" x 21-1/4" x 22"	19.0	85	crate	-
Cement Block - 8" x 8" x 16"		70.9	42	each	-
8" x 12" x 16"		65.3	58	each	-
Cement, Portland	sack	302.1	94	sack	-
(4 sacks per barrel)		302.1	376	barrel	-
Chalk		137	3700	cu. yd.	-
Charcoal - oak		33	890	cu. yd.	-
pine		23	620	cu. yd.	-
Cheese - box (small)	15" dia. x 5-1/4"	46.6	25	box	36.6
box (medium)	15" dia. x 7-1/2"	45.6	35	box	35.8
box (large)	15" dia. x 15"	45.6	70	box	35.8
Cherries - unstemmed	bushel	45	56	bu.	35.3
stemmed	bushel	51.4	64	bu.	40.4
lug box	5-5/8" x 11-7/8" x 19-3/4"	22.3	17	box	-
Cherry (lumber)*		44	3670	M.Bd.ft	-
Chestnut (lumber)*		37	3080	M.Bd.ft	-
Chestnuts	bushel	40.2	50	bu.	31.6
Chickens					
Live, broilers (20 avg.)	Std. crate	9.2	58	crate	-
fowl (12 avg.)	Std. crate	12.3	78	crate	-
Std. crate, empty	24" x 35" x 13"	2.8	18	crate	-
Chloroform		95	12.7	gal.	-
Cinder Blocks -					
8" x 8" x 16"		59.1	35	each	-
8" x 12" x 16"		50.6	45	each	-
Cinders		50	1350	cu. yd.	-
Clay - dry lumps		85	2300	cu. yd.	-
wet lumps		110	2970	cu. yd.	-
wet packed		135	3650	cu. yd.	-
fire		125	3375	cu. yd.	-
Clover seed	bushel	48.2	60	bu.	37.9
Coal - anthracite:					
pea		56	1510	cu. yd.	-
chestnut		53	1430	cu. yd.	-
large egg		53	1430	cu. yd.	-
small egg		55	1485	cu. yd.	-
range		55	1485	cu. yd.	-
coke		27	730	cu. yd.	-
charcoal		20-30	540-810	cu. yd.	-
peat		47-52	1270-1405	cu. yd.	
Coal - bituminous"					
egg		55	1485	cu. yd.	-
nut		48	1295	cu. yd.	-
stove		56	1515	cu. yd.	-
lump		50	1350	cu. yd.	-
screenings		52	1405	cu. yd.	-
Coal - cannel		50	1350	cu. yd.	-
Coconuts, burlap bag					
(100 lb.)	bag		160	bag	-
Coconut oil		58	7.8	gal.	-

Product	Size Container	Lb. per Cu. Ft	No. of Lb.	Per	With Packing Factor
Concrete - cinder or slag		120	3240	cu. yd.	-
gravel or stone		150	4050	cu. yd.	-
average wet mix		138	3730	cu. yd.	-
Copper - cast		550	14850	cu. yd.	-
rolled		560	15120	cu. yd.	-
Cork		15	405	cu. yd.	-
Corn - ear	bushel	28.2	35	bu.	22.1
shelled	bushel	45.0	56	bu.	35.8
sweet corn (green)	bushel	34.6	43	bu.	27.2
crate	12-7.8" x 12-7/8" x 24"	26.1	60	crate	-
Corn meal	bushel	35.4	44	bu.	27.8
Corn oil		58	7.8	gal.	-
Corn syrup		86	11.5	gal.	-
Cotton-gin bale	30" x 48" x 54"	11.4	515	bale	-
std. bale	24" x 28" x 56"	23.6	515	bale	-
comp. bale	20" x 24" x 56"	33.1	515	bale	-
Cotton seed	bushel	25.7	32	bu.	20.2
Cottonseed oil		58	7.8	gal.	-
Cottonwood (lumber)*		37	3080	M.Bd.ft.	-
Cow, live-feeder (avg.)	per head	-	600	head	-
butcher (avg.)	per head	-	800	head	-
heavy steer (avg.)	per head	-	1110	head	-
Cranberries - 1/4 bbl. box	9-1/2" x 11" x 14"	33.1	28	box	-
1/2 bbl. box	12-1/4" x 14-3/4" x 22"	26.1	60	box	
Cream		64	8.5	gal.	-
Creosote		68	9.2	gal.	-
Crude oil		56	7.5	gal.	-
Crushed stone (avg.)		100	2700	cu. yd.	-
Cucumbers	bushel	44.2	55	bu.	34.7
crate	9-3/4" x 13-3/4" x 24"	40.3	75	crate	-
case	5" x 13-1/4" x 19"	35.7	26	case	-
Cypress*		30	2500	M.Bd.ft.	-
Diabase		185	5000	cu. yd.	-
Dolomite		181	4890	cu. yd.	-
Earth - loose, dry loam		76	2050	cu. yd.	-
packed		95	2565	cu. yd.	-
wet		125	3375	cu. yd.	-
Eggplant - hamper	bushel	32.1	40	bu.	25.2
crate	14" x 11-3/4" x 24"	23.6	54	crate	-
Eggs, 30 doz. crate	12" x 12" x 26"	25.4	55	crate	-
Elm - soft*		38	3170	M.Bd.ft	-
rock*		45	3750	M.Bd.ft	-
Emery		250	6750	cu. yd.	-
Endive - basket	bushel	20.1	25	bu.	15.8
hamper	1-1/2 bushel	19.3	36	hamp.	15.1
Ether		46	6.2	gal.	-
Feldspar		160	4320	cu. yd.	-
Fertilizer, commercial	burlap bag	-	100-125-150-200	bag	-
Fir - Douglas		32	2670	M.Bd.ft	-
Eastern		25	2080	M.Bd.ft	-
Fish, fresh - barrel	19" head, 29" stave	63.0	300	barrel	49.5
1/2 barrel	18-1/2" head, 23-1/2" stave	43.8	160	1/2 bbl.	-
Flaxseed	bushel	45.0	56	bu.	35.3
Flint		185	5000	cu. yd.	-
Flour - barrel	19-1/8" head, 30" stave	43.1	215	barrel	33.9
Fuel oil - Furnace grade		56	7.5	gal.	-
Diesel engine		52	7.0	gal.	-
Furniture, Household		7	1915	cu. yd.	-

Product	Size Container	Lb. per Cu. Ft	No. of Lb.	Per	With Packing Factor
Garbage - dry, paper wrapped wet		15-30 50	405-810 1240	cu. yd. cu. yd.	- -
Gasoline		45	6.0	gal.	-
Glass - common window plate or crown 1/4" plate		162 161 158.4	162 161 3.3	cu. ft. cu. ft. sq. ft.	Probably not shipped at this density
Glue		80	2160	cu. yd.	-
Glycerine		79	10.5	gal.	-
Gneiss - solid crushed		160 95	4320 2565	cu. yd. cu. yd.	- -
Grapefruit - Western box Southern box	11-1/2" x 11-1/2" x 24" 12-3/4" x 12-3/4" x 27"	37.0 35.4	68 90	box box	- -
Grapes - basket lug box Western keg basket	bushel 5-5/8" x 16-3/8" x 17-1/2" 15-1/2" dia. x 14" 12 quart	38.6 32.2 29.4 38.6	48 30 45 18	bu. box keg bask.	30.3 - - 30.3
Granite - solid crushed		175 96	4725 2590	cu. yd. cu. yd.	- -
Graphite		170	4590	cu. yd.	-
Gravel - dry wet		95 125	2565 3375	cu. yd. cu. yd.	- -
Greens	bushel	20.1	25	bu.	15.8
Greenstone - solid crushed		187 107	5050 2900	cu. yd. cu. yd.	- -
Groceries - Misc. assorted		30	810	cu. yd.	-
Gum (lumber)*		40	3330	M.Bd.ft.	-
Gypsum		150	4050	cu. yd.	-
Hay, bale bale bale	26" x 30" x 46" 17" x 22" x 43" 14" x 16" x 43"	10.1 12.4 15.2	210 115 85	bale bale bale	7.9 9.7 12.0
Hemlock*		29	2420	M.Bd.ft	-
Hemp seed	bushel	35.4	44	bu.	27.8
Hickory (lumber)*		54	4500	M.Bd.ft.	-
Hickory nuts	bushel	36.2	45	bu.	28.4
Hog, live (average)	per head	-	225-250	hd.	-
Honey		90	12.0	gal.	-
Hornblende		187	5050	cu. yd.	-
Horse, live (average)	per head	-	1200-1500	hd.	-
Horseradish roots	bushel	28.1	35	bu.	22.1
Ice		57	1540	cu. yd.	-
Ice (mfg.) - block block block	11" x 22" x 32" 14" x 14" x 40" 11" x 22" x 56"	55.8 56.2 56.1	250 255 440	block block block	- - -
Ice cream - 2-1/2 gal. can., full empty 5 gal. can, full empty	 9" dia. x 11" 9" dia. x 21" 	 44.4 14.8 45.3 14.2	 18 6 35 11	 can can can can	 34.9 11.6 35.6 11.2
Iron - cast (pig) wrought		450 485	12150 13100	cu. yd. cu. yd.	- -
Ivory		120	3240	cu. yd.	-
Kale	bushel	20.1	25	bu.	-
Kerosene		50	6.6	gal.	-
Lamb, live (avg.)	per head	-	75-85	hd.	-
Lard - barrel	18-3/4" head, 30" stave	88.7	425	barrel	69.6
Lath - standard length 39 in.	Packed in bundles of 50. Avg. bundle - dia. 9 in.	23.4	25	bundle	18.4
Lead - cast		710	19170	cu. yd.	-

Product	Size Container	Lb. per Cu. Ft	No. of Lb.	Per	With Packing Factor
Leather - dry		55	1485	cu. yd.	-
greased		65	1755	cu. yd.	-
Lemons - Western box	10" x 13" x 25"	42.5	80	box	-
Southern box	12-3/4" x 12-3/4" x 27"	35.4	90	box	-
Lentils	bushel	48.2	60	bu.	37.9
Lettuce - hamper	bushel	20.1	25	bu.	15.8
hamper	1-1/2 bushel	20.4	38	hamp.	16.0
basket	8-1/2" x 11-3/4" x 21-3/8"	13.8	17	bask.	-
crate	13-3/4" x 17-1/2" x 24-1/2"	22.0	75	crate	-
1/2 crate	9-1/2" x 13-1/2" x 24-1/2"	22.0	40	1/2 crt.	-
Lime, hydrated	bushel	24.1	30	bu.	18.9
barrel (small)	16-1/2" head, 27-1/2" stave	62	210	barrel	-
barrel (large)		62	320	barrel	-
Limes, Western box	10" x 13" x 25"	42.5	80	box	-
Southern box	12-3/4" x 12-3/4" x 27"	35.4	90	box	-
Limestone - solid		166	4480	cu. yd.	-
crushed		95	2565	cu. yd.	-
Linseed oil		59	7.9	gal.	-
Locust (lumber)*		42	3500	M.Bd.ft.	
Lubricating oil		52	7.0	gal.	-
Magnesite		187	5050	cu. yd.	-
Mahogany*		42	3500	M.Bd.ft.	-
Malt - barley	bushel	22.5	28	bu.	17.7
rye	bushel	25.7	32	bu.	20.2
brewer's grain	bushel	32.1	40	bu.	25.2
Manganese		475	12825	cu. yd.	-
Maple syrup	gallon	82	11	gal.	-
Maple - hard (lumber)*		44	3670	M.Bd.ft.	-
soft*		34	2830	M.Bd.ft.	-
Marble - solid		165	4455	cu. yd.	-
crushed		95	2565	cu. yd.	-
Meal - corn	bushel	35.4	44	bu.	27.8
Mercury		850	-	cu. ft.	-
Mica		185	5000	cu. yd.	-
Milk, bulk		64	8.6	gal.	-
Milk - 5-gallon can	10-1/4" dia. x 19"	68.3	62	can	53.7
10-gallon can	13" dia. x 23"	65.1	115	can	51.1
crate - 20 1/2-pt. bottles	8-1/2" x 12-3/4" x 16-3/4"	31.4	33	can	-
20 pt. bottles	8-1/2" x 12-3/4" x 16-3/4"	51.4	54	crate	-
12 qt. bottles	10-3/4" x 14-1/4" x 18-1/4"	39.6	64	crate	-
Millet	bushel	40.2	50	bu.	31.6
Molasses		90	12	gal.	-
barrel (50 gal.)	20-1/4" head, 34" stave	106.5	675	barrel	83.7
Mortar - lime		110	2970	cu. yd.	-
Mud - flowing		106	2860	cu. yd.	-
packed		125	3375	cu. yd.	-
Muriatic acid, 40%		40	10	gal.	-
Naphtha, petroleum		42	5.6	gal.	-
Nickel		537	14500	cu. yd.	-
Nitric acid, 91%		94	12.5	gal.	-
Oak - red, black*		42	3500	M.Bd.ft	-
white*		48	4080	M.Bd.ft.	-
Oats	bushel	25.7	32	bu.	20.2
Okra - hamper	1/2 bushel	28.9	18	hamp.	22.7
hamper	bushel	27.3	34	bu.	21.5
Oleomargarine (mfg.-tub)	21" head, 34" stave	10.3	70	tub	8.1
cases			15-25-35-65	case	-
Olive oil		58	7.7	gal.	-

Product	Size Container	Lb. per Cu. Ft	No. of Lb.	Per	With Packing Factor
Onions					
dry-basket	bushel	44.2	55	bu.	34.7
bag	17" x 32"	-	50	bag	-
crate	20-1/2" x 11-1/2" x 10-1/2"	40.5	58	crate	31.8
green (with tops)	bushel	25.7	32	bu.	20.2
Oranges - Western box	11-1/2" x 11-1/2" x 24"	43.6	80	box	-
Southern box	12-3/4" x 12-3/4" x 27"	35.4	90	box	-
bushel box	10-3/4" x 10-3/4" x 23-1/2"	41.4	65	box	-
Oysters (shucked or meats)					
crate - with 5.1-gal. cans					
(11-1/2 lb. per gal.)	18" x 12" x 24"	22.3	67	crate	-
- with shells (bags)	bushel	60.3	75	bu.	47.3
Paint, lead and oil		127	17	gal.	-
Paper - average solid		58	1565	cu. yd.	-
newspaper rolls	34-1/2" x 35" dia.	26.0	500	roll	20.4
	51-1/2" x 35" dia.	34.9	1000	roll	27.4
	64-1/4" x 35" dia.	36.3	1300	roll	28.5
Paraffin		56	1510	cu. yd.	-
Parsley - bushel crate	12-3/4" x 12-3/4" x 17"	18.6	30	crate	-
Parsnips	bushel	40.2	50	bu.	31.6
Peaches - basket	bushel	38.6	48	bu.	30.3
basket	1/2 bushel	40.2	25	bask.	31.6
crate	10-1/2" x 11-1/4" x 24"	30.5	50	crate	-
Western box	5-1/2" x 12-1/4" x 19-3/4"	28.6	22	box	-
Peanuts, unshelled	bushel	17.3	22	bu.	13.6
bag		-	100	bag	-
Peanut oil		57	7.6	gal.	-
Pears - basket	bushel	40.2	50	bu.	31.6
Western box	9-5/8" x 12-1/8" x 19-3/4"	38.2	51	box	-
Peas - dry	bushel	48.2	60	bu.	37.9
fresh hamper	bushel	56.2	35	hamp.	44.2
hamper	40 qts.	72.3	45	hamp.	56.8
Pecans - large bag		-	100	bag	-
small bag		-	50	bag	-
Peppers - basket	bushel	20.1	25	bask.	15.8
crate	14-1/8" x 11-3/4" x 24"	19.5	45	crate	-
Petroleum		56	7.5	gal.	-
Phosphate rock		200	5400	cu. yd.	-
Pine - long leaf*		44	3670	M.Bd.ft.	-
North Carolina*		36	3000	M.Bd.ft	-
Oregon*		32	2670	M.Bd.ft.	-
red*		30	2500	M.Bd.ft.	-
white*		26	2170	M.Bd.ft.	-
yellow - long leaf*		44	3670	M.Bd.ft.	-
short leaf		38	3170	M.Bd.ft	-
Pineapples - crate	11" x 12-1/2" x 36"	29.7	85	crate	-
Pitch		70	1900	cu. yd.	-
Plaster of Paris		100	2700	cu. yd.	-
Plums - basket	bushel	45.0	56	bu.	35.3
Western box	5-5/8" x 16-3/8" x 17-1/2"	26.8	25	box	-
Pomegranates - box	6-1/2" x 12" x 24-5/8"	27.0	30	box	-
Popcorn - ear	bushel	56.2	70	bu.	44.2
shelled	bushel	45.0	56	bu.	35.3
Poplar*		27	2250	M.Bd.ft.	-
Porcelain		150	4050	cu. yd.	-
Pork (dressed) - barrel					
(200 lb. net)	18" head, 29" stave	56.2	240	barrel	44.2
Porphyry		172	4645	cu. yd.	-

Product	Size Container	Lb. per Cu. Ft.	No. of Lb.	Per	With Packing Factor
Potatoes - sweet	bushel	44.2	55	bu.	34.7
white or Irish	bushel	48.2	60	bu.	37.9
bag	1-2/3 bu.	49.2	102	bag	-
barrel	17-1/8" head, 28-1/2" stave	48.7	185	barrel	38.2
Prunes - box	5-5/8" x 16-3/8" x 17-1/2"	26.8	25	box	-
box	5-5/8" x 11-7/8" x 19-3/4"	28.8	22	box	-
Pumice		40	1080	cu. yd.	-
Pyrites		315	8500	cu. yd.	-
Quartz		165	4455	cu. yd.	-
Quicklime - solid		95	2565	cu. yd.	-
ground - loose		55	1485	cu. yd.	-
shaken		75	2030	cu. yd.	-
Quinces	bushel	40.2	50	bu.	31.6
Radishes - basket	bushel	27.3	34	bu.	21.5
crate	9-3/4" x 13-3/4" x 24"	21.5	40	crate	-
Redwood*		30	2500	M.Bd.ft.	-
Resin		68	1835	cu. yd.	-
Rhubarb (pie plant)	bushel	40.2	50	bu.	31.6
box	5-1/4" x 11-1/2" x 22"	31.2	24	box	-
Rice, unhulled	bushel	34.6	43	bu.	27.1
Rip-rap stone		65	1755	cu. yd.	-
Rock, crushed (avg.)		100	2700	cu. yd.	-
Romaine - crate	13-7/8" x 18-7/8" x 24-1/2"	17.2	64	crate	-
crate	12-1/4" x 13" x 15-1/4"	19.2	27	crate	-
Rubber goods		94	2540	cu. yd.	-
Rutabagas	bushel	45.0	56	bu.	35.3
Rye	bushel	45.0	56	bu.	35.3
Salt - rock, solid		136	3670	cu. yd.	-
coarse		45	1215	cu. yd.	-
fine		50	1350	cu. yd.	-
barrel (avg.)		280	225	barrel	17.6
Saltpeter		69	1860	cu. yd.	-
Sand - fine - dry		110	2970	cu. yd.	-
wet		125	3375	cu. yd.	-
course-dry		95	2565	cu. yd.	-
wet		120	3240	cu. yd.	-
mixed		115	3100	cu. yd.	-
Sandstone - solid		147	3970	cu. yd.	-
crushed		86	2325	cu. yd.	-
Shale - solid		172	4645	cu. yd.	-
crushed		92	2485	cu. yd.	-
Sheep, live (avg.)	per head	-	125-150	head	-
Shingles - packed in bundles of 200-250.	Size of bundle (avg.) 24" x 20" x 10"	18.0	50	bundle	-
Shorts	bushel	16.1	20	bu.	12.6
Silica		135	3650	cu. yd.	-
Slag - furnace		125	3375	cu. yd.	-
crushed		75	2025	cu. yd.	-
screenings		100	2700	cu. yd.	-
sand		50	1350	cu. yd.	-
Slate		175	4725	cu. yd.	-
Snow, moist-packed		50	1350	cu. yd.	-
Soapstone (talc)		169	4565	cu. yd.	-
Soft drinks - half depth bottle box 24-6 to 8 oz. bottles	12-1/4" x 18-3/4" x 8-1/2"	34.5	39	box	-
full depth bottle box 2- 24 to 32 oz bottles	13-3/8" x 18-1/2" x 12-1/4"	34.2	60	box	-
Sorghum syrup		86	11.5	gal.	-
Soybeans	bushel	48.2	60	bu.	37.9
Soybean oil		58	7.7	gal.	-

Product	Size Container	Lb. per Cu. Ft.	No. of Lb.	Per	With Packing Factor
Spinach - hamper	bushel	16.1	20	bu.	12.6
basket	bushel	21.7	27	basket	17.0
Spruce*		28	2330	M.Bd.ft.	-
Squash	bushel	37.0	46	bu.	29.0
Starch		96	2590	cu. yd.	-
Steel - cast		490	13230	cu. yd.	-
rolled		495	13365	cu. yd.	-
Steer (see Cow)					
Stone - crushed (avg.)		100	2700	cu. yd.	-
rip-rap		65	1755	cu. yd.	-
Straw - bale	17" x 22" x 42"	12.1	110	bale	-
bale	26" x 30" x 46"	8.7	180	bale	-
Street sweepings		32	865	cu. yd.	-
Sugar		100	2700	cu. yd.	-
Sugar - bag (100 lb. net)		-	101	bag	-
barrel (22 lb. empty)	19-1/8" head, 30" stave	69.2	345	barrel	54.3
case 24-5-lb. cartons		-	135	case	-
case 60-2-lb. cartons		-	135	case	-
Sugar cane syrup		85	11.3	gal.	-
Sulphur		125	3375	cu. yd.	-
Sulfuric acid, 87%		112	15	gal.	-
Sweet corn - basket	bushel	36.2	45	bu.	28.4
crate	13" x 13" x 24"	25.6	60	crate	-
Sycamore*		37	3080	M.Bd.ft.	-
Tallow		60	1620	cu. yd.	-
Tanks -					(lb/ft^2 of floor area)
Acetylene	102 cu. ft - Empty	157.5	70	tank	123.7
	-Filled	168.8	75	tank	132.6
	310 cu. ft. - Empty	200	200	tank	157.1
	- Filled	220	220	tank	172.8
Oxygen	150 cu. ft. - Empty	180	80	tank	141.4
	- Filled	207	92	tank	162.6
	300 cu. ft. - Empty	133	133	tank	104.5
	- Filled	153	153	tank	120.2
Tar		65	1755	cu. yd.	-
Terra Cotta		110	2970	cu. yd.	-
Tile - solid		115	3100	cu. yd.	-
partition (construction)		40	1080	cu. yd.	-
Timothy seed	bushel	36.2	45	bu.	28.4
Tin		459	12395	cu. yd.	-
Tomatoes - basket	bushel	44.2	55	bu.	34.7
lug box	7-1/4" x 14" x 17-1/2"	35.1	35	box	-
crate	10-1/2" x 11-1/4" x 24"	29.3	48	crate	-
basket	8-1/2" x 8-3/4" x 20"	20.9	18	bask.	-
basket (paper)	4-1/4" x 8-1/2" x 161/4"	26.5	9	bask.	-
basket (wood)	5-1/2" x 7-1/4" x 16-1/2"	26.3	10	bask.	-
Trap rock		187	5050	cu. yd.	-
Turpentine		54	7.2	gal.	-
Turnips - basket	bushel	44.4	54	bu.	34.1
Vetch seed	bushel	48.2	60	bu.	37.9
Vinegar		64	8.5	gal	-
Walnut (lumber)*		43	3580	M.Bd.ft.	
Walnuts - bulk	bushel	40.2	50	bu.	31.6
bag	2 bushel	40.2	100	bag	-
Water, fresh		63	8.4	bu.	-
Wheat - bulk	bushel	48.2	60	bu.	37.9
bag	1-1/2 bushel	48.2	90	bag	
Willow (lumber)*		31	2580	M.Bd.ft.	-
Wool, pressed		82	2215	cu. yd.	-
Zinc		440	11880	cu. yd.	-