Axioms Relating Truck Size and Weight to Vehicle Controllability

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ABSTRACT

Regulations governing the weights and dimensions of truck combinations can be looked upon as constraining many of the physical properties which determine the dynamic performance of these vehicles. In this paper, a number of generalized axioms are formulated for relating the commonly regulated physical constraints to the stability and control behaviour of vehicles. The axioms are presented covering the key weight and dimensional parameters in the following categories:

- Vehicle configuration (including number of vehicle units, types of units, nature of articulation couplings and steerable axles, number of distribution of axles)
- Length constraints (including tractor and trailer wheelbases, overall length, trailer bed length, overhang to pintle location, bed overhang, dolly drawbar length, tandem axle spacing)
- Width constraints (including width of load bed, width across tires, lateral spacing between suspension springs)
- Height constraints (including overall height, height to the center of tank vessels, floor height)
- Weight constraints (including gross vehicle weight, axle load, load distribution among axles on power units and trailers, loading as derived to satisfy bridge formulae)
- Operational considerations (by which length and width dimensions, together with loading allowances, act to determine the height of the payload center of gravity)

The generalized statements which are offered as "axioms", are expressed in terms of the stability and control characteristics which can be expected to follow from a certain change in each dimensional, loading, or configurational constraint. For example, it is possible to show that a 20% increase in tractor wheelbase will typically result in:

a) a modest degradation in the low speed offtracking of a vehicle combination

b) a modest improvement in the yaw stability, and assumed steering controllability, during severe cornering

c) a modest improvement in the vehicle's stability during braking such that the potential for avoiding jackknife is increased

The elements of each statement are supported by means of reference to prior publications or with direct presentation of data or simplified analyses which illustrate examples of the stated general influence. The illustrations are drawn either from the recently-produced results of the RTAC-sponsored work or from prior research conducted by UMTRI and others. Moreover, the organized statement of axioms is seen as an orderly reference for use by a jurisdiction which is considering the safety implications of changes in truck size and weight allowance.

INTRODUCTION

Regulations governing the weights and dimensions of truck combinations are subject to review and revision as the trucking industry strives to increase productivity, achieve uniformity across jurisdictional boundaries, and incorporate advances in technology. With each new prospective change in such regulations, the policymaking and regulatory authorities must take up the task of evaluating the proposal on behalf of the public good. The basic proposition behind such evalua-

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tions is that all truck combinations are not necessarily equivalent in terms of safety qualities and the potential for abuse to the infrastructure. Thus, there is a legitimate basis for concern that changes in truck weights and dimensions not impose negative consequences upon either the public right-of-way or the motoring public, themselves. Conversely, if proper constraints are placed upon allowable truck configurations and load limits, it is reasonable to expect that the public good may be served by advances in trucking through the allowance of more productive truck combinations.

This paper attempts to address certain aspects of vehicle controllability and maneuverability which are controlled to a large degree by the types of constraints which exist in size and weight regulations. In this context, "controllability" pertains here to the properties of the vehicle that influence the motion response of trailers and, in particular, to their ability to controllably follow the motion inputs at the tractor. Correspondingly, "maneuverability" pertains to the properties influencing the roadway space needed for vehicle operation, beyond the nominal width of the vehicle. Both of these areas of vehicle performance are seen as having potential relevance to public safety. The space requirements issue is also relevant to the maintenance of the roadside as influenced by the intrusion of truck paths beyond the lane edges.

Various studies of the dynamic and static behaviour of heavy-duty vehicles have provided the technical basis for stating certain general relationships by which vehicle configuration variables influence the motion responses of trailers. It is the purpose of this paper to identify those variables and to state those general relationships. Recognizing that truck combinations are complex systems, the reader should be advised that unusual vehicles might be developed for which the generalized relationships expressed here do not hold. Nevertheless, it has been the goal here to make only the most generally applicable statements as an aid to policymaking considerations.

The influence of weight and dimension variables on vehicle performance will be addressed here by means of three general categories of vehicle maneuvers. Namely, vehicle behaviour will be discussed in reference to (a) response to rapid steering, (b) tracking through low-speed turns, and (c) tracking through high-speed turns. In each maneuvering category, the various control issues will be examined in terms of the respective sensitivities to weight and dimension parameters.

RESPONSE TO RAPID STEERING

A principal issue posed by the responses of trailers in a rapid steering maneuver involves the so-called "rearward amplification" phenomenon.(1,2,3) The motion variable upon which the rearward amplification measure is based is the lateral acceleration response. As shown in Figure 1, a left-then-right steering input produces a similar harmonic-looking lateral acceleration response from each of the elements of a multi-unit truck combination. The rearward amplification measure is obtained by comparing the magnitude of the lateral acceleration response of the tractor with that of the rearmost trailer. The measure is defined as the ratio of the peak value of lateral acceleration at the rear trailer to the peak value of lateral acceleration occurring at the tractor. This ratio describes the vehicle's ability to amplify, at the last trailer, the severity of the maneuver which was initiated at the tractor. An amplified level of lateral acceleration is of concern insofar as it portends an increased likelihood of rolling over this rearmost trailer – a phenomenon which has been documented in various studies of the rollover accidents of multi-articulated combinations. (2,4,5)

THE 1ST ORDER SENSITIVITIES OF REARWARD AMPLIFICATION

Research on the subject of rearward amplification has revealed that this response phenomenon is strongly influenced by a number of the parameters which are subject to control through weights and dimension regulations. Each of the primary influences will be discussed, in turn.

NUMBER OF SEMITRAILING ELEMENTS

Among types of truck combinations in common service in North America, the following configurations predominate:

- straight truck
- truck, full-trailer
- tractor, semitrailer
- tractor, semitrailer, full-trailer (conventional, or "A-train" doubles)
- tractor, semitrailer, semitrailer ("B-train" doubles, primarily in Canada)

- tractor, semitrailer, full-trailer, full-trailer ("A-train" triples)

These respective types of truck combinations cover the range from zero to five trailing elements (i.e., counting both dollies and semitrailers) in combination. The number of trailing units, per se, influences the rearward amplification by means of a process in which the motion disturbance is amplified by each trailer as it is propagated toward the rear of the vehicle combination.

Portion of vehicle unit	Amplification factor
From the tractor c.g. to 1st trailer c.g.	1.148
From 1st trailer c.g. to 1st pintle hook	1.382
From 1st pintle hook to 2nd trailer c.g.	1.256
From 2nd trailer c.g. to 2nd pintle hitch	1.402
From 2nd pintlehitch to 3rd trailer c.g.	1.256

The disturbance tending to roll over the last trailer has been characterized in prior research (3) according to a series of these amplification factors. The product of the factors defines the rearward amplification response for an overall vehicle combination. An example analysis (6) of a triples combination of 27-ft A-train trailers (having bias-ply tires) produced the following multiplying factors for each of the respective units:

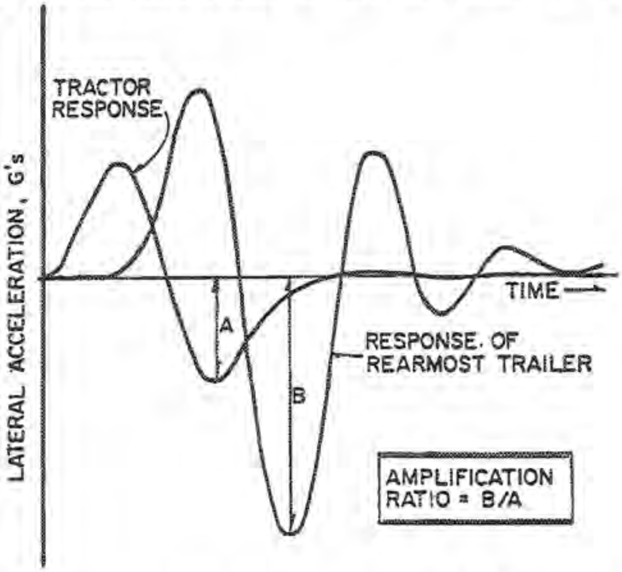
The product of the above factors, yielding a value of 3.50, represents the net rearward amplification of lateral acceleration at the last trailer of the example triples combination. Notice, however, that when the rear trailer is eliminated, the last two factors are dropped from the list such that the product of the remaining factors yields a net amplification value of 2.00. An illustration of the sequential buildup of rearward amplification with additional 27-ft, single-axle, trailers is shown in Figure 2. The data reveal that the rearward amplification level, **A**, increases exponentially with increasing number of trailers, n, of this particular layout according to the approximate relationship,

$$\mathbf{A} = 2.00 + (1.76)^n \quad \text{for } n > 2$$

The clear generalization illustrated by this example and supported by basic analysis is as follows:

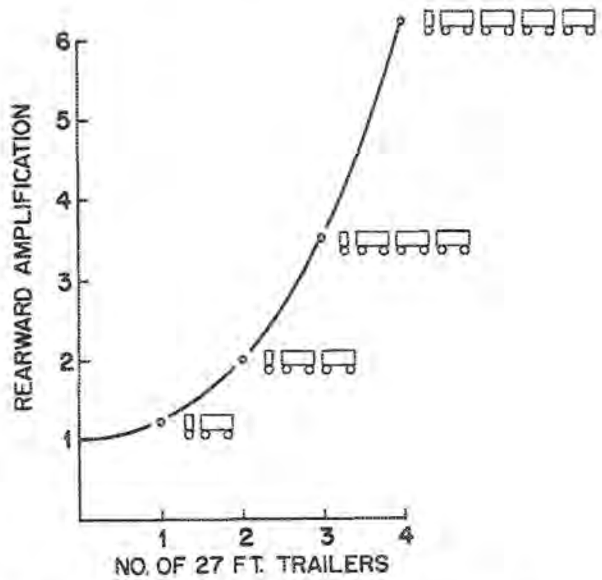
> *The addition of more trailers of the same configuration to a vehicle combination will result in an exponential increase in the rearward amplification response of the vehicle combination.*

The only context in which this general statement would be nullified would be for some hypothetical vehicle in which the respective trailing elements introduce amplification factors which are less than a value of 1.0. No such trailing elements have been identified in normal trucking practice.



Lateral acceleration responses in an obstacle avoidance maneuver defining the amplification ratio

FIGURE 1



The influence of number of 27 ft. trailers on the rearward amplification of A-train combinations

FIGURE 2

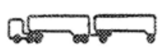
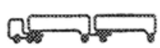
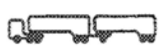
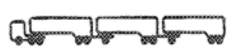
A corollary of the above axiom applies to the elimination of converter dollies from a multitrailer combination, thus constituting a B-train combination in place of the more conventional A-train. The elimination of a converter dolly, of course, serves to reduce the total number of trailing elements and to reduce the number of degrees of freedom for the overall system. For the case of a doubles combination having two 27-ft trailers, for example, the A-train configuration has been shown to exhibit a 65% greater level of rearward amplification than the B-train version.(6) Moreover, the corollary to an "axiom" on the influence of number of trailing units would state that:

> *Elimination of converter dollies (or fixed turntable dollies) from a vehicle combination, thereby constituting a "B-train," will categorically reduce rearward amplification relative to the original A-train configuration.*

An additional beneficial result of the B-train arrangement, per se, rests in the fact that trailers are all coupled by means of fifth wheels. Thus, each individual unit is constrained from rolling relative to the adjacent unit(s) by means of the roll stiffness of the fifth wheel couplings. During a rapid steering maneuver, the lateral acceleration responses tending to roll over each of the subsequent trailers are significantly out of phase with one another.(10) Thus, when one trailer is experiencing a peak lateral acceleration level tending to produce rollover of the trailer, the adjacent unit(s) are experiencing a less-than-peak condition such that they can contribute a stabilizing roll moment to prevent rollover. In general, this feature is so powerful in arresting the rollover impetus resulting from rearward amplification that B-trains offer the potential for dynamic roll stability levels equal to or better than those tractor-semitrailer combinations.

Shown in Figure 3 is a rank order of a large number of vehicle configurations which were analyzed in reference (11) in terms of their proximity to rollover in response to a rapid obstacle-avoidance maneuver. The data represent the Load Transfer Ratio (LTR) measure which describes the peak ratio of the difference in total left and right wheel loads to the total load on each independently rolling unit of the overall vehicle combination (deleting the load carried on the steering axle of the tractor, however, since this axle is typically so softly suspended that it does not significantly influence the roll stability outcome of the tractor/front semitrailer unit). When the LTR measure has peaked at a value of 0.50, for example, the difference between left and right wheel loads is equal to half of the "total" weight of the independently rolling unit. A value of 1.0, of course, indicates complete liftoff of all wheels on the unit (except the tractor steering axle) at some time in the maneuver. For vehicles that do suffer the "complete" load transfer response at some unit, another measure termed "rollover margin" (RM) is used to show how close the unit came to

Rank order of LTR, RM and Period for referenced vehicles

Conf	picture	TT	LTR	RM	Period
2.5		C	0.285	100	3
4.1		C	0.294	100	3
4.2		C	0.332	100	3
1.1		B	0.384	100	3
2.2		C	0.387	100	3
3.3		B	0.401	100	3
1.2		B	0.408	100	3
2.4		A	0.408	100	3
2.1		C	0.436	100	3
1.5		B	0.45	100	3
1.3		B	0.475	100	3
3.2		B	0.477	100	3
3.1		B	0.501	100	3
3.4		B	0.501	100	3
2.3		C	0.513	100	3
1.4		B	0.625	100	3
2.5		A	0.649	100	3
2.2		A	0.785	100	2.5
2.1		A	0.795	100	2.5
2.3		A	0.813	100	3
4.1		A	1	0.473	2.5
4.2		A	1	0	3

Rank order of vehicles examined in reference (11) for immunity to rollover in an obstacle-avoidance maneuver

FIGURE 3

actually rolling through the additional angle needed for complete rollover. When the rollover margin is zero, the unit has rolled over. The data show that, in response to a maneuver which produced a peak value of 0.15 G's of lateral acceleration at the tractor, the peak value of the load transfer ratio ranges from about 0.29 to complete rollover, with LTR = 1.00 and Rm = 0.

The point of presenting these data here is to illustrate the tremendous benefit that roll coupling provides for resisting a "dynamic rollover" response with multi-trailer combinations in a rapid steering maneuver. The data show that virtually all of the A-trains (i.e., non-roll-coupled combinations) lie at the poor end of the performance spectrum, with the two triples combinations suffering LTR = 1.0 due to complete liftoff at their rearmost trailers. While B-train doubles and "C-train" doubles (referring to combinations in which a roll-coupled dolly having a steerable dolly axle is employed in place of a conventional A-dolly) show LTR values which stand well below (and thus better than) the performance exhibited by A-trains, it is interesting to note that the roll-coupled triples benefit from the fact that, with increasing number of units, the accumulated phase lag in the lateral acceleration response of the respective units along the train renders a very modest resultant roll moment at any given time in the maneuver, thus, even though a C-train triples combination will exhibit a substantial degree of rearward amplification of lateral acceleration, the net outcome of this property, in terms of increased likelihood of rollover in dynamic maneuvers, is negligible. The only caveat that must be placed upon this finding is that the roll stiffness of the connecting dolly elements must be rather high to ensure that large roll displacements are prevented during occasions of peak roll moment transmission between trailers. The general observation is as follows:

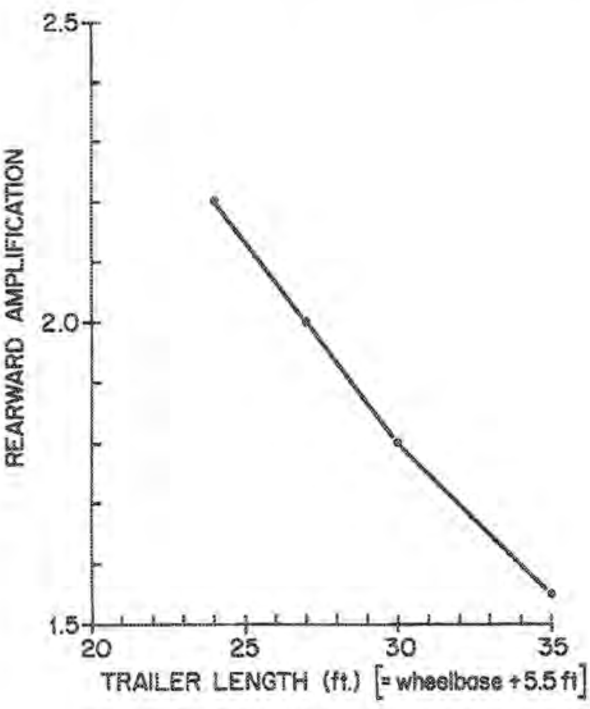
Multi-trailer combinations which are stiffly roll-coupled together will provide a high resistance to rollover in transient steering maneuvers as a result of phase lags in the response of successive units. This characteristic resistance will increase with the number of roll-coupled units in the combination.

INCREASED WHEELBASE ON TRAILING UNITS

Research has shown that the length dimensions which establish the trailer wheelbases, the overhang placement of pintle hitches, and the length of dolly drawbars are important in determining the rearward amplification level of a combination vehicle. (1,2,3,6,7) Shown in Figure 4, for example, trailer lengths from 24 through 35 feet are seen to produce values of rearward amplification which cover the range from 2.3 to 1.6, respectively, in a 5-axle A-train double. In these data, the variation in overall length directly influences the wheelbase of the trailers, with dolly drawbar and pintle overhang dimensions remaining fixed. A general statement that can be drawn from the illustrated data and from basic analyses (3,7) is the following:

Given the common layout of trailers used in general freight transportation, the rearward amplification level reduces strongly with an increase in the trailer wheelbase dimension.

The influence of dolly drawbar length, on the other hand, shows a mixed picture of response sensitivity. Although it is possible to show that, in a given vehicle configuration, an increased drawbar length serves to reduce rearward amplification, analysis (17) shows that the influence of drawbar length on this measure is not necessarily monotonic. Moreover, the influence of drawbar length amplification cannot be readily generalized.



The influence of trailer length (and wheelbase) on rearward amplification for a 5-axle A-train double

FIGURE 4

The distance from the center of the rear axle (or rear tandem) to the pintle hitch location, defined as the pintle overhang dimension, is known to impose a clear and monotonic influence on rearward amplification performance. Namely,

An increase in the pintle overhang dimension will categorically produce an increase in rearward amplification.

By way of explanation, the pintle overhang dimension simply represents an extension of the lever arm with which the yaw motion of a trailer produces lateral displacement of the pintle hitch. Since this lateral motion effectively "steers" the dolly which is coupled to the pintle hitch, increasing pintle overhang increases the steer input to the dolly and thus serves to increase amplification gain. (3)

INCREASED LOADING

While the addition of load to a heavy-duty vehicle obviously alters the value of inertial parameters, it also serves to alter the cornering properties of the tires. The load-related mechanism which appears to have the most influence on rearward amplification involves the curved relationship between tire cornering stiffness and vertical load, as illustrated in Figure 5. The net effect of this curvature property is that the tire exhibits a lower level of cornering stiffness, per pound of wheel load, when the overall tire load value is higher. Computations made in a study of 5-axle doubles combinations popular in the U.S. (8) show that a 6% increase in Gross Combination Weight, GCW, results in an approximate 3% increase in rearward amplification.

Since the influence of increased loading is predictable because of the universality of the "curvature relationship" in the tire's cornering properties, it appears that the following generalization is warranted:

Increases in the gross weight of a given multi-articulated truck combination will result in a modest increase in the rearward amplification level.

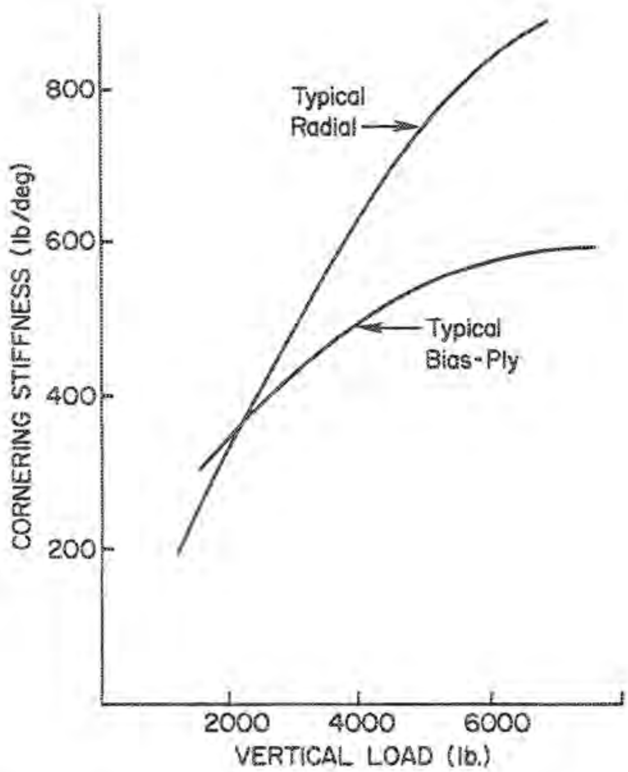
OTHER INFLUENCES ON REARWARD AMPLIFICATION

Research has shown that there are a number of additional operational variables which have a significant impact upon the rearward amplification behaviour of a given vehicle combination. Prominent among these factors are the forward speed of the vehicle and the construction and treadwear condition of the installed tires. While the mention of such factors in a discussion of size and weight considerations may be somewhat tenuous, the mechanics are cited here only for completeness and to aid those concerned with broad policies on the setting and enforcement of truck regulations.

The forward speed of the vehicle is known to have a first-order influence on rearward amplification response.(1,2,3) Data presented in reference 2 for a Michigan-style double tanker reveal a sensitivity of rearward amplification to velocity, V (mph), that closely fits the linear relationship.

Rearward Amplification = 0.06 V - 0.75

For this strongly amplifying vehicle, a speed of 30 mph is needed to attain a rearward amplification value above 1.0. Another analytical study of the speed sensitivity of doubles having trailer lengths from 20 through 40 feet reveals, also, that the amplification ratio does not exceed a value of 1.0 until the vehicle speed has exceeded at least a



The influence of vertical load on the cornering stiffness parameter

FIGURE 5

value of 30 mph.(1) Thus, it is primarily at highway speeds that rearward amplification response reaches a level that is of concern for traffic safety. A generalization that applies to most multi-articulated truck combinations is the following:

> *Rearward amplification does not exceed unity at speeds below approximately 30 mph but rises with a first-order dependence upon speed in the range of speeds normally associated with highway travel.*

One significant aspect of the dependence of rearward amplification upon travel speed is the greater hazard which is imposed by speeding in the case of vehicles which exhibit inherently high levels of rearward amplification. Thus, jurisdictions allowing vehicles having inherently high rearward amplification may be inclined to rigidly enforce speed restrictions on such vehicles.

In a similar vein, since the rearward amplification phenomenon is most excited by rapid steering activity such as may arise in avoiding an obstacle, there is reason for concern with the operation of strongly amplifying vehicle types in dense, high-speed traffic. That is, the rearward amplification response tends to reach a peak when relatively high frequency steer inputs are applied--such as in steering quickly to avoid another vehicle or object. The experience of rear trailer rollover with Michigan-style double tankers (2) and truck/full-trailers in California (5) seems to establish that operation in dense traffic, especially with the conflicts posed by frequent merging movements on urban freeways, is an unfavorable application for vehicles exhibiting inherently high amplification levels. Although one could say that all types of safety hazards are reduced whenever a vehicle is removed from the conflicts of traffic, both the physics and the limited accident experience seem to support the following general observation:

> *The peculiar sensitivity of the rearward amplification phenomenon to the higher range of steer input frequencies suggests that strongly amplifying vehicles will pose the greatest hazard in congested, high-speed, traffic.*

An additional issue concerns the strong influence of tire type and state of treadwear on rearward amplification. It is clear that the nominal cornering stiffness level of the installed tires along the entire vehicle combination acts as an important determinant of the rearward amplification behaviour. Namely, as the cornering stiffness value rises, the rearward amplification level will decline significantly. Results of a linear analysis of vehicle response, for example, show that substitution of bias-ply tires with radials in a conventional 5-axle, U.S.-style double will yield an approximate 30% reduction in rearward amplification.(9) Accordingly, changes in tire technology or usage, (for example, adoption of wide-base singles in place of dual tire sets) should be studied so as to identify any possible reductions in cornering stiffness such as might degrade rearward amplification performance.

SIGNIFICANCE FOR TRANSPORTATION OF BULK HAZARDOUS MATERIALS

Since the ultimate safety hazard posed by the rearward amplification phenomenon is rear trailer rollover, there is special cause for concern in the transportation of bulk hazardous materials in tank vehicles exhibiting a high level of rearward amplification. This concern is based upon the simple observation that rollover constitutes a highly aggressive accident event for a heavy-duty vehicle and is by far the most common type of highway incident in which bulk tank vessels become ruptured. In a study of gasoline tanker accidents in Michigan over a two-year period, for example, 24 out of 25 accidents producing significant spillage of product from a bulk tank involved a rollover accident.(10) Of course, this result simply reveals that most truck accidents involve collisions with passenger cars and other objects such that the structural integrity of transport tanks is not jeopardized. Since rollover is the overwhelming accident type threatening release of hazardous substances, it follows that vehicles having high levels of rearward amplification should not be used in such transport applications.

Recognizing, further, that B-train configurations may exhibit moderate levels of rearward amplification but be highly resistant to dynamic rollover due to the roll-stiff coupling arrangement, the B-train layout is seen as especially attractive for the transport of bulk hazardous materials in rather productive truck combinations. The B-train is also especially suited to tanker applications since such vehicles typically involve "married" combinations for which interchangeability of front and rear trailers is not an issue.

The intuitively satisfying statement that follows from those observations is:

Vehicle configurations exhibiting a relatively high potential for rollover in rapid steering maneuvers (and under steady turning conditions, for that matter) are especially undesirable for the transportation of hazardous materials in bulk.

TRACKING THOUGH LOW-SPEED TURNS

The operation of differing types of vehicle configurations in low-speed turns poses a group of control issues concerning the space which is required and the directional control of units having rather widely spread tandem axle groups. Although the mechanisms which explain these respective phenomena differ greatly from one another, the issues are conveniently grouped by the fact that they all apply to low-speed operation in tight turns such as on intersections-at-grade. Four issues will be addressed as follows:

(a) concerning space requirements at intersections,

- the inboard paths of trailer wheels ("low-speed offtracking")
- the outboard-swinging trajectory of the left-rear tip of a trailer in right-hand turns ("swing-out")

(b) concerning directional control in tight turns

- tractor jackknife promoted by widely spread trailer tandem axles
- tractor plow-out promoted by widely spread tandem axles on tractor

As will be shown, each of these response properties is influenced by dimensional and configuration features such as may become altered through size and weight regulations.

GENERAL NATURE OF THE PROBLEM WITH LOW-SPEED OFFTRACKING

When vehicles maneuver at low speed through relatively tight-radius turns, such as at highway intersections, the rear wheels of each trailing unit tend to track toward the inside of the curve in the well recognized process termed "low-speed offtracking."(12) Shown in Figure 6 is an illustration of the paths of tractor and trailer wheels in a right-hand intersection turn. The represented vehicle is comprised of a 48-ft semitrailer, which is the current de-facto norm in the U.S., coupled to a tractor having a short, 144-inch, wheelbase. The tractor is shown to be following a circular arc which places the outside edge of the left front steering tire at a radius of 45 feet. The illustrated turn is shown with wheel paths laid over an example pavement-edge boundary which corresponds to the common U.S. design for rural highway intersections, per the "WB-50" design vehicle, as specified by the American Association for State Highway and Transportation Officials (AASHTO).(13)

This illustration clarifies the conflict which is experienced with 48-ft semitrailers on much of the U.S. road system as a result of the low-speed offtracking phenomenon. Namely, either (a) the trailer tires tend to encroach beyond the pavement edge approximately 3/4 of the way through the turn, as shown, or (b) the truck driver, wishing to avoid such encroachment, steers closer to and perhaps slightly into the adjacent lanes carrying other traffic so that trailer tires clear the inside pavement edge. (14) Thus, the low-speed offtracking issue can be looked upon as one which poses a potential burden of roadside maintenance due to wheelpaths encroaching beyond the pavement edge, or one which poses some accident risk and, perhaps, impeded traffic flow due to operation at or across the roadway centerline. In either case, the magnitude of the problem is indicated by a simple measurement of the peak value of offtracking, defined as the maximum offset prevailing between tractor wheelpaths and trailer wheelpaths in an intersection turn.

THE INFLUENCE OF UNIT WHEELBASE

The magnitude of the low-speed offtracking response is known to depend primarily upon the summation of the squares of the wheelbases of all of the trailing units in the vehicle combination.(12,15) Although the transient offtracking process such as illustrated in Figure 6 cannot be conveniently characterized by an algebraic relationship, example offtracking results obtained through numerical integration techniques do readily illustrate the wheelbase sensitivity. Shown in Figure 7, for example, the influence of trailer wheelbase on maximum low-speed offtracking is shown for both 5-axle U.S.-style doubles and a 5-axle tractor-semitrailer combination. These data represent the peak offtracking exhibited in a turn which was produced when the outside edge of the left tire on the tractor's steering axle followed a 35-ft reference radius (i.e., the approximate path that a driver would follow in attempting to negotiate the intersection without causing trailer tires to encroach the pavement edge). Since the double incorporates two trailing elements, each at the indicated wheelbase values, the data for the double lie above that for the tractor semi-trailer.

Noting the offtracking values for the most popular doubles and single combination vehicles in the U.S., it is instructive to consider the slope of the wheelbase sensitivities in the vicinity of these current "norms." The offtracking of the doubles combination increases at a rate of 0.85 ft per foot of increased per-trailer wheelbase, while the offtracking of the semitrailer combination increases at a rate of 0.6 ft per foot of semitrailer wheelbase.

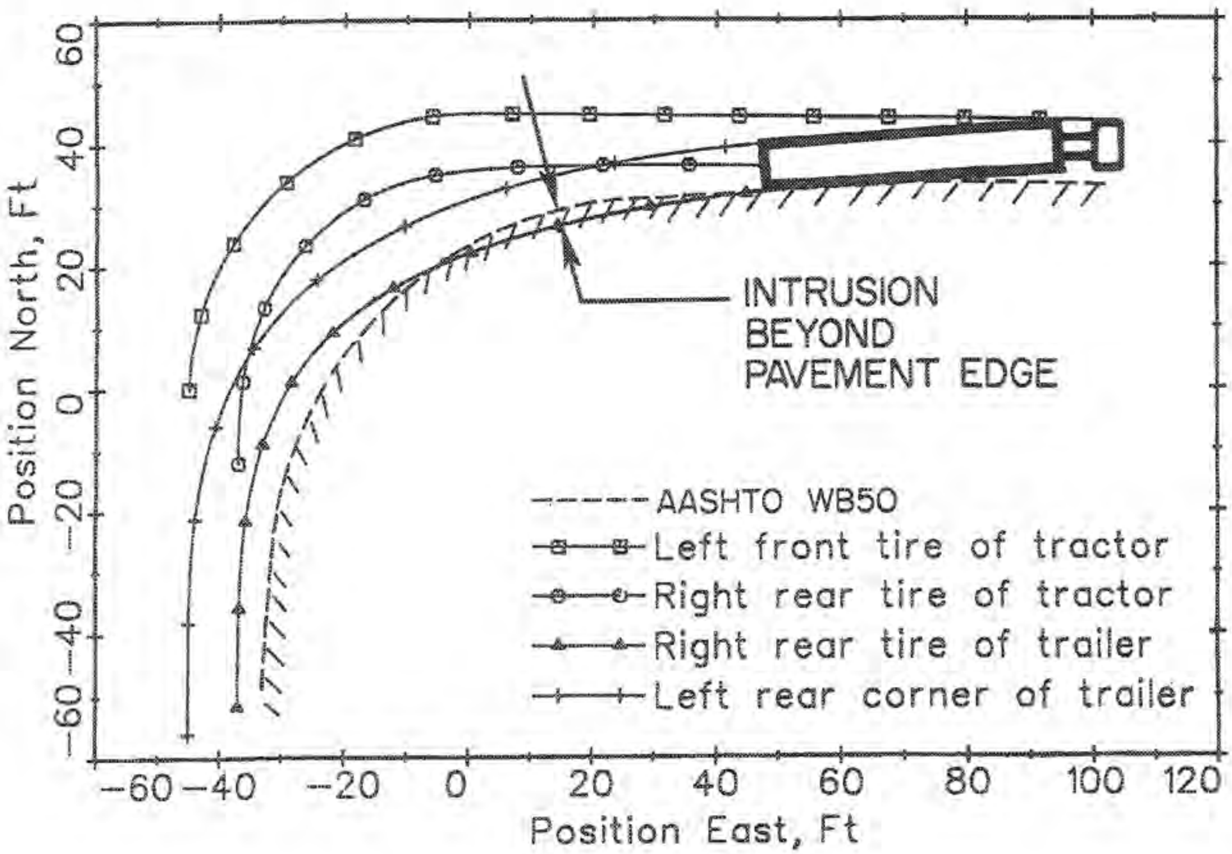
Recognizing that the total bed length available on the doubles combination increases two feet for each foot increase in the indicated wheelbase dimension, one could say that increases in bed length would be obtained at considerably less "cost," in terms of increased low-speed offtracking, with the example doubles combination than with the single (assuming that increases in wheelbase follow increases in bed length, one-for-one).

It is also apparent that, since the 48-ft semitrailer (having a wheelbase of 40.5 feet) tends to completely "use up" the space which was provided through the most common protocol used for intersection design in the U.S.,(14) the strong sensitivity of low-speed offtracking with further increases in wheelbase suggests that something of an impasse has been reached in the U.S. at the current time.

A general observation that can be stated from the overall issue of length sensitivities is as follows:

> *Incremental increases in trailer wheelbase produce a first-order increase in low-speed offtracking. The rate of increase (feet of offtracking per foot of wheelbase) rises with the absolute value of the wheelbase such that modern semitrailers having wheelbase values near 40 feet produce approximately 0.6 feet of additional offtracking at intersections for each foot of additional wheelbase.*

Considering the relative contributions of tractor and semitrailer wheelbase dimensions to the over-



Offtracking in a low-speed turn

FIGURE 6

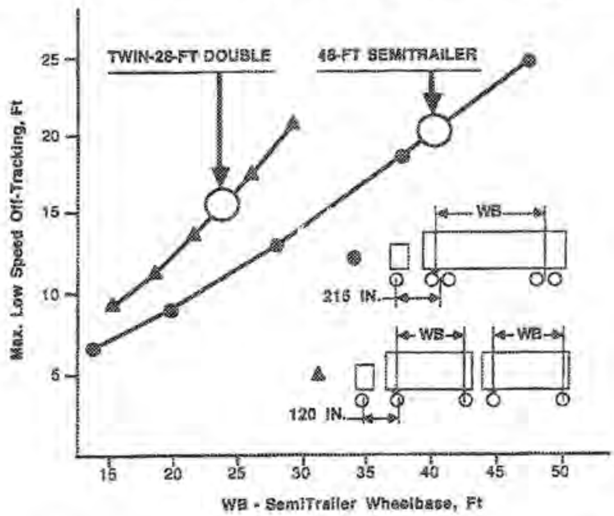
all result in low-speed offtracking. Figure 8 shows the lower significance of changes in tractor wheelbase compared to changes in the wheelbase of a long (say, 48-ft) semitrailer. The figure shows results computed for a reference tractor semitrailer combination which was represented with respective changes in the tractor-only and then trailer-only wheelbase. The corresponding general observation pertaining to tractor wheelbase is that:

Incremental increases in tractor wheelbase produce a modest increase in low-speed offtracking. The rate of increase (feet of offtracking per additional foot of tractor wheelbase) is on the order of 0.35 ft/ft for tandem axle tractors in common North American application.

When equivalent-length trailers are employed in multi-trailer combinations in A-,B-, and C-train configurations, small variations in low-speed offtracking performance can be typically observed. The contrast in performance between A- and B-trains derives from the fact that effective wheelbase of the lead trailer in a B-train is made longer than the corresponding trailer in an A-train. As shown for an example rig in Figure 9, the center group of axles on the B-train is typically placed more aft such that requirements for proper load distribution are satisfied. It is also typical practice, however, to employ a somewhat larger kingpin setting dimension on the lead trailer to further unburden the center group of axles. In typical Canadian vehicles, the net outcome of these two dimensional protocols is an increase in low-speed offtracking due to the longer effective wheelbase of the lead trailer. For trailer lengths in the vicinity of 27 ft, B-trains exhibit on the order of 4% greater low-speed offtracking than A-trains having the same basic distribution of axles.(11)

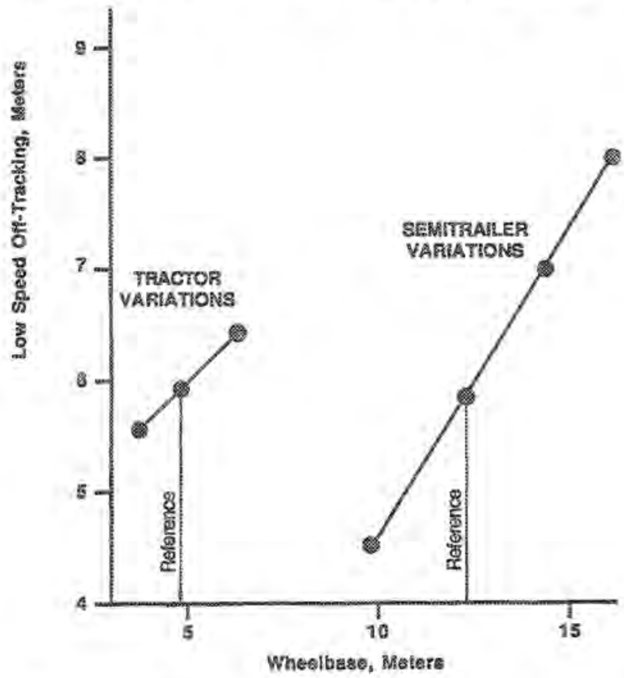
On the other hand, C-train configurations having identical axle placements as corresponding A-train configurations exhibit on the order of 4% less low-speed offtracking than the A-train.(11) This benefit derives from the fact that, with the dolly axle on C-trains steering toward the outside of the turn, the second trailer is towed from a more outboard radius than in an equivalent A-train. Thus, the C-train dolly acts effectively like a "stinger", providing an aft placement for the tow coupling between trailers. The particular improvement in offtracking that will derive in a specific case will depend upon the mechanical properties of the dolly steering system insofar as greater resistance to steering (such as needed for good dynamic behaviour) tends to reduce the stinger effect and to increase low-speed offtracking. The general statement that embodies the distinctions by coupling configuration is as follows:

Because of characteristic differences in placement of axles and coupling points, A-,B-,



Influence of trailer wheelbase on maximum low-speed offtracking in a 35-ft reference radius, intersection turn

FIGURE 7



Influence of tractor and semitrailer wheelbase on peak low-speed offtracking

FIGURE 8

and C-trains show modest differences in low-speed offtracking, for equivalent bed-length trailers. Relative to the corresponding A-train, B-trains exhibit somewhat greater, and C-trains show somewhat less, low-speed offtracking.

THE SWING-OUT PROBLEM

Recognizing that the wheelbases of long semi-trailers cannot be extended significantly without excessive offtracking penalties, longer semitrailers can be laid out with an extended bed overhang such that increases cubic capacity is obtained without a further increase in wheelbase. The advent of semitrailers which may be operated with a large rear overhang presents the possibility that, in say a right-hand turn, the left rear corner of the trailer will tend to swing toward the left early in the maneuver, with the possibility of intruding momentarily into the adjacent traffic lane, as shown in Figure 10. To first order, the "swing-out" motion is related to the ratio of the two length dimensions, A/L, where,

A = distance from trailer kingpin to rear extremity of trailer

L = trailer wheelbase (kingpin to center of trailer axle group)

Using this nondimensional ratio, Figure 11 presents the magnitude of the swing-out dimension produced by selected examples of semitrailers which were 53 feet long and which were analyzed for the 45-ft reference turn assumed in the AASHTO protocol for intersection design, cited earlier.(14) The results show that the swing-out excursion rises nonlinearly with the (A/L) value, and can approach a value of one foot when (A/L) is in the vicinity of 1.5. It should be noted that A/L values of this magnitude, and greater, are feasible through the use of sliding trailer bogie equipment which is popular for both balancing load distribution and for adjusting wheelbase to improve offtracking in tight maneuvering areas. Swing-out dimensions of approximately twice the indicated magnitudes can be obtained when the tractor is steered at is maximum "cramp angle" through a 90-degree intersection maneuver.

Clearly, the swing-out phenomenon poses a safety issue. That is, with the truck driver (a) beginning his intersection maneuver rather near to the left edge of his lane while (b) putting his attention on tractor path and the inboard offtracking of right-side trailer wheels, the left rear corner of the trailer can swing across the centerline into the opposing traffic lane. The swing-out motion thus would occur without particular note by the truck driver. Further, the height of the typical trailer bed is such that the swing-out motion would probably threaten contact with automobiles at the vulnerable elevation of the windshield.

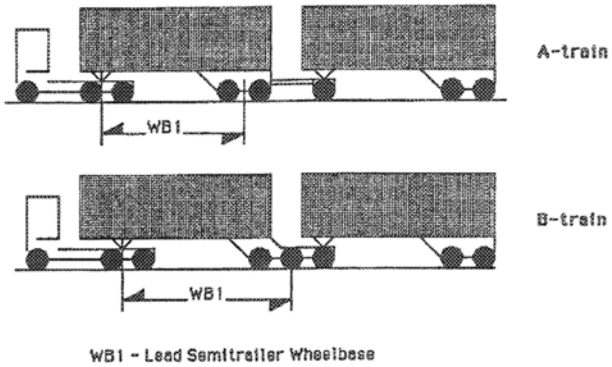
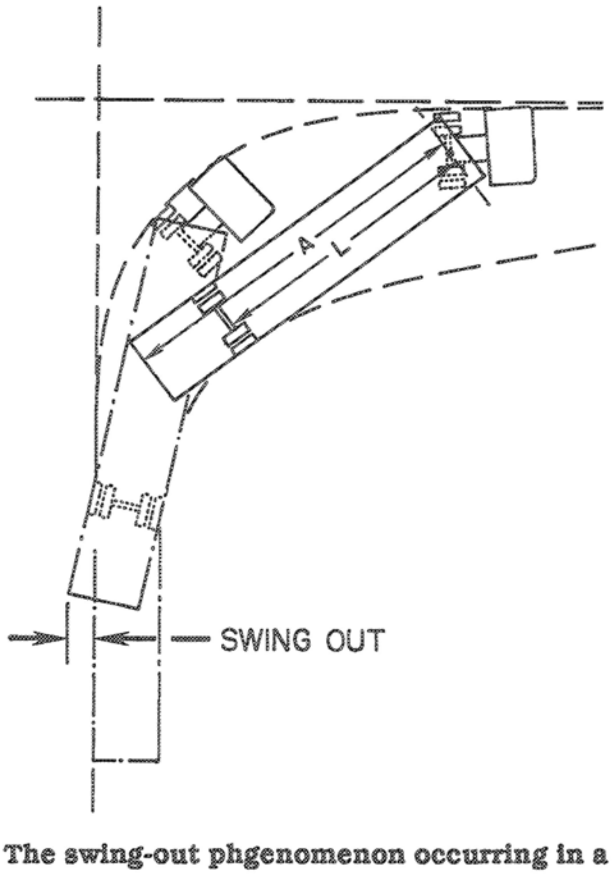


Illustration of effectively longer wheelbase of lead trailer in a B-train combination relative to that of an "equivalent" A-train

FIGURE 9



The swing-out phgenomenon occurring in a low-speed turn with a semitrailer having a relatively high value of A/L

FIGURE 10

The general observation is:

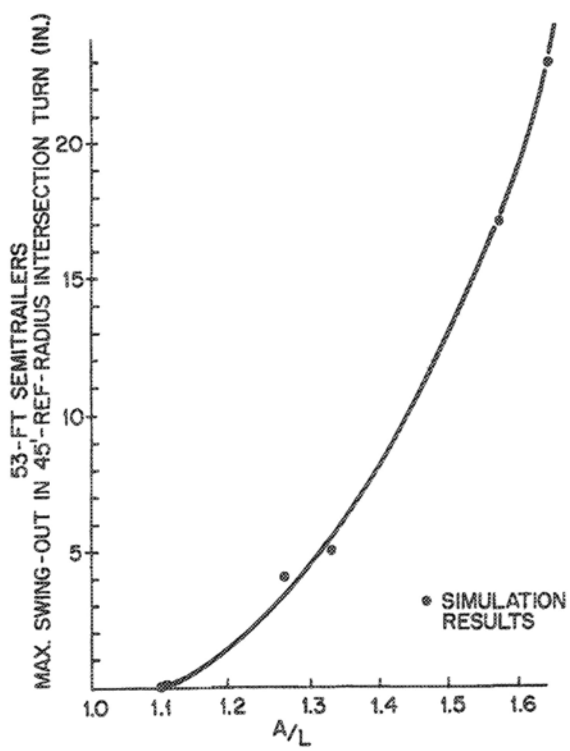
> *The outside rear corner of a semitrailer may "swing out" into the path of opposing traffic during intersection turn maneuvers if the ratio, A/L, is sufficiently large. Swing-out can reach a magnitude which approaches common intervehicular clearances when A/L approaches a value of approximately 1.5.*

Another incidental safety consideration arising from the overhang which prevails on very long semitrailers when wheelbase must be constrained to get acceptable low speed offtracking involves the rear underride impact problem.(15) That is, the permanently-overhung rear end of the trailer constitutes a permanent hazard for rear underride collisions by passenger cars. Accordingly, size and weight regulations serving to permit such trailers in highway service may need to address rear underride protection lest this very lethal hazard is inadvertently made more prevalent on the highway.(14)

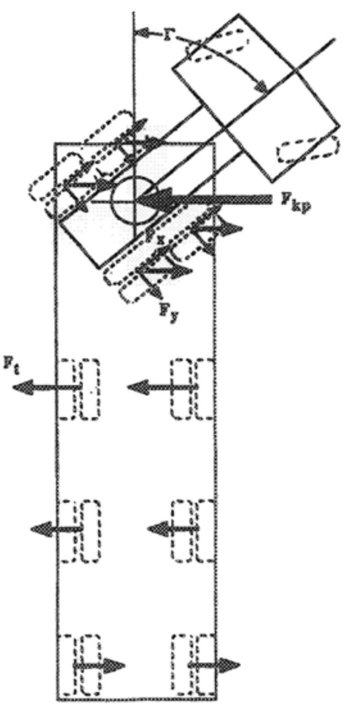
TRACTOR JACKKNIFE IN TIGHT-RADIUS TURN ON A LOW-FRICTION SURFACE

When a tractor-semitrailer combination executes a tight-radius, right-angle turn, the tandem axle set on the trailer develops a yaw moment which resists the turning motion. The turn-resistive moment developed by a trailer tandem is reacted by tire shear forces developed at the tractor tires. With the fifth wheel coupling located approximately over the tractor's rear suspension, it follows that the predominant reactive forces are developed at the tires on the tractor's rear axle(s). If the demand for tractor rear tire forces is sufficiently high, given the prevailing level of tire/road friction, the tractor may experience a jackknife-type of loss-of-control partway through an intersection turn. Even though this loss-of-control result would proceed rather slowly because of the low operating speed, the resulting vehicle motions could imperil other traffic.

Shown in Figure 12 is an illustration of the phenomenon described above. We see that equal and opposite lateral forces are developed at the trailer tires as a result of the slip angles developed when the spread trailer axles travel at zero speed about a common instantaneous center of rotation. It is straightforward to show that the lateral force, F_{y5}, which must be developed at the fifth wheel



The influence of A/L on maximum swing-out
FIGURE 11



A spread axle set on a semitrailer produces lateral forces, F_t, in an intersection turn, thus developing a friction demand at the tractor tandem
FIGURE 12

coupling in order to satisfy equilibrium under these conditions is described by the following relationship:

$$F_{y5} = 2[C_{alpha} / R] [d^2 / L]$$

where

C_{alpha} = sum of the cornering stiffness of all tires on a trailer axle

R = instantaneous radius of turn

d = half spread of a trailer 2-axle tandem

L = trailer wheelbase (measured to the geometric center of the tandem)

This relationship reveals that the ratio of the spread squared to the wheelbase of the trailer is the primary geometric determinant of the magnitude of the lateral force at the fifth wheel in a low-speed turn. In turn, the lateral force at the fifth wheel will be approximately equal to the total traction forces developed at the tractor rear axle(s) (assuming that the vehicle proceeds at constant speed through the maneuver). If we ratio the shear forces on the tractor rear tires to the vertical load carried on those tires, we obtain a simplified measure of the friction "demand" which is imposed for satisfactory completion of the maneuver.

Plotting a set of such friction demand measures against the geometric term, (d^2/L), Figure 13 shows that the abscissa variable constitutes a good first-order predictor of the frictional requirements posed by the tandem layout on a semitrailer. While these results derive from simple cases in which each tractor rear and trailer axle carries nearly the same level of load, the (d^2/L) predictor does adequately address the widely differing arrangements of trailer axles which are shown. In cases involving tridem axle layouts, the (d) and (L) values in the abscissa variable are established assuming that the effective wheelbase is measured to the center of the tridem (such that the center tridem axle does not contribute to generation of a turn-resistive moment). Likewise, with the quad-axle trailer, the effective wheelbase is measured to the center of the quad, with "inner" and "outer" tandems, so to speak, acting at respectively differing values of (d).

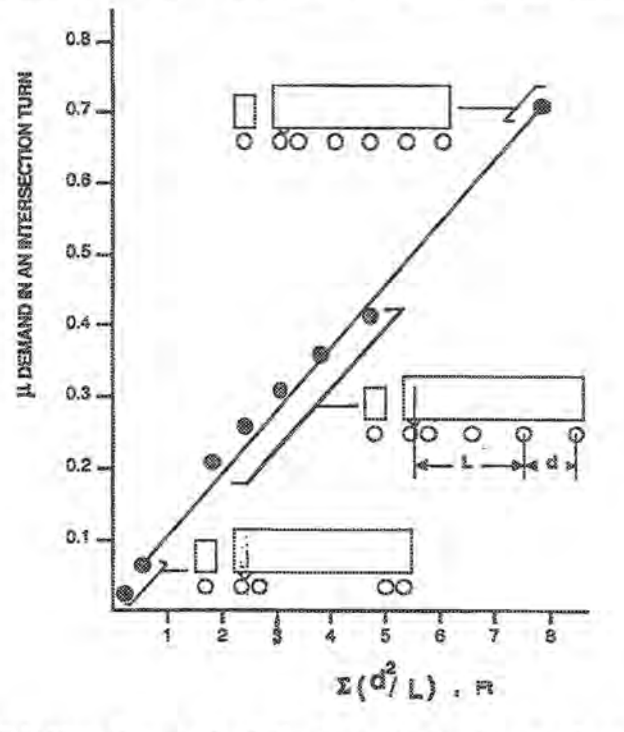
Recognizing that mu values in the vicinity of 0.15 represent the nominal range of, say, snow-covered surfaces while 0.4. represents a quite poor, wetted, pavement, a generalization on the described sensitivity can be stated as follows:

> *Trailers with widely spread axle arrangements tend to promote tractor jackknife during tight-radius turning. Tractor jackknife can develop during intersection turns:*
>
> *- on snowy pavement when $(d^2/L) > 2$ (ft.)*
>
> *- on poor wet pavement when $(d^2/L) > 5$ (ft.)*

Even beyond the binary context implied by the reaching of a friction limit in these simple analyses, higher levels of (d^2/L) imply steadily increasing risk – recognizing that additional friction demands are also developed by the driver's simultaneous application of throttle and, thus, the generation of drive thrust at the tractor's rear tires.

TRACTOR PLOWOUT ON LOW MU

Another peculiar anomaly which presents a control problem on tight turns with low friction surface conditions involves tractors having a relatively wide-spread set of rear axles, given the overall wheelbase. Analysis of such vehicles has



Friction demand at the tractor tandem axles as a function of the S (d^2/L) term describing trailer axle placment

FIGURE 13

shown (9) that the tractor's front tires will saturate in side force before the rear tires in a vehicle satisfying the following inequality:

$$(a / b) [d / (L=d)] > 1$$

where:

- a = distance from steering axle to the centroid of tractor axle loads
- b = distance from center of tractor tandem to the centroid of tractor axle loads
- d = half-spread dimension across the equivalent tractor tandem
- L = tractor wheelbase (equal to a + b)

Careful inspection of this expression will indicate that only a tractor with a rather unusually wide-spread tandem layout, given the wheelbase, will suffer the peculiar "front-first" saturation response. A simplified analysis indicates that when such a saturation condition does occur, the vehicle will be limited in path radius, regardless of additional steer input. If this condition occurs while negotiating, say, an intersection turn, the tractor may proceed along a radius which results in excursions into the paths of other vehicles or pedestrians. In short, the condition does amount to loss of directional control.

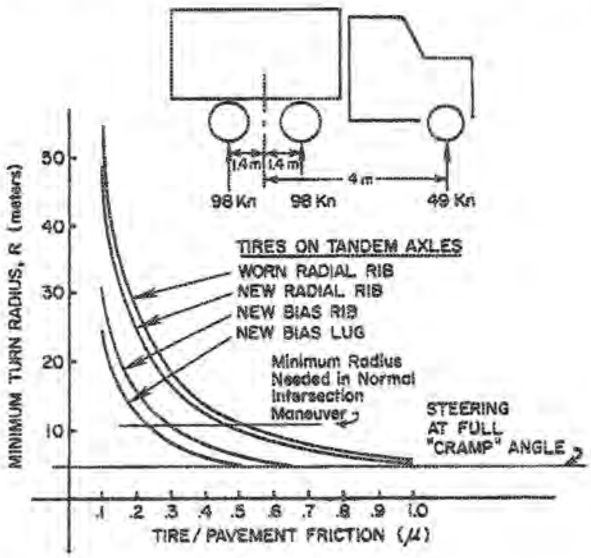
An example illustration of the minimum path radii which can be achieved, as a function of the tire/pavement friction level at which side force saturation will occur, is presented in Figure 14. These example results represent the demanding case in which a large value for the tandem spread dimension is coupled with a short-wheelbase vehicle having a strong rearward bias in loading. The figure shows that the minimum achievable path radius rises as the friction level goes down, thus making it difficult to achieve a normal intersection turn when the friction level is below approximately 0.5, assuming worn radial-ply tires on the tandem axle wheel positions. Note that the tires installed on the rear axle positions influence the minimum turn capability because they determine, through their "cornering stiffness" property, the magnitude of yaw-resistive moment which is developed in a given-radius turn. These observations support the following general statement:

Tractors having a widely-spread tandem axle set and relatively short wheelbase may not respond to further steering beyond some minimum radius turn, under low friction conditions. This problem worsens with wider spread, shorter wheelbase, and more rearward weight bias among the tractor axles.

HIGH-SPEED OFFTRACKING

While the trailers of articulated vehicle track inboard of the tractor during slow speed turns, the tracking relationships change as speed is increased. When such vehicles travel around a curved path at increasing speed, the inboard offtracking begins to diminish and actually becomes zero at some speed. At higher values of speed beyond this point, the trailer tires track to the outside of the path of the tractor tires.(17) This outboard or "high-speed" offtracking phenomenon is thought to be of potential significance to traffic safety insofar as the potential exists for the rear of the trailer to strike an object on the outside of the curve or for trailer tires to encounter an outboard curb, thus tripping the vehicle and promoting rollover.

The extent to which outboard offtracking occurs is dependent upon the basic low-speed offtracking response of the vehicle, given the turn radius, and certain additional properties which govern the outboard-tracking tendency with increased levels of lateral acceleration. Shown in Figure 15 is an



The influence of tire placement on the path radius limitation of a 3-axle truck having a very wide tandem spread relative to the wheelbase

FIGURE 14

illustration of the process from inboard to outboard offtracking with increasing lateral acceleration for two example vehicle configurations, namely, a tractor with 48-ft semitrailer and an A-type doubles combination having two 28-ft trailers. We see that the tractor semi-trailer, with its greater inboard offtracking at zero lateral acceleration (or speed) exhibits less high-speed offtracking at a given acceleration value than does the double, which experiences less zero-speed offtracking by virtue of its multiple articulations and short trailers.

Analysis (18) has shown that the slope of the relationship between offtracking and lateral acceleration is determined solely by the overall length of the vehicle combination and the cornering stiffnesses of the installed tires, regardless of the number or type of articulation joints. This, in the figure, the longer doubles combination shows a somewhat steeper relationship than is apparent with the tractor-semitrailer.

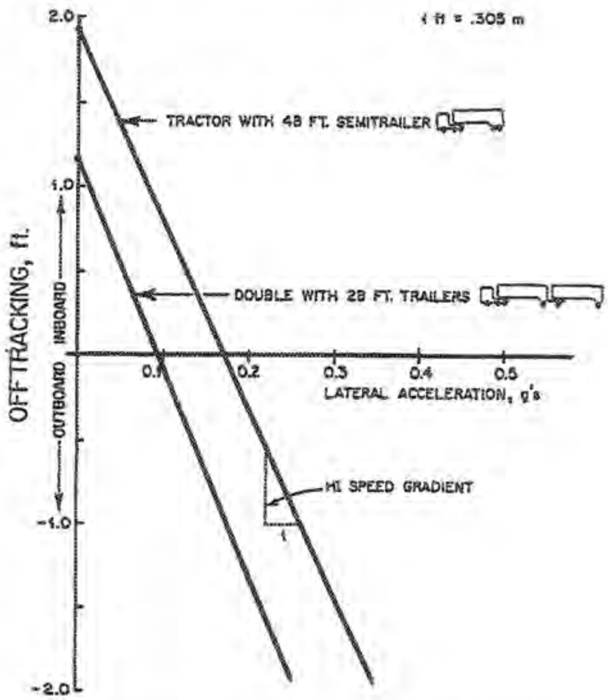
Listed below under the column labelled "steady state" are the net outboard offtracking responses exhibited by various vehicle configurations for the case of a steady 600-ft radius curve which is traversed at a speed of 55 mph.

Table 1 – High-speed offtracking of selected truck combinations

Vehicle	Offtracking, Ft Steady state	"Dynamic"
Tractor w/48" Semi	0.52	0.98
Turnpike A-DBL, 48' trailers	1.10	1.49
Rcky Mtn. C-DBL, 48'/28' (nom.) trailers	----	1.72
Rcky Mtn. A-DBL, 48'/28' (nom.) trailers	1.33	2.24
B-train DBL, 28' (nom.) trailers	----	1.75
Conventional A-DBL, 27' (nom.) trailers	1.43	2.79
C-Triple, 28' (nom.) trailers	-----	3.28
A-Triple 28' (nom.) trailers	2.13	5.31

In addition to the "steady-state" results which derive from a classical linear analysis of high-speed offtracking, the adjacent column presents the considerably larger values of dynamic high-speed offtracking which represent numerical computations of the peak overshoot in lateral excursion of the rearmost axle in a rapid obstacle-avoidance maneuver at 62.5 mph. Although based upon a more complex set of maneuvering dynamics, these results indicate that a transient overshoot in high-speed offtracking can occur in response to an abruptly applied steering input.(11) The results show that the A-train triple, with 27- or 28-ft trailers, is in a class by itself with regard to the extent of the dynamic lateral excursion. Also, B-train and C-train variations on a basic multi-trailer layout produce very substantial improvements in performance over the corresponding A-trains listed here (primarily due to the same mechanisms as serve to improve rearward amplification). Insofar as the magnitudes of the dynamic values represent a considerable lateral dimension relative to spaces that may be available on the highway, it would appear that the dynamic rather than static aspects of high-speed offtracking may pose the most serious prospect for inadvertent collisions or curb-strikes at the edge of the traffic lane.

It should be noted that all of the above vehicle configurations were considered to be operated with radial-ply tires which produce less high-speed offtracking. With bias-ply tires, the slope of the offtracking/lateral acceleration relationship for steady-state turning would be approximately twice that observed with radials, such that the steady-state results shown here would approach twice the indicated magnitudes.



Example offtracking behavior of tractor-semitrailer and doubles combination on 500-ft (152 m) radius curve
FIGURE 15

Moreover, one can observe that the fundamental relationships governing outboard offtracking support the following general statement:

At increased levels of lateral acceleration, trailing axles tend to offtrack to the outside in a steady turn. The outboard offtracking response in a steady turn is maximized in vehicle combinations which are A) relatively long, overall but, B) articulated at multiple joints such that individual trailer length is relatively short.

The paths of trailer tires can be even further displaced from those of the tractor under transient steering conditions. The extent of transient overshoots in the paths of trailing axles are greatest with long A-trains comprised of many short trailers.

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