THE REARWARD AMPLIFICATION RESPONSE OF MULTIPY-ARTICULATED TRUCK COMBINATIONS

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SYNOPSIS:

Certain multiply-articulated truck combinations are known to exhibit lightly damped trailer yaw motions in response to rapid inputs of steering. This paper clarifies the yaw response phenomenon and illustrates this characteristic for ten vehicle combinations which are currently in use in the U.S. The phenomenon of interest is described in terms of the amplification of lateral acceleration level experienced at the rear-most trailer of the combination with respect to the lateral acceleration level achieved at the truck or tractor. This so-called "rearward amplification" behavior is of interest because it threatens the premature rollover of the rear-most unit due to excessive lateral acceleration peaks.

Results from two types of computerized simulation are presented; one representing a linear treatment of the vehicle and producing frequency response characteristics, and the other representing a rather complete nonlinear treatment of the vehicle and producing time history responses in an emergency obstacle-avoidance maneuver. The results show very large differences in the tendency of various combination vehicles to amplify lateral acceleration.

THE REARWARD AMPLIFICATION RESPONSE OF MULTIPLY-ARTICULATED TRUCK COMBINATIONS

WITH INCREASING ECONOMIC PRESSURES to improve the productivity and energy efficiency of trucking in the U.S., there has been an interest in reconsidering the limitations which are placed upon the size, weight, and configuration of commercial vehicles. While various analyses of the economics of size and weight increases (e.g., (1)*) have illustrated that larger and heavier trucks will render a net reduction in the total cost of moving freight, certain of the questions related to safety implications have not been clearly demonstrated. The purpose of this paper is to present research results pertinent to one aspect of the overall safety characteristics which may distinguish different truck combinations.

The performance characteristic of interest here concerns the exaggerated yaw motions which can occur at the rear-most trailers of multiply-articulated vehicle configurations in response to dynamic steering inputs. As will be shown, such motions are present in certain tractor-semitrailers (having only one articulation point) but appear to a much more pronounced degree in vehicle configurations having more than one articulation point. The safety concern arising from this type of behavior involves the risk that the rear-most trailing element will suffer rollover in steering maneuvers which are, otherwise, too low in severity to cause rollover of the rest of the combination. In that regard, the phenomenon has been said to lead to "premature" rollover of the last trailer (2). All other accident causation factors being equal, it is expected that vehicles having a greater degree of this characteristic will become overinvolved in certain peculiar accidents in which the rear trailer rolls over by itself, with the forward units in the vehicle combination remaining upright.

Such an hypothesis was confirmed in an investigation of serious accidents involving "double-bottom" gasoline tankers in the State of Michigan in 1977 (2). This investigation built upon previous analyses (3,4,5) of the dynamics of articulated vehicles to evaluate the behavior of the specific Michigan vehicle of interest. Previous researchers had shown that when a relatively rapid steering input was applied, a lightly damped oscillation would appear in multiple-trailer combinations. Also, various parametric sensitivities had been shown, illustrating that the lightly damped behavior was influenced by a number of geometric and mass-placement parameters.

In the Michigan study, it was found that the Michigan double gasoline tanker embodied many of the less favorable variations in parameters which promoted the "premature rollover" of the second trailer. Further, it was found that at least half of the accidents resulting in rollover of the Michigan double tanker involved rollover of the rear trailer only. More recently, a study of tank truck accidents in the State of California (6) showed that approximately half of the rollovers involving truck/full trailer tankers and two-thirds of the rollovers with double tankers involved the rear trailer only. It was noted that the majority of these accidents have involved filled tanks such that sloshing of the fluid load was not a factor.

Accordingly, it would appear that the dynamic response characteristic leading to premature rollover is a behavioral feature which is of some real significance to the accident record. In the presentation which follows, the relative

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*Numbers in parentheses designate references at end of paper.

performance of various combination vehicles is compared, in the context of response to rapid steering inputs. It is suggested that the relative tendency for premature trailer rollover constitutes a characteristic which should be weighed together with all other safety and economic considerations in the deliberations of those making policy on truck size and weight.

VEHICLE DESCRIPTIONS

Shown in Figure 1 are the vehicles which were analyzed for response to rapid steering inputs. Ten vehicles are shown, including the Michigan double-bottom tanker and the California truck/full trailer tanker for reference, and eight other combinations which are in more-or-less common service in various parts of the U.S. An exception to the "common service" proviso is the "B-Train" version of the double trailer combination having 27-foot trailers. While such vehicle combinations have been introduced recently in certain regions of the Northwestern U.S., the concept is primarily a Canadian development. The B-Train arrangement constitutes a tractor-semitrailer-semitrailer combination, with a rigid extension of the frame of the lead trailer incorporating a fifth wheel hitch for coupling the second semitrailer. The particular B-Train combination represented here is identical to the vehicle designated as the "65-foot conventional double" except for the hitch configuration employed at the inter-trailer coupling.

Overall, the vehicles were selected to embrace those configurations which are known to be of interest in regard to prospective changes in regulations involving allowable truck configurations. In the simulation work which was done, the vehicles were each characterized using the nominal geometric parameters listed in Table 1. The table reveals that vehicles were considered to be loaded to their full gross weight levels. Although many of the longer configurations are known to be rather commonly loaded in service with lighter density freight, such that full gross weight is not typically achieved, the full gross condition was chosen for uniformity and to represent a "worst case" selection. Notwithstanding the "worst case" scenario, it is known that variations in absolute weight of payload are not of first-order significance to the phenomena of interest, as long as the payload mass center location is fixed.

Payload was placed on each vehicle to provide somewhat simplified approximations of common loading. Note that, while the two tractor-semitrailer combinations are identical, geometrically, to the lead units appearing in certain of the doubles and triples combinations, the axle loadings are quite different, as constrained either by common axle load limitations or by bridge formula considerations. Also, it should be noted that, in normal service, trailers which are coupled in doubles or tiples combinations are commonly loaded with a slight forward bias in the fore/aft distribution of load. This practice is recognized as contributing a small improvement in trailer yaw behavior over that achieved with the uniform load distributions represented here.

The payload masses were placed at the specific height which is determined by: (a) the tank layout, in the case of the two tank vehicles or (b) at a height of 85 inches above the ground, in the case of the van-type vehicles. The height of the sprung masses of the empty van trailers was taken to be 60 inches in all cases. All vehicles were represented with radial-ply tires and with suspension characteristics which were thought to be representative of common practice.

COMPUTERIZED SIMULATIONS EMPLOYED

The response characteristics of the selected vehicles were evaluated using a relatively simple, linear model and also using a more comprehensive model employing various nonlinear features. The two separate computer models were employed so as to provide:

a) the benefits of linear analysis in describing a phenomenon which is inherently frequency-sensitive, and

b) a comprehensive treatment of the nonlinear system so that transient responses involving large levels of lateral load transfer could be quantified.

The linear model, reported previously in Reference (7), provides a yaw plane representation of the vehicle, involving the lateral velocity and yaw rate of the tractor, and the articulation of the coupled elements in the horizontal plane. The model neglects pitch and roll motions and assumes a linear relationship between tire side force and slip angle, given cornering stiffness values pertaining to the static loads carried on each respective axle. Articulation angles are assumed to be small such that conventional small angle approximations apply.

The nonlinear model is a time-domain simulation capable of predicting the directional and roll response of multiply-articulated vehicles in steering maneuvers which approach complete rollover of the combination. The model assumes that the forward velocity of the lead unit of the combination remains constant during the maneuver. Each sprung mass is then treated as a rigid body with five degrees of freedom—lateral, vertical, yaw, roll, and pitch. The axles are treated as beam axles which are free to roll and bounce with respect to the sprung masses to which they are attached. The model provides comprehensive treatment of those nonlinearities in suspension and tire behavior which significantly influence the yaw/roll response of trucks up to limit maneuvering conditions. The model has been documented in Reference (8).

RESULTS OBTAINED FROM LINEAR ANALYSIS

The linear model of yaw plane behavior was employed to compute the response of the selected vehicles to a continuous sinusoidal input

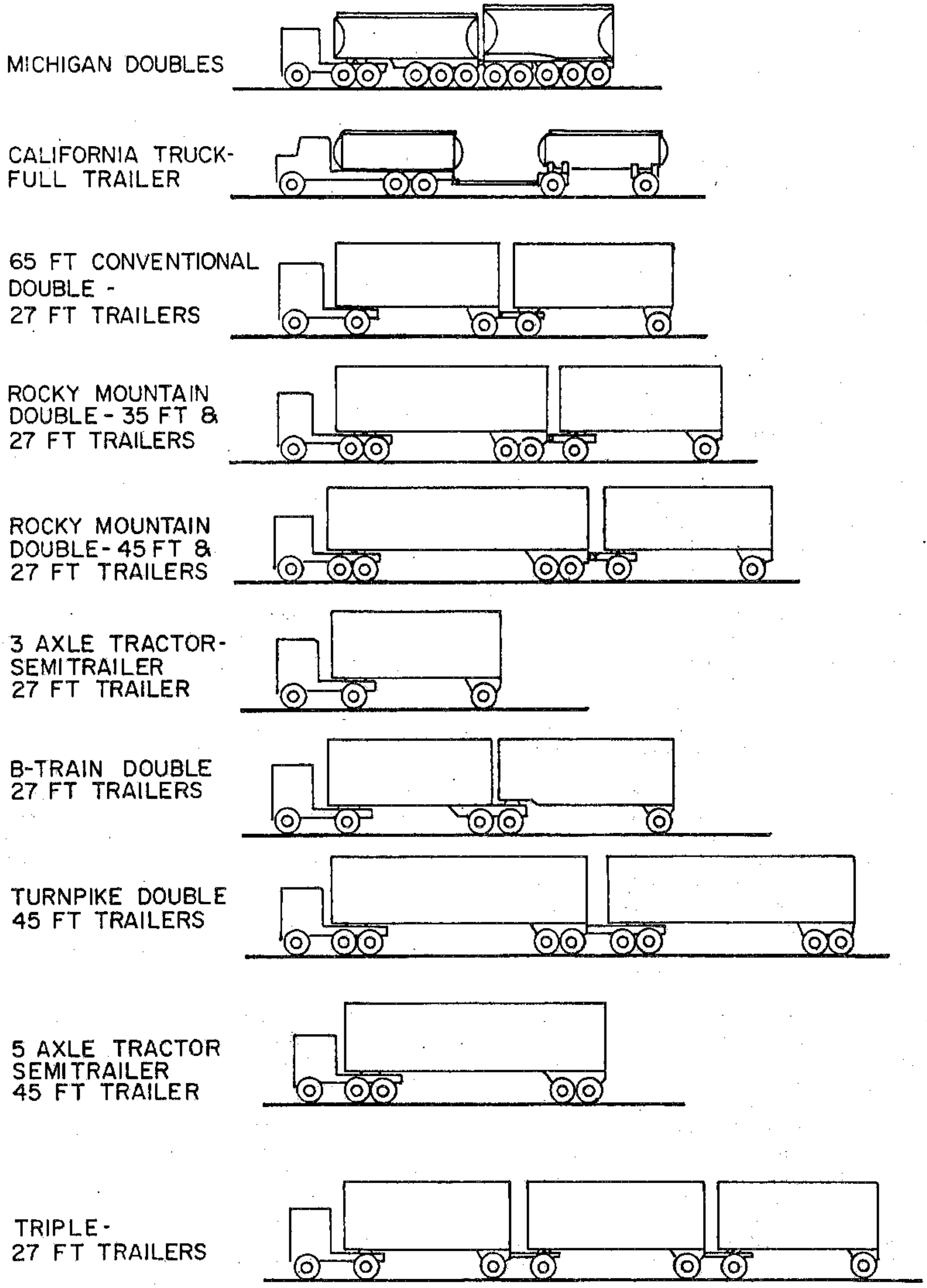


Figure I. Selected Vehicles

VEHICLE	WHEELBASE* (in)				OVERHANG (in)		TONGUE LENGTH (in)		AXLE LOADS (lb/1000)											Gross Weight
	Lead Unit	1st Trailer	2nd Trailer	3rd Trailer	1st Trailer	2nd Trailer	1st Dolly	2nd Dolly	1	2	3	4	5	6	7	8	9	10	11	
Michigan Double	136	206	125		58		68		14.5	16	16	13	13	13	12.8	12.8	13	13	13	150
California Truck Full Trailer	235	222					148		10.5	15.8	15.8	19	19							80
65' Conventional Double	120	252	252		36		80		10	17.5	17.5	17.5	17.5							80
Rocky Mountain Double 35' + 27'	144	312	252		72		80		12	14	14	14	14	16	16					100
Rocky Mountain Double 45' + 27'	144	432	252		72		80		12	15	15	15	15	17	17					106
3-Axle Tractor-Semi	120	252							10.5	20	20									51
B-Train Double	120	252	252		** *** 80/36				10	17.5	17.5	17.5	17.5							80
Turnpike Double	144	432	432		72		80		12	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4			127
5-Axle Tractor-Semi	144	432							12	17	17	17	17							80
Conventional Triple	120	252	252	252	36	36	80	80	10	17.5	17	17	17	17	17					112.5

* Wheelbase of truck or tractor is measured from center of steering axle to center of single or tandem group.
Wheelbase of trailer unit is measured from kingpin to center of rear axle or tandem group.

** Spread distance between axles at the center-coupling.

*** Distance from first trailer axle to center-coupling fifth wheel.

Table I. Overall Parameters Describing the Selected Vehicles of steering. Such a computation constitutes a classical means of examining a linear system over the full spectrum of input frequencies. The analysis is rationalized from the observation that drivers can apply steering inputs over a broad range of nominal frequencies, ranging from the long period inputs associated with normal lane changing, to the relatively short period steering reversals which might be applied in an emergency obstacle-avoidance maneuver. As will be shown, however, the frequency response results must be interpreted carefully, recognizing that they represent vehicle behavior under the condition of a steady-state oscillation, while all rapid steering maneuvers on the highway are inherently transient in nature.

Shown in Figure 2 are the frequency response results obtained at a forward velocity of 55 mph for nine of the ten selected vehicles. (The triples combination is not present in these data since the yaw plane model is not formulated to handle the needed number of articulations for that configuration.) The figure plots an "Amplification Ratio" measure on the ordinate and the swept range of steer input frequencies on the abscissa. The ordinate measure represents a gain function and describes the ratio of the lateral acceleration amplitude occurring at the rear-most trailer to the lateral acceleration amplitude at the tractor or truck. The amplification ratio is seen as directly indicating the proclivity toward premature rollover of the rear trailer element insofar as:

a) the denominator of the ratio scales the nominal severity of the "maneuver input" as it is achieved at the lead unit of the combination, and

b) the numerator term scales the rear trailer response level in a measure which directly determines the moment tending to produce rollover.

We see that at very low frequencies, representing mild maneuvers such as the normal lane-change or passing maneuver, the amplification ratio is equal to unity. That is, the response of the rear-most vehicle element is identical in amplitude to that of the tractor. As the input frequency approaches 3 to 4 rad/sec, all of the vehicle combinations numbered 1 through 7 begin to show an amplified rear trailer response. The 65-foot conventional double and the California truck/full trailer are seen to approach peak values near 2.0, for example, and the Michigan double tanker exhibits an amplification ratio exceeding 4.0. As the steer input frequency increases further, a characteristic attenuation is observed.

For practical purposes, it is generally recognized that ergonomic constraints on human steering input effectively limit the upper range of frequencies to approximately 3 to 3.25 rad/sec (i.e., steer inputs having approximately 2-second nominal period). Nevertheless, it is clear that large levels of amplification can be achieved within that range by certain of the selected vehicles.

It would appear that the level of amplification is larger for the multiply-articulated vehicles which are shortest in overall length (and which thus employ the shorter individual trailer lengths). Previous research (e.g., (3)) has shown that the amplification ratio decreases with increasing length of individual trailers and increases with increasing number of units in the combination. Thus, the pattern of decreasing amplification ratio, seen in Figure 2 over the sequence of configurations 1 through 5, derives from the increases in individual trailer length distinguishing each successive configuration from the preceding one. In the case of the turnpike doubles configuration, vehicle number 8, we see that with 45-foot-long trailers, the amplification behavior is virtually nil.

It is interesting to observe the differences in amplification level between the 65-foot conventional double, number 3, and the B-Train double, number 7. The elimination of the pintle hitch articulation point in the case of the B-Train is seen to powerfully reduce the amplification behavior of the vehicle. (Recall from Table 1 that both vehicles were otherwise identical except for the elimination of the pintle hitch.)

It is also apparent that the three-axle tractor-semitrailer (with short, 27-foot semitrailer), number 6, shows a slight peaking in amplification ratio while the five-axle tractor-semitrailer (with long, 45-foot semitrailer), number 9, shows only an attenuating response. Clearly, the major differences in the amplification behavior of these two tractor-semitrailer combinations derives from the trailer lengths and not from the differences in axle number or loading levels.

Shown in Figures 3a through 3i are individual frequency response plots for each of the nine vehicles whose amplification ratios were presented in Figure 2. The Figure 3 data show the lateral acceleration amplitude of each of the primary elements in each vehicle configuration, ratioed to the steering wheel input amplitude. The ordinate scale is logarithmic, expressing the ratio in decibels. The abscissa variable is the steer input frequency, presented on a linear scale. These plots serve to clarify, in a gross sense, the means by which differing vehicles exhibit either an increasing or decreasing amplification ratio in response to a sinusoidal steer input. Note that the amplification ratio is derived from the measures shown in Figure 3 by the relation:

$$\text{Amplification Ratio} = \frac{A_y/\text{DSW(Rear Trailer)}}{A_y/\text{DSW(Tractor)}}$$

The 65-foot conventional double, in Figure 3c, is characteristic of many vehicles exhibiting amplification ratios which are well above 1.0 We see that with increasing steer frequency, the tractor, semitrailer, and full trailer all exhibit a falloff in lateral acceleration gain (with respect to steer input). Amplification of the rear trailer's lateral acceleration with

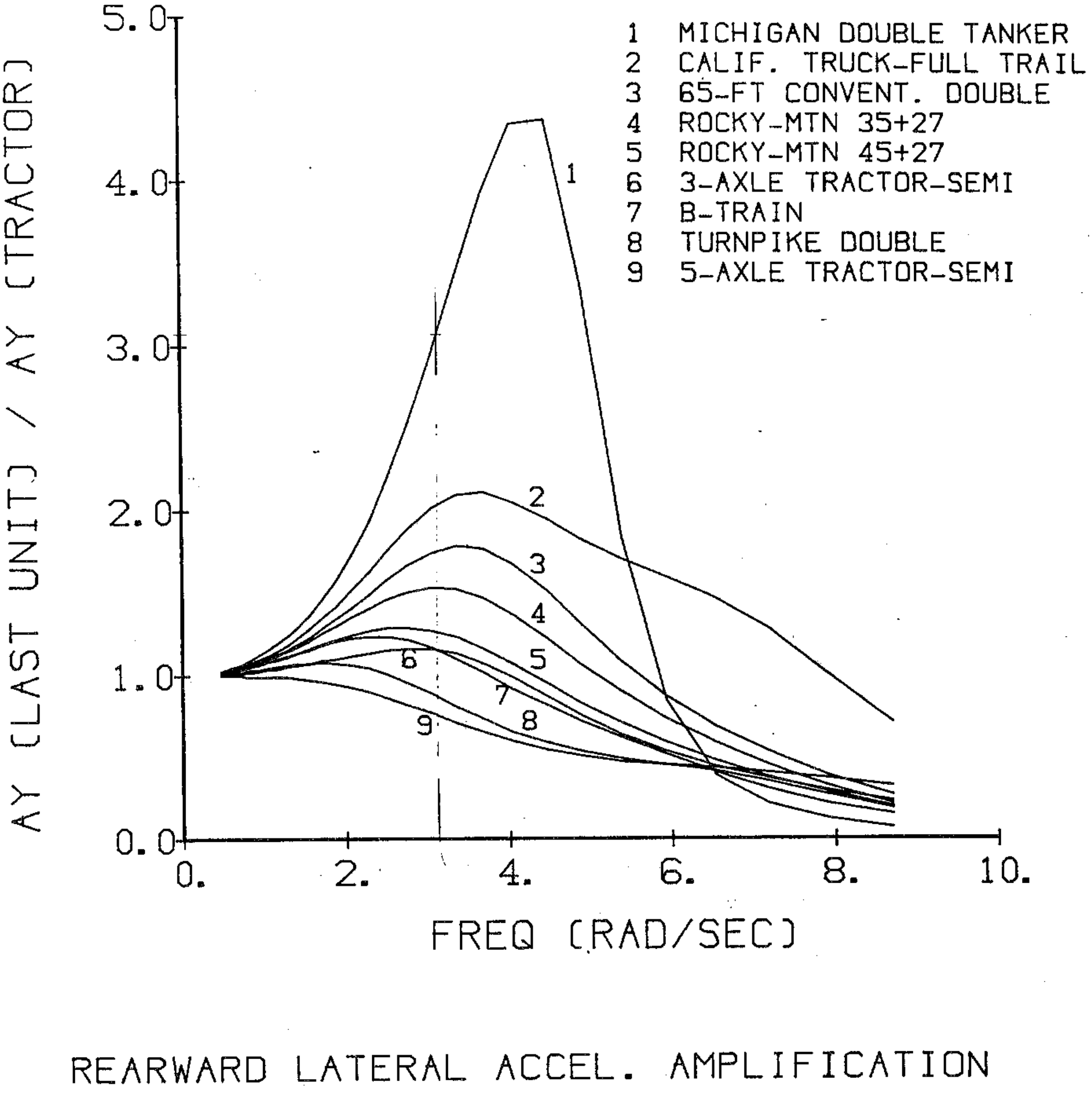
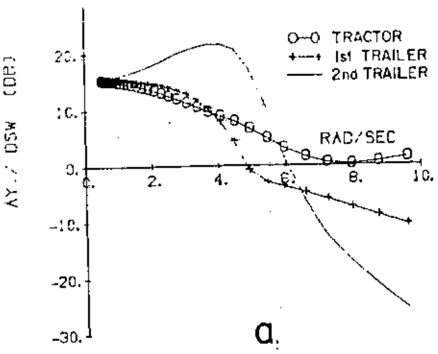
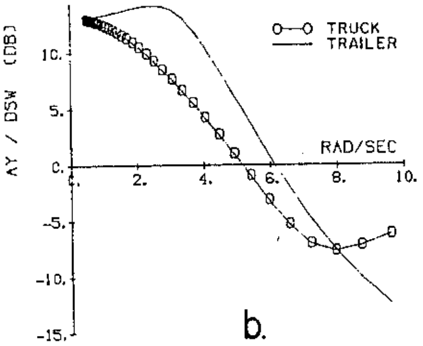


Figure 2. Influence of steer input frequency on rearward amplification (for the case of a steady state steering oscillation)



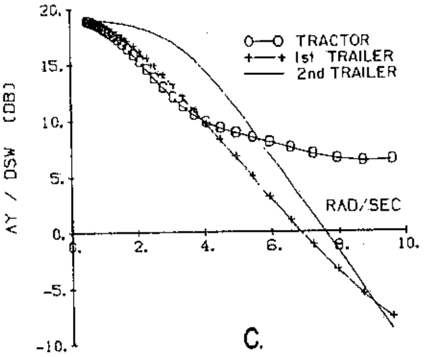
a.

MICHIGAN DOUBLE



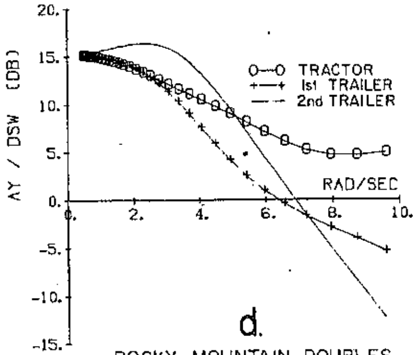
b.

CALIFORNIA TRUCK-FULL TRAILER



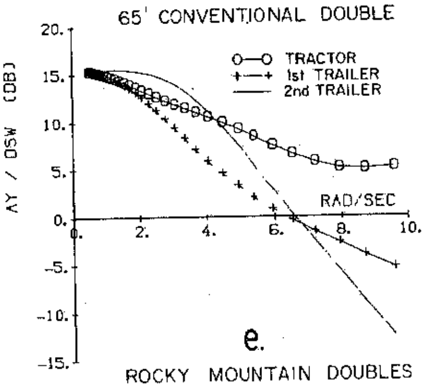
c.

65' CONVENTIONAL DOUBLE



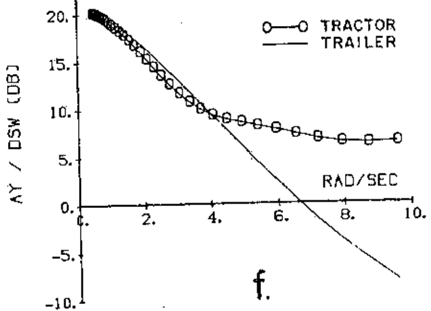
d.

ROCKY MOUNTAIN DOUBLES
(35' & 27' TRAILERS)



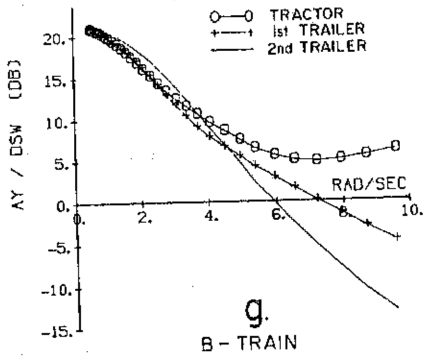
e.

ROCKY MOUNTAIN DOUBLES
(45' & 27' TRAILERS)



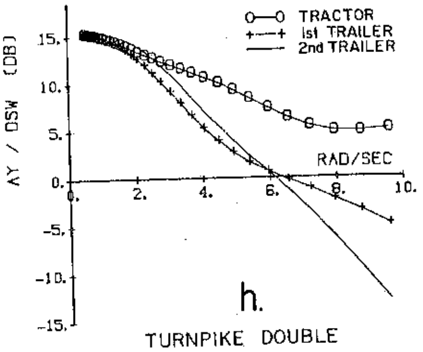
f.

3-AXLE TRACTOR-SEMITRAILER



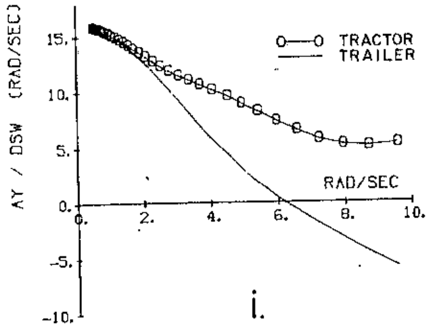
g.

B-TRAIN



h.

TURNPIKE DOUBLE



i.

5-AXLE TRACTOR-SEMITRAILER

Figure 3a-i. Frequency response results showing the lateral acceleration response to tractor steer input for each of the major elements.

respect to the tractor occurs in such vehicles simply because the tractor response is falling off at a rate which exceeds that of the rear trailer. The maximum amplification ratio is obtained at the point at which the maximum difference exists in the gain levels of the tractor and rear trailer in Figure 3c.

By way of comparison with the 65-foot conventional double, Figure 3g reveals that the B-Train achieves its lower amplification ratios by effecting a stronger attenuation in the rear trailer lateral acceleration gain while otherwise leaving the tractor and first trailer responses relatively unchanged.

Looking at the Michigan double tanker, Figure 3a, a distinct resonance in the lateral acceleration response of the rear trailer to tractor steering input accounts for the much greater amplification ratio level which was seen in the vicinity of 4 rad/sec. Thus, in contrast to the case cited above with the 65-foot conventional double, the Michigan vehicle accrues much of its amplification through a resonant phenomenon rather than simply by means of differences in attentuation rate between tractor and rear trailer.

Perhaps the most unusual case among the vehicles producing large values of amplification ratio is the California truck/full trailer, shown in Figure 3b. It is immediately apparent from Figure 3b that the high "tail" which was seen on the amplification ratio curve for the California vehicle in Figure 2, derives from the remarkably strong attentuation seen in the truck's response in the frequency range above 3 rad/sec. That is, the truck of the truck/full trailer combination is highly sluggish in response to steering at higher frequencies. Together with the mildly resonant response of the trailer, the net amplification ratios are high—although the implication is that unusually large levels of steer input amplitude would be required to achieve higher frequency maneuvering.

In the case of the five-axle tractor-semitrailer, the lateral acceleration response of the trailer attenuates more rapidly than does that of the tractor, as shown in Figure 3i, such that the amplification ratio remains below 1.0 throughout the frequency range.

Moreover, the linear analysis is useful for establishing that:

1) Amplification ratios significantly greater than 1.0 are attained in the practically-achievable range of steering frequencies between approximately 1.0 and 3.0 rad/sec.

2) Maximum amplifications occur at the higher end of that frequency range.

3) A very substantial spread in the values of amplification ratio exists among contemporary vehicle combinations found in the U.S. (although frequency response analysis provides only a "first cut" at the relative levels distinguishing vehicles from one another).

4) Substantially differing mechanisms appear to be involved in the rear-amplified lateral acceleration response of various vehicle configurations.

RESULTS OBTAINED USING THE NONLINEAR MODEL

Simulation runs using the nonlinear model were designed to provide a characterization of vehicle response in an emergency obstacle-avoidance maneuver. In previous research (2), such maneuvers were conducted through an open-loop technique in which a single sinusoid of steering was applied at a selected value of forward velocity. The period of the steering sine wave was set at 2.0 seconds, approximating what is thought to be the highest frequency at which substantial steering amplitudes can be reasonably applied (and, of course, seeking to excite the rearward amplification phenomenon). Vehicle response to such maneuvers was characterized in terms of an amplification ratio employing the peak values of the lateral acceleration time histories measured at the rear trailer and tractor, respectively.

While this method was quite satisfactory for examination of the Michigan double tanker, later research has revealed that certain vehicles exhibit a sufficiently asymmetric lateral acceleration response at the tractor that the amplification measure becomes meaningless. That is, the denominator term was seen to reflect an anomalous feature of the tractor behavior (namely, the asymmetry feature which appears to have no importance to overall vehicle control), rather than serving to scale the severity of the maneuver.

Accordingly, a closed-loop maneuver scheme was developed whereby the tractor was steered to follow an idealized "obstacle-avoidance" trajectory. The trajectory, itself, comprised that ground-fixed path (in longitudinal, X, and lateral, Y, coordinates) which is subtended by a vehicle unit having a time history of lateral acceleration, in body-fixed coordinates, of

$$\ddot{y} = A \sin \omega t \qquad (1)$$

where

A is the lateral acceleration amplitude
t is time
ω is frequency in rad/sec

This acceleration history produces the lateral displacement history, $y(t)$,

$$y(t) = \frac{L}{T}\left[t - \frac{T}{2\pi}\sin\left(\frac{2\pi t}{T}\right)\right] \qquad (2)$$

where

L is the total lateral displacement
T is the period of the original waveform

If we assume that the vehicle travels at relatively high speed, such that heading angles remain small, given the narrow lateral constraints of the highway, then the body- and ground-fixed coordinate systems remain aligned such that the ground path, $Y(X)$, is produced.

$$Y(X) = \frac{L}{T}\left[\frac{X}{V} - \frac{T}{2\pi}\sin\left(\frac{2\pi X}{TV}\right)\right] \qquad (3)$$

where

Y is the lateral displacement achieved at the longitudinal position, X

V is the forward velocity

The vehicle lateral acceleration amplitude, A, can be related to the path parameters by the relation

$$A = 2\pi L/T^2 \qquad (4)$$

Thus, it can be seen that the path, Y(X), is characterized by:

1) a selected value of total lateral displacement, L, which is directly proportional to the nominal lateral acceleration amplitude, A,

2) a total longitudinal length, X = V/T, over which the lateral displacement is achieved, and

3) a form which, when traversed, will assure a symmetric and basically harmonic lateral acceleration experience by the tracking vehicle.

Using this ground path, simulation runs were arranged as follows:

a) The total lateral displacement, L, was varied from run to run in an iterative search for the condition in which the peak lateral acceleration at the rear-most trailer was seen to reach 0.3 g's. By this approach, the rearward amplification behavior of each vehicle would be evaluated in a condition approaching, but below, the rollover threshold.

b) The total longitudinal length, X, was fixed for the conditions of velocity, V = 80 ft/sec (55 mph) and nominal time period, T = 2 seconds. Thus, the highway speed condition is provided and the vehicle becomes excited at that frequency level which was discussed as constituting the worst reasonable case for consideration of rearward amplification.

Shown in Figures 4 and 5 are the time domain lateral acceleration and Y(X) path forms employed. The example path shows a layout producing a 6-foot total lateral displacement which is achieved in 2 seconds by means of a lateral acceleration history which peaks at approximately 10 ft/sec^2.

The simulation was implemented in the closed-loop mode by means of a "driver model" which determined, at each instant of time, the steering input needed to minimize the differences between the desired future path of the vehicle and the estimated future vehicle position. This driver control computation scheme is described in Reference (9).

The bar charts presented in Figures 6 and 7 illustrate the values of the nominal steering wheel input period and the resulting tractor lateral acceleration periods obtained by the driver model's "operation" of each vehicle over the obstacle-avoidance path. We see that while the mere achievement of the desired path assures that all vehicles exhibit virtually identical values of period in their tractor lateral acceleration responses, the California truck/full trailer stands out as requiring an unusually short steering input period in attaining the required path.

Examining steer inputs further, Figures 8a, b, and c show example steering waveforms applied by the driver model in following the obstacle-avoidance path. Figures 8a and 8b are fairly characteristic of the overall set of vehicles, as was suggested in the bar chart above, except for the case of the California truck/full trailer shown in Figure 8c. In 8a and 8b we see steering waveforms which involve initial left-and-right steering rotations having a nominal period of approximately 2 seconds, with one or two subsequent path correction overshoots. The lower steering amplitude applied in the case of the 65-foot conventional double, in Figure 8a, reflects the fact that with the higher amplification behavior of this vehicle, the 0.3 g limiting acceleration on the rear trailer is reached with only a rather small steering input at the tractor. The turnpike double, on the other hand, is seen in Figure 8b to require much larger steering inputs to cover the larger lateral displacement at which its rear trailer exhibits a 0.3 g lateral acceleration response.

As shown in Figure 8c, the California truck/full trailer requires both large amplitude and unusually high frequency steering to attain the 0.3 g lateral acceleration peak in its trailer response. Thus while the path layout implies a truck lateral acceleration response having a nominal 2-second period, the sluggish response of the truck requires that a higher frequency input be applied. Note that the maneuver in question involves a decidedly transient condition in which response characteristics are very different from those examined by means of the steady-state frequency response analysis. Clearly, the sluggish response of the truck portion of this vehicle configuration calls for a questionably realistic steering input in achieving the defined maneuvering criteria.

Shown in Figures 9a through 9j are lateral acceleration time histories illustrating the responses of the ten selected vehicles in their respective "reference case" obstacle-avoidance maneuvers. The plots show the phase lags characterizing tractor and subsequent trailer responses, as well as the apparent amplification phenomena by which rear-located trailers exhibit amplified levels of lateral acceleration. Note that the maximum amplitude trailer response, and the occasion of highest propensity for rollover, occurs in the "second peak" following the steering input. If the maneuver severity were increased so as to produce rollover in this initially-left-going maneuver, the rear trailer would roll over toward the left lane, onto its left side.

Examining the various cases, the following results deserve mention:

1) In Figure 9a, the response of the Michigan double tanker shows a tractor response level of only approximately 0.1 g for achievement of the 0.3 g peak at the second (or "pup")

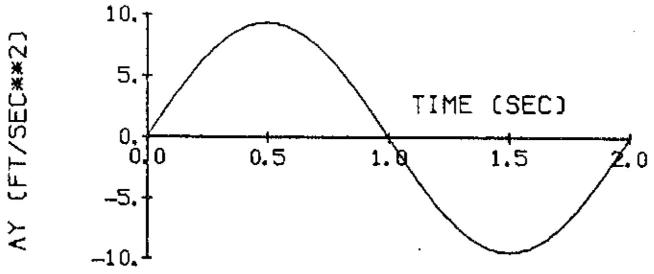


Figure 4. Time history of Ay from which Y(X) path is generated

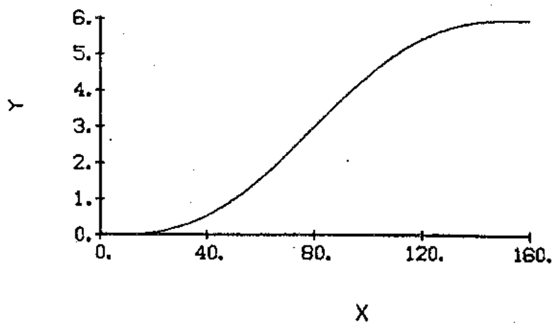


Figure 5. Y(X) path for which the Y amplitude was varied from run to run (6 ft example shown)

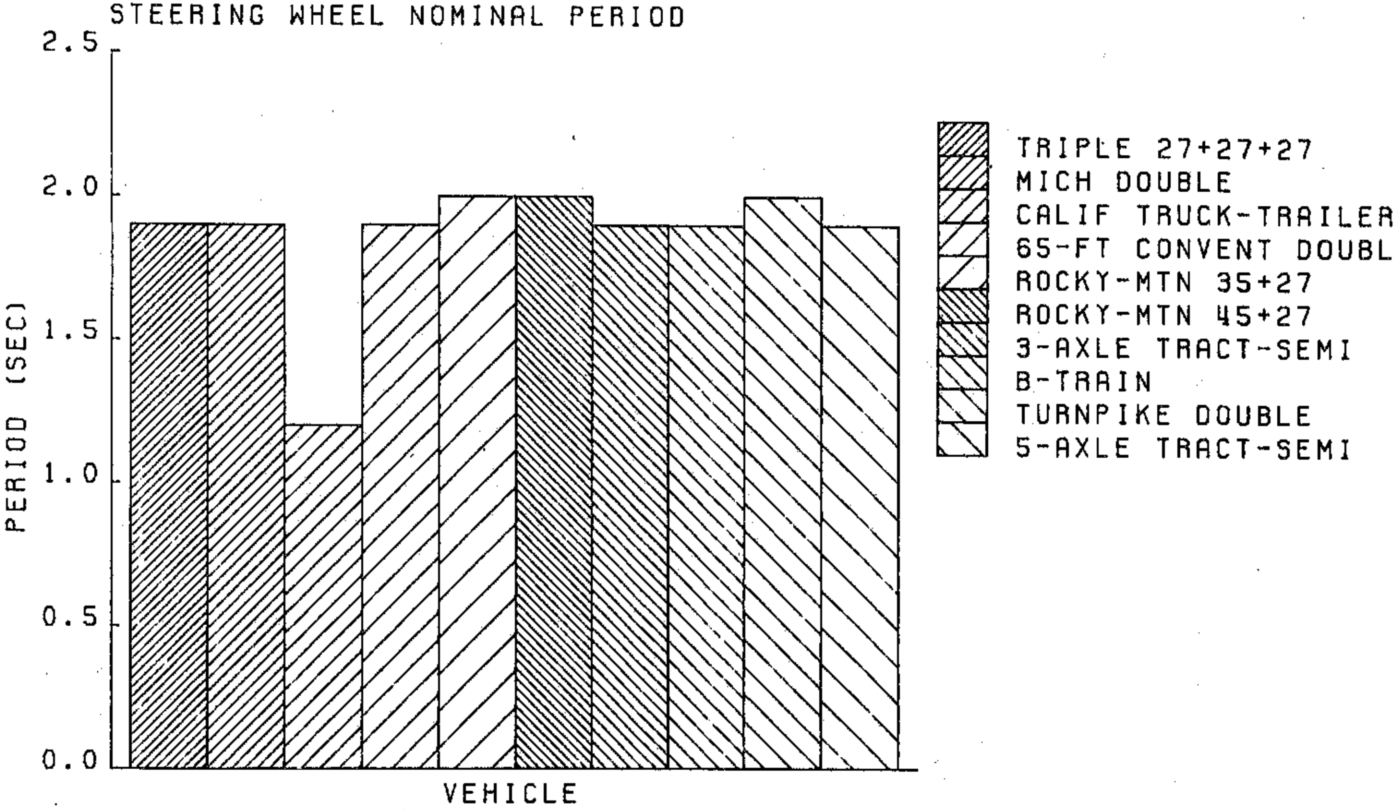


Figure 6. Nominal steering input periods applied with each vehicle in negotiating the obstacle avoidance path

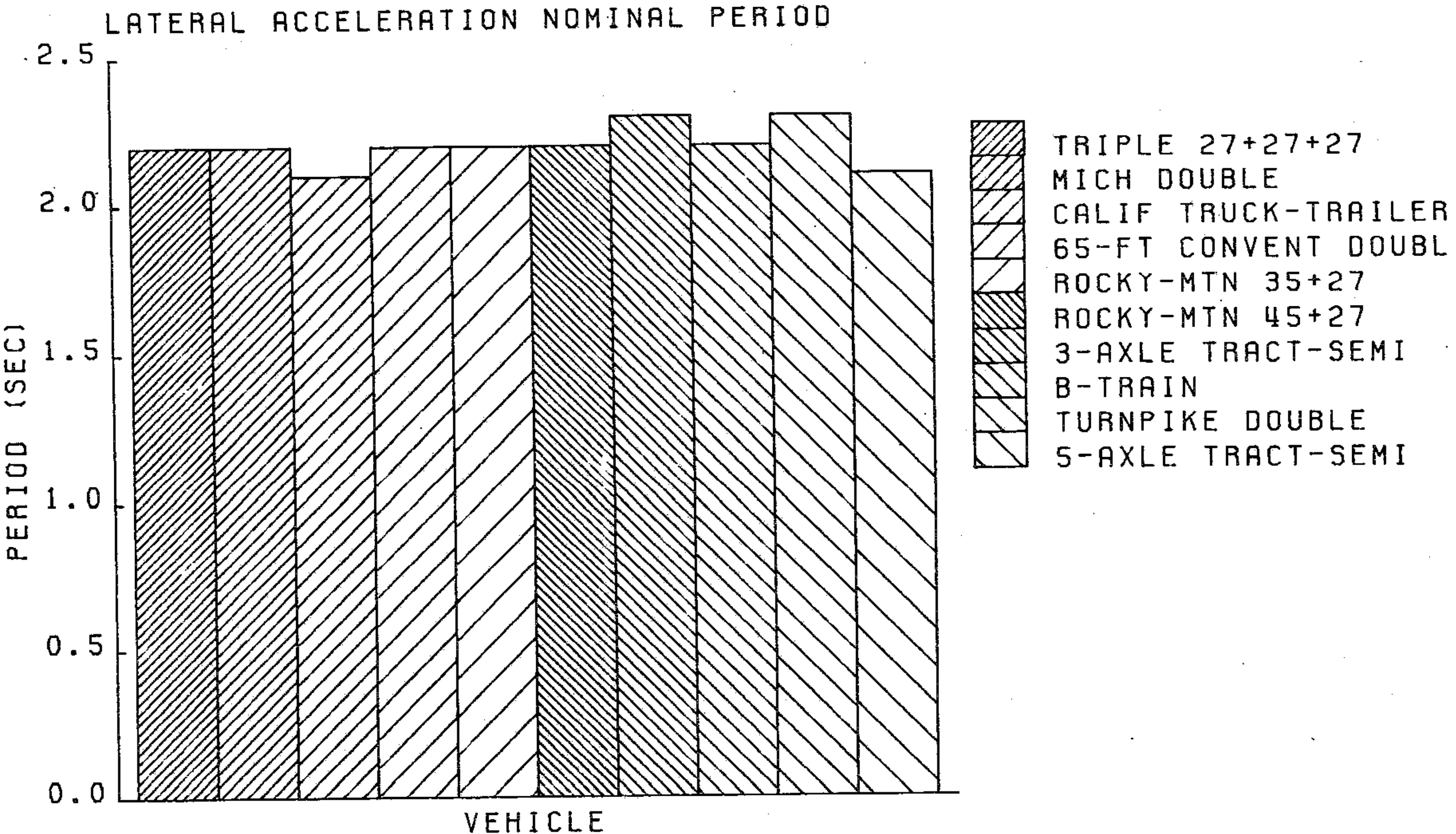
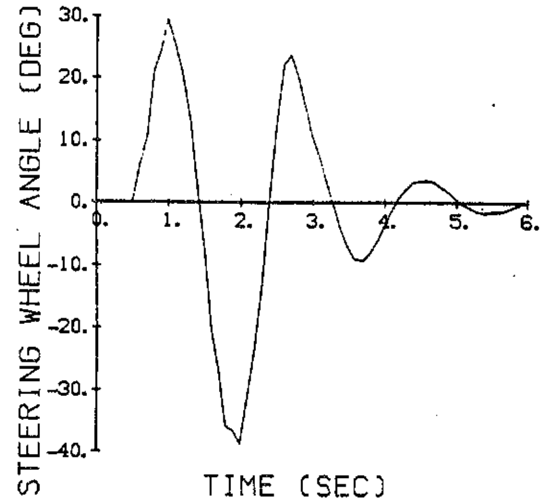
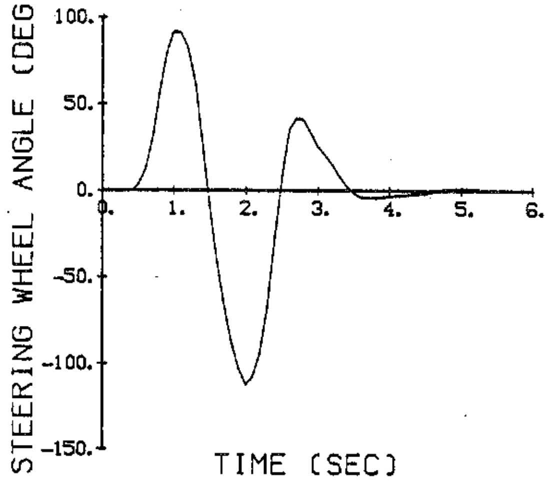


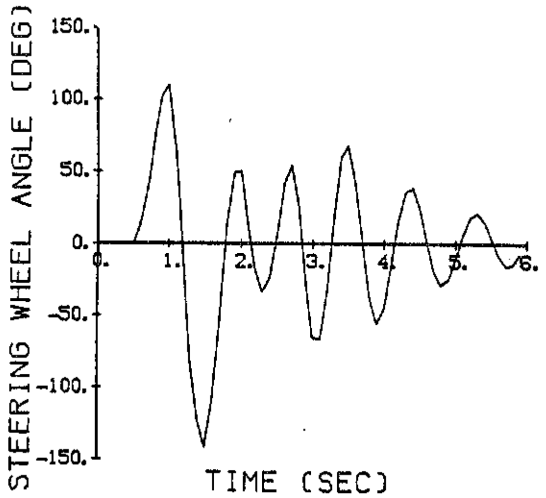
Figure 7. Nominal period of lateral acceleration response of each power unit in the obstacle avoidance maneuver



a. 65 FT DOUBLES (27 FT TRAILERS)



b. TURNPIKE DOUBLES



c. CALIFORNIA TRUCK FULL TRAILER

Figure 8a-c. Steer inputs applied in negotiating the obstacle avoidance maneuver

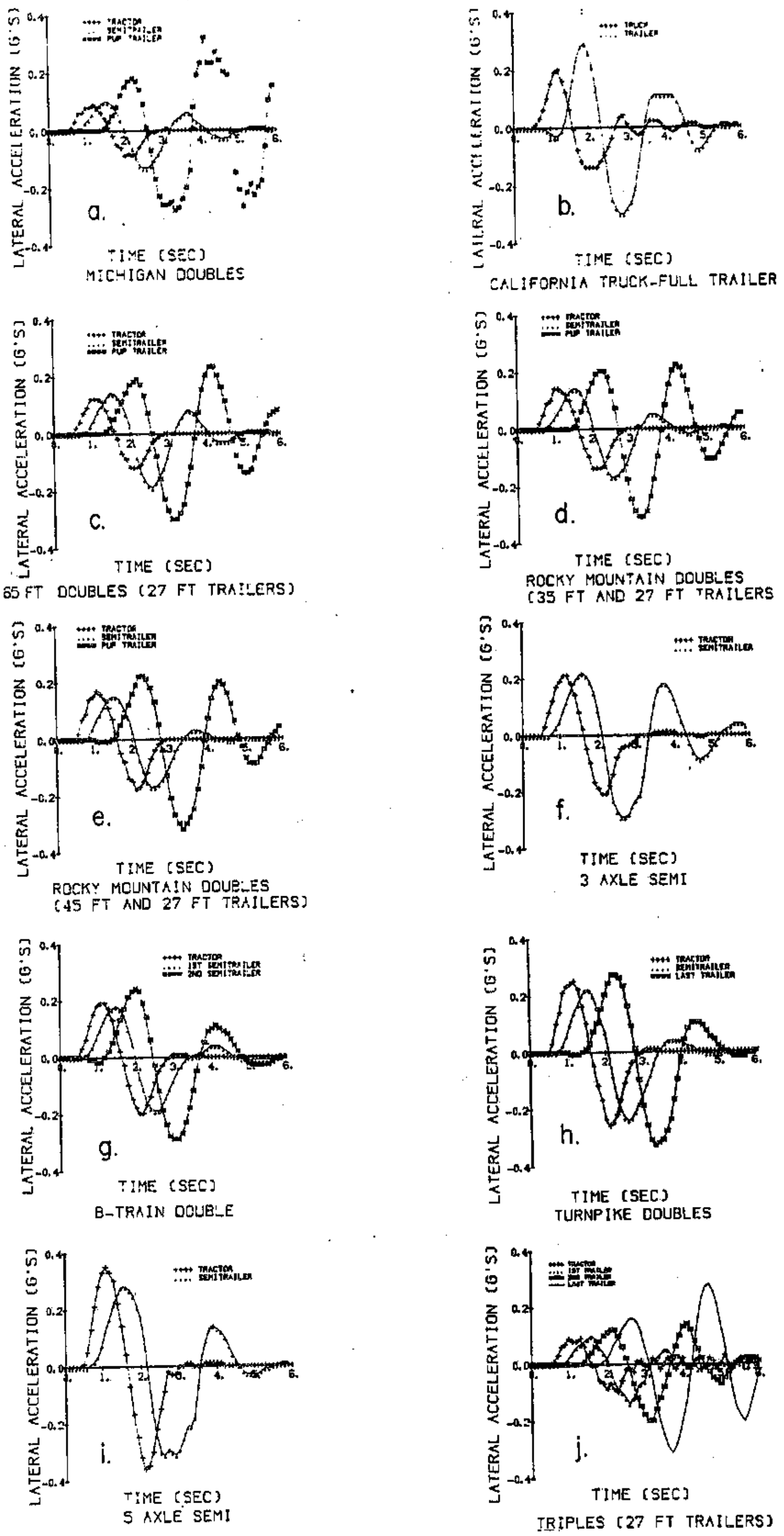


Figure 9. Lateral acceleration responses in the obstacle avoidance maneuver

trailer. Note that the second peak exhibited by the semitrailer is substantially amplified above the tractor response level.

2) In the case of the longer of the Rocky Mountain Doubles, Figure 9e, it is instructive that the first trailer, which is 45 feet long, shows a significantly reduced peak response with respect to the tractor while the second, 27-foot, trailer exhibits a substantial amplification. Interestingly, in the case of the turnpike double, Figure 9h, the second trailer is still substantially higher in response amplitude than is the first, although both trailers are the longer, 45-foot, variety. Clearly, the mechanical behavior of full trailer configurations, generally, involves an inherent ability to amplify, with the strength of the amplification determined heavily by length parameters. A detailed analysis of the mechanics by which full trailers produce amplified responses can be found in Reference (10).

3) While the response of the B-Train is notable for its substantial reduction in amplification in comparison to the 65-foot conventional double (see Figures 9c and 9g), an important further distinction is not apparent from the presented response data. We note that the response of the second trailer of the B-Train shows a substantial phase lag with respect to the preceding trailer such that the critical "second peak" occurs at a time at which the lateral acceleration of the lead trailer is nearly zero. Since the basic makeup of the B-Train involves a rigid roll coupling between the trailers, this phase lag characteristic implies a very substantial increase in effective rollover resistance. That is, the lead trailer, with its diminished lateral acceleration response, has the ability to aid in providing the roll reaction moments needed to maintain roll stability at the occasion of the peaking in the second trailer's response. This feature, which further enhances the overall safety quality of B-Train configurations, is described more rigorously in Reference (11).

4) The response of the triple, shown in Figure 9j, reveals a continuing amplification in the peaks of each successive trailer. The final "accumulated" amplification level is seen to be of the same order as that exhibited by the Michigan double.

The overall results from the nonlinear simulation are summarized in the bar charts shown in Figures 10 and 11. Figure 10 shows the rearward amplification exhibited by each of the ten vehicles for the case involving a peak lateral acceleration level of 0.3 g at the rearmost trailer. The amplification measure was calculated, in these data, using the 0.3 g peak lateral acceleration value at the last trailer ratioed to the nominal lateral acceleration amplitude, A, associated with the path layout, as described earlier. The path itself, then, defines the "severity" of the maneuver.

We see in Figure 10 that lateral acceleration levels are registered both higher and lower than the values that were obtained in the frequency response analysis. Although the Michigan double, for example, registers an amplification level which is slightly lower than that found in the frequency response analysis, the 65-foot conventional double registers considerably higher, and the California truck/full trailer considerably lower, than shown earlier. Clearly, these differences are attributable to fundamental distinctions between the transient and steady-state response of dynamic systems. It is obvious, for example, that while the obstacle-avoidance path is nominally configured around a two-second sine wave of acceleration, the single-cycle input actually introduces a broad bandwidth excitation of the vehicle. Further, strong nonlinearities influence the result in the simulation of the transient maneuver case. It is to be noted again, however, that the results presented for the truck/full trailer are subject to question because of the unusually high steering frequencies required. More work appears to be needed to fully evaluate the amplification behavior of such vehicles.

Although various distinctions can be made between the two types of analysis, it should be noted that the obstacle-avoidance maneuver was intended to illustrate the comparative magnitude of the amplification behavior of the selected vehicles, while the frequency response analysis was intended to illustrate the spectrum of frequency sensitivities.

Another means of characterizing the relative magnitude of the amplification responses is presented in Figure 11. The figure shows the value of the total lateral displacement, L, of the path at which the rearmost trailer produces a 0.3 g peak value of lateral acceleration. The triple and the Michigan double, for example, are seen to yield the 0.3 g response of the last trailer with only a two-foot lateral displacement (at 55 mph and a nominal maneuver period of two seconds). Clearly, higher values of this lateral displacement measure are desirable since they imply that the driver of such vehicles could "get away with" maneuvering to clear much larger obstacles without risking the premature rollover of the rear-most trailer. In this sense, the high amplification vehicles would be said to be "less forgiving," thus effectively reducing the safety maneuvering options of the driver.

CONCLUDING REMARKS

Having illustrated that large differences exist in the amplification behavior of contemporary U.S. vehicles, a key question remains as to the direct connection between amplification level and the likelihood of rollover accident involvement. The projection of accident involvement is an inherently thorny matter because such a large number of variables can also be influenced in the actual in-service operations of the respective vehicle configurations. In certain cases, vehicle configurations such as triples have been admitted into service only under special maintenance and driver-selection agreements and only on certain designated routes—and the safety records have been

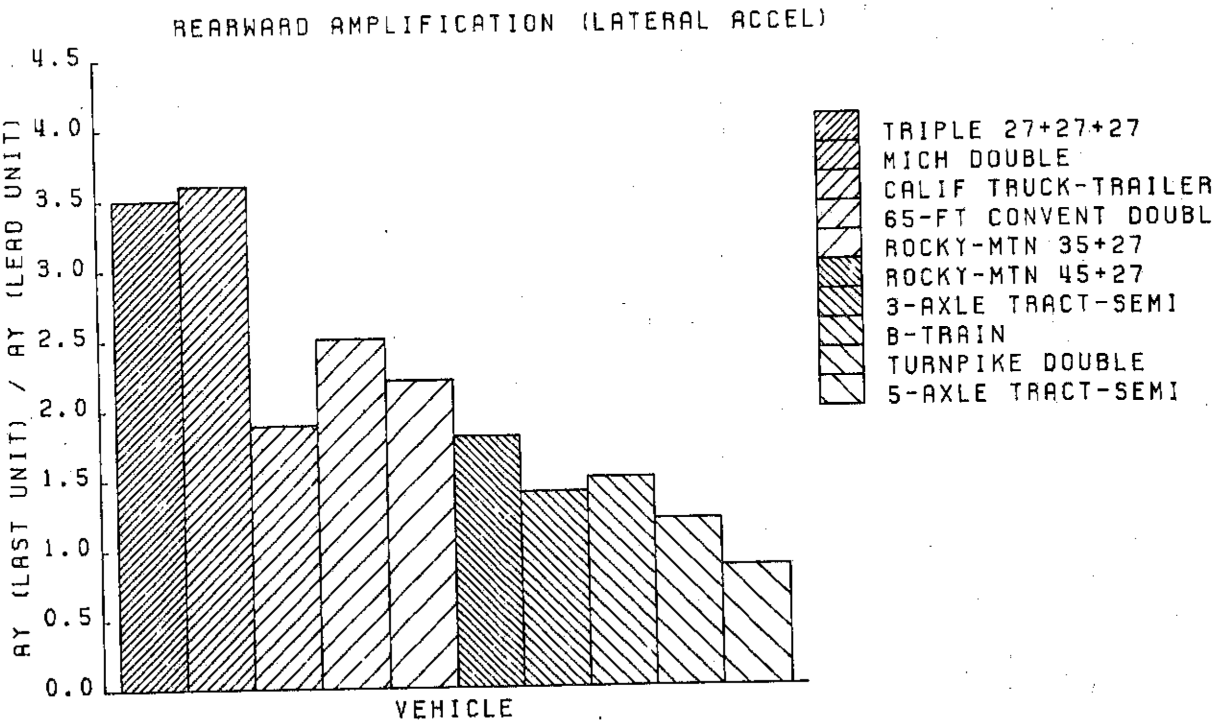


Figure 10. Rearward amplification levels exhibited in obstacle avoidance maneuver

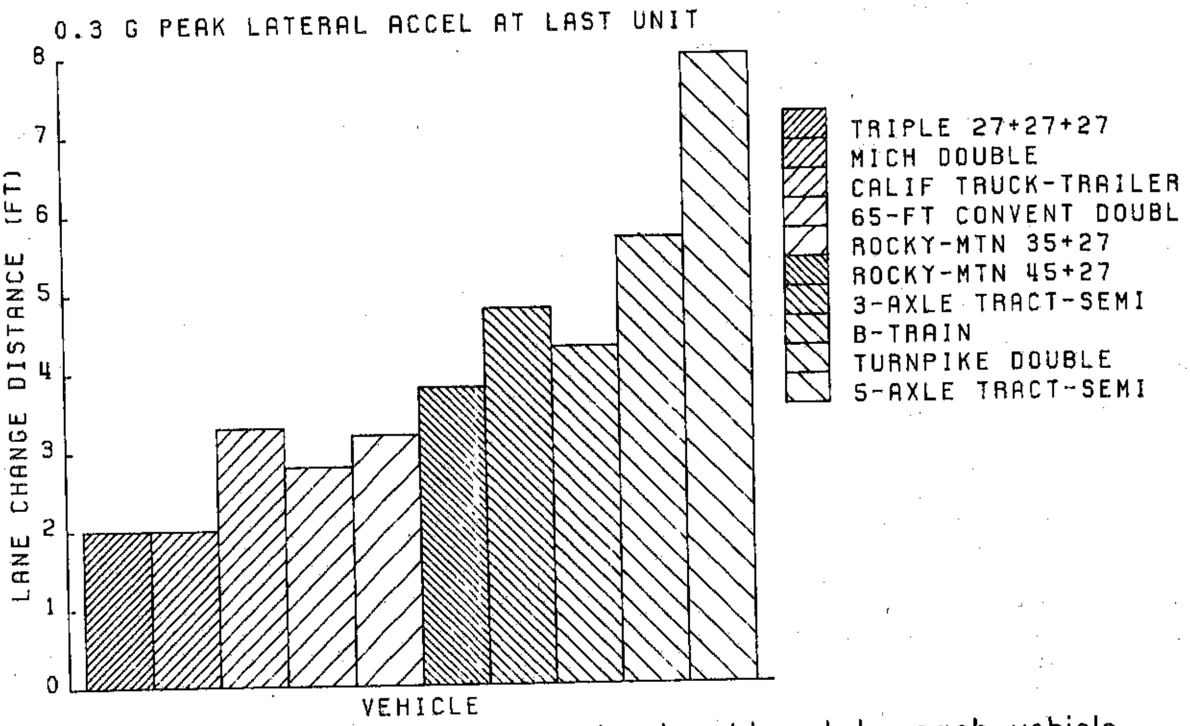


Figure 11. Lateral displacement level achieved by each vehicle before exhibiting a 0.3g peak in the last trailer's response

very good. Thus it cannot be said, categorically, that vehicles with high amplification ratios will necessarily do poorly in the field.

Perhaps more general direction can be obtained, however, when vehicles are considered for general freight service and are to be driven by the general truck driving population. Unless such vehicles would be characteristically loaded with freight which differed from configuration to configuration in such a way as to compensate amplification problems with reductions in mass center height (an unlikely prospect), it would appear that a high incidence of rollover involvement should accompany high values of amplification ratio. In the cases for which accident data provide a substantive assessment (2,6), this relationship is nominally confirmed.

A final practical aspect of the safety issue is, "what is the particular nature of the threat imposed by the type of rollover which results peculiarly from an amplification problem?" On the basis of Michigan and California experience with tankers (and believed to be supported by the accident experience of common carriers operating doubles), the rear-trailer rollover event occurs predominantly as a single-vehicle accident event. That is, no other vehicles are typically struck and the truck driver is not threatened by the trailer rollover incident, itself. Thus, such accidents are primarily property-damage incidents, except for the case in which hazardous commodities, such as are carried in bulk tanks, may become released through the rollover impact. Such hazardous commodity problems, of course, were the focus of concern in the cited studies involving Michigan and California tankers. Notwithstanding the above remarks concerning the fact that rear trailer rollover accidents seem to be primarily property damage incidents, it should be recognized that many other accident scenarios can develop in which vehicle occupants and pedestrians may be in jeopardy. It should also be noted that the amplified responses, per se, can be excited through other steering scenarios than simply the "obstacle-avoidance" maneuver employed here as an evaluation method. Alternative scenarios might include:

a) The case of a driver falling asleep, drifting off the road, and then imparting an abrupt steering correction, upon being awakened by the off-road ride vibrations.

b) The case of the driver observing, through his mirrors, that the last trailer tires are running on the shoulder due to road crown, side wind, etc., and then imparting an abrupt steering correction, especially if a bridge crossing is just ahead.

Moreover, the rearward amplification behavior of certain vehicle configurations can only be looked upon as a safety deficiency in current trucking practice. Approaches such as the B-Train layout and other schemes offering tamed amplification response in otherwise highly productive vehicle combinations should be encouraged.

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