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The Influence of Rear-Mounted, Caster-Steered Axles on the Yaw Performance of Commercial Vehicles

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Abstract

The so-called "booster axle" —an axle mounted at the extreme rear of the vehicle whose load is adjustable under operator control and which usually has caster-steered wheels— is examined for its influence on the yaw performance of commercial vehicles.

Booster axles are attractive in certain applications where vehicle loads are large, but a high level of low-speed maneuverability is desired. The addition of a booster axle can increase the legal load limit of such a vehicle significantly without altering low-speed offtracking behavior. Booster axles are relatively common in cement mixer trucks, which carry high loads, but require good maneuverability at the construction site. Booster axles are sometimes used on semitrailers designed to transport construction equipment.

This paper reports on the findings of computer-aided analyses examining the destabilizing influence of booster axles on the yaw plane behavior of straight trucks and tractor semitrailer combinations. The UMTRI Simplified Handling and Yaw/Roll Computer Models are used as computational tools. The understeer gradient of the subject unit vehicles is examined with the aid of Pacejka's handling diagram, and the boundaries of stable yaw plane performance are found. The influence of booster axles on the high speed offtracking performance of semitrailers is examined.

The freely-castering booster axle is found to generally degrade vehicle handling and yaw stability, but it is argued that substantial performance improvement might be obtained with advanced designs.

The Roads and Transportation Association of Canada
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Introduction

This paper reports on the findings of computer-aided analyses examining the destabilizing influence of rear-mounted, caster-steered axles on the yaw plane behavior of straight trucks and tractor semitrailer combinations. These so-called "booster axles" are described, and previous research on their effect on vehicle performance is described. The understeer gradient of the subject unit vehicles is determined through the use of the UMTRI Simplified Handling Model. Results are presented with the aid of Pacejka's handling diagram, and the boundaries of stable yaw plane performance are found. The UMTRI Yaw/Roll Model is used to examine vehicle performance in the time domain. The influence of booster axles on the high speed offtracking performance of a tractor-semitrailer vehicle is also examined.

Booster Axles

The term "booster axle" refers to a single axle, trailing arm-like suspension, retrofitted to the rear of a vehicle, and configured to allow operator control of the amount of load carried by this axle. Booster axles are generally distinguished from other "tag axles" by their extreme rearward position on the vehicle and by their unusually long trailing arm. The load control system generally includes the ability to lift the booster axle completely free of the ground, and to "stow" the mechanism in a vertical position for travel in the lightly-loaded condition. A mixer truck with its booster axle in this position is shown in Figures 1 and 2.

The configuration of the booster axle allows its tire-to-road contact point to be located considerably aft of the nominal "rear end" of the vehicle, substantially lengthening the wheelbase vis-a-vis *axle load regulations*, and resulting in the ability of the vehicle to carry considerably greater loads than would be the case without the booster axle, while remaining within legal load limits. In order to load all axles effectively, the additional load allowed by the use of the booster axle must be added to the vehicle at a position which is quite far aft, thus contributing to a significant rearward shift in c.g. position of the loaded vehicle.

The extreme rearward position of the booster axle has the effect of substantially increasing the "spread" of the multi-axle rear suspension of the vehicle. If a standard, non-steering axle were used for the booster axle, unacceptable increases of tire scuffing and tire wear and reductions of low speed maneuvering capability due to the increase in effective wheelbase might result. To avoid such practical problems, booster axles are usually equipped with "steerable" axles. Most often, these are self-steering, or castering, axles. (However, some booster axles are steered in a controlled fashion through an hydraulic steering mechanism coupled to the front axle steering system.) The majority of booster axles use completely "free" caster steering, but others use caster-steer axles with "centering force" mechanisms which promote the development of some tire side force before steering takes place.

Conceptually, the load control mechanism of booster axles could take many forms. In practice, booster axles are generally raised and lowered either with an hydraulic cylinder or with air springs. In general, the operator is allowed to set actuator fluid (hydraulic oil or air) pressure which, in turn, establishes the static load on the booster axle. In a common installation on cement mixer trucks, this is accomplished by "dialing in" the yardage of the cement load using a "calibrated" control on the side of the truck or in the cab.

Previous Research

In a study conducted at UMTRI, Winkler, et. al.[1][1], examined the influence of self-steering booster axles on the stability of a unit truck through computer simulation. The yaw response of a heavily-loaded cement mixer truck was examined when the vehicle was equipped with (i) a non-steering booster

[1] Numbers in brackets refer to references given at the end of the paper.

axle and (ii) a freely-castering, self-steering booster axle.

The UMTRI study hypothesized that the additional load, added to the extreme rear of the vehicle when the tag axle was used, would have a significant destabilizing effect on the vehicle's yaw performance. If a *non-steerable* axle were used, it was predicted that this destabilizing influence would be largely offset by the stabilizing effect of the increase in wheelbase. However, if a freely-castering, self-steering axle were used, no increase in effective wheelbase would result (since no additional tire side force is produced)[2] and the vehicle yaw stability would suffer accordingly.

The hypothesis was solidly confirmed by the subsequent computer study. At 55 mph, the open loop vehicle was found to be yaw stable in low level turning maneuvers when equipped with a *non-steerable* booster axle. However, when equipped with the freely-castering, steerable booster, the open loop vehicle was decidedly unstable. The study report states:

> The particularly interesting feature of this instability is that it is present at very low levels of lateral acceleration. Whereas (other poor performing vehicles examined in the study) required that a certain level of lateral acceleration be achieved before precipitating directional instability at highway speeds, this vehicle appears to exhibit little or no lateral acceleration stability margin at 55 mph (88.5 kph).

While the UMTRI study concentrated on the performance of heavily-loaded vehicles equipped with booster axles, more recent work by Woodrooffe [2] has investigated the influence of booster axles on vehicles in the empty condition. Although the design intent is for the booster axle to be raised clear of the roadway when the vehicle is empty, vehicle operators can make mistakes in this regard, sometimes with disastrous results. Woodrooffe's investigation was motivated in part by a recent fatal accident in British Columbia involving a mixer truck equipped with a booster axle.

As declared in its title, Woodrooffe's paper reviews a test program seeking to demonstrate the influence of load imbalance (maladjustment) of self-steering booster axles. The test program involved two vehicles, viz.:

- A five-axle mixer vehicle equipped with twin steering axles, tandem rear axles plus a booster axle. This booster axle was of the freely castering, self steering variety. Booster axle load was set by an operator control calibrated in "yards" of concrete.
- A six-axle tractor semi-trailer consisting of a three axle tractor plus a trailer equipped with a tandem axle suspension plus booster axle. This booster axle was self-steering but included a "centering force" mechanism. Both booster axle load and the "centering force" were established by air pressure regulation.

The vehicles were tested in the empty condition, since the thrust of the study was to demonstrate the adverse effect of maladjusted booster axle loading wherein the booster axle supports "too much" of the vehicle weight.

Being limited in available vehicle motion instrumentation, Woodrooffe chose to characterize vehicle response primarily through observing tire slip angle at the rear-most, non-booster axle (termed 'the rear axle' hereafter), as a function of lateral acceleration and booster axle load. Actually measured were the vehicle velocity and the turn radius ascribed by each axle group during steady turning on a nominal 25 m radius turn. Slip angles were deduced from these measures taken from successive runs at velocity levels providing lateral accelerations from 0.02 to 0.2 g's. It was hypothesized that

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[2] Here, "effective" wheelbase is in relation to *yaw* behavior, and it is noted that without the advantage of tire side forces (completely lost because of the freely-castering steer behavior), the booster axle tires have no influence on wheelbase vis-a-vis yaw performance. This contrasts with the previous notion that the booster axle increases wheelbase vis-a-vis the legal issues of load carrying capacity.

maladjustment of the booster axle would result in excessive slip angle at the rear suspension, implying an oversteer condition and potentially unstable response in the unit vehicle, and excessive outboard offtracking of the trailer of the combination vehicle.

For both test vehicles, Woodrooffe's experiments did, indeed, demonstrate the expected negative quality of excessive increase of rear axle slip angles with increasing booster axle load levels. At the rather modest steady turn level of 0.12 g's, the rear axle slip angle of the unit truck was seen to grow from approximately 2° to 8° to 18° as the booster axle loading was adjusted from "up" to "5.5 yds" to "7.9 yds." Regarding the results for the tractor semi-trailer vehicle, repeated measurements of rear axle slip angles in the 6 and 7 degree range during turns at 0.23 g's are reported. With no air pressure supplied to the steering "centering force" mechanism, this level of slip was attained with 40 psi delivered to the booster axle load mechanism. With equal pressure delivered to both the load and the "centering force" mechanism (the design condition), rear axle slip angle was observed to be 3 degrees at the 40 psi setting, but rose rapidly thereafter to 6 degrees at 60 psi.

The Study Vehicles

This study examines the performance of three vehicles similar to the vehicles of the previous studies noted above. These were (i) a 4-axle unit truck, (ii) a 5-axle unit truck, and (iii) a six-axle tractor-semitrailer. The first vehicle is similar to the UMTRI study vehicle and the latter two are similar to the Woodrooffe study vehicles.

Pertinent geometry and axle load data for these three vehicles are presented in Figures 3, 4, and 5. As reflected in the data tables of these figures, the three vehicles were each examined in the "empty" and the "loaded" condition. In each of these conditions, performance was calculated as a function of booster axle loads. In the loaded condition, the nominal "proper" booster axle load was assumed to be 12,000 lb (5443 kg), but calculations were also conducted for "maladjusted" booster axle load "settings" of 9000, 6000, 3000 and 0 lbs (4082, 2722, 1361, and 0 kg). Loading of the vehicle is not altered with changing booster axle load, so that, at the lower settings, loading of the nearby tandem suspension tires becomes quite excessive. With the vehicles in the "empty" condition, the "proper" booster axle load is, of course, 0 lb. Maladjusted loads of successive 2000 lb (907 kg) increments are also used. In these cases, the nearby tandem tires may become very lightly loaded.

All tire data used in the calculations were representative of steel-belted radial tires, and included the nonlinear influence of vertical load on cornering stiffness. The steering axles of the unit trucks were "equipped" with 385/65R22.5 wide-base singles. The tractor steer axle and all of the booster axles used single 11R22.5 tires. All other "standard" rear and trailer axles used dual 11R22.5 tires. The majority of calculations were conducted assuming free caster steering of the booster axle tires. As reference, a limited number of calculations were conducted with non-steering booster axles.

Performance of the Unit Vehicles

Handling Diagram and Stability Plane Results

Regarding the unit vehicles, the purpose of the study was to examine the influence of booster axle load on handling performance and yaw stability. The primary computational tool used for this purpose was the UMTRI Simplified Handling Model.[3,4] This model uses closed form analysis to calculate the steady state turning performance (path curvature, lateral acceleration, etc.) of a vehicle as a function of steer angle and forward velocity. Results of the calculation are presented graphically. One useful presentation is the "handling diagram," initially developed by Pacejka. As shown in Figure 6, this is a plot of lateral acceleration vs. the function

$$L_r \cdot \rho - \delta_{sw}/N \quad (1)$$

where:

L_r is the reference wheelbase

ρ is path curvature

δ_{sw} is steering wheel angle, and
N is steering ratio.

The plot is produced for a fixed value of forward speed (but varying path curvature).

At constant speed, the understeer gradient of a vehicle, U, can be shown to be

$$U = \frac{d\left(\delta_{sw}/_N - L_r \bullet \rho\right)}{d(a_y)} \qquad (2)$$

Thus, the slope of a vehicle's performance curve on the handling diagram is indicative of its understeer/oversteer quality of the vehicle. A "linear vehicle" will produce a straight line (constant slope) on the handling diagram, but the nonlinear tire properties of truck tires, which are considered by the Simplified Model, generally result in curved plots as shown in the figure. This form indicates that at low severity turning (low lateral acceleration) the vehicle is understeer, but changes to oversteer at high maneuvering levels.

In the oversteer region (positive slope), there is a "critical slope." Where the vehicle performance produces a positive slope of lower value than the critical slope, the vehicle is unstable in open loop performance. That is, the speed at which the plot was produced, is the "critical speed" at the level of lateral acceleration at which the slope of the plot equals the critical slope. At higher accelerations, the vehicle is unstable in yaw at that speed. Figure 6 shows the understeer, oversteer, stable and unstable regions of performance for the representative vehicle performance plot.

The shape of the handling diagram is a function of speed for a nonlinear vehicle. Thus, a family of curves, each representing performance at one velocity, can be plotted for a given vehicle. If the critical point of instability is determined for each curve, the functional relationship between critical speed and lateral acceleration is defined. MacAdam [5] plotted the locus of such points on the velocity-acceleration plane to illustrate the regions of stable and unstable performance. The Simplified Model also presents results in the form of MacAdam's "stability plane" plot, as illustrated in Figure 7.

The Unit Vehicles in the Loaded Condition

Figures 8 and 9 present the handling diagram results for the 4-axle and the 5-axle unit trucks, respectively, in their loaded conditions. The set of curves on each plot show the results for the various conditions of booster axle loading and steering as described in the "Booster Axle Key" in each figure. All of the data in Figures 8 and 9, as for all other handling diagrams herein, are for a forward velocity of 55 mph (89 kph).

Figures 10 and 11 show the stability plane results for the same vehicles in the loaded condition and with the same variations of booster axle condition. These data, as explained above, show the families of "critical" points which would derive from handling diagrams for many different velocities.

The data of these figures clearly indicate that, when equipped with a ***non-steering***, properly loaded booster axle ("Fixed Steer, 12,000 lb"), these vehicles are understeer and, therefore, yaw stable over the majority of the operating range. They become oversteer at 55 mph, only when operating in excess of 0.3 g's. Lateral accelerations in the area of 0.35 g's are required to depress critical velocity well down into the operating range.

However, when the booster axle is allowed to steer freely, the handling quality of the vehicle degrades substantially, regardless of booster axle loading. These fully loaded vehicles become oversteer at relatively low levels of turning severity. In the worst case (the 4-axle vehicle with 12,000 lb booster load), the vehicle is oversteer at 0 g's when operated at 55 mph. Further, for both vehicles, the critical velocity is well down into the operating range at maneuver levels of 0.25 g's, and is as low as 20 mph at 0.3 g's.

It is particularly instructive to note that, once the handling quality of these *loaded* vehicles is markedly degraded by the introduction of the *free steering* , then the handling quality is not particularly sensitive to booster axle load. In the four figures, the several "Free Steer" curves clearly group together, and are distinguished from the "Fixed Steer" curve. Further, the small differences that do exist between the individual "Free Steer" curves generally indicate that vehicle response becomes more unstable as more load is placed on the booster axle. In fact, handling quality is slightly better with no booster axle load, even though this results in the rear tandem axles being grossly overloaded. On reflection, this seems reasonable, for virtually no matter how badly the non-steering axles are overloaded, they will provide some small increment of stabilizing tire side force, while the freely-castering tires of the booster axle will provide none.

The Unit Vehicles in the Empty Condition

Figures 12 and 13 contain the handling diagrams for the 4-axle and 5-axle unit vehicles, respectively. Once again, a family of curves representing performance at various booster axle load conditions is presented in each figure. Each handling diagram is for a forward velocity of 55 mph (89 kph).

Figures 14 and 15 are the companion stability plane plots for the empty vehicles. These data represent the loci of critical points which would derive from handling diagrams generated for many forward velocities.

The plots in these four figures display distinctly less curvature (are more linear) than those for the loaded vehicle. Because of the generally low level of loading, all the tires of these empty vehicles are operated in their more linear performance regime. Thus, the empty vehicles are more nearly "linear vehicles" than are the loaded vehicles, and this fact is reflected in the plotted results.

The data contained in these four figures clearly show that the understeer and stability qualities of these *empty* vehicles is extremely sensitive to booster axle load. With the booster axle raised, the vehicles are solidly understeer throughout the performance range examined. Since a critical speed does not exist for an understeer vehicle, this condition does not even appear on the stability plane plots. As the booster axle load is increased in 2000 lb (907 kg) increments, the results show a rapid progression toward oversteer. At booster axle loads of 4000 and 6000 lbs respectively, the 4-axle and 5-axle vehicles have become oversteer. An additional increase of 2000 lbs of booster axle load makes each vehicle extremely oversteer. These latter two loading conditions appear on the stability plane for each vehicle. At the highest booster axle loads, the critical velocity has descended to the 20-25 mph range (32-40 kph), even at zero lateral acceleration. Such vehicles would be extremely difficult to control, even in maneuvering situations which would normally present modest challenge to a driver.

These findings are certainly not surprising. They are of the same general nature as those for the loaded vehicle—that is, the vehicle becomes more oversteer and unstable at lower speeds as load is transferred from the "normal" rear axle to the freely steering booster axle. Because of the overall light load condition, the *percentage* loss in stabilizing rear tire side force is simply larger for a given increase in booster axle load.

Results in the Time Domain

The results discussed above are all of a closed form type and provide insight into the handling and stability quality of the unit vehicles on a theoretical basis. Largely to provide the reader with greater intuitive insight, a few results were calculated in the time domain using the UMTRI Yaw/Roll Model.[6] This simulation model was used to conduct the "RTAC A maneuver" on the two loaded vehicles. This maneuver was developed by Ervin and Guy in their work for RTAC [7], and is used to produce reference measures of static rollover threshold, steady-state yaw stability, and high-speed offtracking.

The maneuver begins with a constant radius turn at 100 kph (62 mph) and with a radius producing 0.2 g's lateral acceleration. After 10 seconds, the maneuver switches to a ramp-steer producing an ever-tightening spiral path leading eventually to rollover. The steady-state portion of the maneuver uses a "driver model" or "path follower" as a closed-loop controller; the second portion of the maneuver is open-loop using a predetermined rate of steer angle increase.

The rate of steering increase is low, such that this portion of the maneuver is quasi steady-state as long as the vehicle remains stable.

In the context of the RTAC measures, the steady-state portion of the maneuver is used to determine high speed offtracking, and the open loop portion is used to measure understeer gradient, steady-state yaw stability, and static rollover threshold.[7]

Figures 16 and 17 are plots of the lateral acceleration time history of the loaded 4-axle and 5-axle unit vehicles, respectively. Each figure contains the time history for several runs in which the loading and steering condition of the booster axle was varied. These include 0, 6000, and 12,000 lb loads on a freely steering booster axle and 12,000 lb load on a non-steering booster axle.

The portion of the maneuver between ten and fifteen seconds is most germane here. At the ten-second time point, the control function switches to open-loop, and the stability or instability of the vehicle becomes evident. Both of the unit vehicles are stable only when the booster axle is equipped with the fixed steering axle. When free caster steering is used on the booster axle, the vehicles quickly diverge and eventually roll over. Divergence is generally more rapid as the load on the free steering axle increases from 0 to 12,000 lbs. These time response results are clearly in agreement with the analytical results presented earlier.

It is worthwhile to note that, while the vehicles are unstable in open-loop, the driver model is successful at stabilizing the closed-loop system in the early portion of the maneuver. Particularly for the 4-axle vehicle, the driver model has some difficulty, however, as indicated by the overshoot and oscillatory response in the 4-to-6 second range. (The "accuracy" of the drive model at representing typical human drivers is unknown.)

Performance of the Tractor-Semitrailer

The steady-state yaw stability quality of a tractor-semitrailer vehicle is dominated by the properties of the tractor; trailer properties are only secondary in this regard.[8] On the other hand, properties of the trailer are very important as regards offtracking performance and the general "tracking fidelity" of the vehicle.[9] In this study, the UMTRI Yaw/Roll Simulation Model was used to examine the influence of the booster axle on the high-speed, steady-state and transient offtracking performance of the six-axle tractor-semitrailer of Figure 5.

Steady-state offtracking was examined using the "RTAC A maneuver" described in the previous section. Thus, results reported are for the condition of a steady turn at 100 kph (62 mph) and 0.2 g's lateral acceleration. Transient offtracking was examined using the "RTAC B3 maneuver."[7] This maneuver is a rapid path change which produces a sinusoidal lateral acceleration response at the tractor. Magnitude of the sinusoidal response is approximately ± 0.15 g's and the period is 3 seconds. The forward velocity of the vehicle is 100 kph (62 mph). The transient offtracking measure is the maximum "overshoot" of the rear-most trailer axle relative to the final lateral path displacement of the tractor.

The steady-state and transient offtracking performance of the loaded and the empty tractor-semitrailer vehicle in the RTAC maneuvers is reviewed in Figures 18 and 19, respectively. In the loaded condition, there is a clear trend for increasing load on the freely steering booster axle to increase the offtracking response. However, in these relatively low severity maneuvers, offtracking does not become particularly excessive. Steady-state offtracking reaches a peak of 0.51 m (1.7 ft) with a 12,000 lb booster axle load. Transient offtracking peaks at 0.31 m (1.0 ft) under the same loading conditions. These measures, however, are strongly influenced by the non-linear behavior of tires. At some more severe maneuvering level, we would expect the booster axle load condition to become more influential in determining whether or not the fixed trailer axle tires reached lateral force saturation. Under such conditions, offtracking would become more sensitive to booster axle load.

This argument tends to be supported by the offtracking response of the empty vehicle shown in Figure 19. Because of the general condition of light tire loads, increasing booster axle load (and the corresponding reduction of load at the fixed axles) more readily promotes side force saturation at the tires of the fixed axles. The non-linear nature of the system is readily apparent in Figure 19 where the steady-state offtracking is seen to leap from 1 to 11 meters as booster axle load increases from 4000 to 6000 lb (and the load on each of the fixed trailer axles drops from 5740 lb to 3140 lb). However, even in this latter condition, transient offtracking still does not become particularly excessive.

The time history of the acceleration response of the tractor-semitrailer vehicle in the "B" maneuver provides the explanation for the low levels of transient offtracking. These time histories, shown in Figure 20, clearly indicate that the trailer "tracking" response is degrading as booster axle load increases, but the tendency is for the response to become "sluggish" rather than to "overshoot." The general loss of side force capability at the trailer tires results in an inability of the trailer to respond adequately in this relatively high-frequency, transient maneuver.

Conclusions, Comments, and the Prospects for Better Booster Axles

Results presented in this paper clearly indicate that the application of booster axles using free caster steering to commercial vehicles virtually always degrades the handling performance of those vehicles. In the case of unit vehicles, use of such axles promotes an oversteer response and the attendant tendency toward yaw instability. When applied to the semitrailer of a tractor-semitrailer combination, booster axles promote excessive steady-state offtracking, while apparently producing sluggish trailer response in transient maneuvers. In *all* cases, increasing the load carried by the booster axles tends to produce greater degradation of handling quality. This is true even in the fully loaded condition where low booster axle loads may result in gross overloading of the nearby fixed axles of the vehicle.

We hasten to point out that culpability in this result lies in the property of "free caster steering" and not in the characteristic, extreme rearward location of the booster axle. Indeed, locating axles at the extremes of the vehicle, either fore or aft, rather than near the center, is attractive for promoting vehicle stability. However, the advantage of the booster axle location can be realized only through the application of the tire side force capability at that location. That advantage is completely discarded along with those side forces when free caster steering is used. Indeed, the transfer of load from fixed tires capable of generating side force, to castered tires incapable of that contribution, is the essential reason for loss of handling quality when freely castering booster axles are used.

It follows, then, that the booster axle may hold potential for improving vehicle stability, if only the potential side force capability of its tires were effectively utilized. While using conventional, non-steering axles does not seem practical, controlled steering axles, or caster steering axles with significant centering force mechanism do seem to hold promise. Both of these solutions have been applied in limited numbers. Controlled steering axles, whose steering mechanism is linked hydraulically to the front axle steering system, have been used on unit vehicles. The many styles of self-steering axles used on B-dollies could be applied to booster axle applications.

A method for estimating the performance which might be achieved by a unit vehicle using self-steering axles with centering force mechanisms is illustrated in Figure 21. Common centering mechanisms on self steering axles resist steering until some minimum level of tire side force is achieved. Thereafter, they steer substantially with little additional side force. Prior to steering they behave as a fixed axle; once steering begins, they behave approximately as a free steering axle. The figure illustrates how these two properties could be expected to combine on the handling diagram. Note that the *slope* of the handling diagram —and thus the stability implications— in the upper performance regime is unaffected by the fact that performance was improved in the lower regime. The primary performance improvement might be expected only at maneuvering levels in which steering does not occur. Thus, the greatest acceptable resistance to steering is desirable.

Controlled steering of rearward axles has been used successfully in applications other than booster axles. Linkage steered axles have been used successfully on especially long semitrailers, and they have been shown to be effective in B-dolly applications.[10] In addition to establishing the proper steering ratio, a key element in achieving good dynamic performance is maintaining a high level of stiffness in the steering linkage.

While freely steering booster axles appear to be categorically undesirable as regards vehicle control and stability, improved booster axle designs deserve consideration in future research and development programs.

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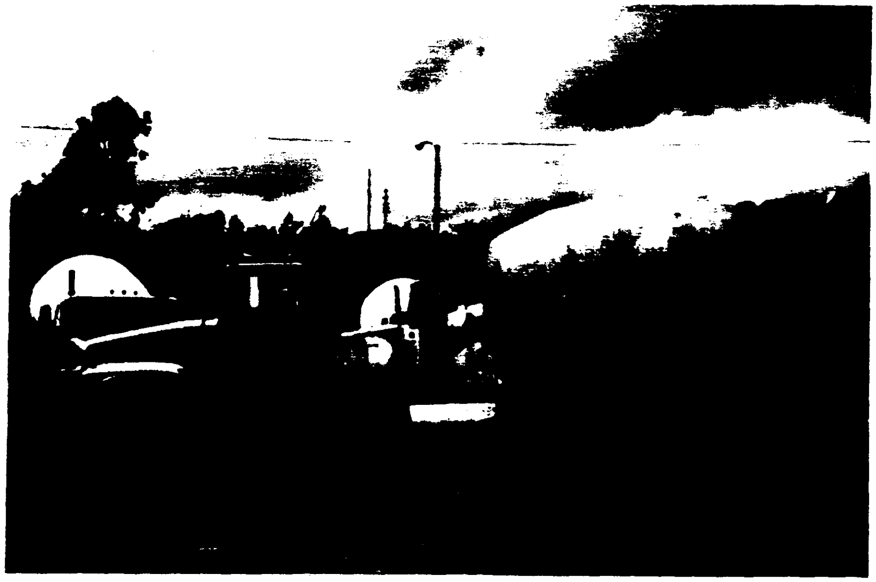


Figure 1. Photograph showing the side view of a unit truck equipped with a booster axle in the raised position.

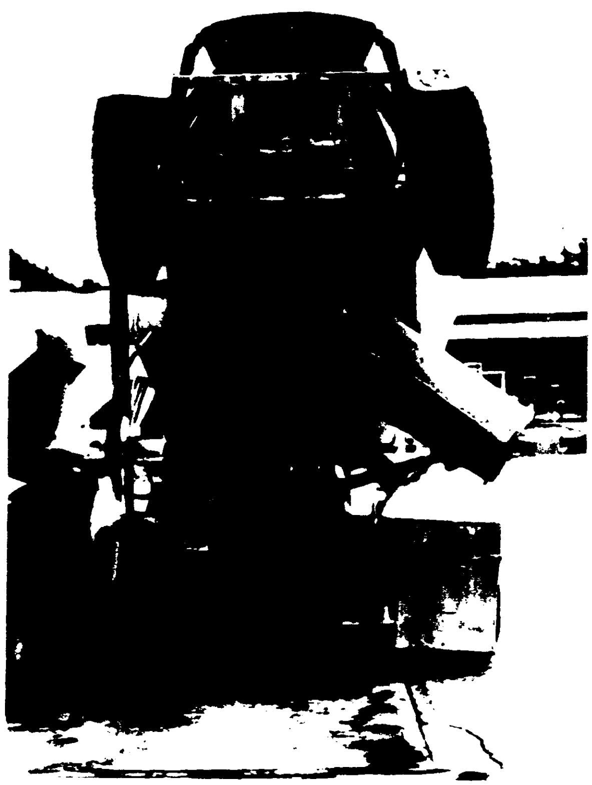
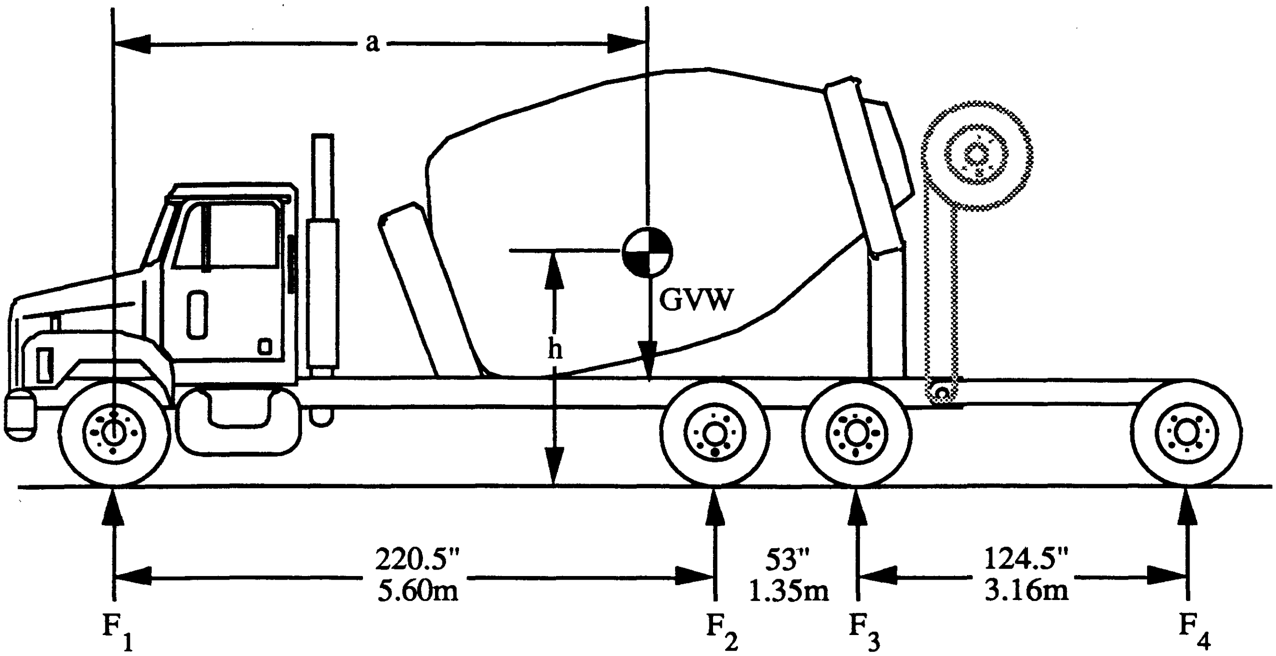


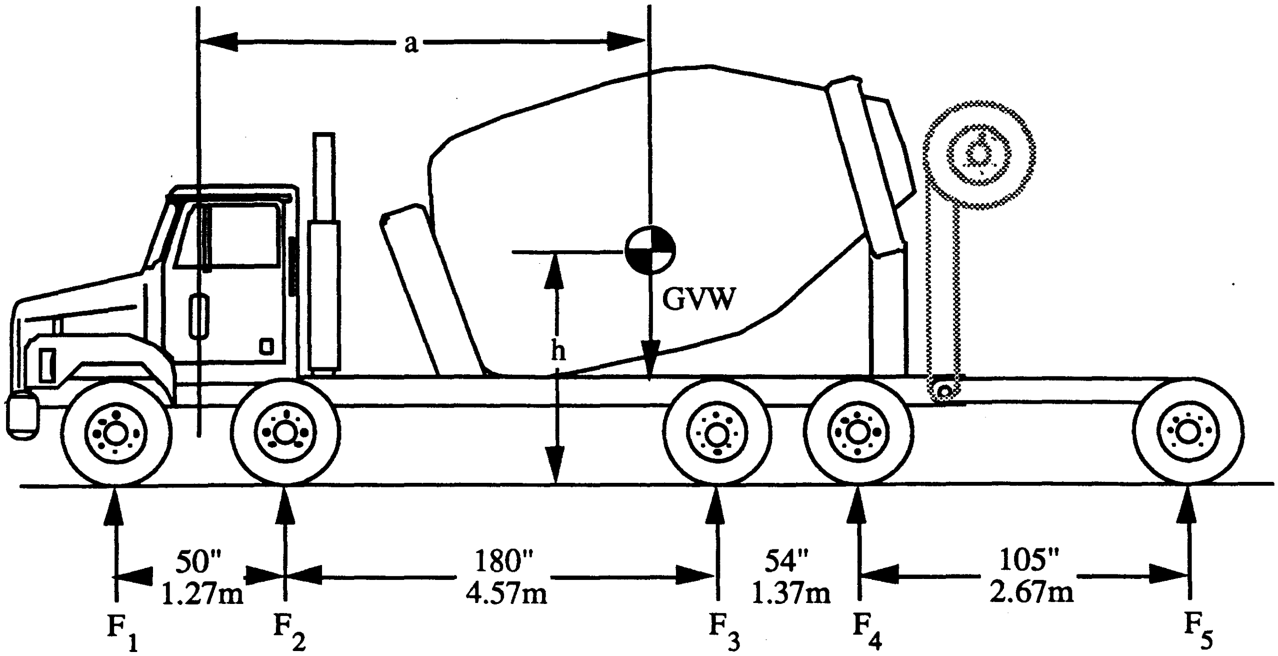
Figure 2. Photograph showing the rear view of a unit truck equipped with a booster axle in the raised position.



Four-Axle Mixer Truck—Loaded Condition			
GVW: 68,000 lb = 30,845 kg	a: 208.25 in = 5.29 m		h: 75 in = 1.90 m
Axle Loads (lb—kg):			
Booster Axle	*Other Axles*		
F4	*F1*	*F2*	*F3*
0—0	10,660—4,835	28,650—12,996	28,650—12,996
3,000—1,361	12,500—5,670	26,250—11,907	26,250—11,907
6,000—2,722	14,200—6,441	23,800—10,796	23,800—10,796
9,000—4,082	16,200—7,348	21,400—9,707	21,400—9,707
12,000—5,443	18,000—8,165	19,000—8,618	19,000—8,618

Four-Axle Mixer Truck—Empty Condition			
GVW: 26,000 lb = 11,790 kg	a: 152 in = 3.86 m		h: 52.5 in = 1.33 m
Axle Loads (lb—kg):			
Booster Axle	*Other Axles*		
F4	*F1*	*F2*	*F3*
0—0	10,000—4,536	8,000—3,629	8,000—3,629
2,000—907	11,220—5,089	6,390—2,899	6,390—2,899
4,000—1,814	12,440—5,643	4,780—2,168	4,780—2,168
6,000—2,722	13,670—6,201	3,165—1,436	3,165—1,436

Figure 3. Geometry and Axle Loads of the Four-Axle Mixer Truck



Five-Axle Mixer Truck—Loaded Condition

GVW: 80,000 lb = 36,290 kg   a: 160.75 in = 4.08 m   h: 75 in = 1.90 m

Axle Loads (lb—g):

Booster Axle	Other Axles			
F5	*F1*	*F2*	*F3*	*F4*
0—0	12,285—5,572	12,285—5,572	27,715—12,572	27,715—12,572
3,000—1,361	12,965—5,881	12,965—5,881	25,535—11,583	25,535—11,583
6,000—2,722	13,640—6,187	13,640—6,187	23,360—10,596	23,360—10,596
9,000—4,082	14,320—6,496	14,320—6,496	21,180—9,607	21,180—9,607
12,000—5,443	15,000—6,804	15,000—6,804	19,000—8,618	19,000—8,618

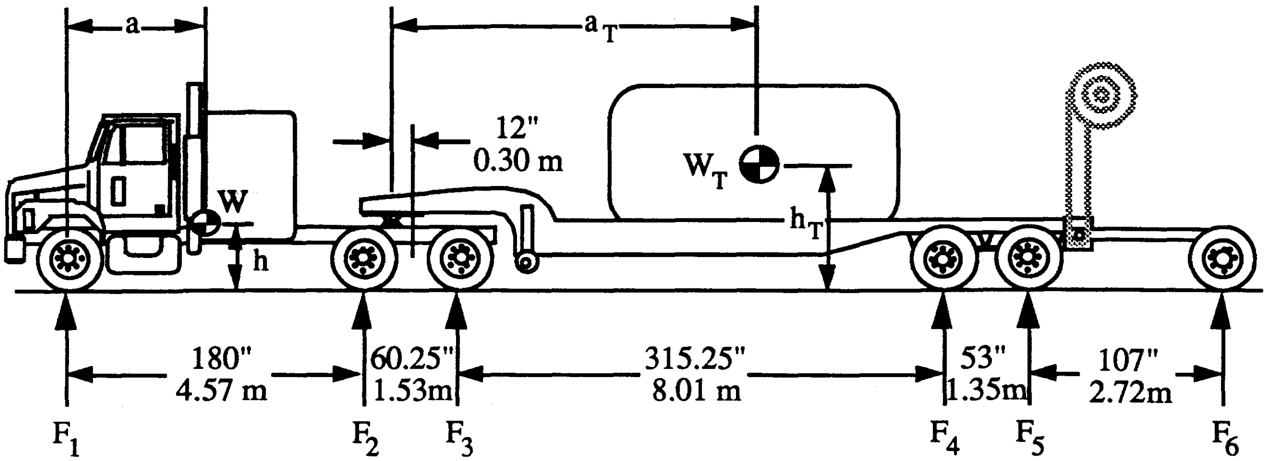
Five-Axle Mixer Truck—Loaded Condition

GVW: 30,000 lb = 13,610 kg   a: 139 in = 3.53 m   h: 52.5 in = 1.33 m

Axle Loads (lb—g):

Booster Axle	Other Axles			
F5	*F1*	*F2*	*F3*	*F4*
0—0	6,000—2,722	6,000—2,722	9,000—4,082	9,000—4,082
2,000—907	6,465—2,933	6,465—2,933	7,035—3,191	7,035—3,191
4,000—1,814	6,920—3,139	6,920—3,139	6,080—2,758	6,080—2,758
6,000—2,722	7,370—3,343	7,370—3,343	4,630—2,100	4,630—2,100
8,000—3,629	7,825—3,549	7,825—3,549	3,175—1,440	3,175—1,440

Figure 4. Geometry and Axle Loads of the Five-Axle Mixer Truck



Four-Axle Mixer Truck—Loaded Condition			
W: 17,500 lb = 7940 kg		a: 102 in = 2.59 m	h: 38 in = 0.97 m
W_T: 81,500 lb = 36,970 kg		a_T: 255.25 in = 6.48 m	h_T: 75 in = 1.90 m
Axle Loads (lb—kg):			
Booster Axle	*Other Axles*		
F_6	*F_1*	*F_2 plus F_3*	*F_4 plus F_5*
0—0	10,735—4,869	34,090—15,463	54,175—24,574
3,000—1,361	10,800—4,899	35,070—15,908	50,130—22,739
6,000—2,722	10,870—4,931	36,040—16,348	47,090—21,360
9,000—4,082	10,930—4,958	37,020—16,792	42,050—19,074
12,000—5,443	11,000—4,990	38,000—17,237	38,000—17,237

Four-Axle Mixer Truck—Empty Condition			
W: 17,500 lb = 7940 kg		a: 102 in = 2.59 m	h: 38 in = 0.97 m
W_T: 12,000 lb = 5440 kg		a_T: 256 in = 6.50 m	h_T: 38 in = 0.97 m
Axle Loads (lb—kg):			
Booster Axle	*Other Axles*		
F_6	*F_1*	*F_2 plus F_3*	*F_4 plus F_5*
0—0	9,220—4,182	11,750—5,330	8,530—3,869
2,000—907	9,260—4,200	12,400—5,625	5,740—2,604
4,000—1,814	9,310—4,223	13,050—5,919	3,140—1,424
6,000—2,722	9,350—4,241	13,700—6,214	450—204

Figure 5. Geometry and Axle Loads of the Six-Axle Tractor Semitrailer

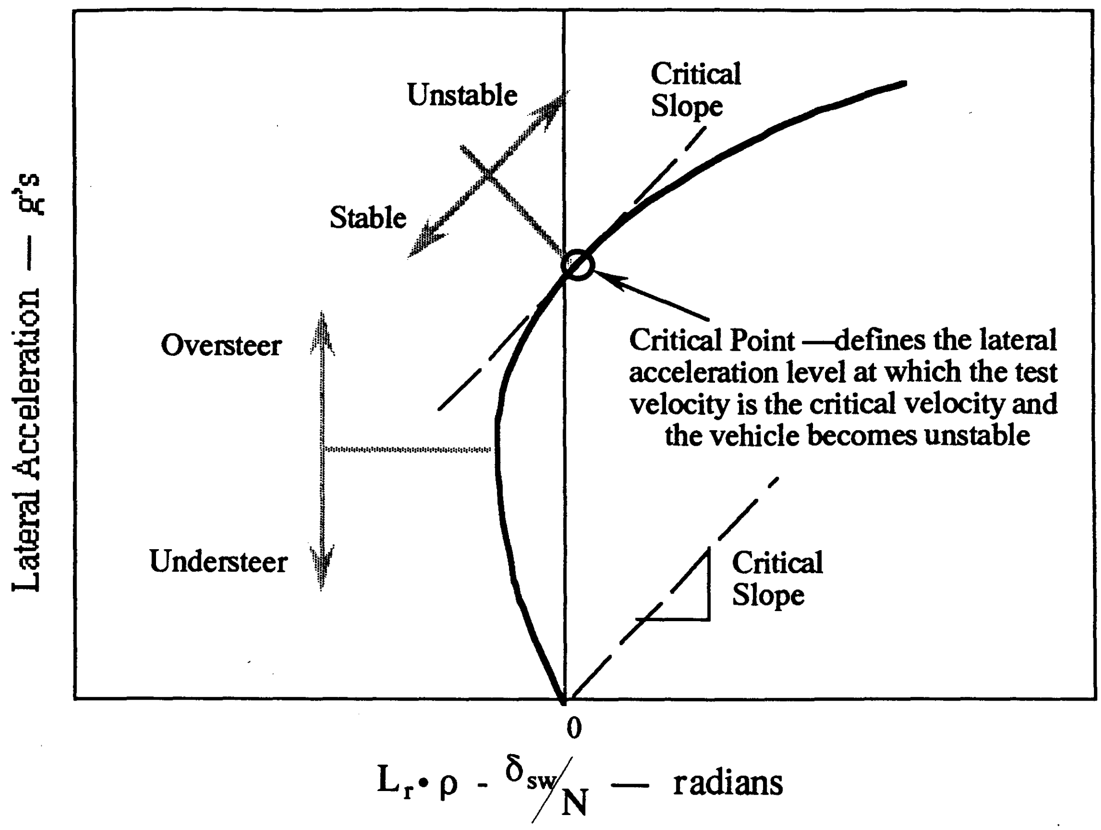


Figure 6. The handling diagram effectively presents the steady-state handling properties of the non-linear vehicle.

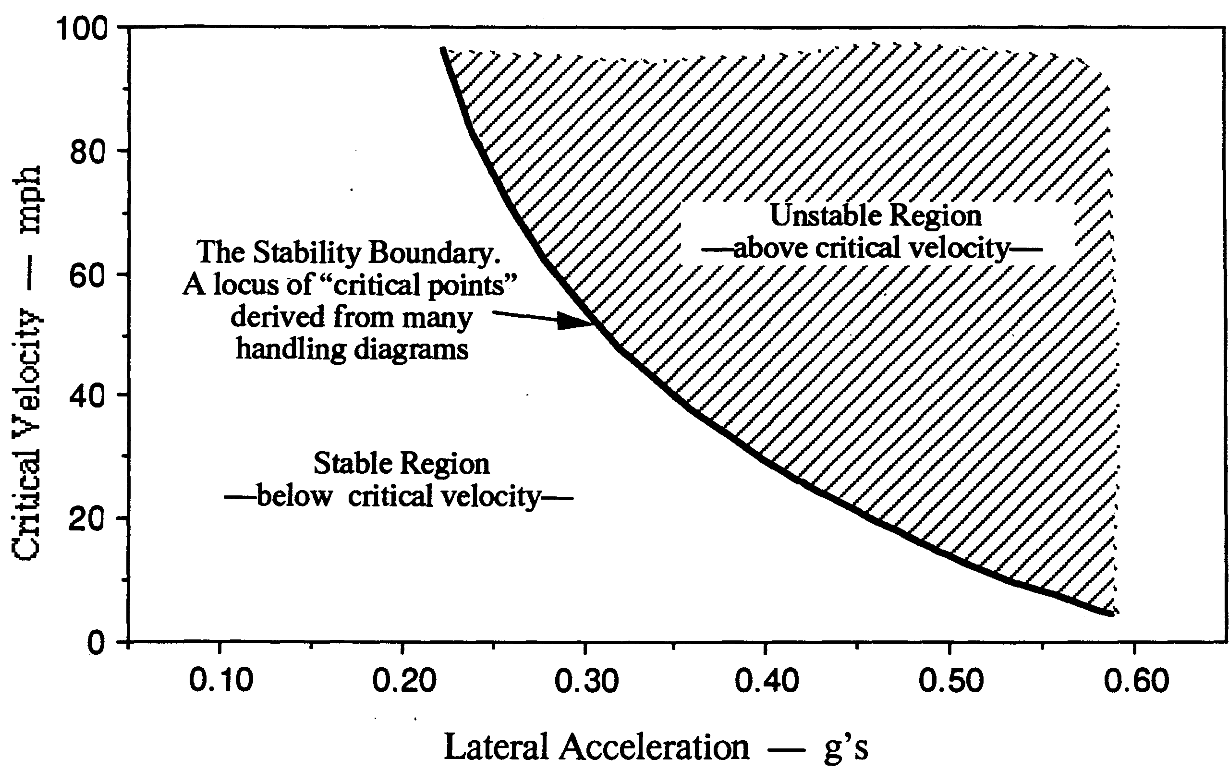


Figure 7. The stability plane diagram shows the regions of stable and unstable yaw performance.

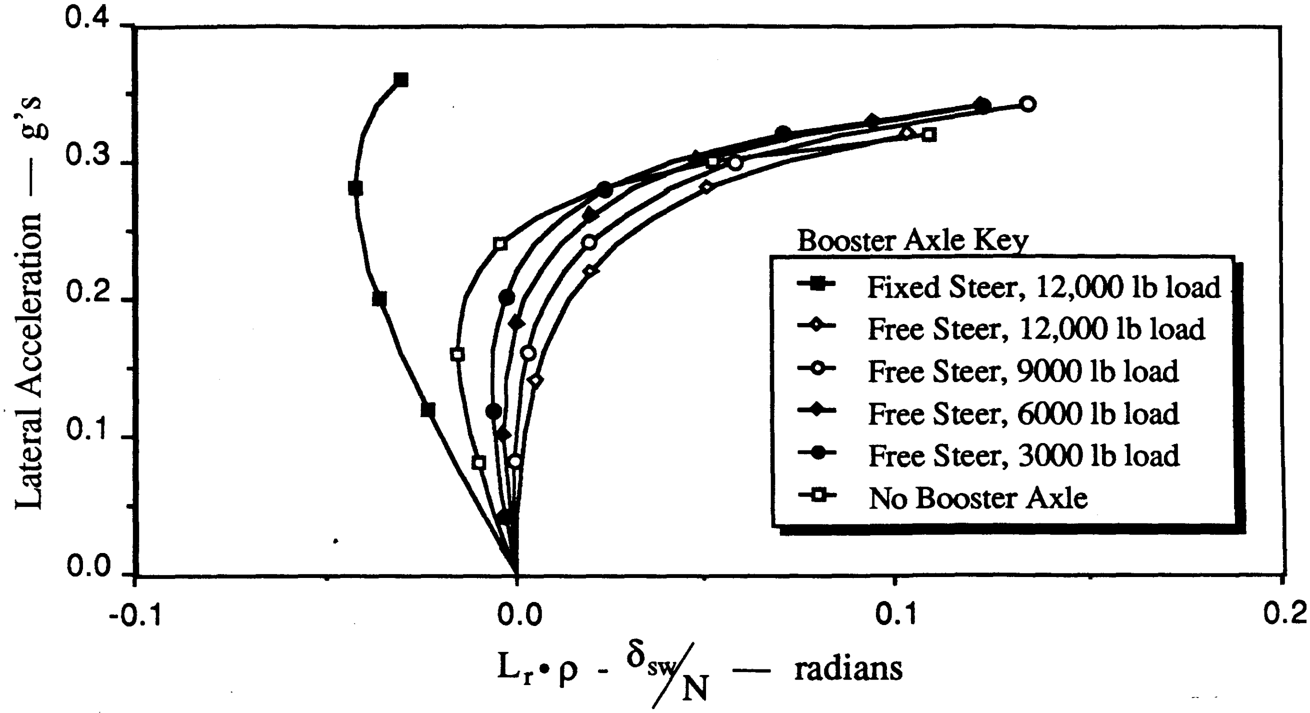


Figure 8. The handling diagram of the 4-axle unit vehicle in the loaded condition

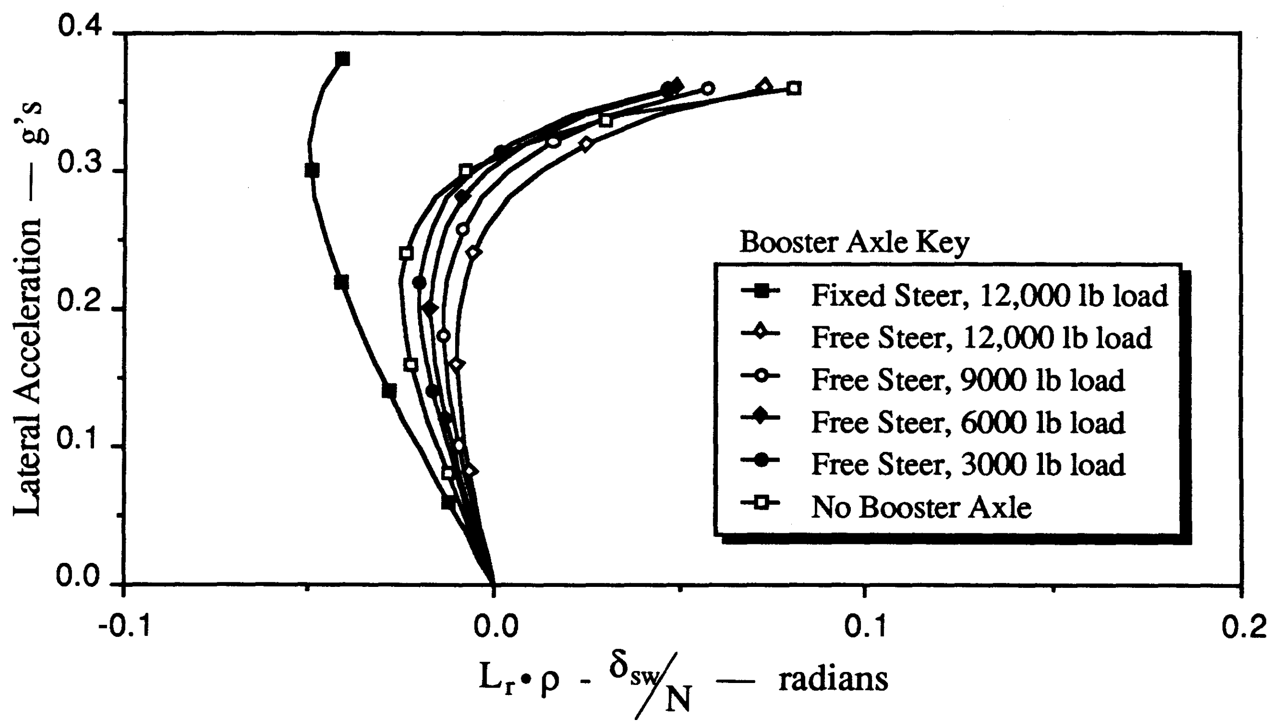


Figure 9. The handling diagram of the 5-axle unit vehicle in the loaded condition

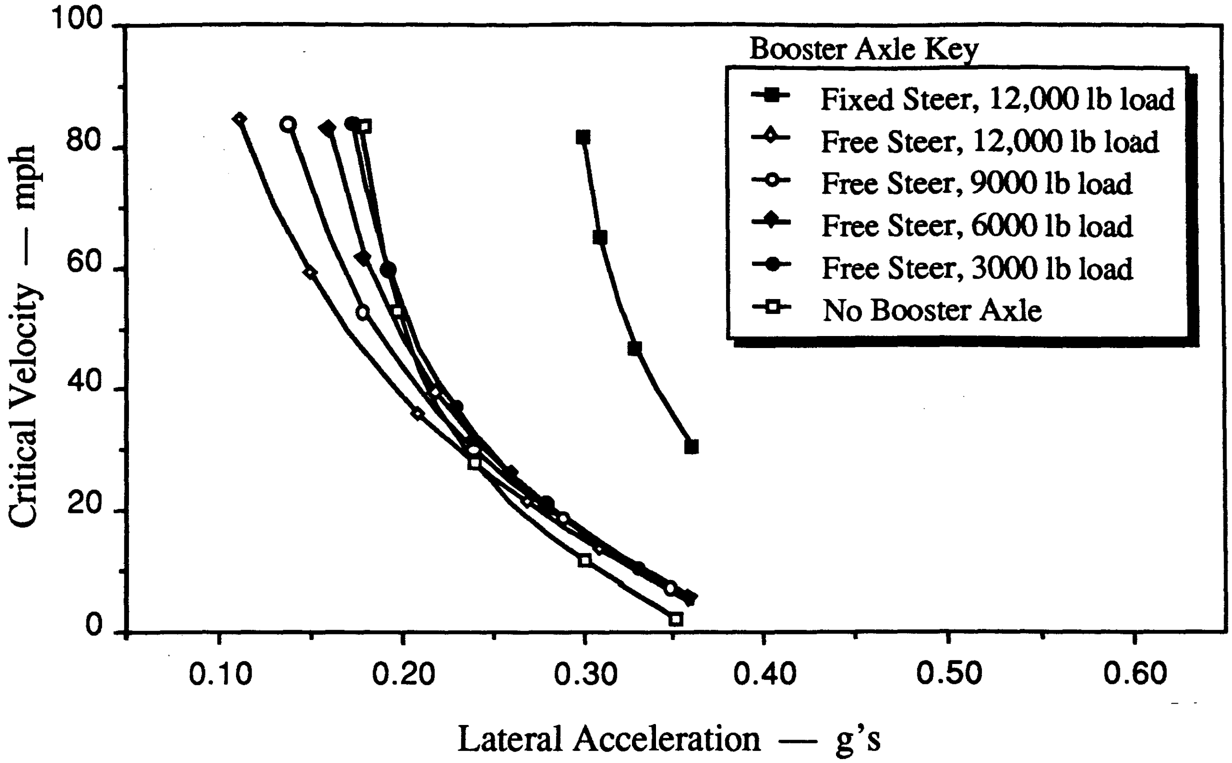


Figure 10. The stability plane diagram of the 4-axle unit vehicle in the loaded condition

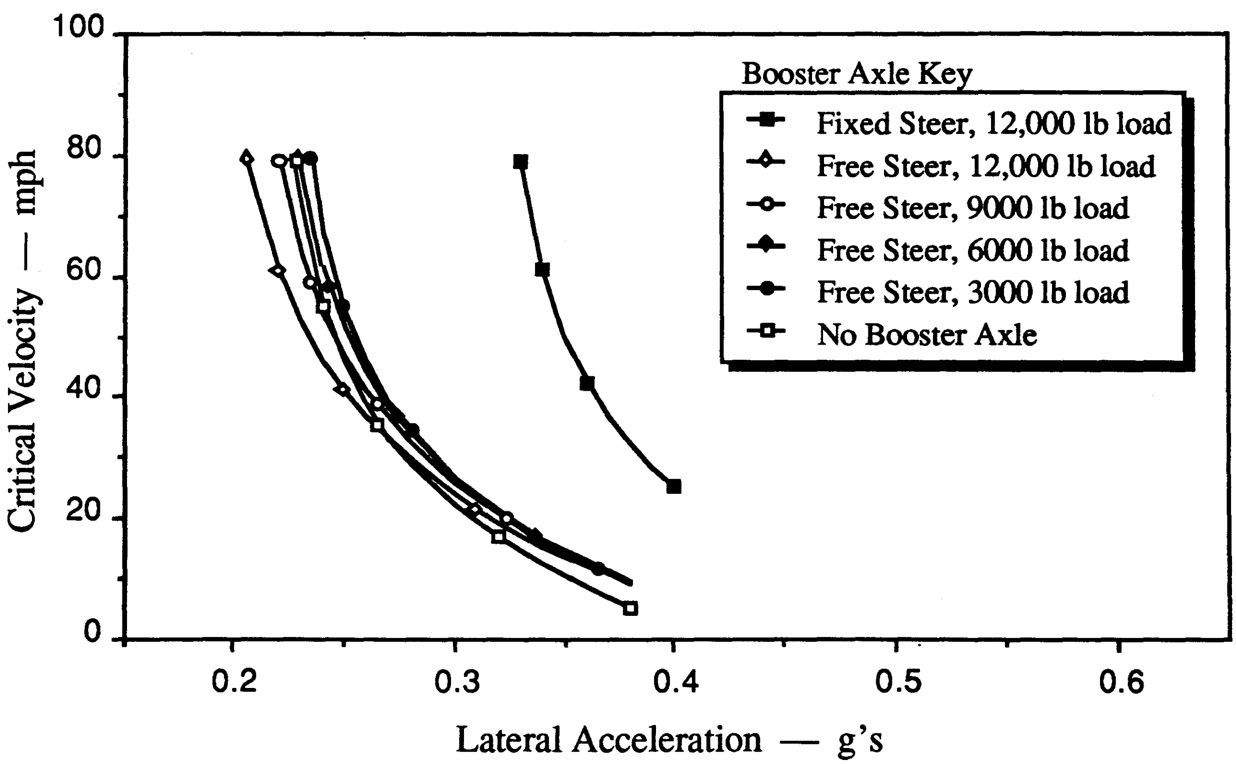


Figure 11. The stability plane diagram of the 5-axle unit vehicle in the loaded condition

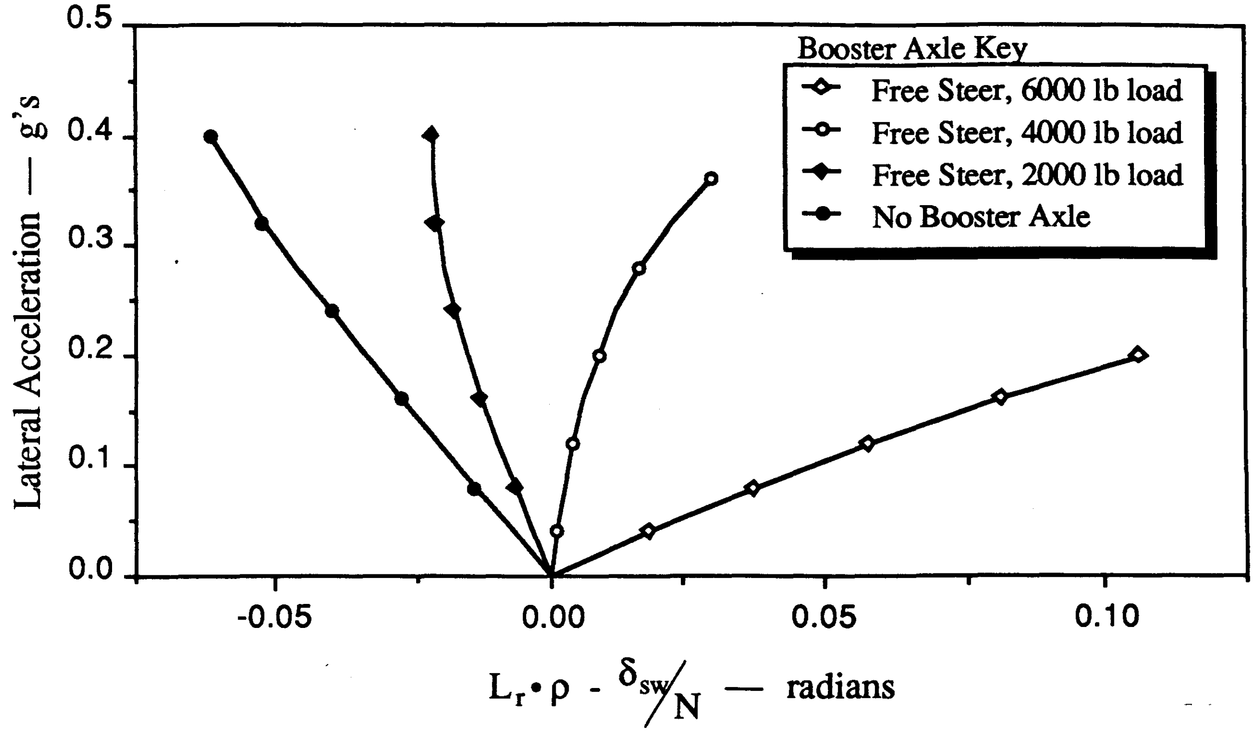


Figure 12. The handling diagram of the 4-axle unit vehicle in the empty condition

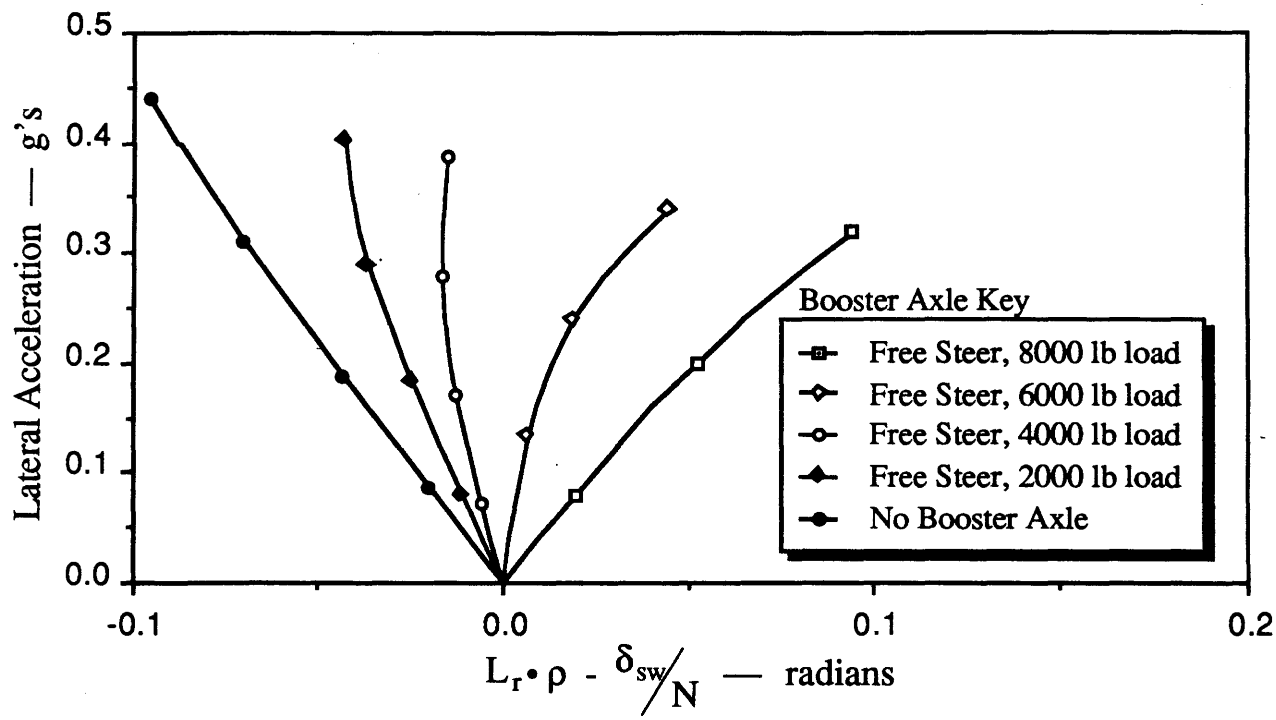


Figure 13. The handling diagram of the 5-axle unit vehicle in the empty condition

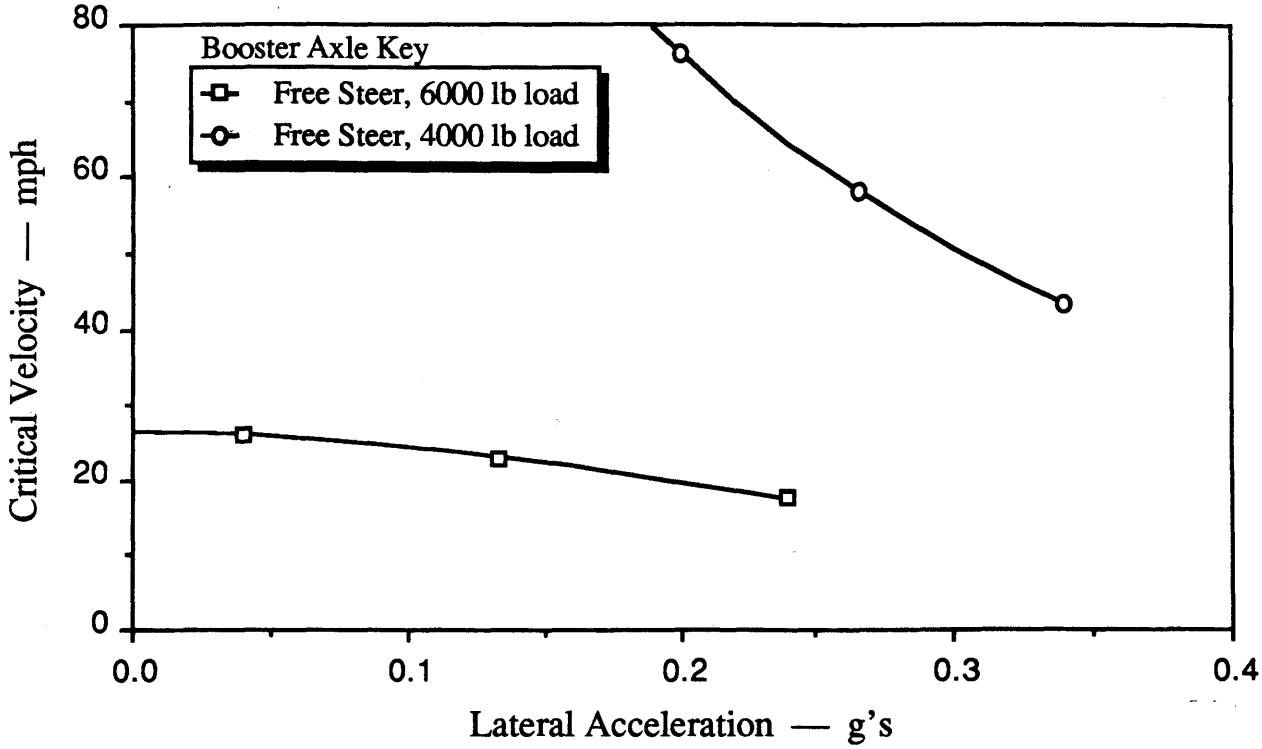


Figure 14. The stability plane diagram of the 4-axle unit vehicle in the empty condition

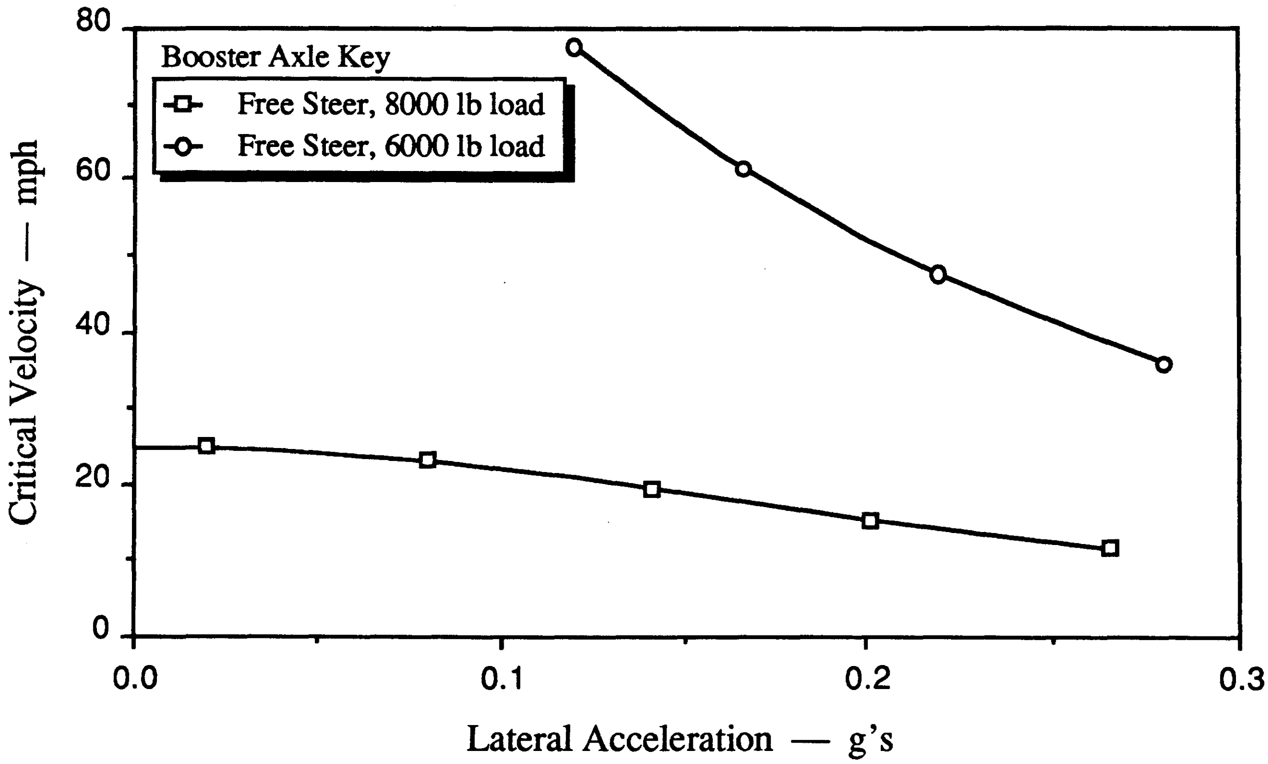


Figure 15. The stability plane diagram of the 5-axle unit vehicle in the empty condition

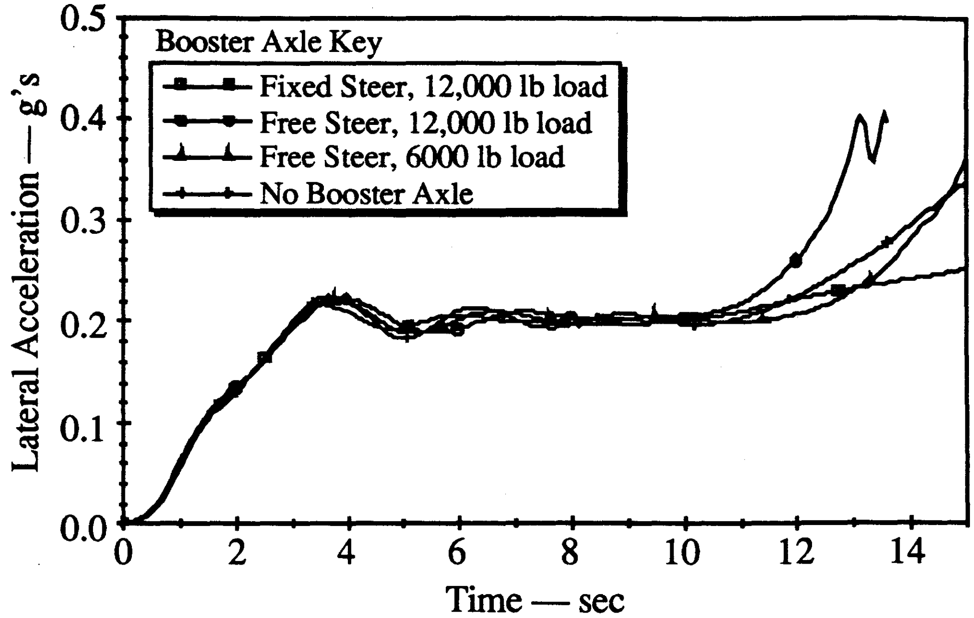


Figure 16. Lateral acceleration time history of the loaded 4-axle unit vehicle in the RTAC "A" maneuver

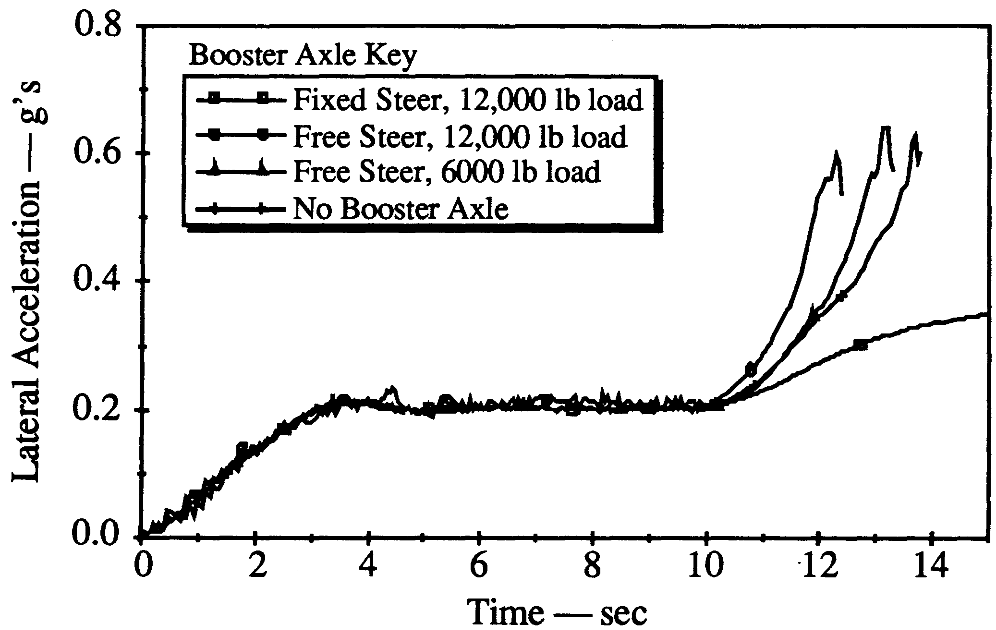


Figure 17. Lateral acceleration time history of the loaded 5-axle unit vehicle in the RTAC "A" maneuver

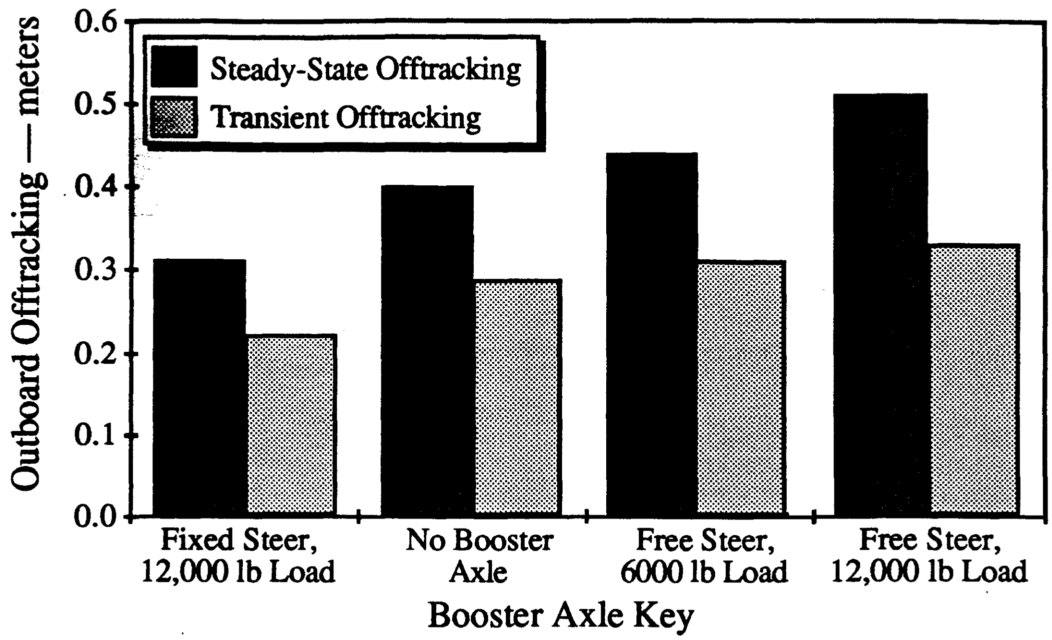


Figure 18. The high-speed offtracking performance of the loaded 6-axle tractor-semitrailer vehicle

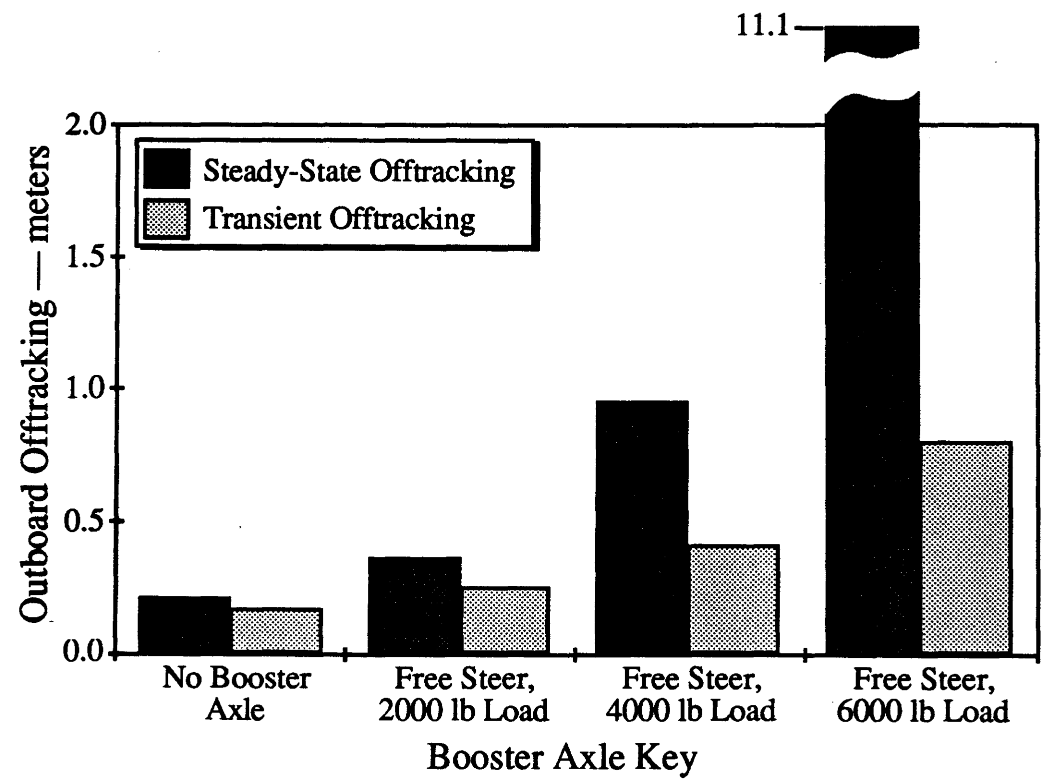


Figure 19. The high-speed offtracking performance of the empty 6-axle tractor-semitrailer vehicle

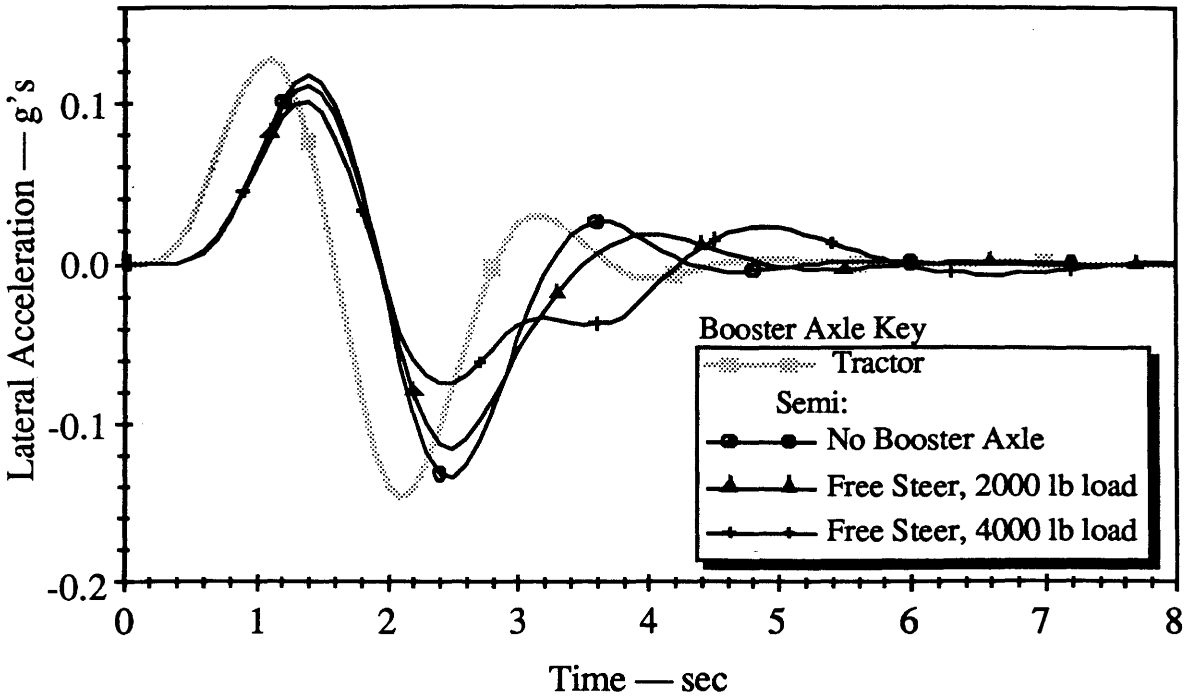


Figure 20. Lateral acceleration time history of the empty 6-axle tractor-semitrailer vehicle in the RTAC "B" maneuver

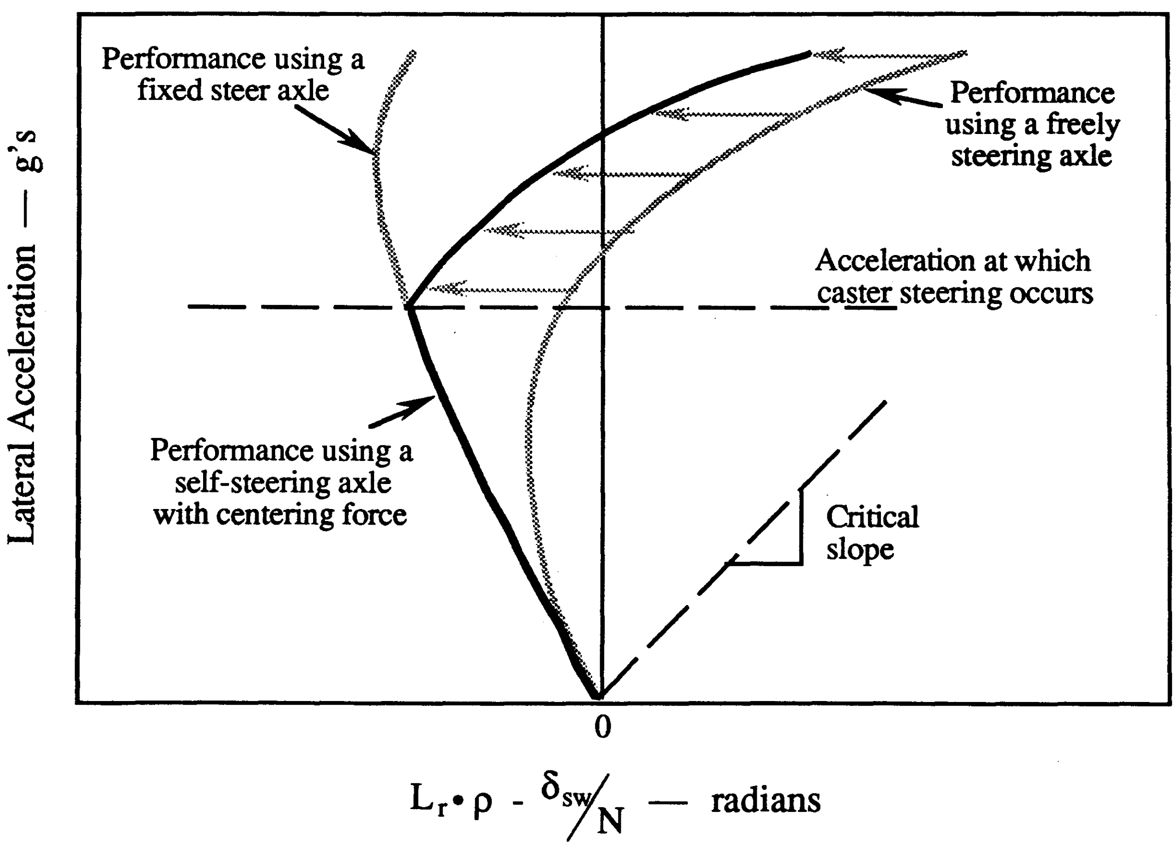


Figure 21. A method for estimating the handling performance achieved by a unit vehicle using self-steering axles with centering force mechanisms

SESSION 3 – SAFETY AND ACCIDENTS

Chairman: Albert Stevens, University of New Brunswick

Speakers

1. **The Analysis of Fleet Specific Accident Experience of Five Fleets Operating in Western Canada**
   G. Sparks, University of Saskatchewan
   A. Horosko, Saskatchewan Highways and Transportation

2. **Commercial Vehicle Accidents: The Data Gathering Experience**
   M.E. Wolkowicz, Ministry of Transportation, Ontario

3. **Safety Trade-offs for Increased Weights and Dimensions in New Zealand**
   P.H. Baas, D. White, Department of Scientifc and Industrial Research, New Zealand

4. **Analysis of Publicly Available Data on Accidents Involving Heavy Vehicles**
   D. Mason, F.R. Wilson, A.M. Stevens, University of New Brunswick

5. **Equipment Related to Accidents Involving Heavy Truck Drivers in Quebec While Carrying Out Jobs Both On and Off the Road**
   F. Ruest, Université du Québec, Rimouski