UMTRI-86-18

THE INFLUENCE OF LOAD DISTRIBUTION ON THE DYNAMIC BEHAVIOR OF ROADWAY COMBINATION VEHICLES

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16. Abstract

Operators of doubles combination vehicles (tractor with semitrailer and full trailer) must deal with different loading distributions on the vehicles in the course of normal operations. The weight of the two trailers of a single vehicle may vary with differing loads, as may the weight distribution between the front and rear of an individual trailer. It is known that the distribution of weight among the axles of a combination vehicle will affect its dynamic performance on the road. This study examines the influence of trailer loading on (1) braking efficiency, (2) rearward amplification, and (3) yaw damping of typical twin 28-foot doubles combination vehicles. The influence of (1) total payload, (2) payload distribution between trailers, and (3) payload distribution within the trailers is examined. The general findings of the study are: (1) Braking efficiency of the doubles is quite sensitive to inter-trailer load distribution and to intra-trailer load distribution of the second trailer. Optimum load distribution requires the c.g. of the payload to be located somewhat aft of center. (2) Rearward amplification of the doubles is moderately influenced by total load, with amplification increasing as load increases. Load distribution within the second trailer (but not the first) also has a significant influence. (3) Yaw damping of the doubles proved to be remarkably insensitive to loading conditions. Adequate yaw damping levels were found in all loading conditions.

17. Key Words doubles combination vehicle, braking efficiency, braking, lane change, rearward amplification, yaw damping	**18. Distribution Statement** UNLIMITED

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CONTENTS

1.0 INTRODUCTION

Operators of doubles combination vehicles (tractor with semitrailer and full trailer) must deal with different loading distributions on the vehicles in the course of normal operations. The weight of the two trailers of a single vehicle may vary with differing loads, as may the weight distribution between the front and rear of an individual trailer. It is known that the distribution of weight among the axles of a combination vehicle will affect its dynamic performance on the road. Roadway Express has expressed concern regarding the safety and performance qualities of their doubles vehicles as those qualities might be affected by the range of trailer loading conditions which prevail in the field.

This study examined the influence of trailer loading on (1) emergency braking capability, (2) emergency maneuvering capability, and (3) directional stability in normal running of Roadway Express' doubles combination vehicles. The influences of (1) total payload, (2) payload distribution between trailers, and (3) payload distribution within the trailers were examined.

The measure of emergency braking performance used was braking efficiency. This is a classic measure of the braking performance capability of any highway vehicle. Braking efficiency is the deceleration capability of the vehicle expressed as a percent of the highest possible deceleration attainable, as established by the prevailing friction qualities of the road. Braking efficiency is generally less than 1.0, and higher values represent better performance.

Rearward amplification was used as the measure of emergency maneuvering capability. It is generally desirable for the trailers of a doubles to track the same path as the tractor during emergency maneuvers. During rapid evasive maneuvers, however, the second trailer of the doubles generally exaggerates the motion of the tractor in a "crack-the-whip" fashion. This "amplification" of motion by the rear element of the vehicle generally limits emergency maneuvering capability of the doubles by promoting second trailer rollover. Rearward amplification of 1.0 would be most desirable, since this would imply that the last trailer followed the path of the tractor.

Yaw damping was used as the measure of directional stability in normal running. Relatively low levels of directional stability are sometimes evidenced by the back-and-forth hunting, or wagging, motion of the second trailer of doubles as they travel at highway speed. This quality is only loosely related to rearward amplification, and is usually not as substantive a safety concern, although it is a very visible phenomenon that can create a negative image of the vehicle in the minds of both the truck driver and other motorists. In addition to being related to yaw damping, field experience suggests that it is also related to lash at the pintle hitch joint. Higher values of yaw damping would tend to reduce this wagging action.

These performance measures, as exhibited by a typical Roadway doubles, were examined using several computer simulation programs developed by UMTRI. The programs used were (1) the "Constant Deceleration Braking" program, (2) the "Linear Yaw Plane" program, and (3) the "Yaw-Roll" program. The "Braking" program was used to predict the braking efficiency measure. The "Linear Yaw Plane" program was used as the primary source for calculating rearward amplification and yaw damping coefficient. The

"Yaw-Roll" program, a more complicated, non-linear handling program, was used to make additional checks on the rearward amplification and damping calculations.

The "test vehicle" used in all the calculations was a typical Roadway doubles as identified by data provided by Roadway. Loading configurations were established, in part, by data provided by Roadway, and, in part, by the author's judgement.

The test vehicle and the test loading matrix are discussed in more detail in Section 2.0. Braking calculations and results are discussed in Section 3.0. Sections 4.0 and 5.0, consider rearward amplification and yaw damping, respectively. Section 6.0 provides a summary of the results.

2.0 TEST VEHICLE AND LOADING

2.1 The Vehicle.

The test vehicle simulated is a doubles combination composed of a conventional, 153-inch-wheelbase, 2x4 tractor towing twin 28-foot, single-axle van trailers, and using a single-axle A-dolly. Specifically, the vehicle units are:

Tractor:	White, WCL-42TB, 45" setback front axle
Trailers:	Fruehauf, FGGW-X-FL-1-28-WS-102
Dolly:	Todco, Jifflox 6000

(We note that Roadway also uses other tractors including a 162-inch-wheelbase White and a Mack conventional. The White used was chosen since we understand it to be the most numerous in the fleet, but we note that use of the other tractors could not be expected to produce any significant change in the findings of the study.)

The geometry and empty weights of the vehicle are shown in Figure 1.

The most important vehicle descriptive data beyond that shown in the figure are tire and brake data. Roadway uses 275 R 22.5 tires inflated to 100 psi at all axles. Tires of a variety of manufacturers are used. In this study, tire data derived from tests of Michelin 275 R 22.5 tires were used.

Rockwell Q, S-cam brakes are used at all axles. The tractor front axle uses 15" x 4" brakes while 16.5" x 7" brakes are used at all other axles. Type 16 actuators are used on the front tractor brakes, type 24 actuators are used on the rear tractor and dolly brakes, and type 30 actuators are used on the trailer brakes. All axle brakes are equipped with 5.5-inch slack adjusters. Actuator size and slack length were used to "scale" UMTRI brake data on 15 x 4 and 16.5 x 7 brakes to obtain the brake torque-to-brake line pressure gain used in the simulations.

To represent suspensions, tractor and trailer leaf spring suspension data which best matched the load rating and spring rate ratings provided by Roadway were taken from UMTRI files for use in these simulations. While such approximations were surely adequate for the tractor and trailers, the suspension of the Todco dolly was so unusual that UMTRI had no data on hand which could be used. UMTRI obtained suspension drawings as well as spring (Lord Lastosphere LS-5000-1) data from Todco engineering and used these to generate the suspension data required.

2.2 The Test Loading Matrix.

The primary variable of interest in this study was, of course, loading condition. It was intended to examine the performance of the Roadway double over the full range of loading conditions which are currently "in use" or might reasonably be used by Roadway.

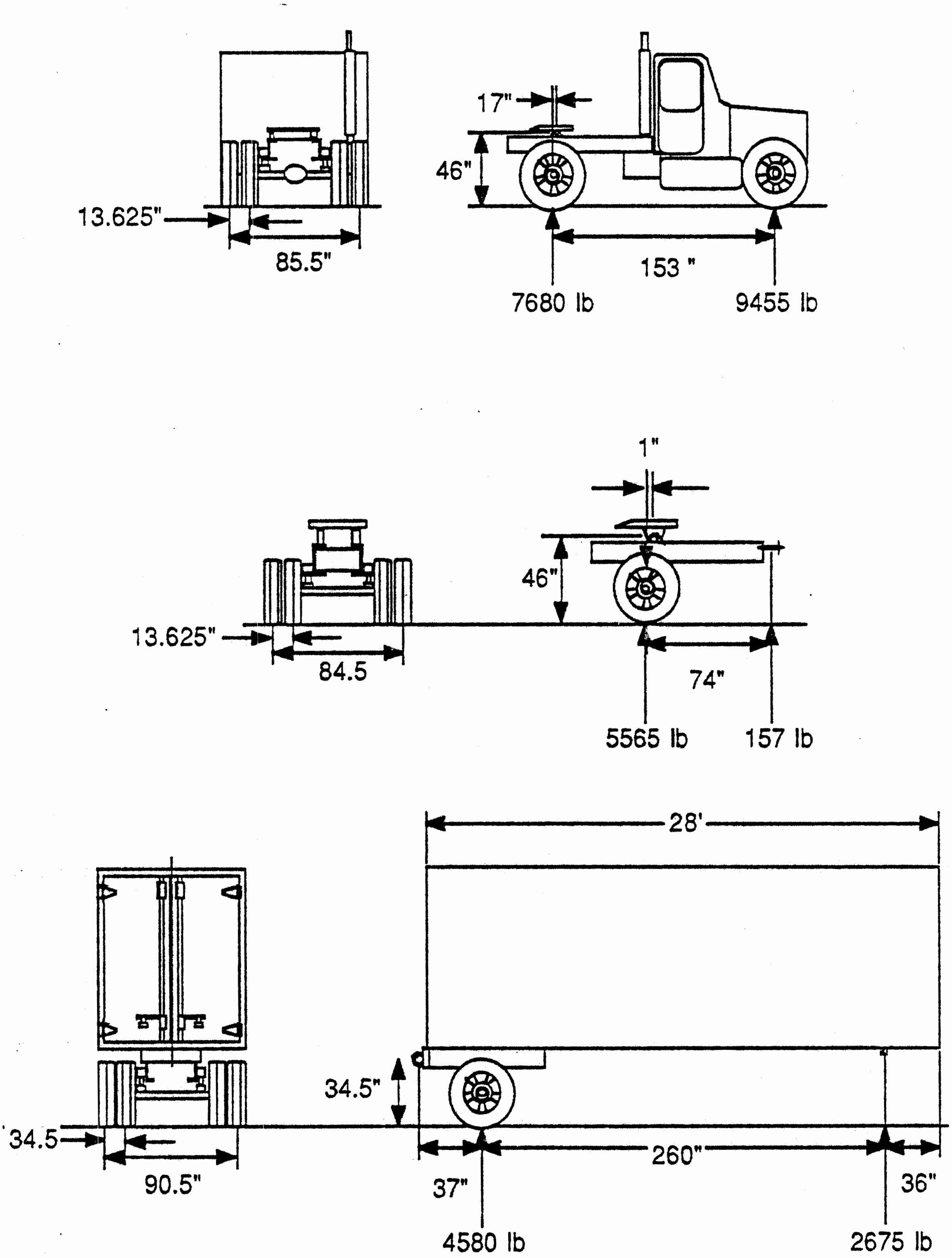

Figure 1. The Roadway double

In this context, "loading conditions" refers to (1) total payload weight, (2) inter-trailer payload distribution, and (3) intra-trailer payload distribution.

Data relating to total payload and inter-trailer distribution were made available by Roadway. These data were of the weight of the payload on first and second trailers, respectively, of 167 Roadway doubles as they left the terminal yard. We understand these data were gathered "randomly" from several different groups and from several different localities. The 167 data points are plotted as "1st trailer payload" vs. "2nd trailer payload" in Figure 2. (The 45-degree line plotted in Figure 2 indicates the condition of equal trailer loading.) As a matter of interest, these data clearly show a tendency for Roadway personnel to arrange doubles configurations such that the heavier of the two trailers is placed in the lead. Some numerics which result from these data are:

	Average	Maximum	Minimum
Total Payload, lbs:	36,870	51,630	20,264
Percent of Total in 1st Trailer:	54.2	83.5	23.5

Although not shown in these data, we also understand that doubles sometimes leave the terminal with one or the other trailer completely empty, simply as a way of conveniently transporting empty trailers to other terminals.

Given this information, a basic test load matrix consisting of 36 loading conditions was defined. This matrix is shown in Figure 3. (The test matrix is represented by the solid data points, superimposed on the open, field data points supplied by Roadway. Note that the negatively sloped, 45-degree lines are lines of constant total payload.) Total payload of the test matrix ranges from zero to 50,000 pounds. The range of inter-trailer payload distribution covers the full range of Roadway practice plus conditions in which one or both of the trailers is completely empty. This basic matrix was implemented with the additional condition that the center of gravity of payload within each trailer was centrally located within the cargo box. Center of gravity height of all loads was representative of medium density, LTL freight.

Field data describing actual intra-trailer payload distribution were not available. Accordingly, judgements had to be made as to how to augment the basic loading matrix to represent appropriate variations in this condition. Firstly it was assumed that mid-range trailer loads (15,000 lbs in our matrix) would be the most significant loading condition in this regard. The logic here is: high end loads must be relatively centrally located in order that individual axle loads remain within legal limits; low end loads, inasmuch as they are smaller percentages of the total unit vehicle weight, are not as powerful at shifting vehicle c.g. position, and thus altering tire loading and, ultimately, vehicle performance.

Thus, the five loading conditions indicated in Figure 4 were chosen for variations of intra-trailer load distributions. For these conditions, the 15,000-lb trailer loads were shifted to a "forward" position wherein only 30% of the trailer payload was borne by the trailer axle, and to a "rearward" positon wherein 70% of the payload was borne by the trailer axle. (The 5,000- and 25,000-lb. loads remained centrally located.) This introduced 16 additional loading conditions to the testing matrix, namely:

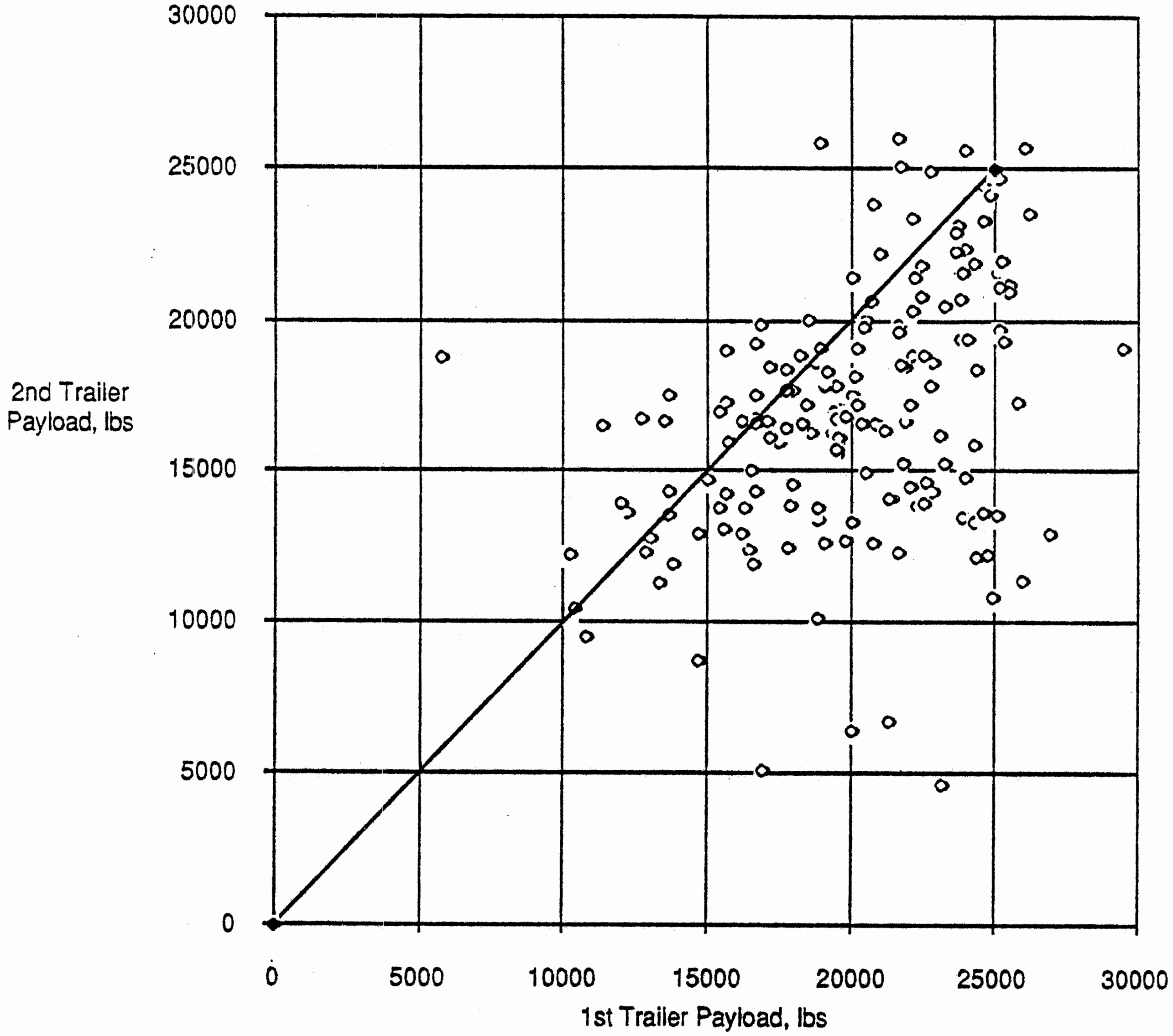

Figure 2. Roadway double: trailer payload data

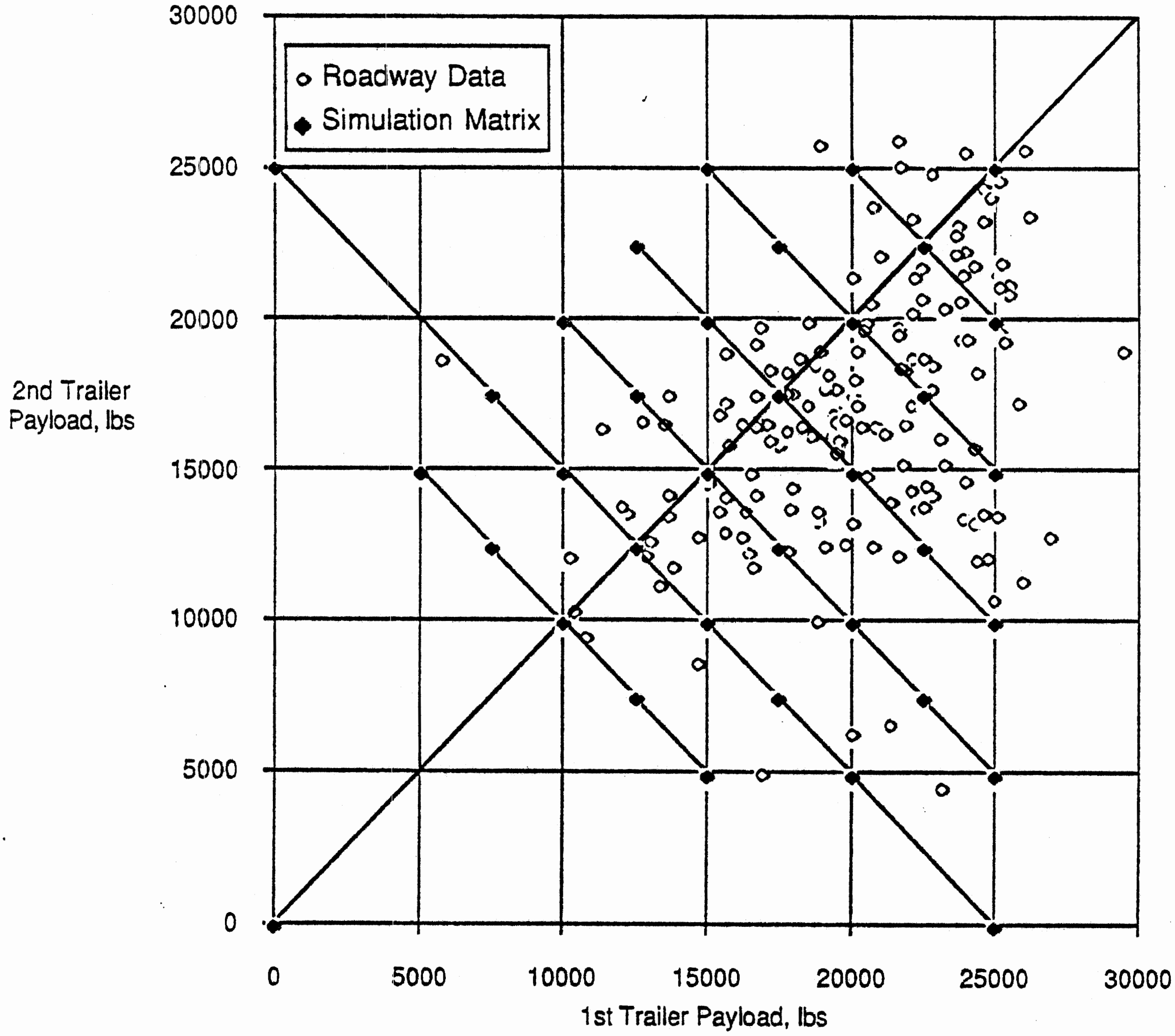

Figure 3. The basic test loading matrix

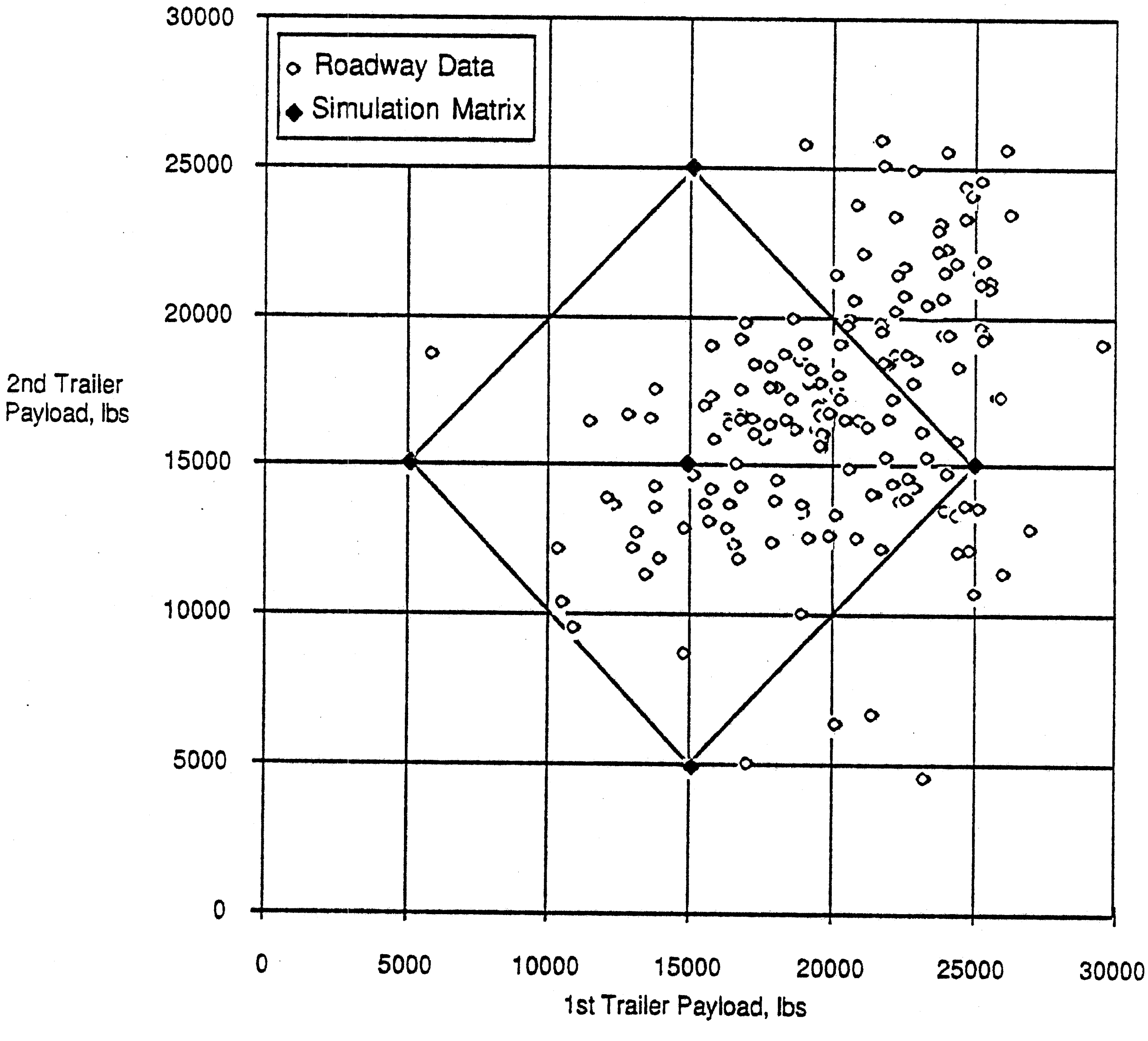

Figure 4. The five load conditions chosen for variations of intra-trailer load distribution

First Trailer Payload, lb	Second Trailer Payload, lbs
15K Forward	5K Centered
15K Rearward	5K Centered
15K Forward	25K Centered
15K Rearward	25K Centered
5K Centered	15K Forward
5K Centered	15K Rearward
25K Centered	15K Forward
25K Centered	15K Rearward
15K Forward	15K Forward
15K Forward	15K Centered
15K Forward	15K Rearward
15K Centered	15K Forward
15K Centered	15K Rearward
15K Rearward	15K Forward
15K Rearward	15K Centered
15K Rearward	15K Rearward

Simulation runs were conducted, and calculations of braking efficiency, rearward amplification, and yaw damping were made for each of the 52 loading conditions described.

3.0 BRAKING PERFORMANCE CALCULATIONS.

Braking performance calculations were conducted using UMTRI's "Constant Deceleration Braking" program. This program simulates the steady-state braking performance of commercial vehicles of configurations ranging from single unit vehicles to triples. Multi-trailer vehicles can be equipped with either converter or turntable style dollies. The program calculates steady-state deceleration achieved as a result of applied brake line pressure. Steady-state load transfer is determined so that friction utilization can be calculated at each axle of the vehicle and the occurrence of wheel lock may be determined. Peak and slide tire/road friction properties are accounted for properly. The program does not perform calculations relating to the transient performance which occurs at the onset of braking, as associated, for example, with air system response times or pitch dynamics response times.

The program can be operated in a mode wherein brake pressures are incremented from low to high levels so that deceleration and friction utilization at each wheel can be determined as a function of brake pressure. The program will also calculate braking efficiency as a function of deceleration level. A vehicle's braking efficiency is the maximum deceleration it can achieve on a given surface without wheel lock, divided by the peak tire/road friction coefficient of that surface. (Deceleration "without wheel lock" is classically of interest, since the occurrence of wheel lock generally indicates the loss of directional control.) In this calculation, braking efficiency is determined by dividing the deceleration, in g's, by the maximum friction utilization generated at any of the several axles of the vehicle.

Friction utilization is, of course, the ratio of brake force to vertical load at the tire/road interface. If the percentage distribution of brake force among the several axles of the vehicle were to be precisely equal to the percentage distribution of vertical load among the axles, then the friction utilization at all the wheels would be equal to one another and would be equal to the deceleration level, in g's. To the extent that these distributions are not perfectly matched, the "over-braked" axles exhibit friction utilizations in excess of the deceleration level, and "under-braked" axles show lower friction utilization. (Whenever the friction utilization of an axle attempts to exceed the tire/road friction coefficient, wheel lockup occurs.) Braking efficiency is the ratio of vehicle deceleration to the highest prevailing friction utilization coefficient. As such, braking efficiency at a given deceleration level indicates the level of road friction which must prevail for the vehicle to achieve that deceleration without wheel lock. For example, a vehicle displaying 100% braking efficiency at 0.4 g's requires a road of only 0.4 friction coefficient to achieve that level of deceleration without wheel lock. A vehicle with 50% braking efficiency at that deceleration, would, however, require a road of 0.8 friction coefficient to achieve the same stopping performance.

Finally, for commercial vehicles without load-proportioned braking or anti-lock braking, the percentage distribution of braking effort among the axles of a vehicle remains fairly constant as braking effort, and therefore, deceleration, rises from moderate to high levels. As deceleration increases, however, we know that dynamic load is transferred from rearward to forward axles of the vehicle. Thus it is clear that vertical load distribution varies with deceleration, and it follows that braking efficiency must also vary with deceleration.

Simulation calculations were conducted over decelerations ranging from less than 0.1 g's to more than 0.4 g's. From these simulation runs, braking efficiency was calculated for deceleration levels of 0.1, 0.25 and 0.4 g's. These braking efficiency results are present as functions of the various vehicle loading conditions explored. Numerical listing of all results appear in the Appendix. The following discussion is based on graphical presentations of the results.

Figure 5 presents braking efficiency as a function of (a) the total payload and (b) the inter-trailer payload distribution, at 0.1, 0.25, and 0.4 g deceleration levels, respectively. In each of the plots of this figure, the ordinate represents braking efficiency, the abscissa represents percent of payload in the 2nd trailer, and total payload is distinguished as a plotting parameter.

The figure shows that, when intra-trailer load distribution is centered, then:

1) The braking efficiency of the loaded, Roadway double is quite sensitive to the inter-trailer load distribution, and

2) Braking efficiency of the Roadway double is rather insensitive to the total payload weight (when that weight is in the 20,000 to 50,000 pound range). When both trailers are empty, however, braking efficiency falls significantly.

Since deceleration causes a general forward shifting of load, even across the dolly, the optimum static loading pattern for braking is one in which the second trailer carries more than half of the payload. Forward dynamic load transfer suggests that this effect is stronger at higher levels of deceleration. The figures show that optimum load of the second trailer is just slightly over 50% of the total at 0.1 g deceleration, and increases to over 60% at 0.4 g. At these optimum loading conditions, braking efficiency is in the 90% range. When inter-trailer load distribution is biased forward relative to these optimums, braking efficiency is lowered due to rear trailer axles being relatively over braked, and rear trailer wheels will be the first to lock. Of course, similar statements hold for the lead trailer when loading is rearward relative to the optimum. In order to ensure that braking efficiencies do not fall below 60% in the 0.1 to 0.4 g deceleration range, second trailer loading must lie between about 40% and 80% of the total load. And finally, braking efficiency of the empty vehicle is in the 50 to 55% range.

Figures 6 through 8 present selected results showing the influence of intra-trailer load distribution on braking efficiency. On each graph, braking efficiency is plotted on the ordinate and payload position (forward, centered, and rearward) in either the first or second trailer is indicated on the abscissa. Deceleration is distinguished as a plotting parameter, and each graph is associated with one position on the basic, inter-trailed payload distribution loading matrix.

Figure 6 deals with intra-trailer load distribution in one medium weight trailer when it is combined with another, lightly loaded trailer. The results show that in these cases, the lightly loaded trailer tends to limit braking efficiency, and load distribution within the heavier trailer is usually not important. This notion is violated only at high decelerations, with a light front trailer. In this case, enough load is transferred from the second to the first trailer, to allow second trailer loading to become significant.

Figure 7 shows the results for combinations composed of one medium weight, and one "grossed out" trailer. In these cases, intra-trailer load distribution in the lighter trailer is quite important, regardless of whether it is the first or second trailer. In either position, the

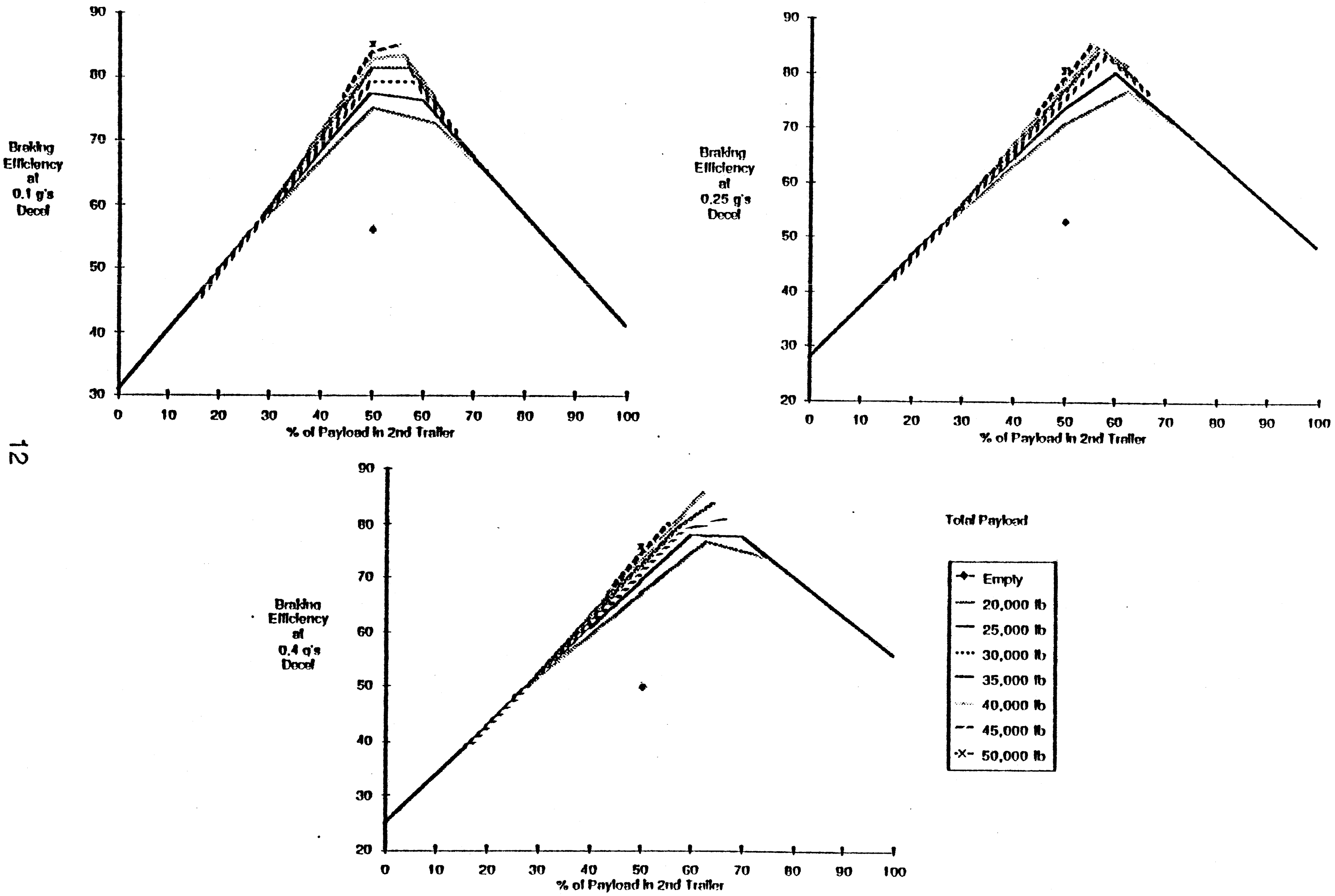

Figure 5. Braking efficiency as a function of total payload and inter-trailer payload distribution

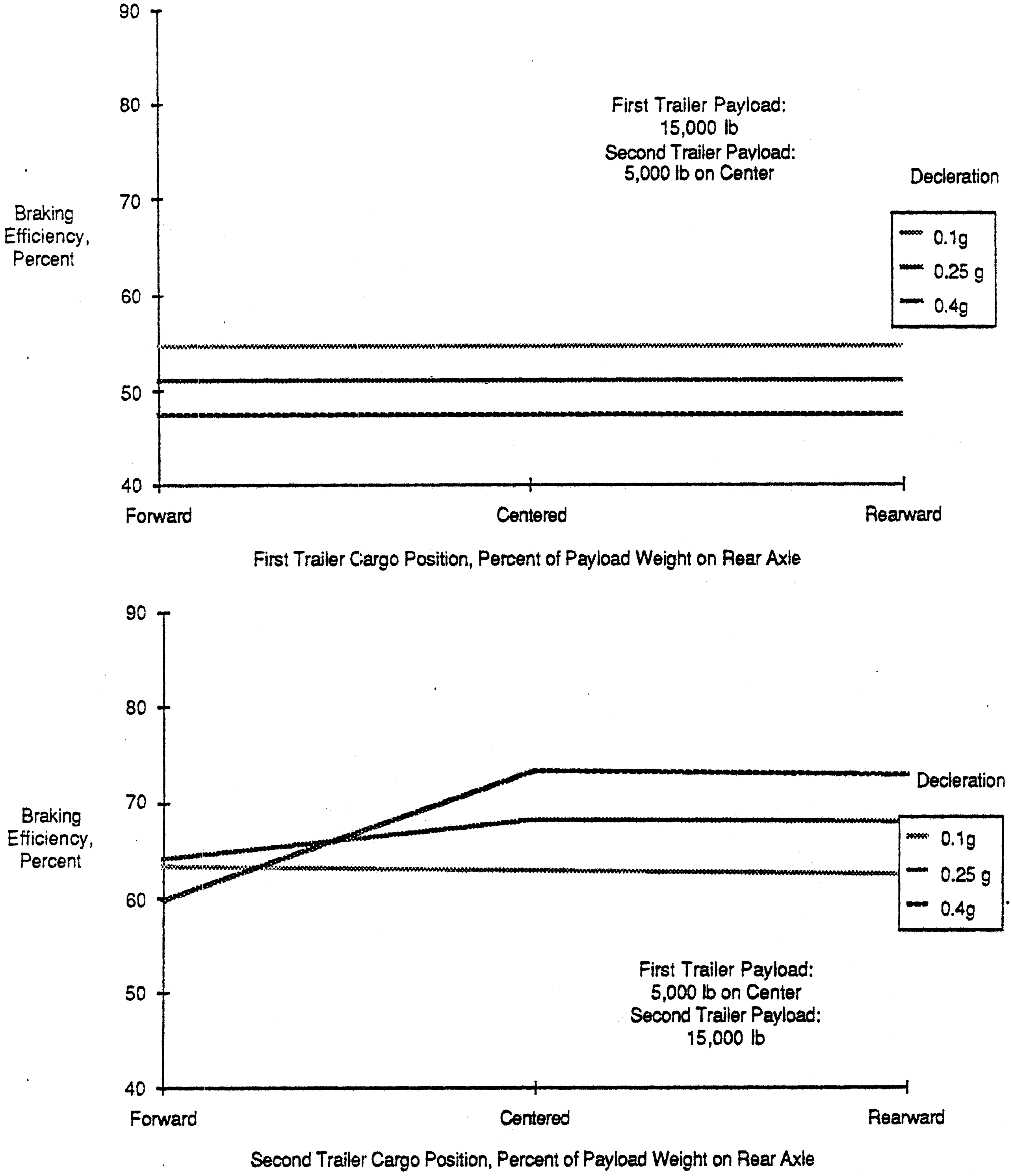

Figure 6. The influence of intra-trailer load distribution on the braking efficiency of doubles with two medium weight trailers

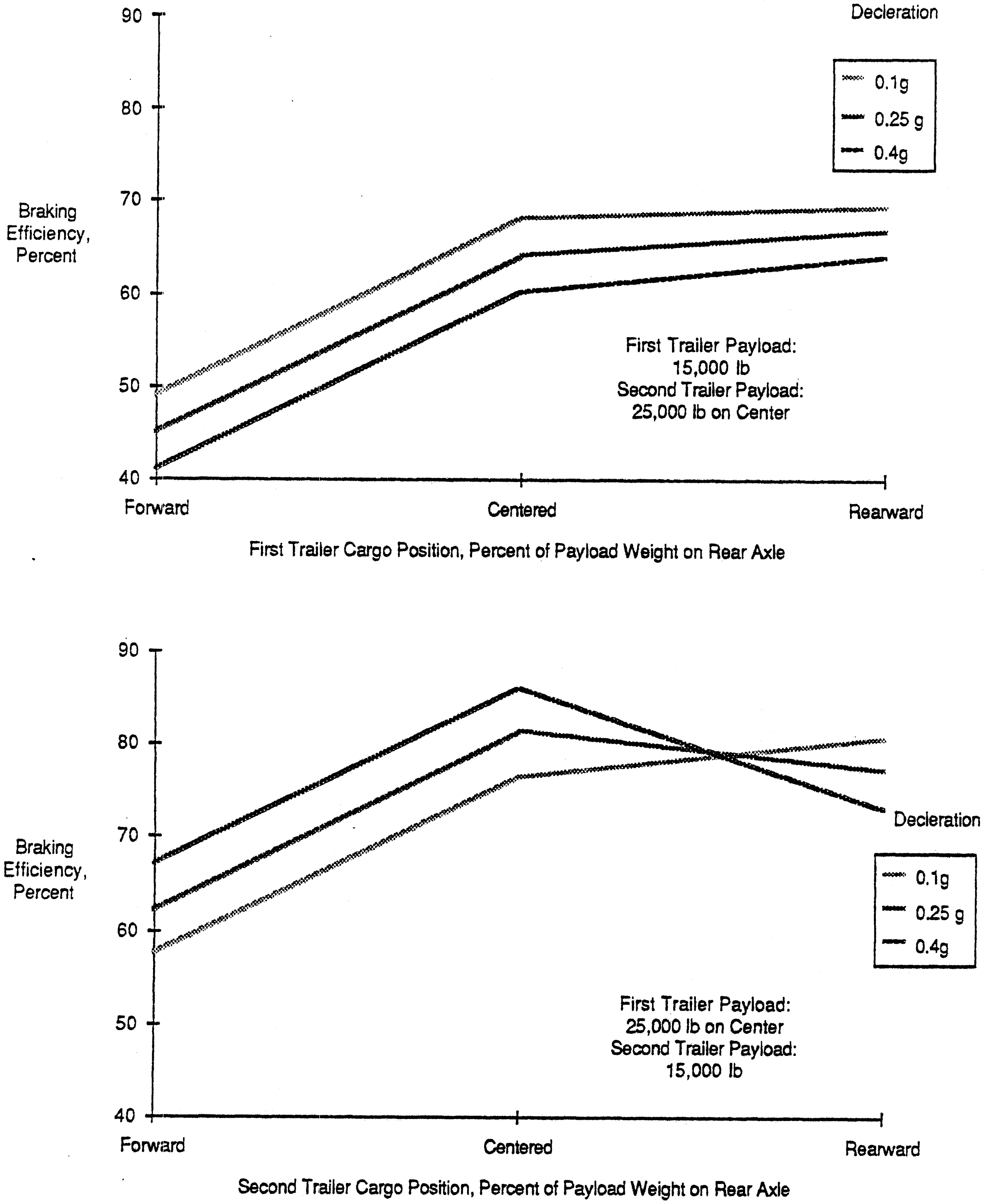

Figure 7. The influence of intra-trailer load distribution on the braking efficiency of doubles with one medium and one heavy trailer

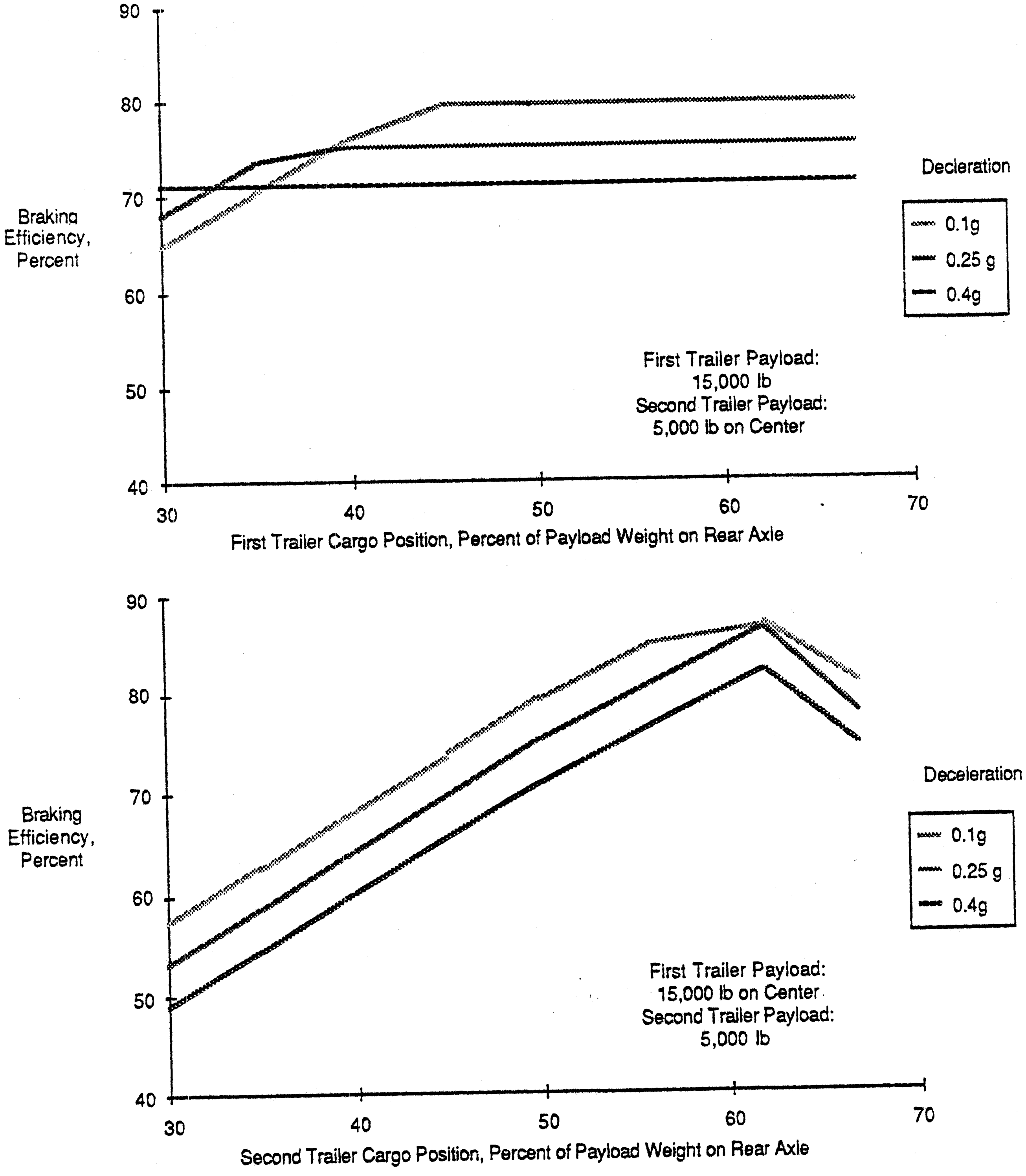

Figure 8. The influence of intra-trailer load distribution on the braking efficiency of doubles with two medium weight trailers

lighter trailer is generally expected to be the first to approach wheel lock, so that its intra-trailer load distribution is important. With only three weight distributions, the fidelity of the results is insufficient to identify optimum loading patterns. However, particularly when the rear trailer is the lighter, if 60% braking efficiency is to be maintained, no less than about 40% of the load in that trailer must be carried by the trailer axle.

To improve the fidelity of the findings, several more intra-trailer load distribution conditions, beyond those defined in Section 2.0, were tested for the situation in which both trailers contained 15,000 pounds of payload. In Figure 8, the abscissa still represents intra-trailer payload distribution, but the labeling has been changed to percent of trailer payload on the rear trailer axle. Five additional load positions (now totaling eight) were added between the "forward" and "rearward" extremes used previously, so that the fidelity of the results is improved. These graphs show that, for trailers of moderate and nearly equal loading:

1) Second trailer payload position tends to be more critical, with an optimum position (for braking) in the 60 to 65% rearward region.

2) First trailer payload position is relatively insignificant, except when that position is quite forward and deceleration levels are fairly low.

When static load of the trailers is equal, forward dynamic load transfer would imply that the second trailer axles would unload during braking, tending to make that trailer critical with respect to braking efficiency. The results bear this out, and reinforce the general finding that slightly rearward loading produces optimal results by counteracting forward, dynamic load transfer.

In closing this section, it should be noted that the braking performance of all, real commercial vehicle is rather variable. That is, the performance of the braking system, and especially the mechanical friction brake, varies significantly over time. These variations can result from maintenance condition, history of use (or abuse), brake temperature, or even ambient temperature and humidity. Such variables are known to produce substantially different performance from even the right and left wheel brakes on the same axle (which, presumably, would have as nearly equal "life histories' as possible). The brake systems of the vehicles simulated herein, however, are assumed to display consistent performance, at what we believe to be "average" or "representative" levels, for the fitted components. Thus, the results that have been presented here cannot be expected to be precise "stop-by-stop" predictions of braking performance, but rather, representative of aggregate performance trends.

4.0 MANEUVERING PERFORMANCE CALCULATIONS

It is very well established in the literature that maneuvering quality of the tractor-semitrailer portion of an A-train doubles combination vehicle is virtually unaffected by the presence of the full trailer. This is so because the "wagon-tongue" steering mechanism provided by the conventional A-dolly requires very little force to generate the needed steering action. As a direct result, only these same small lateral forces are "fed forward" through the pintle, and they are too small to significantly influence the motion of the tractor-trailer.

Accordingly, there is nothing about the maneuvering capability of the tractor-trailer portion of the doubles which would set the doubles apart from the single articulated vehicle; rather, it is the maneuvering response of the full-trailer portion which generates a difference. It is equally well established in the literature that, in rapid, evasive maneuvers (quick lane changes being the most common example), the second trailer of the doubles suffers from a "crack-the-whip" phenomenon in which this trailer substantially exaggerates, or amplifies, the motions of the tractor. This amplification is best expressed as the peak lateral acceleration of the rear trailer ratioed to the peak lateral acceleration of the tractor. Figure 9 illustrates both the rearward amplification phenomenon and measure.

Rearward amplification of many doubles configurations can approach or exceed 2.0. Since lateral acceleration is the basic impetus of rollover, rearward amplification tends to promote premature rollover of the second trailer in rapid lane-change maneuvers, thereby limiting the emergency maneuvering capability of doubles.

Rearward amplification is a frequency-sensitive phenomenon. That is, the level of rearward amplification displayed depends on the rapidity of steering. Rearward amplification is actually quite low in the steering frequency ranges characterizing everyday driving. Amplification rises with frequency to a peak, usually within the range of the drivers' capability to rapidly input steering. Above this frequency level, rearward amplification begins to drop again, but this is generally at such a high frequency as to only be of academic interest. The single numeric commonly used to characterize this property is the peak rearward amplification occurring within the usable frequency range.

Rearward amplification is also speed sensitive. Rearward amplification increases with forward speed, but speed condition does not generally influence the sensitivity of other variables. Thus, in this study, speed influences the absolute level of rearward amplification, but not the relative values as result from changes in loading. All simulations in this study were conducted at 62 mph (100 kph).

The UMTRI "Linear Yaw Plane" model was used to determine the peak rearward amplification of the Roadway double in all of the various loading configurations studied. This model is a relatively simple handling model which allows a cost effective approach to determine handling properties for a large sample of test vehicles. The model's major distinction from more complicated models is the fact that it assumes a linear model for the calculation of tire forces and does not modify tire properties as a function of side-to-side load transfer during a run. (Changes in tire properties due to the major changes in payload were accounted for in all runs.)

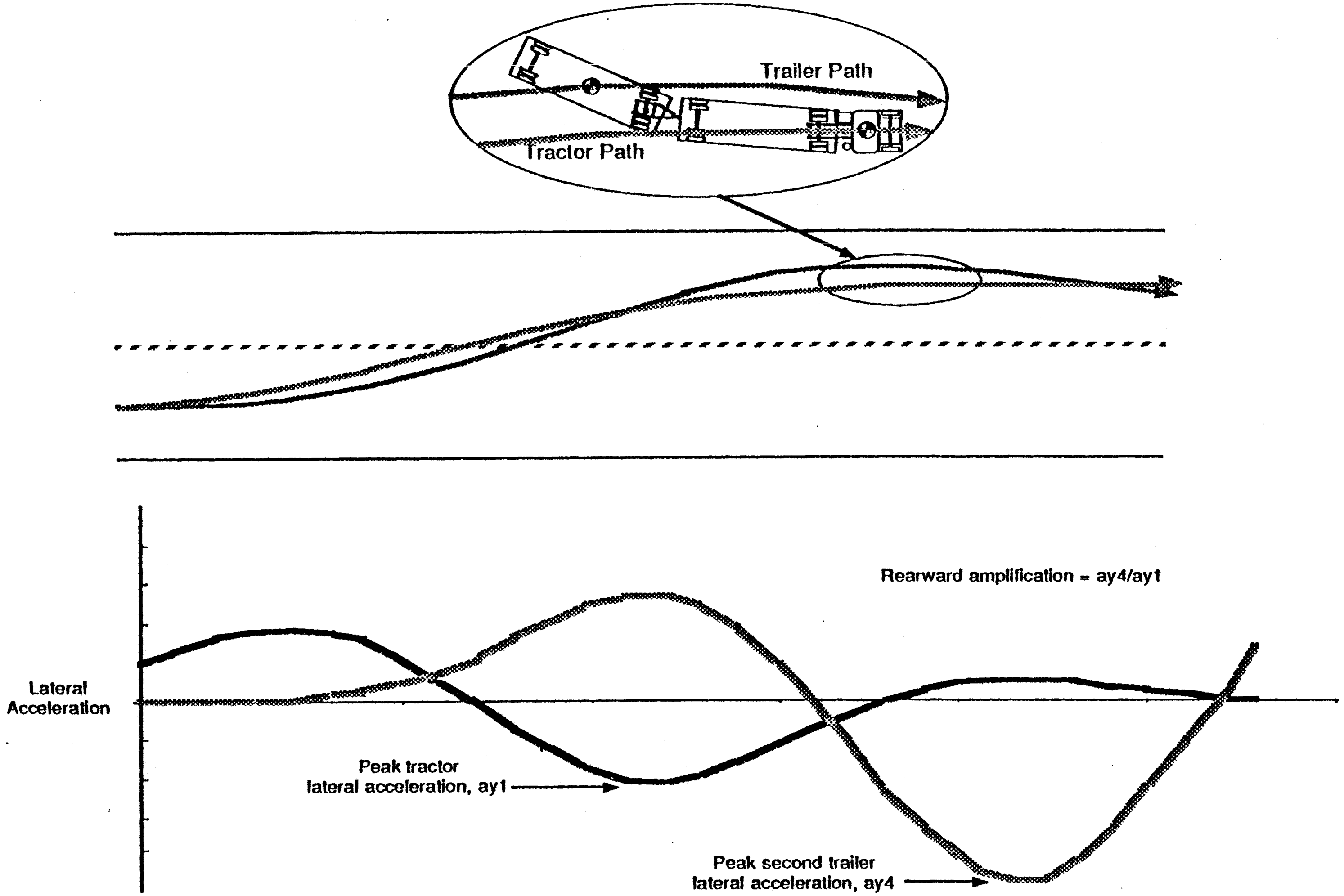

Figure 9. In a rapid lane change maneuver, rearward amplification results in "crack-the-whip" action of the rear trailer, sometimes resulting in rear trailer rollover.

Additionally, the UMTRI "Yaw/Roll" model was used in a limited number of loading matrix positions as a check. Generally, this model predicted higher levels of rearward amplification than did the linear model (as would be expected from theory), but confirmed the basic trends of loading sensitivity.

Figure 10 illustrates the sensitivity of rearward amplification to the total weight of the payload. The figure shows that rearward amplification increases moderately with total load. This is simply reconfirmation of a well-known influence. This sensitivity results from the fact that the relative cornering stiffness of truck tires generally decreases with increasing load.

Figure 10 also shows a very slight sensitivity of rearward amplification to inter-trailer load distribution, wherein rearward amplification declines as the percentage of total load in the second trailer increases. Fancher's work supplies an explanation. He has shown that rearward amplification of the whole vehicle can be viewed as the product of local rearward amplifications, namely, (1) from the tractor c.g. to the first trailer c.g., (2) from the first trailer c.g. to the pintle, and (3) from the pintle to the second trailer c.g. In many instances, the largest component of the total is the second element listed. Shifting load forward from the second trailer to the first would tend to exaggerate this component. Nevertheless, we view the level of sensitivity to inter-trailer load distribution as small, and probably not sufficiently powerful to be sustained in the presence of real world variables (particularly the trailer-to-trailer mix of tire brand, tire wear, and tire inflation pressures which may exist in practice).

Figures 11 and 12 illustrate the influence of intra-trailer load distribution on rearward amplification. The horizontal quality of the plots in Figure 11 shows that the fore-aft location of cargo in the first trailer has literally no influence on rearward amplification. The slope of the plots in Figure 12 shows that rearward amplification increases as cargo load is shifted rearward in the second trailer. The strength of this influence appears to be somewhat less, but nearly as strong as the influence which total load has on rearward amplification.

In summary, the Roadway double shows a significant tendency for rearward amplification to increase as the total payload weight increases. Sensitivity to inter-trailer load distribution is judged to be insignificant, and sensitivity to intra-trailer load distribution is significant in the second trailer only. The general range of rearward amplification (1.7 to 1.9) suggests that this property plays an important role in limiting the emergency evasive maneuvering capability of the Roadway doubles.

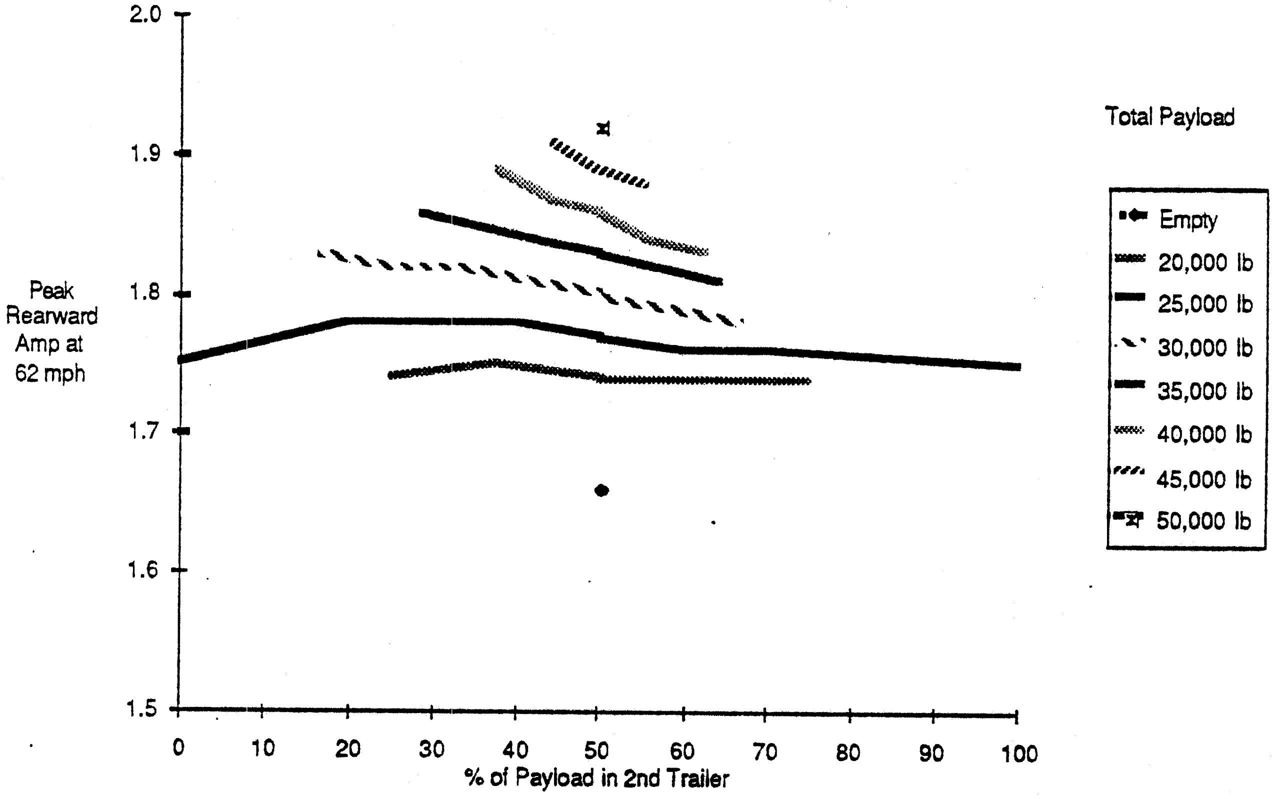

Figure 10. The influence of total payload weight and inter-trailer load distribution on peak rearward amplification

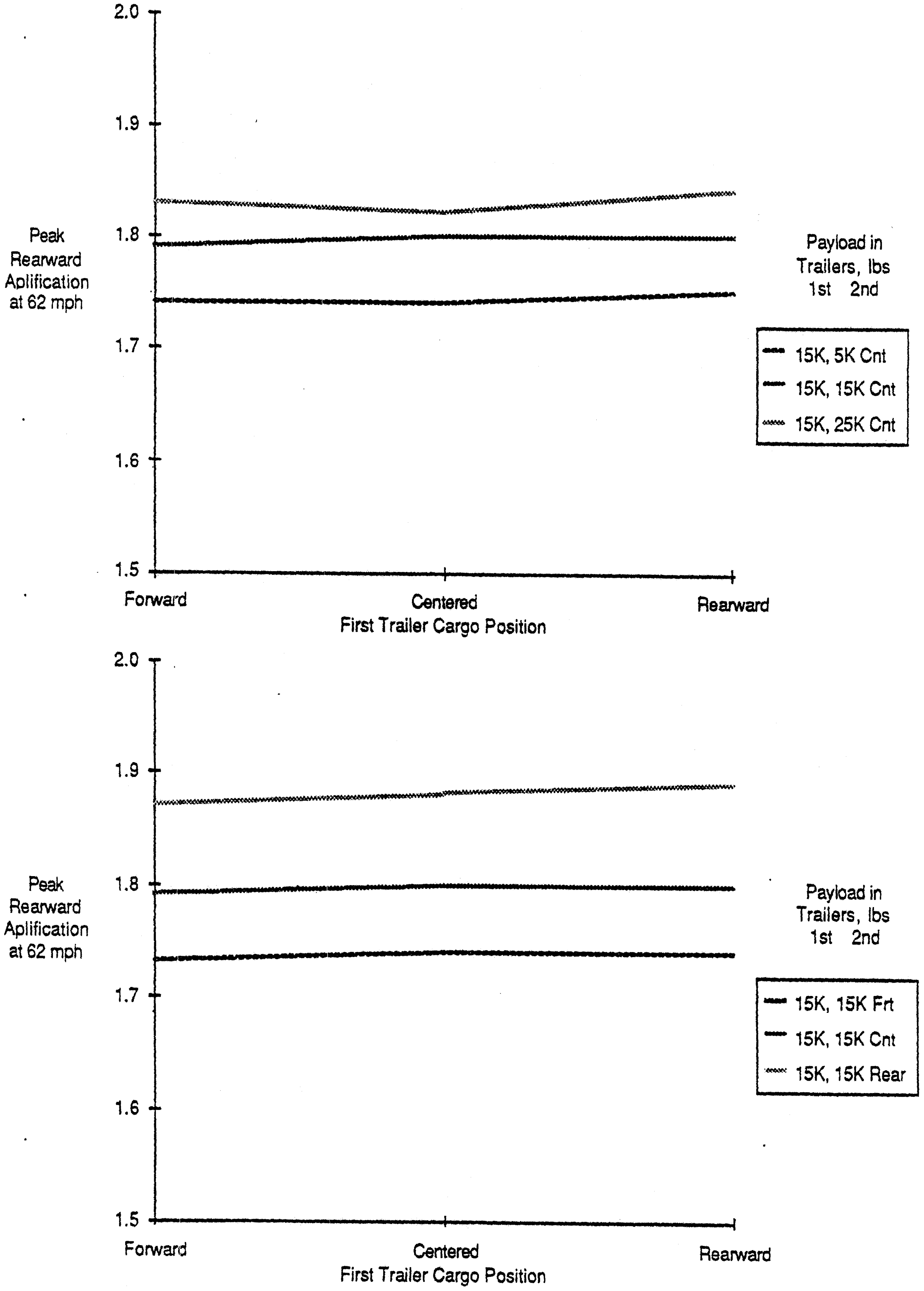

Figure 11. The influence of load distribution within the first trailer on peak rearward amplification

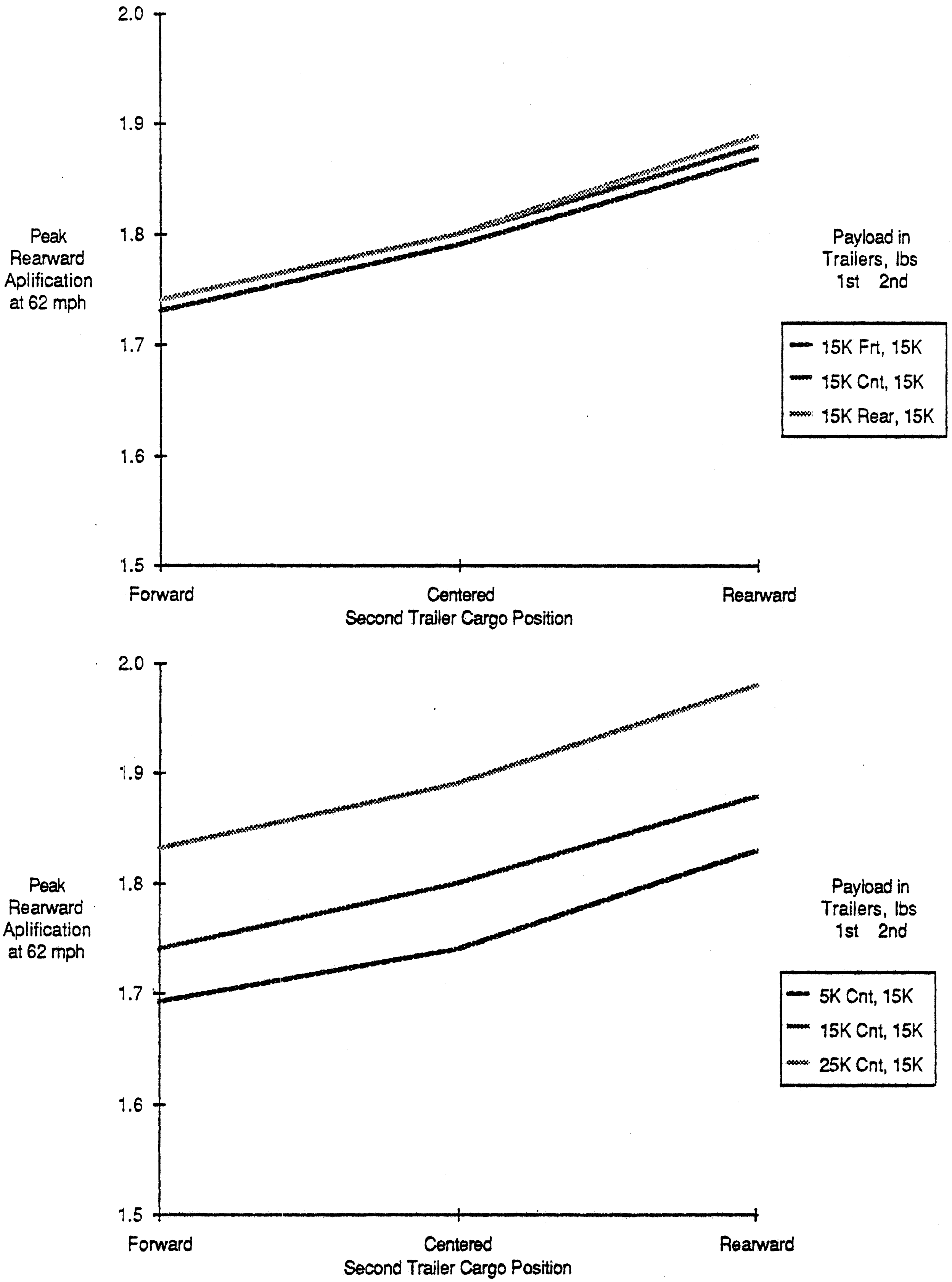

Figure 12. The influence of load distribution within the second trailer on peak rearward amplification

5.0 DIRECTIONAL STABILITY CALCULATIONS

In normal, straight-ahead running at highway speeds, doubles combination vehicles often display a back-and-forth "wagging" or "hunting" action of the second trailer. To the vehicle dynamicist, this action is immediately suggestive of a dynamic system with at least one, very lightly damped, root.

In the yaw plane (i.e., in the plan view), the four units of the doubles combination vehicle constitute a five-degree-of-freedom mechanical system with four natural modes of oscillation. Each of these modes of motion is composed of a specific "mix" of lateral motion and yaw motion of each unit, and each has characteristic natural frequency and damping ratio. At least one of these modes of motion is known to be dominated by motions of the dolly and pup trailer, and this mode typically has the lowest damping ratio of the four. It is reasoned that, when damping of this mode is particularly low, oscillating motions of the pup should be easily excited in normal running at highway speeds.

On the other hand, there have been many reports from the field wherein vehicles which were particularly prone to pup oscillations were readily cured of the problem through the use of air "snubber" pintle hitches (i.e., by using hitching hardware which effectively eliminates any lash at the pintle hitch). These reports would suggest that pup oscillations were not associated with lightly damped behavior of an essentially linear system, but rather with a low displacement limit cycle whose existence depended on the highly non-linear lash element at the hitch.

The influence of lash at the pintle has not been previously investigated, and UMTRI's simulation programs are not, as yet, equipped to do so. Accordingly, we were limited to investigating the suspected linear damping ratio, and inferring what we can about the influence of lash.

The "Linear Yaw Plane" program was used for this investigation, also. This program has a mode of operation in which, rather than producing time histories of specific vehicle motions, the basic, linear analysis properties of the vehicle can be calculated. The program was used to perform these calculations, and the minimum damping ratio of the system (i.e., that damping ratio of the lightest damped mode of motion) was extracted from the results for each of the loading conditions described in Section 2.0. The "Yaw/Roll" simulation program was used in a limited number of cases to confirm the results. This program operates only in the time domain so that modal damping ratios are not directly available. Rather, it was necessary to infer damping ratio from time domain results. A "pulse steer" maneuver, in which a sharp, very brief, steering pulse is introduced simply to excite trailer motion, was used. Having excited trailer oscillations, effective damping of the system can be calculated using the log of the ratio of the magnitudes successive peaks of trailer motion (logarithmic decrement). Assuming that only the lightest damped mode of motion survives for substantial time, this technique, applied late in the maneuver, should produce a good approximation of the damping ratio of the most lightly damped root of the system.

Finally, system damping is a function of forward speed, generally decreasing as speed increases. These analyses were conducted assuming a speed of 62 mph (100 kph).

The results of the linear analysis appear in Figures 13, 14, and 15. These results show that, regardless of loading condition, the damping ratio of the lightest damped mode of motion lies between 0.23 and 0.27. These are judged to be adequate damping ratios to assure good performance in this regard.

While Figures 14 and 15 indicate that intra-trailer load distribution has virtually no influence on minimum damping of the Roadway double, even the mild trends with respect to total load and inter-trailer load distribution, displayed in Figure 13, are not considered particularly significant. First, damping ratio is, in part, a function of the moments of inertia of the system. In our program, a reasonable algorithm was developed to calculate a representative moment of inertia for each trailer, given the weight of the load carried by that trailer. A few additional calculations using slightly different moments of inertia have shown that the mild trends displayed in Figure 13 are as much or more a result of the algorithm chosen to calculate moment of inertia, as they are a result of the payload changes indicated. Further, variations in field operating conditions (tire condition and, especially, the manner in which load is spaced in the box so as to determine the moment of inertia of the load) can easily be expected to override the trends shown in the figure.

The calculations based on the results from the "Yaw/Roll" model predict damping ratios in the 0.2 to 0.3 range for the loading conditions tested (with most conditions falling in the 0.22 to 0.28 range). The general procedure used proved to be of relatively low fidelity, producing fairly "noisy" results, so that the mild trends seen in the linear analysis could not be confirmed or denied. However, both the general magnitude, and the relative insensitivity to loading conditions, of the damping of the Roadway double were confirmed.

These results would tend to confirm the interpretation of field experience which attributes second trailer "wagging" in normal running, primarily to lash at the pintle hitch. That is not to say that insufficient damping would not aggrevate the problem in many configurations, but rather that the damping exhibited by the doubles studied here (fairly typical of LTL trucking) can be judged to be sufficient as to not rank as a "cause" of such behavior.

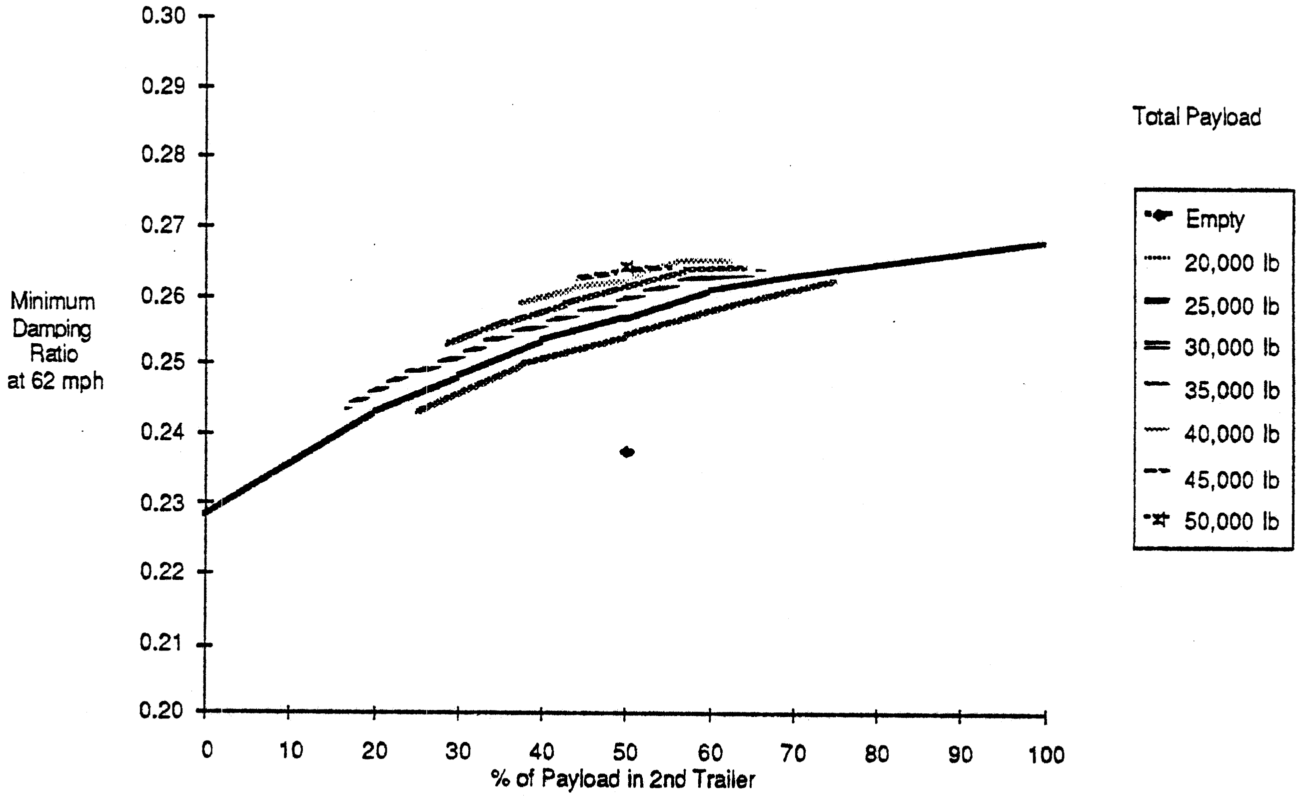

Figure 13. The influence of total payload and inter-trailer load distribution on the minimum yaw damping ratio

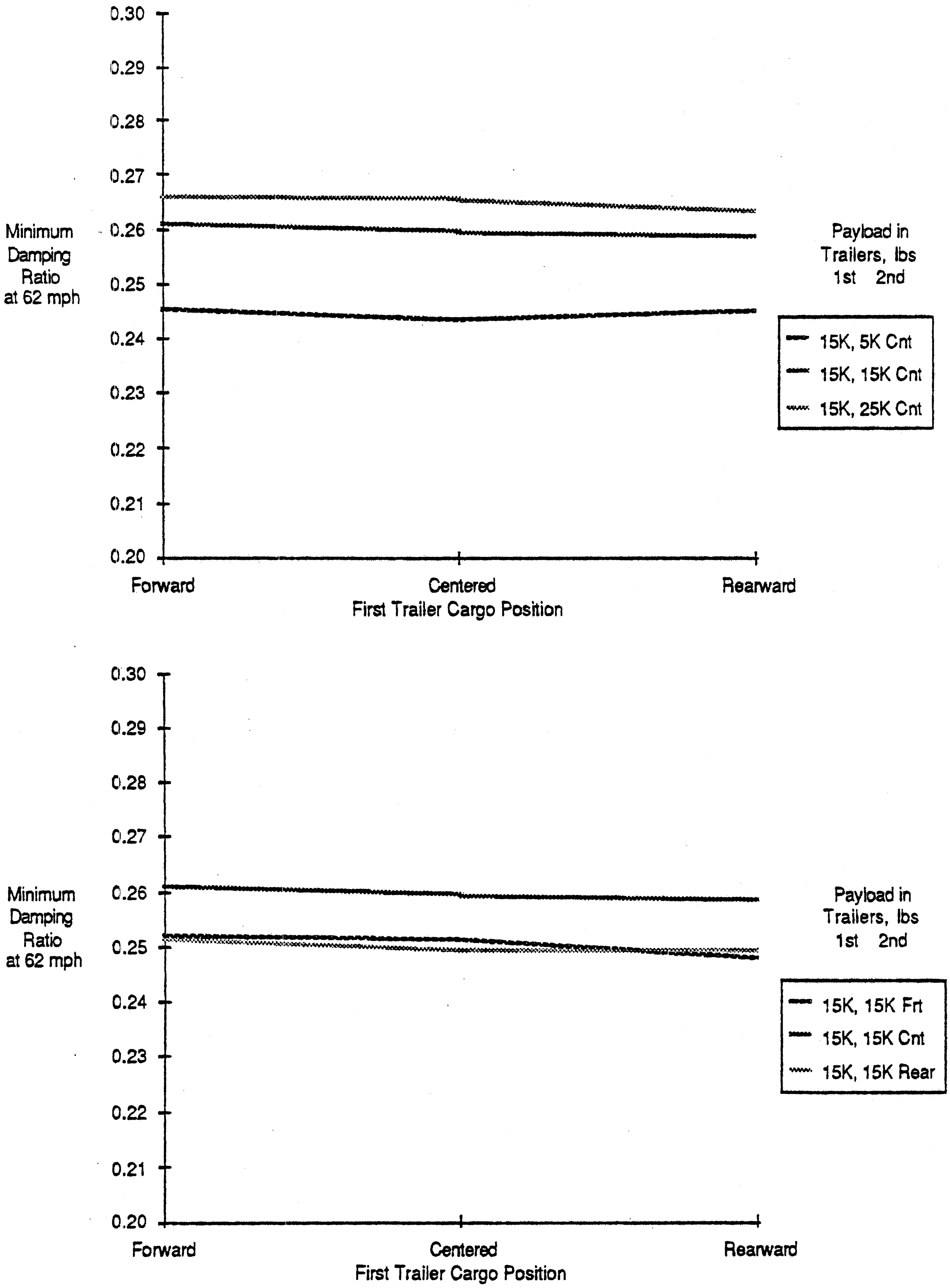

Figure 14. The influence of load distribution within the first trailer on the minimum yaw damping ratio

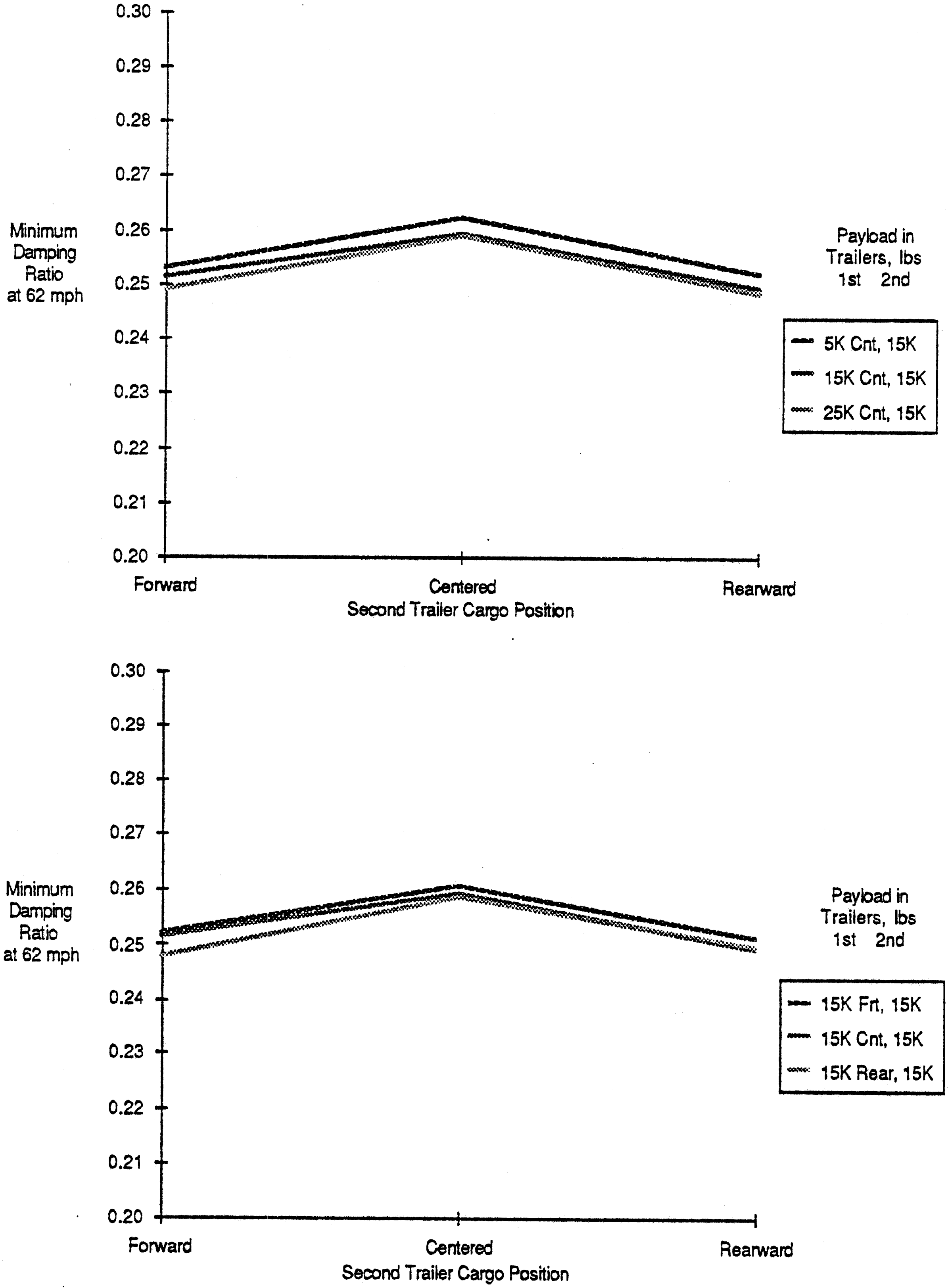

Figure 15. The influence of load distribution within the second trailer on the minimum yaw damping ratio

6.0 SUMMARY OF RESULTS.

This project has shown that, for the configuration of doubles combination vehicles commonly used by Roadway:

(1) Emergency braking performance, as measured by the braking efficiency of the vehicle, is quite sensitive to the distribution of load between the two trailers of the vehicle. This performance measure is also sensitive to the location of loading within the trailers, especially the second trailer. In the 20,000- to 50,000-pound range, however, braking efficiency is only slightly sensitive to the total weight of the payload. Since load is transferred to forward axles during braking, a somewhat rearward loading pattern is ideal. Braking efficiencies in the area of 90% can be obtained with slightly rearward-biased loading patterns. To ensure that braking efficiency remains above 60%, the second trailer should generally carry no less than 40% and no more than 80% of the total payload. Within the second trailer, the rear axle should carry no less than about 40% of that trailer's payload.

(2) The emergency evasive maneuvering capability, as measured by rearward amplification, shows significant sensitivities to loading conditions. Rearward amplification is significantly influenced by total load, with amplification increasing toward 1.9 as load increases. Load distribution within the second trailer (but not the first) also has a significant influence, with more forward loading patterns improving performance. Inter-trailer load distribution has only a small influence on rearward amplification. The general range of rearward amplification (1.7 to 1.9) suggests that this property plays an important role in limiting emergency evasive maneuvering capability.

(3) Directional stability, as measured by the damping ratio of the most lightly damped root of the vehicle in the yaw plane, was found to be remarkably insensitive to loading condition. While some mild sensitivities were discerned, none were felt to be strong enough to be significant under real-world operating conditions. The level of damping observed (minimum damping ratio of about 0.25) is adequate, and low damping is not seen as a potential "cause" of excessive, second trailer oscillation. These results tend to confirm the reports from the field, that second trailer oscillation in normal travel results from pintle hitch lash.

In general, these findings might be interpreted to suggest that the best "compromise" in loading practice would be for a central to slightly forward bias of intra-trailer loading (to avoid increasing rearward amplification) and a slightly rearward bias in inter-trailer load distribution (to avoid low braking efficiency.)

APPENDIX

Case	Trailer 1	Trailer 2	Total	% Payload	"Constant Deceleration Braking" Program			"Linear Yaw Plane" Program		"Yaw/Roll" Program	
					Braking Efficiency Level at			Rearward	Minimum	Rearward	Minimum
Number	Payload	Payload	Payload	Trailer 2	0.1 g's	0.25 g's	0.4 g's	Amplification	Damping Ratio	Amplification	Damping Ratio
1	0	0	0	50.0	56.1	52.9	49.6	1.66	0.238	1.62	0.244
3	15000	5000	20000	25.0	54.5	50.9	47.5	1.74	0.243	1.96	0.293
4	12500	7500	20000	37.5	64.8	60.9	57.3	1.75	0.250		
5	10000	10000	20000	50.0	75.0	70.8	67.0	1.74	0.254		
6	7500	12500	20000	62.5	72.4	76.9	76.5	1.74	0.258		
7	5000	15000	20000	75.0	62.8	68.3	73.3	1.74	0.262	1.91	
8	25000	0	25000	0.0	30.9	27.6	24.7	1.75	0.228	2.02	0.252
9	20000	5000	25000	20.0	49.5	46.2	51.4	1.78	0.243		
10	17500	7500	25000	30.0	58.8	55.3	51.9	1.78	0.248		
11	15000	10000	25000	40.0	68.1	64.4	60.7	1.78	0.253		
12	12500	12500	25000	50.0	77.4	73.4	69.3	1.77	0.257	2.02	0.260
13	10000	15000	25000	60.0	76.0	80.1	78.0	1.76	0.261		
14	7500	17500	25000	70.0	67.3	72.3	77.3	1.76	0.263		
15	0	25000	25000	100.0	41.0	48.3	55.6	1.75	0.268	1.88	0.217
16	25000	5000	30000	16.7	45.2	42.0	38.8	1.83	0.244		
17	22500	7500	30000	25.0	53.8	50.4	47.0	1.82	0.249		
18	20000	10000	30000	33.3	62.3	58.7	55.1	1.82	0.253		
19	17500	12500	30000	41.7	70.8	67.0	63.1	1.81	0.256		
20	15000	15000	30000	50.0	79.3	75.1	71.0	1.8	0.259	2.11	0.270
21	12500	17500	30000	58.3	79.0	83.1	78.7	1.79	0.262		
22	10000	20000	30000	66.7	71.0	78.0	80.9	1.78	0.264		
23	25000	10000	35000	28.6	57.7	54.2	50.3	1.86	0.253	2.26	0.258
24	22500	12500	35000	35.7	65.6	61.8	57.7	1.85	0.256		
25	20000	15000	35000	42.9	73.5	69.4	65.0	1.84	0.259		
26	17500	17500	35000	50.0	81.3	76.9	72.2	1.83	0.261		
27	15000	20000	35000	57.1	81.2	84.4	79.2	1.82	0.264		
28	12500	22500	35000	64.3	73.8	78.7	83.9	1.81	0.264	2.22	0.235
32	25000	15000	40000	37.5	68.1	64.1	60.2	1.89	0.259	2.28	0.244
33	22500	17500	40000	43.8	75.4	71.2	66.8	1.87	0.261		
34	20000	20000	40000	50.0	82.7	78.0	73.4	1.86	0.262		
35	17500	22500	40000	56.3	83.4	84.9	79.9	1.84	0.265		
36	15000	25000	40000	62.5	76.5	81.3	86.0	1.83	0.265	2.25	0.225
29	25000	20000	45000	44.4	77.1	72.6	68.1	1.91	0.262		
30	22500	22500	45000	50.0	83.8	79.0	74.1	1.89	0.263		
31	20000	25000	45000	55.6	85.2	85.3	80.1	1.88	0.264		
2	25000	25000	50000	50.0	85.1	80.0	75.7	1.92	0.264	2.37	0.201

					"Constant Deceleration Braking" Program			"Linear Yaw Plane" Program		"Yaw/Roll" Program Results	
Case	Trailer 1 Payload		Trailer 2 Payload		Braking	Efficiency	Level at	Rearward	Minimum	Rearward	Minimum
No.	Pounds	Position	Pounds	Position	0. 1 g's	0. 25 g's	0. 4 g's	Amplification	Dampimg Ratio	Amplification	Damping Ratio
3. 0	15, 000	Centered	5, 000	Centered	54. 5	50. 9	47. 5	1. 74	0. 243		
3. 1	15, 000	Forward	5, 000	Centered	54. 5	50. 9	47. 5	1. 74	0. 246		
3. 2	15, 000	Rearward	5, 000	Centered	54. 5	50. 9	47. 5	1. 75	0. 245		
7. 0	5, 000	Centered	15, 000	Centered	62. 8	68. 3	73. 3	1. 74	0. 262		
7. 1	5, 000	Centered	15, 000	Forward	63. 2	63. 9	59. 5	1. 69	0. 253		
7. 2	5, 000	Centered	15, 000	Rearward	62. 4	67. 9	72. 9	1. 83	0. 252		
20. 0	15, 000	Centered	15, 000	Centered	79. 3	75. 1	71. 0	1. 80	0. 259	2. 11	0. 270
20. 1	15, 000	Forward	15, 000	Forward	57. 2	53. 0	48. 8	1. 73	0. 252		
20. 2	15, 000	Forward	15, 000	Centered	64. 7	68. 0	71. 0	1. 79	0. 261	2. 06	0. 265
20. 3	15, 000	Forward	15, 000	Rearward	64. 4	67. 8	70. 9	1. 87	0. 251		
20. 4	15, 000	Centered	15, 000	Forward	57. 2	53. 0	48. 8	1. 74	0. 251	2. 18	0. 306
20. 5	15, 000	Centered	15, 000	Rearward	80. 7	77. 7	74. 8	1. 88	0. 249	2. 14	0. 253
20. 6	15, 000	Rearward	15, 000	Forward	57. 2	53. 0	48. 8	1. 74	0. 247		
20. 7	15, 000	Rearward	15, 000	Centered	79. 3	75. 1	71. 0	1. 80	0. 258	2. 05	0. 227
20. 8	15, 000	Rearward	15, 000	Rearward	80. 7	77. 7	74. 8	1. 89	0. 249		
32. 0	25, 000	Centered	15, 000	Centered	68. 1	64. 1	60. 2	1. 89	0. 259		
32. 1	25, 000	Centered	15, 000	Forward	49. 0	45. 1	41. 1	1. 83	0. 249		
32. 2	25, 000	Centered	15, 000	Rearward	69. 4	66. 8	64. 1	1. 98	0. 248		
36. 0	15, 000	Centered	25, 000	Centered	76. 5	81. 3	86. 0	1. 83	0. 265		
36. 1	15, 000	Forward	25, 000	Centered	57. 5	62. 2	67. 0	1. 82	0. 266		
36. 2	15, 000	Rearward	25, 000	Centered	81. 0	77. 0	73. 0	1. 84	0. 263		