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TRAILER BRAKE PERFORMANCE

J. E. Bernard
C. B. Winkler
J. D. Campbell
R. K. Gupta

Final Technical Report

September 1976

Highway Safety Research Institute
The University of Michigan

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ADDENDUM TO FINAL TECHNICAL REPORT

TRAILER BRAKE PERFORMANCE

Contract No. DOT-HS-5-01152

1. In the "Acknowledgements" the Airstream Representative is Mr. K. Kroll.

2. The abbreviation "gvw" means "gross vehicle weight".

3. On page 59, the second footnote to Table 3.11 should read "tandem."

4. In the third paragraph on page 96, the third sentence should read "In this way, calculations can be . . ."

5. On page 153, the GMC C5500 pickup listed in Table A.2 is an error, the tow vehicle was a GMC C3500 pickup.

6. On page 172, in the fourth paragraph of Section B.6.2 Vehicle Loading, the text should read ". . . such that (1) with the tow vehicle and trailer load and trailer properly hitched (i.e., with proper load equalization) to its nominal match tow vehicle, the static trailer axle load was equal to the manufacturer's recommended gross axle weight rating, and (2) with . . ."

7. In Figure 5.1, page 132, the notations "$\ddot{X}TV$" and "$\ddot{X}CV$" should read "$\ddot{X}_{TV}$" and "$\ddot{X}_{CV}$", respectively.

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16. Abstract

The goals of this research project were threefold, namely, (1) to elucidate the mechanics of combination-vehicle braking (where "combination vehicles" refers to passenger car-trailer and pickup truck-trailer combination vehicles), (2) to structure a rationale for measuring trailer braking properties, and (3) to formulate a set of guidelines by which tow and trailing vehicles can be properly matched to provide acceptable combination-vehicle braking performance. The report describes analytical and empirical work aimed toward attaining these goals, including parameter sensitivity studies employing digital computer simulation and full-scale track testing of five tow vehicles and five trailers. Parameter measurements of the test trailers were also included.

A simple and practical two-step "rule" which provides for reasonable assurance of a minimum braking performance of combination vehicles is proposed and validated for a number of sample cases. The first step of the rule is composed of a test methodology for determining the inherent braking capability of trailers alone. The second step uses this "trailer alone" measure to determine a minimum weight tow vehicle for a given trailer which will provide reasonable assurance of acceptable combination-vehicle braking performance. The rule's validity requires the assumption that the tow vehicle conforms to FMVSS 105-75 and that certain in-use factors are maintained within reasonable bounds.

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Mr. J. Boissonneault and his staff were responsible for the preparation of vehicles employed in full-scale testing.

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Kelsey-Hayes - Mr. D. Brenner

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TABLE OF CONTENTS

1.0 INTRODUCTION

This document constitutes a final report on a research study entitled "Trailer Brake Performance" which was conducted by the Highway Safety Research Institute of The University of Michigan. The study was supported by the National Highway Traffic Safety Administration of the U.S. Department of Transportation under Contract DOT-HS-5-01152.

The goals of the research were threefold, namely

a) to elucidate the mechanics of combination vehicle* (CV) braking,

b) to structure a rationale for measuring trailer braking properties, and

c) to formulate a set of guidelines by which tow and trailing vehicles can be properly matched to provide acceptable combination vehicle braking performance.

The next section of this report gives an overview of the project, providing a rationale for our interest in the braking performance of trailers taken alone.

Following this background information, a section concerned with empirical work is presented. This section is divided into two parts, the first discussing component testing for items such as trailer brakes, tires, suspensions, and inertial properties; the second presenting the results of the full-scale vehicle tests.

Next, in Section 4.0, a summary of the simulation and analysis performed in support of the testing is presented. The simulation is concerned with providing a detailed understanding

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*Throughout this document, the term "combination vehicle" will be used to refer to passenger car-trailer and pickup truck-trailer types in which the tow vehicle is commonly equipped with an hydraulic brake system. Specifically excluded are the larger articulated vehicles in which both tow vehicle and trailer commonly employ air brake systems.

of the mechanics of the brake performance of the vehicles tested and the analysis builds on the simulation and test results in order that a methodology for formulating guidelines for the proper matching of tow and trailing vehicles might be obtained.

HSRI's view of appropriate guidelines for the matching of tow and trailing vehicles to ensure a minimum level of combination-vehicle braking performance is presented in Section 5.0. Finally, conclusions and recommendations are presented in Section 6.0.

2.0 BACKGROUND

2.1 The Objectives

NHTSA has stated two primary objectives for this research study, namely:

1) To determine the characteristics of the towed and towing vehicle, including geometry, brake design features, and usage factors which have a major influence on the brake performance of the vehicle combination.

2) To develop and recommend a specification and test rationale by which satisfactory brake performance of the combination can be assured by controlling the brake performance of the towed vehicle in a safety standard.

In the Introduction to this report, these two objectives were restated, dividing the second into two elements, namely, the measurement of trailer brake performance and a rationale for the matching of combinations.

From the onset, it was quite clear that the first NHTSA objective could be met. The state of the art of vehicle dynamics is sufficiently advanced such that the tools required to satisfactorily meet this goal are available. But it was not obvious, a priori, that NHTSA's second stated objective would yield to satisfactory solution. In particular, the possibilities for success in meeting this second objective hinge on the findings associated with the first.

Consider two extreme possibilities. First, that many characteristics of towed and towing vehicles might be found to have a major influence on the braking performance of the combination vehicle. In this case, the possibility of success in meeting the second objective would be severely limited. Any proposed guideline with sufficient technical complexity to simultaneously deal with several important factors would likely prove to be impractical. Conversely, a guideline of sufficient simplicity to be practical would probably be inadequate.

At the other extreme, consider a finding suggesting that only one or two important factors affect combination vehicle braking performance. In this case, success in the second objective would be assured simply by placing adequate bounds on these factors.

To be sure, the real situation lies between these extremes. But the statement of the two extremes serves to illustrate an important, implicit element of the first objective—to identify and remove from consideration those factors which, due to the physics of the process or the influence of common practice, have secondary or negligible influence on combination vehicle braking.

Whatever the complexity of the braking process, it is important to note that NHTSA's second objective has two implicit requirements. First, it is the brake performance of the towed vehicle which is to be controlled. Thus, a methodology for measuring the inherent braking capability of the trailer, independent of the tow vehicle, is required. Second, by regulating the towed vehicle's performance, the combination vehicle performance is to be assured. The implication here is that the potential degradation of braking performance accruing from the addition of a trailer to a tow vehicle must be satisfactorily limited. This report will show that this can be accomplished through a procedure whereby the measured capabilities of a given trailer are employed to define an acceptable class of tow vehicle for that trailer.

2.2 The Methodology

Both analytical and empirical activities were undertaken to address the objectives of the study. The work done can be classified into several areas, primarily analysis, component testing, and full-scale vehicle testing. Figure 2.1 illustrates the interactions between the several activities of the program.

The diagram shows that analysis was the central element of the program. This activity began early and continued throughout the study. Early in the study, a program of trailer component testing was undertaken to provide the necessary parametric data for analysis. The analysis led to a fuller understanding of the mechanisms of CV braking, and to the development of the vehicle test methodology. This methodology was implemented in a vehicle test program whose results supplemented and validated the analytical results. As a final stage of analysis, guidelines for the matching of CV's were developed and their validity tested by comparison with test results.

This document will show that the study was successful in the attainment of NHTSA's goals. Because of a fortuitous combination of basic mechanics, common design practices, and the influence of established safety standards (particularly FMVSS 105-75), it is possible to recommend test procedures and guidelines for matching tow and trailing vehicles to achieve acceptable CV braking performance.

This report, then, will conclude by describing a two-step process. The first step is composed of a test methodology for the determination of the inherent braking properties of trailers taken alone. The second step is the use of this "trailer alone" information to determine a category of tow vehicles for a given trailer which will provide reasonable assurance of acceptable combination vehicle braking performance.

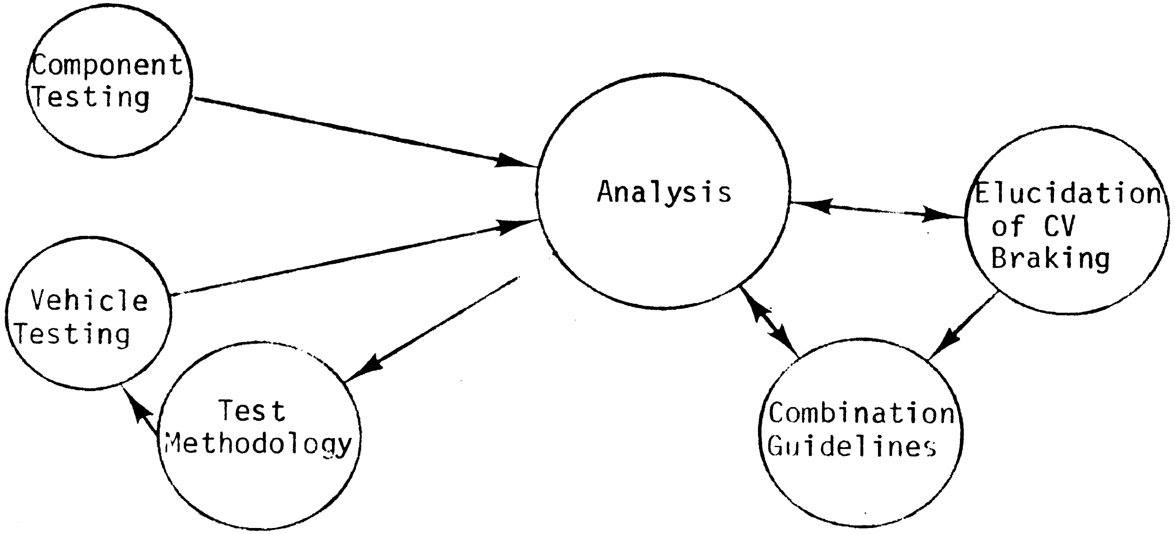

Figure 2.1 A flow chart of project activities.

3.0 EMPIRICAL WORK

This section presents the data which derive from measurements made on five tow vehicles and five trailers identified in Table 3.1. The tow vehicles included a compact, an intermediate, and a full-sized passenger car, plus 3/4- and one-ton pickup trucks. The trailers included a small, intermediate, and a large conventional hitch travel trailer, a large fifth wheel-type travel trailer and a fifth wheel-type farm trailer. Note that the tow vehicles are numbered 1 through 5 and trailers A through E. These designations will be used throughout this text. Further identification and general data for these vehicles appears in Appendix A.

Data gathered fall into two general categories, viz., component parameters and full-scale performance data. In the following sections, findings concerning components of the vehicles, including trailer tires, brakes, inertial and suspension properties, electric brake and surge brake actuators, and load equalizing hitches, will be discussed. Later, full-scale test results from tow-vehicle-alone testing, trailer-alone testing, and combination-vehicle testing will be reviewed.

3.1 Component Testing

A substantial amount of component testing was conducted on the five test trailers to gather parametric data descriptive of the trailers as vehicle/tire systems reacting to the braking process. There were three classes of measurements, namely, tire, brake system, and chassis parameters. These parameter measurement activities will be discussed in the following subsections.

Table 3.1. Test Vehicles

Test Vehicle Designation	Manufacturer	Model	Type
Trailers:			
A	Starcraft	Starmaster 6	Pop-Up Camper Trailer
B	Fleetwood	Prowler "H"	20-ft. Travel Trailer
C	Airstream	Sovereign	31-ft. Travel Trailer
D	Holiday Rambler	5th Estate	32-ft. 5th Wheel Travel Trailer
E	Donahue		5th Wheel Farm Utility
Tow Vehicles:			
1	Chevrolet	Nova	Compact
2	AMC	Matador	Intermediate
3	Chevrolet	Impala Wagon	Full Size
4	GMC	K2500	4WD 3/4-ton Pickup
5	GMC	C3500	1-ton Pickup

3.1.1 Tire Testing. Tire tests of the five trailer tires were conducted using the HSRI Mobile Tire Tester (Figure 3.1). This work was done at the Bendix Automotive Development Center at New Carlisle, Indiana. Tire tests were conducted on the same surface as were vehicle tests.

The five tires and the vertical load test conditions for these tires appears in Table 3.2. The tires associated with the two smaller trailers were tested at vertical loads which simulated wheel loads under trailer loaded and trailer empty conditions. For tires of the three larger trailers, only trailer empty loads were simulated since the brake torque required to produce significant longitudinal slip at higher loads exceeded the capability of the Mobile Tire Tester.

Table 3.2. Tire Test Conditions

		Vertical Tire Load (lb)	
Trailer	Tire	Empty Vehicle Simulation	Loaded Vehicle Simulation
A	Mobiliner 5.30x12	720	1000
B	Dayton-78 7.75x15	720	1250
C	Goodyear 7.00x15	1200	--
D	Goodyear 8.55x15 STS	1260	--
E	Sears 12.00x16.5LT	1000	--

The peak and slide values of normalized brake force attained for each tire tested appear in Figure 3.2. The values shown derive from the average of five runs conducted at each test condition.

It is of interest to note that the peak-to-slide ratios of normalized brake force displayed by this tire sample range from 1.19 to 1.50 and averages 1.38. Such high ratios are more typical of truck tires than passenger car tires.*

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*As reported in [1], the peak-to-slide ratio of normalized longitudinal shear forces on dry pavement ranges from 1.2 to 2.0 for truck and bus tires, while values of 1.0 to 1.2 are more typical for passenger car tires.

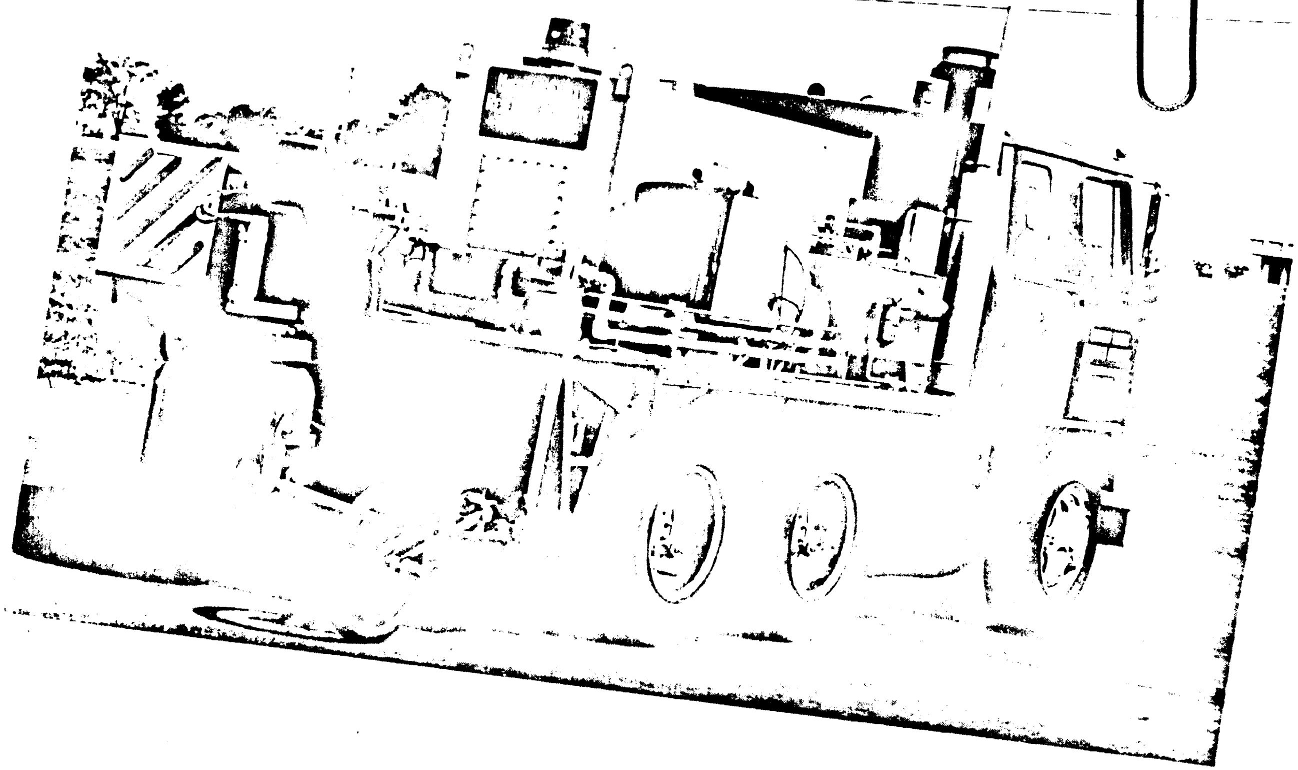

Figure 3.1. The Mobile Tire Tester.

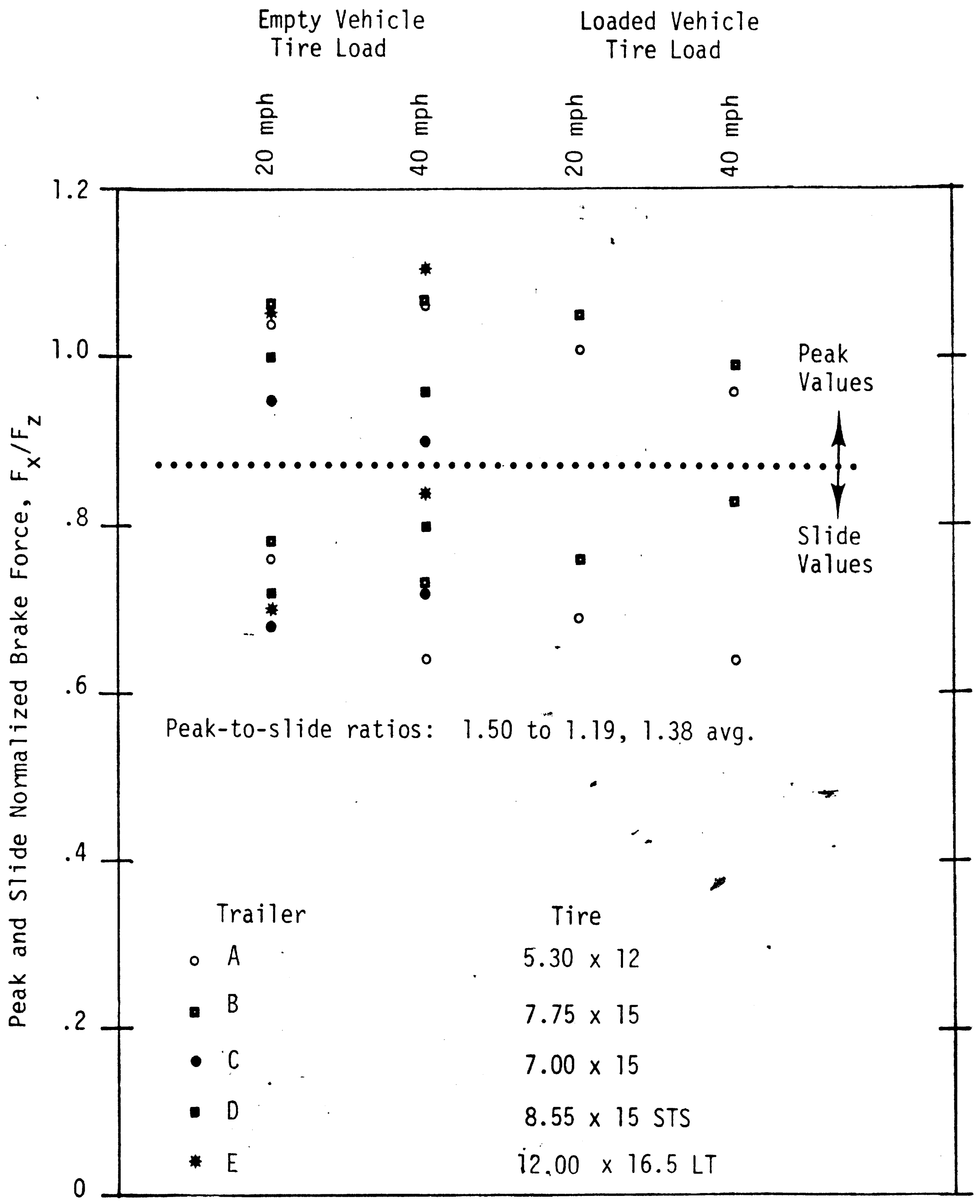

Figure 3.2. Peak and slide traction of trailer tires.

3.1.2 Brake System Testing

Friction Brake Tests

The effectiveness of the trailer brakes was examined through inertial brake dynamometer testing. The dynamometer test program was conducted at the facilities of the Greening Testing Laboratory of Detroit, Michigan.

Table 3.3 identifies the brakes for each of the trailers. Four different brakes are represented. Three are electric brakes and one is an hydraulic brake actuated by a surge hitch. The Kelsey-Hayes 12 x 2 inch electric brake was employed on two of the test trailers.

Table 3.3. Trailer Brakes

Trailer	Brakes
A	Bendix 7 x 1-3/4 Hydraulic
B	Fayette 10 x 2 Electric
C	Kelsey-Hayes 12 x 2 Electric
D	Dexter 12 x 2 Electric
E	Kelsey-Hayes 12 x 2 Electric

In the dynamometer program, five sample brakes were tested. Two samples of the Kelsey-Hayes brake were employed, one with a hub and drum assembly from trailer C and one with similar hardware from trailer E. The hydraulic brake was actuated in the usual manner used in the dynamometer testing of automobile hydraulic brakes. However, it was necessary to construct special equipment for the actuation of the electric brakes. As shown in the schematic diagram of Figure 3.3, the hydraulic pressure signal produced by the standard dynamometer actuation system was converted to a high current electrical signal which actuated the electric brakes.

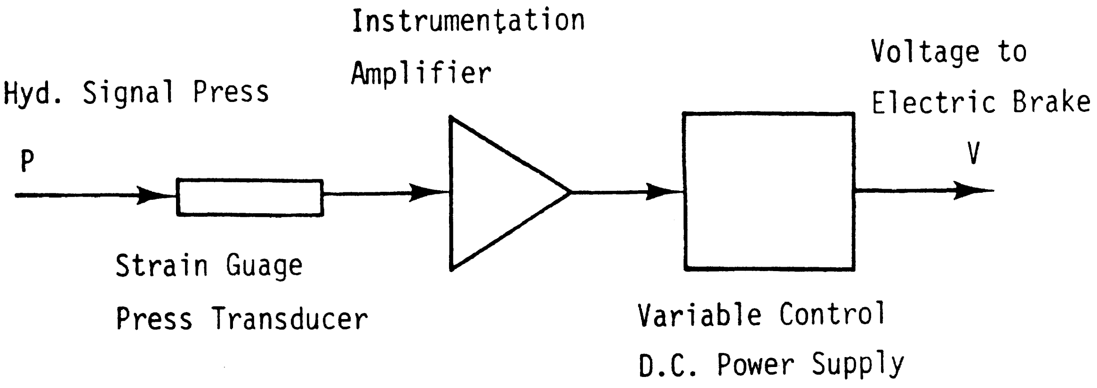

Figure 3.3. Electric brake actuation system.

Each of the five brakes was tested for pre-burnish and post-burnish effectiveness. Inertial loading was equivalent to the static gvw wheel load of the trailer on which the brake was used.

Each effectiveness test consisted of six stops from an equivalent dynamometer speed of 60 mph.* The highest level stop was conducted at an actuation level yielding a brake torque equivalent to a 1.2 g deceleration (based on static fully loaded wheel loads and the rolling radius of the trailer tire) or at the maximum brake torque available, whichever was less. (In any case, electric brakes were limited to 12 volts actuation.) The remaining stops were conducted at actuation levels of 1/6, 1/3, 1/2, 2/3, and 5/6 of this maximum. Initial brake temperatures for each stop were between 150°F and 200°F.

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*The brake from trailer A was an exception. The combination of dynamometer top speed and the small rolling radius of the trailer tire limited maximum speed to 48 mph.

The burnish procedure consisted of 200 stops from an equivalent dynamometer speed of 40 mph at an actuation level producing an average deceleration of 12 fpsps.* Brake temperatures at the initiation of each burnish step were held between 230°F to 270°F.

The results of the dynamometer effectiveness tests appear in Figures 3.4 through 3.7. Note that on each graph a reference torque level, equivalent to a deceleration of either 5 or 10 ft/sec^2, has been indicated to facilitate interpretation of the data. At this torque level, the wheels-unlocked brake force would be sufficient to decelerate, at the indicated level, a vehicle whose weight equaled the simulated static wheel loads.

Figure 3.4 shows the results for the trailers C and E electric brakes tested. Since these were two separate samples of the same model brake, the variance in the results is surprising, even in view of the fact that different hub and drum hardware (as used on trailers C and E) were employed, as well as different inertial loadings appropriate for the two trailers. Although we have no evidence to implicate the source of variance between the two sets of test results, possible candidates include test procedure, hub and drum differences, inertial load differences, and inherent variance between brake samples. However, in view of the fact that brake torques substantially different from any of these dynamometer values were apparently measured during vehicle testing, variance between samples seems to be a reasonable explanation.

An examination of all the dynamometer data indicates that the burnish process tended to reduce the maximum brake torque available from the electric brakes tested. This appeared to result from earlier saturation of the brake rather than a change in the brake torque/voltage gain. The post-burnish 12-volt values for

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*It was initially planned to accomplish the burnish in a constant torque control mode. However, hysteresis and variability in the input/output relationships, particularly of the electric brakes, made this impractical.

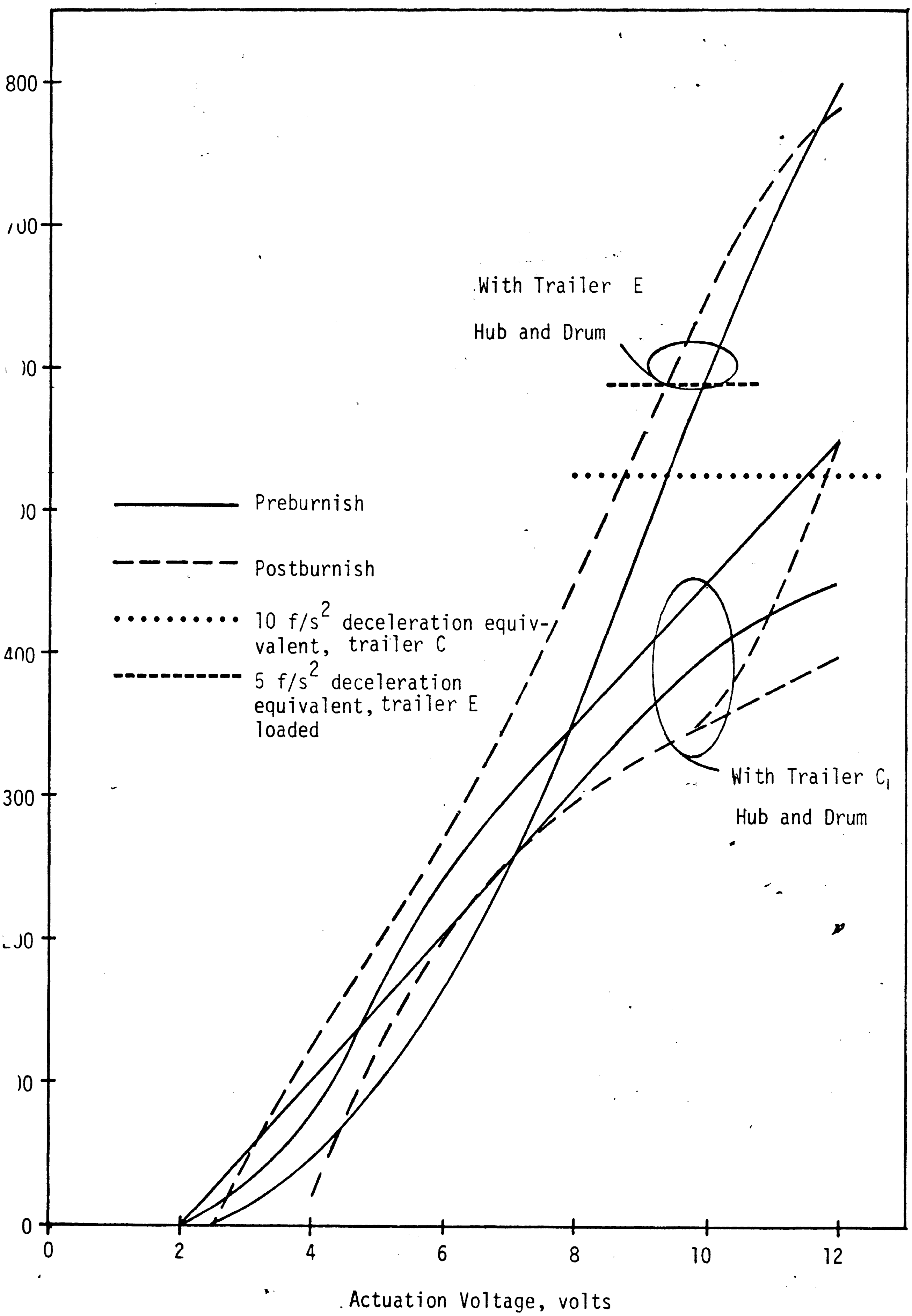

Figure 3.4. Dynamometer test results: Trailers C and E brakes, 12 x 2 electric brakes.

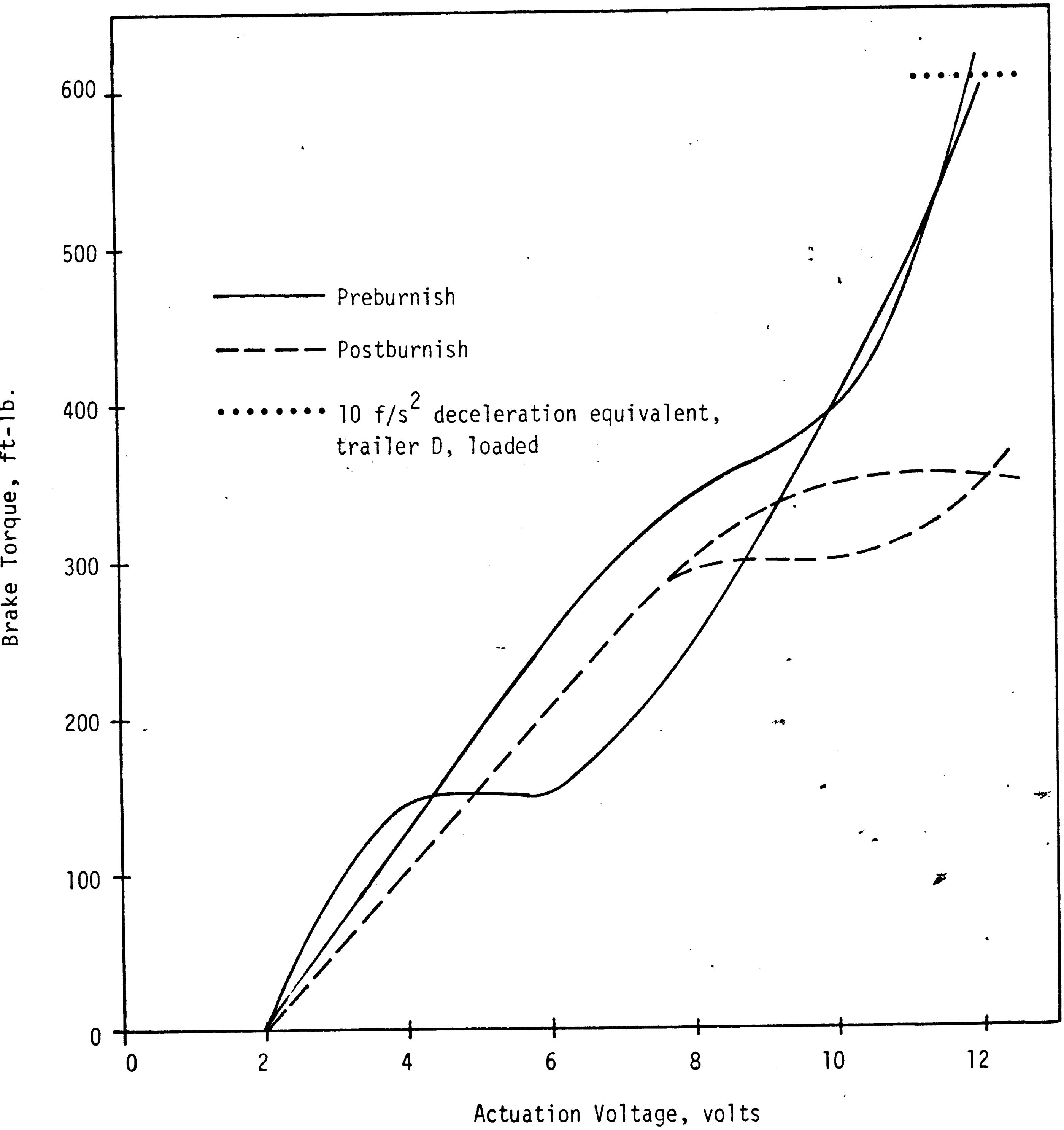

Figure 3.5. Dynamometer test results: Trailer D, 12 x 2 electric brakes.

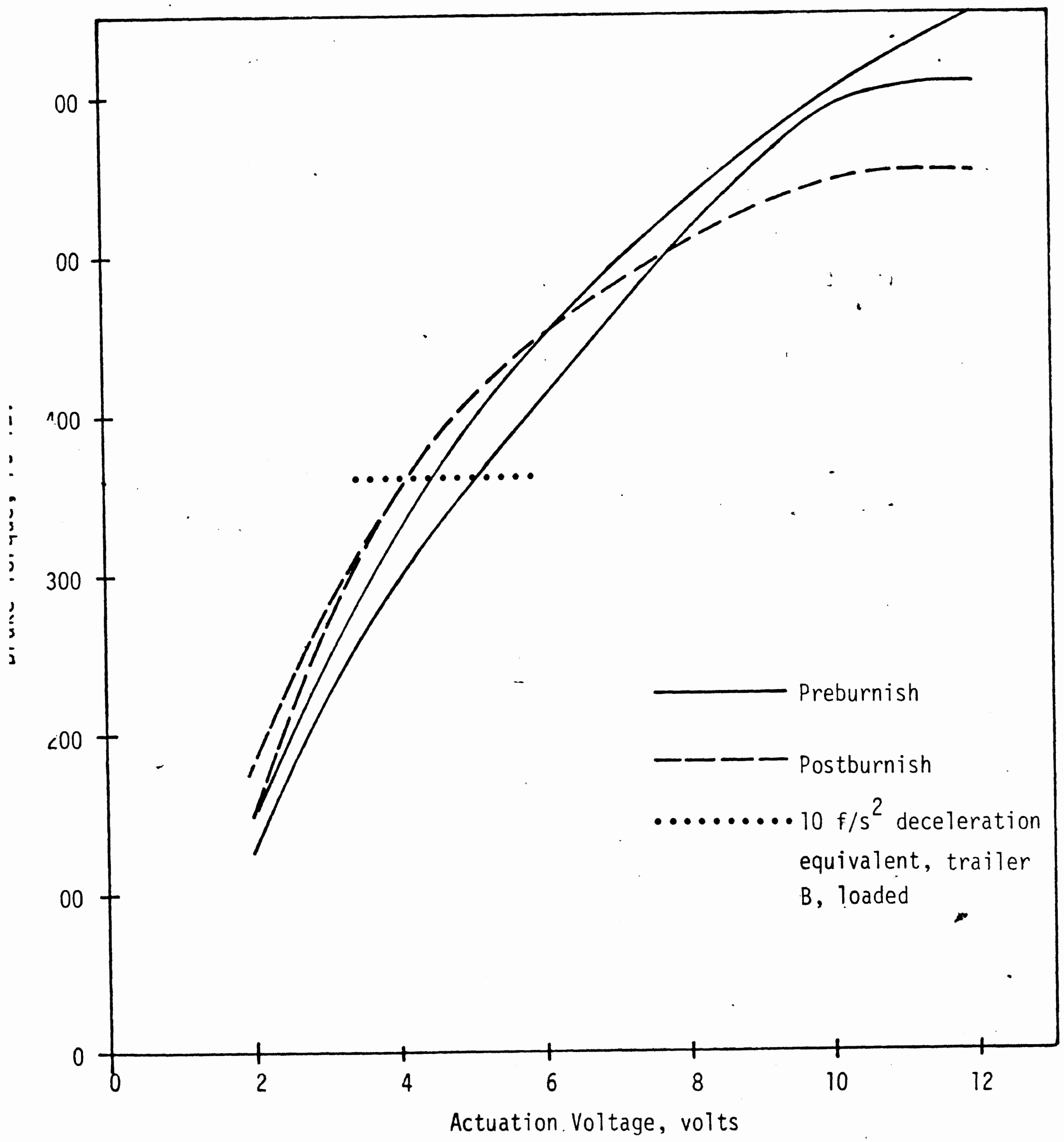

Figure 3.6. Dynamometer test results: Trailer B 10 x 2 electric brakes.

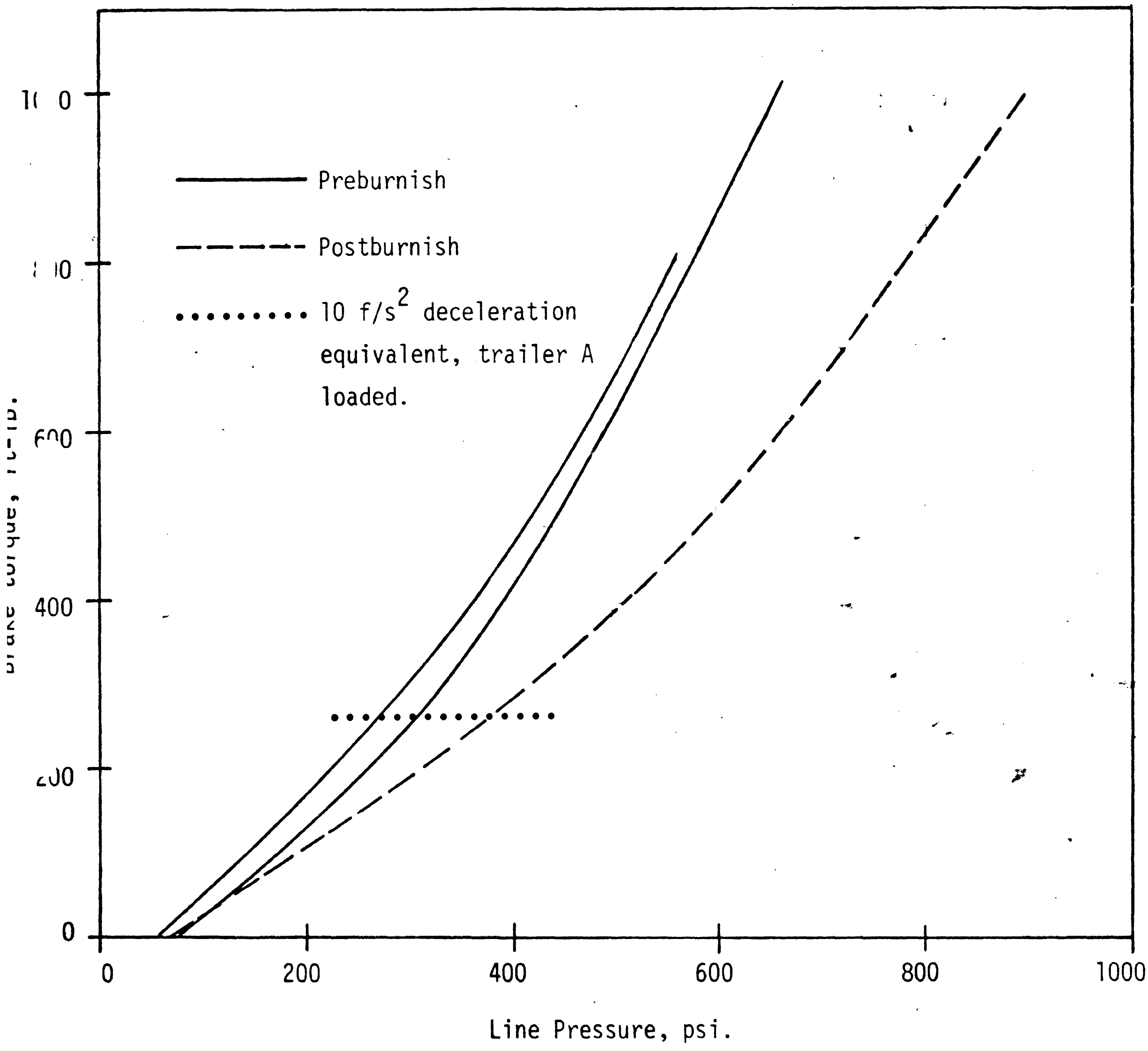

Figure 3.7. Dynamometer test results: Trailer A, 7 x 1-3/4 hydraulic brakes.

the electric brakes were surprisingly low, reaching a maximum of 800 ft-lbs for one 12 x 2 inch brake (Figure 3.4) and falling below 400 ft-lb for another (Figure 3.5).

Results from the hydraulic brake tests were somewhat different from those for electric brakes. As in the case of the electric brakes, burnish appeared to decrease brake effectiveness, where, in this case, the decrease was effected by a distinct change in the brake torque/line pressure gain. But, in both pre- and post-burnish states the maximum brake torque attained 1000 ft-lb.

Evaluating the results of the hydraulic brake tests may be somewhat more difficult than it is in the case of the electric brakes, because the maximum available actuation level is not readily apparent. For electric brakes, the maximum actuation level is determined by the tow vehicle electric system and is well represented as 12 volts. Further, the actuation level may be considered as an independent variable, controlled directly by the driver. For the hydraulic brake system using surge actuation, however, the actuation level is a dependent variable, affected by the weight of tow vehicle and trailer as well as the level of tow vehicle brake force.

The simplified block diagram of Figure 3.8 illustrates the interrelationship of vehicle parameters and trailer brake actuation level under the conditions of a constant deceleration, no-wheels-locked stop. In order to examine the maximum trailer brake actuation level that might be available, consider the trailer subsystem alone and assume a maximum deceleration level of 32.2 ft/sec^2. This acceleration level implies a total trailer retarding force * equal to the trailer weight. Using this retarding force, the parameters of the loaded trailer A as used in the vehicle test program, and the dynamometer curves of Figure 3.7, it can be shown that the maximum line pressure would be approximately 680 psi using post-burnish effectiveness curves or 520 psi using the lower of the two pre-burnish effectiveness curves.

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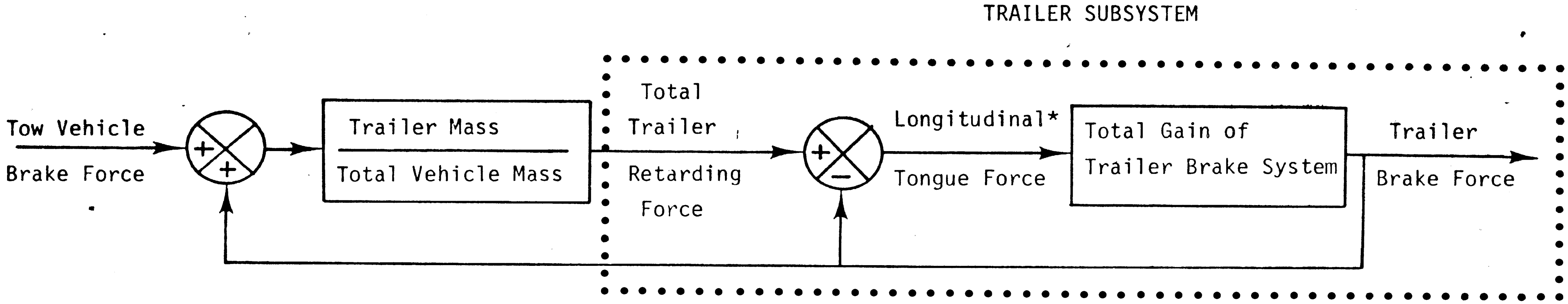
*That is, brake force plus compressive longitudinal hitch force.



*The longitudinal tongue force is the trailer brake system actuation force.

Figure 3.8. Block diagram of combination vehicle with surge trailer braking.

Given these pressures, the maximum available brake torque for this brake system ranges from 700 ft-lb in the pre-burnish state to 620 ft-lb post-burnish. However, these values apply only to the given vehicle/brake/applicator system under the assumed conditions expressed above.

Actuation System Tests

Brake system parameter testing also included an examination of the brake application devices to be used in the vehicle test program. This included the Bendix "Sur Act III" surge hitch used on Trailer A and a Kelsey-Hayes No. 81740 electric brake controller which was used to apply the trailer brakes on the other four trailers. Trailer A was delivered with the surge hitch, and the Kelsey-Hayes controller was chosen because of its high market penetration.

Figure 3.9 is a simplified cut-away drawing of the surge hitch. In this device, compressive longitudinal hitch forces are transmitted to the master cylinder and are thus used to apply the trailer brakes. The spring and shock absorbers are serial elements which enhance dynamic performance by preventing "chugging" between tow vehicle and trailer, but they have no effect on steady-state performance. The desired gain of the surge hitch (K_{SH}), i.e., the relationship between hitch force and output fluid pressure, is therefore determined by master cylinder area. However, Coulomb friction between the sliding torque and the bearing pads also affects steady-state performance.

Parameters measured for the surge hitch were those affecting steady-state performance, viz., master cylinder area and Coulomb friction coefficient of the bearings. Master cylinder area was determined to be one in^2. The friction coefficient was determined by experiment based on the model of Figure 3.10. In this procedure, the master cylinder was removed from the hitch such that the only resistance to motion of the sliding tongue derived from

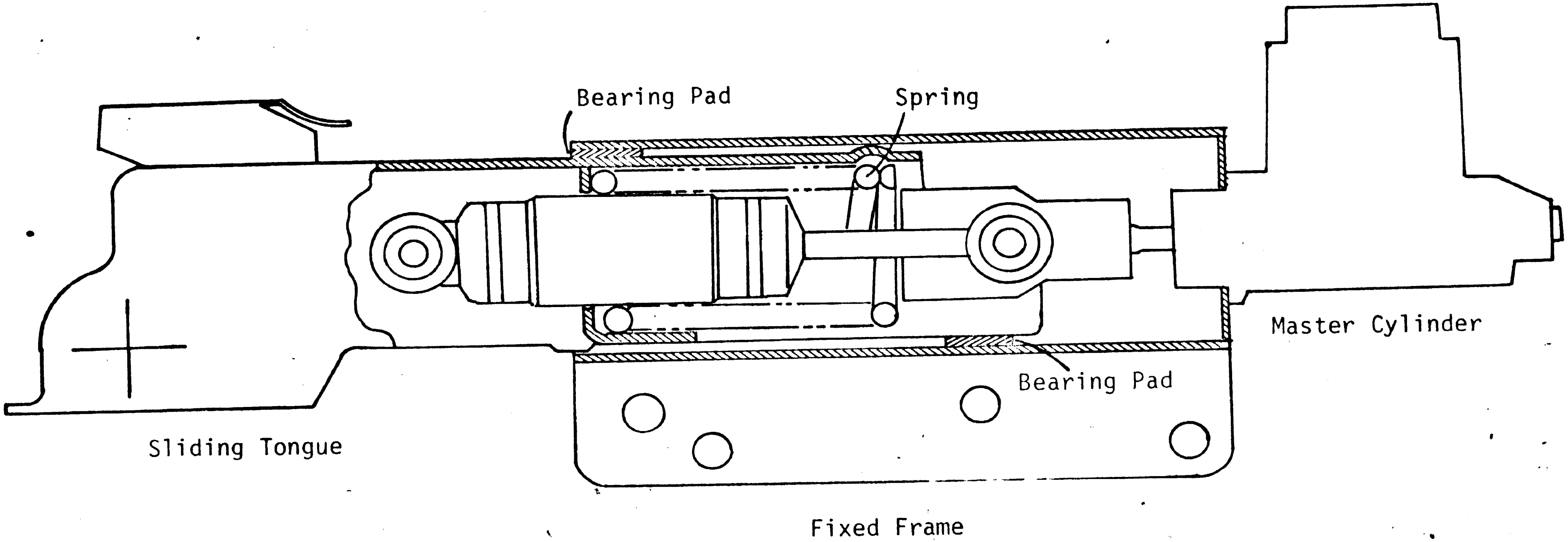


Figure 3.9. Surge Hitch Cutaway Drawing

$$\mu' = \frac{F_x}{F_z} = 0.54 \qquad \mu = \frac{F_{f1}}{F_{n1}} = \frac{F_{f2}}{F_{n2}} = 0.14$$

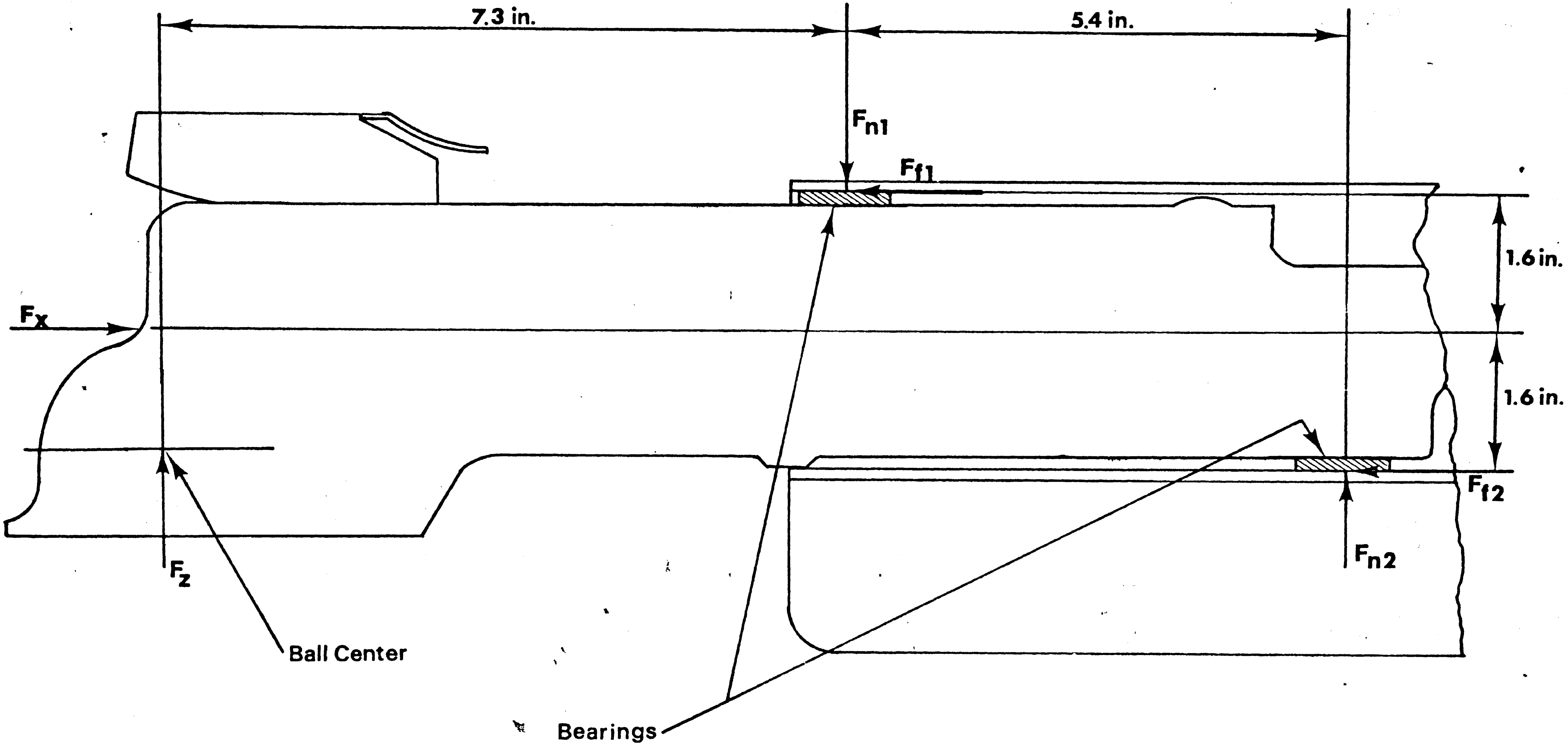


Figure 3.10. Surge hitch friction test.

the friction forces (F_{f1} and F_{f2}). A constant F_z force (as shown in the figure) was applied, followed by the application of sufficient F_x to produce motion of the tongue. Repeat tests were conducted at various levels of F_z commensurate with the tongue load range expected for trailer A. The results indicated an apparent friction coefficient ($\mu' = F_x/F_z$) of $\mu' = 0.54$, which reduces to a bearing friction coefficient ($\mu \equiv F_{f1}/F_{n1} = F_{f2}/F_{n2}$) of $\mu = 0.14$, according to the following analysis.

Summing the forces in Figure 3.10 in the vertical and horizontal directions, respectively, yields:

$$F_z - F_{n1} + F_{n2} = 0 \tag{3.1}$$

$$F_x - F_{f1} - F_{f2} = 0 \tag{3.2}$$

Summing moments about the point of intersection of the lines of action of F_x and F_{n1} yields:

$$1.6F_{f1} - 1.6F_{f2} + 5.4F_{n2} - 7.3F_z = 0 \tag{3.3}$$

For impending slip,

$$F_{f1} = \mu F_{n1} \tag{3.4}$$

$$F_{f2} = \mu F_{n2} \tag{3.5}$$

$$F_x = \mu' F_z \tag{3.6}$$

From Equations (3.1), (3.4), (3.5), and (3.6) and from (3.2), (3.4), (3.5), and (3.6) the following expressions obtain:

$$F_{n1} = \frac{\mu + \mu'}{2\mu} \qquad (3.7)$$

$$F_{n2} = \frac{\mu - \mu'}{2\mu} F_z \qquad (3.8)$$

Substituting (3.7) and (3.8) into (3.3) and solving for μ yields:

$$\mu = \frac{10 \pm \sqrt{100 - 17.28\mu'}}{3.2} \qquad (3.9)$$

where the negative sign corresponds to the desired solution. (The positive sign yields a negative value for the normal force F_{n2}.)

The electric brake control system is illustrated, functionally, in the schematic diagram of Figure 3.11. A parameter

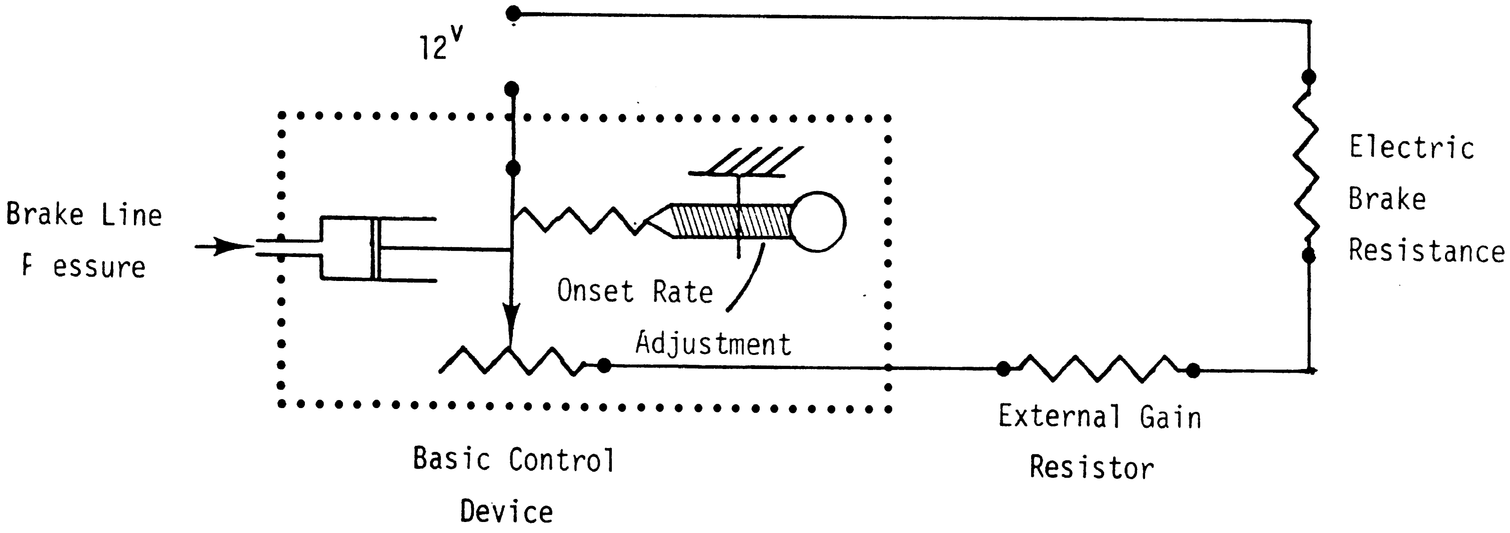


Figure 3.11. Electric brake control system schematic.

measurement activity was undertaken to establish the line pressure/resistance relationship of the Kelsey-Hayes controller used for the electric trailer brakes throughout this project. The range of results obtained over the full range of onset rate adjustment is shown in Figure 3.12. The segmented character of the measured results is indicative of the low resolution of the controller. Note that segments of very high slope will lead to extremely rapid changes in trailer braking with tow vehicle line pressure, and horizontal segments indicate areas of little or no change in trailer braking with changes in tow vehicle line pressure.

3.1.3 Trailer Chassis Parameter Testing. The final category of parameter measurements were those of the trailer chassis. Included in this category were geometric measurements (wheelbase, etc.), pitch plane inertial properties (center of gravity position, weight, and moment of inertia in the empty condition), and vertical suspension deflection characteristics.

Inertial properties were measured using the HSRI Pitch Plane Inertial Properties Measurement Facility. This device is pictured in Figure 3.13 with testing on trailer C in progress. The results derived for the five test trailers appear in Table 3.4. The probable error estimates indicated in the table derive from an error analysis of the test procedure and are based on the expected accuracy of the instrumentation and of various geometric and inertial properties of the test facility.

In measuring suspension properties, two different setups were used. The first two trailers (A and C) were tested using temporarily constructed equipment as shown in Figure 3.14. Later in the program, a permanent suspension test facility was completed and used for testing of the remaining three trailers. Figure 3.15 shows trailer E being tested on this facility.

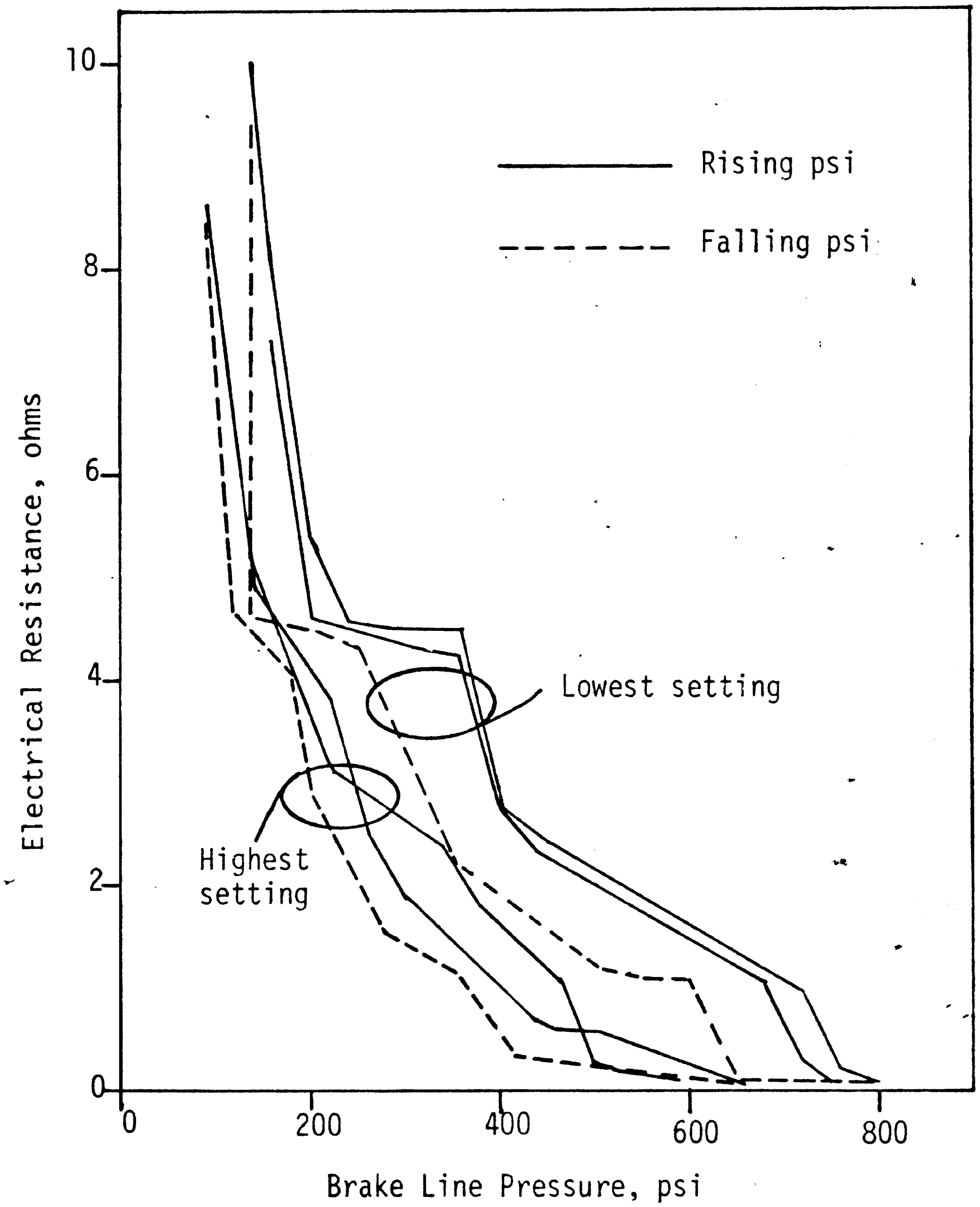


Figure 3.12. Electric Brake Controller Properties

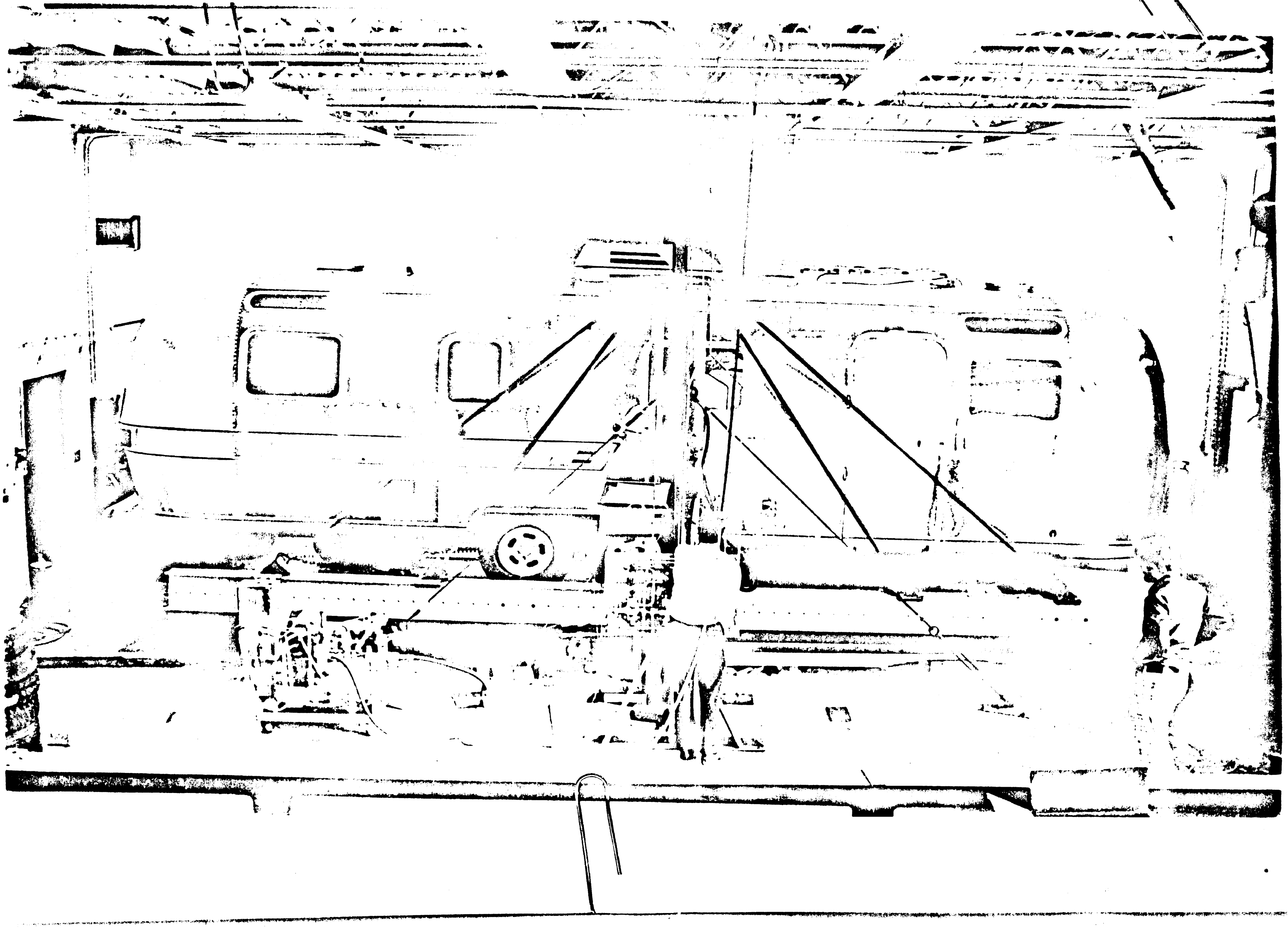
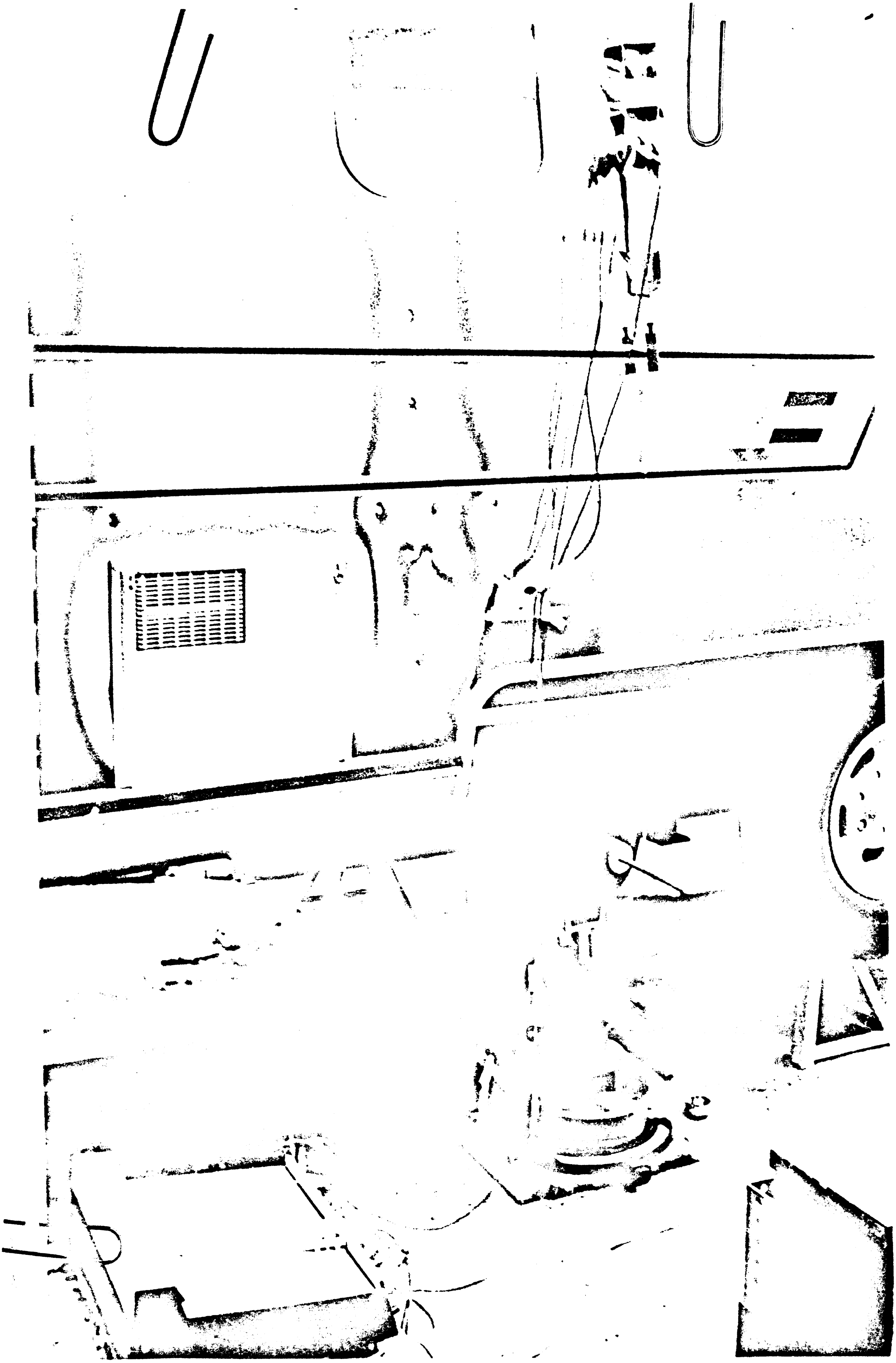
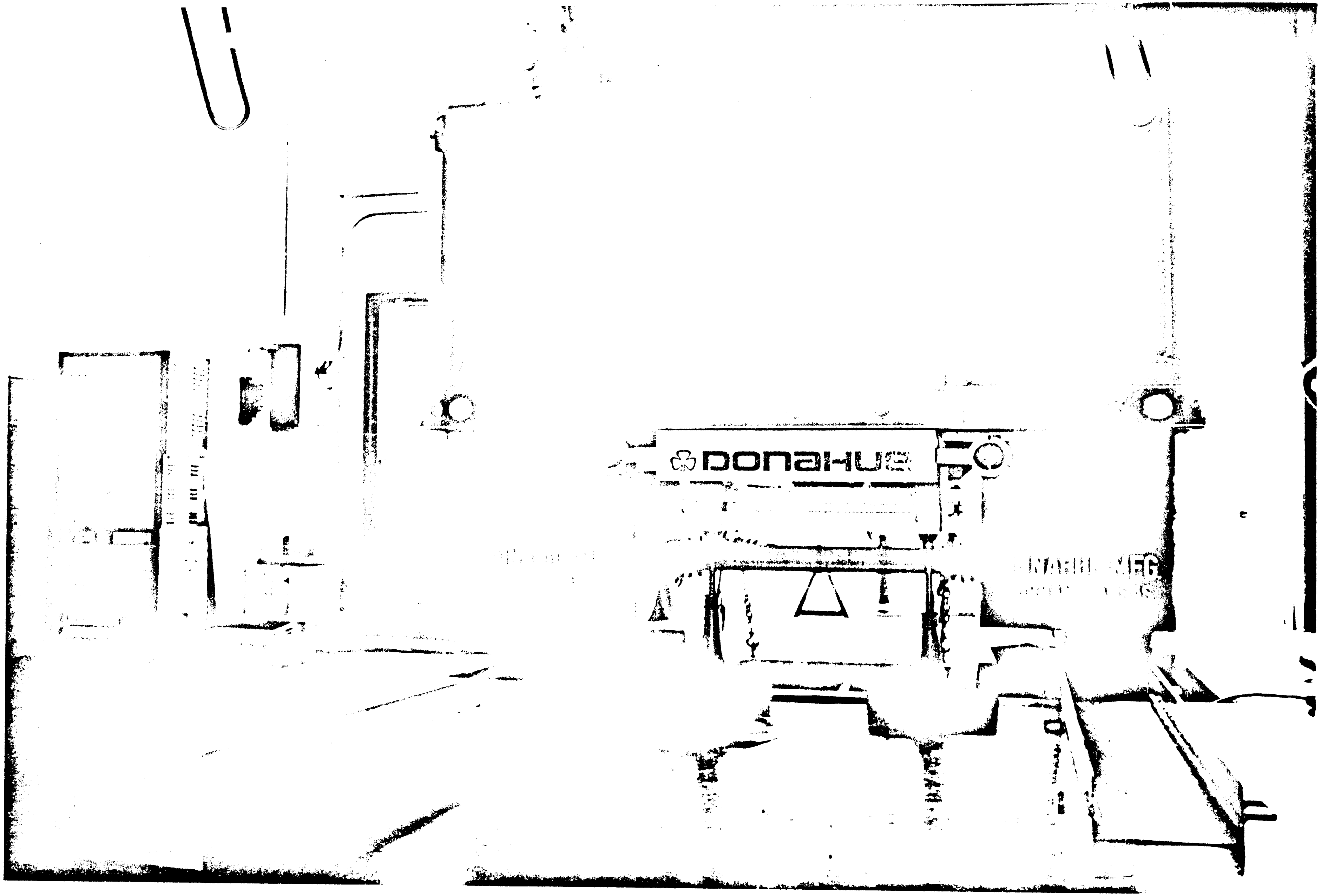


Table 3.4. Pitch Plane Inertial Properties of the Trailers.

	Trailer A	Trailer B	Trailer C	Trailer D	Trailer E
Center of Gravity Postion (Inches)					
Forward of Suspension Center	15.5 0.5	15.7 0.4	21.2 0.3	57.3 0.3	34.8 0.3
Above Ground Level	28.1 ± 1.0	38.9 ± 0.6	42.4 ± 1.5	49.9 ± 0.7	34.9 ± 0.8
Pitch Moment of Inertia About c.g. (in-lb-sec^2)	7800 ±1300	40,700 ±1,500	123,400 ±7,200	253,300 ±6,700	79,200 ±2,500

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Suspension testing varied somewhat, depending on the configuration of the particular trailer suspension. The differences in testing depended on whether the vehicle was equipped with single-axle, multiple-independent-axle, or multiple-tandem-axle suspensions. The different procedures used are reflected in the coordinates used for the plotting of the resultant data. The data are displayed in Figures 3.16 through 3.20.

Later, in the discussion of the vehicle tests, it will become evident that, in some cases, suspension properties had a significant effect on braking performance through the mechanism by which they distribute vertical load among the axles of multiple-axle trailer suspensions. Thus, brief consideration to the load distribution properties of the multiple-axle trailer suspensions used in the program will be given here.

Trailers B and D were equipped with four leaf spring and walking beam tandem suspensions, respectively. Each of these suspension types have geometric properties that distribute the static suspension load nearly equally between the two axles.

Trailer C was equipped with two independently-suspended axles. Thus, the distribution of static suspension load between axles is dependent on the pitch attitude of the vehicle. To examine the sensitivity of load distribution to pitch angle for trailer C, the model of Figure 3.21 will be used. In the model, a total axle spring rate of 1330 lb/in approximates the suspension data shown in Figure 3.18. The total axle tire spring rate of 3570 lb/in (1785 lb/in per tire) is taken from tests made on the trailer C tire. The axle spread is shown to be 33 inches. The model yields a sensitivity for small angles of

$$\frac{\Delta F}{\theta} = 280 \text{ lb/deg}$$

That is, for one degree change in pitch angle, 280 lb. will transfer from one axle to the other when total suspension load is held constant. Using the wheelbase of the trailer to convert this sensitivity to a function of hitch height variation (ΔH) yields $\Delta F/\Delta H = 110$ lb/in.

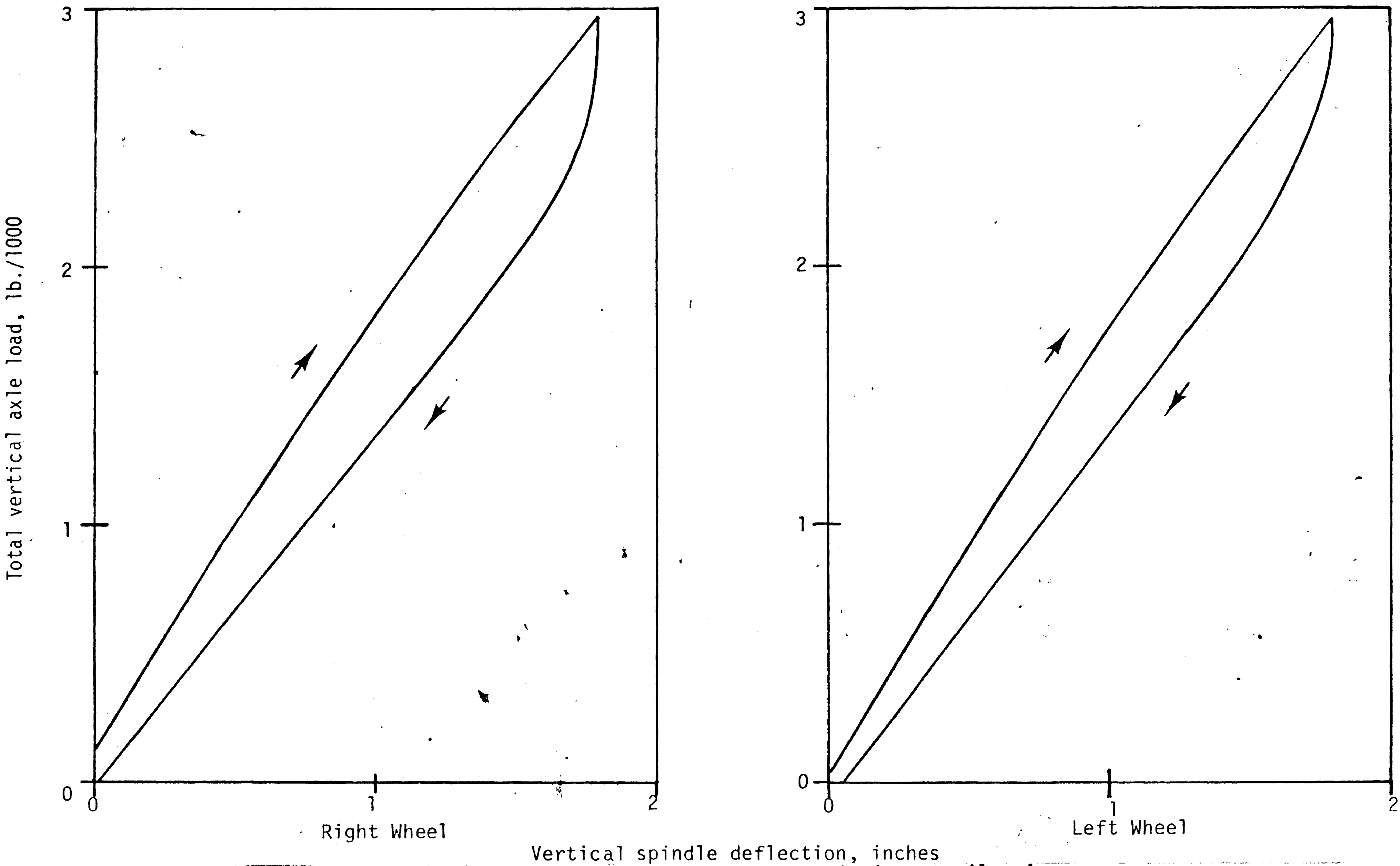

Figure 3.16. Vertical suspension deflection characteristics: trailer A

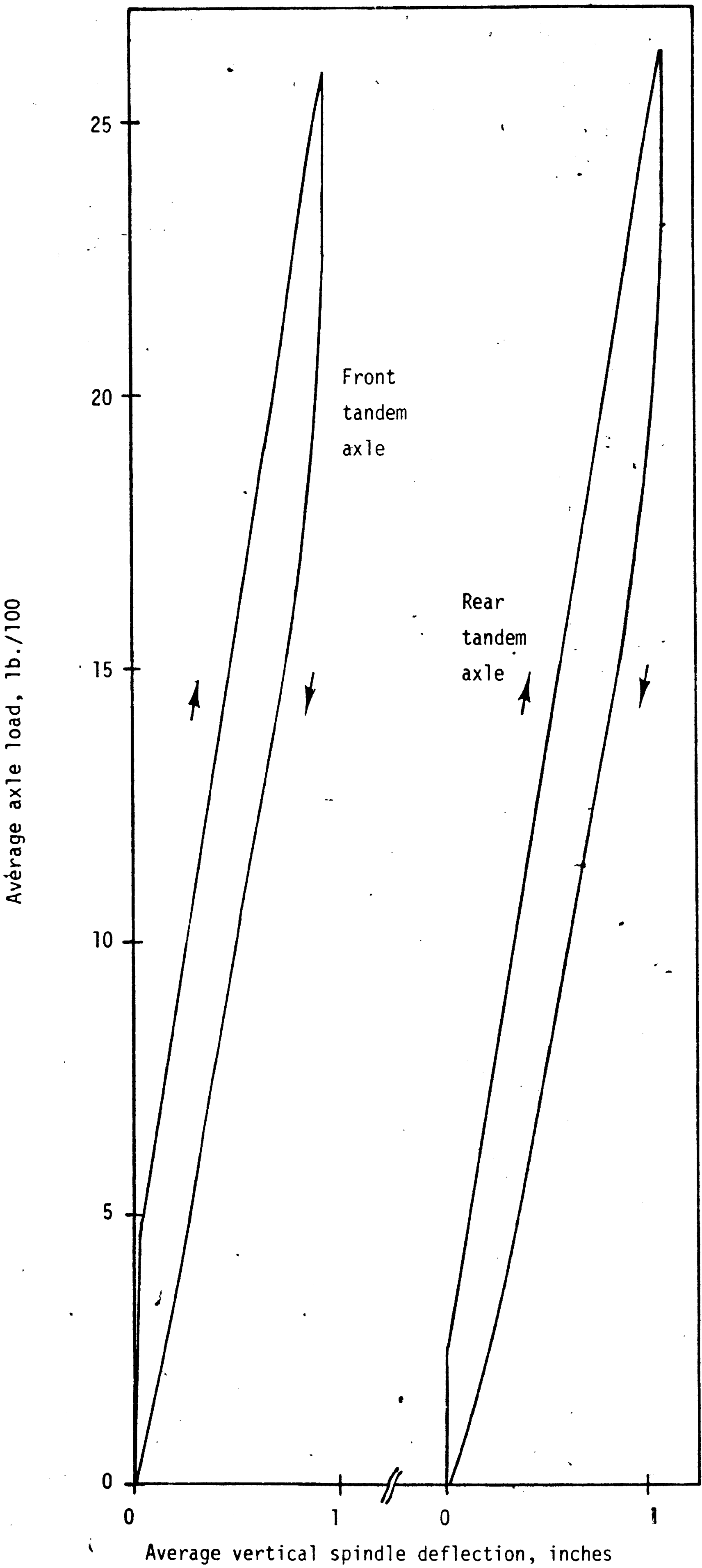

Figure 3.17. Vertical suspension deflection characteristics: trailer B

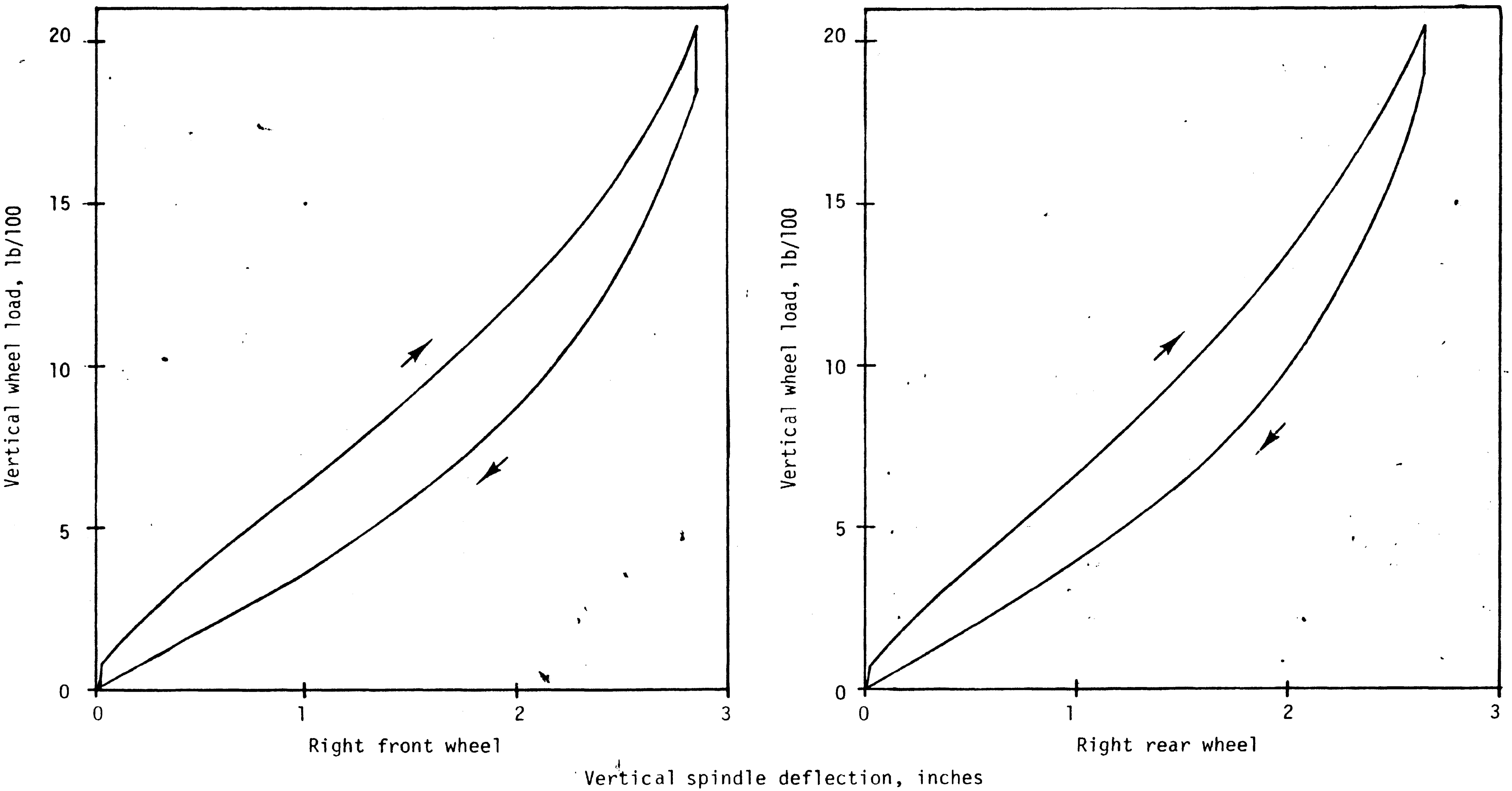

Figure 3.18. Vertical suspension deflection characteristics: trailer C, two of four independently suspended wheels.

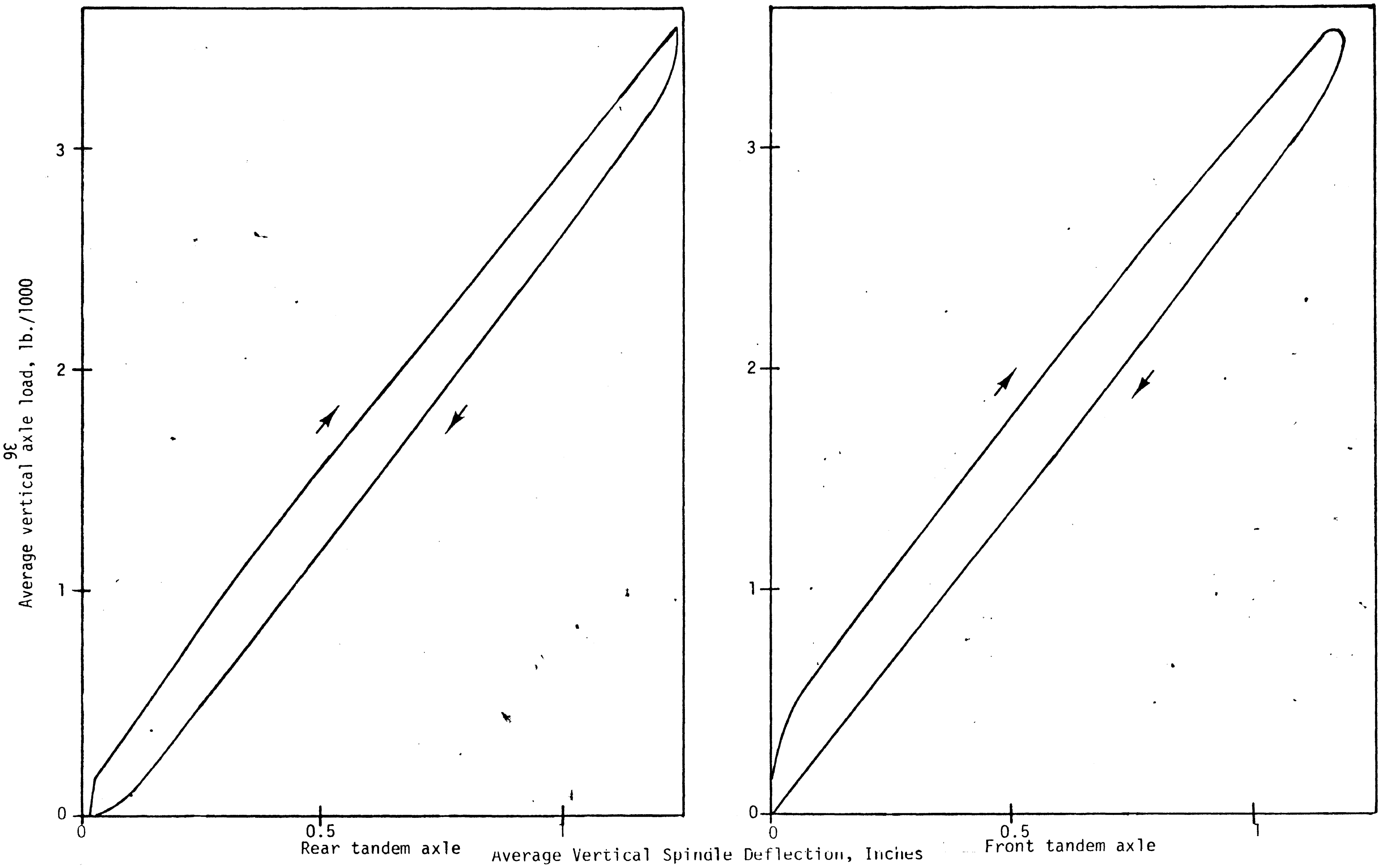

Figure 3.19. Vertical suspension deflection characteristics: trailer D

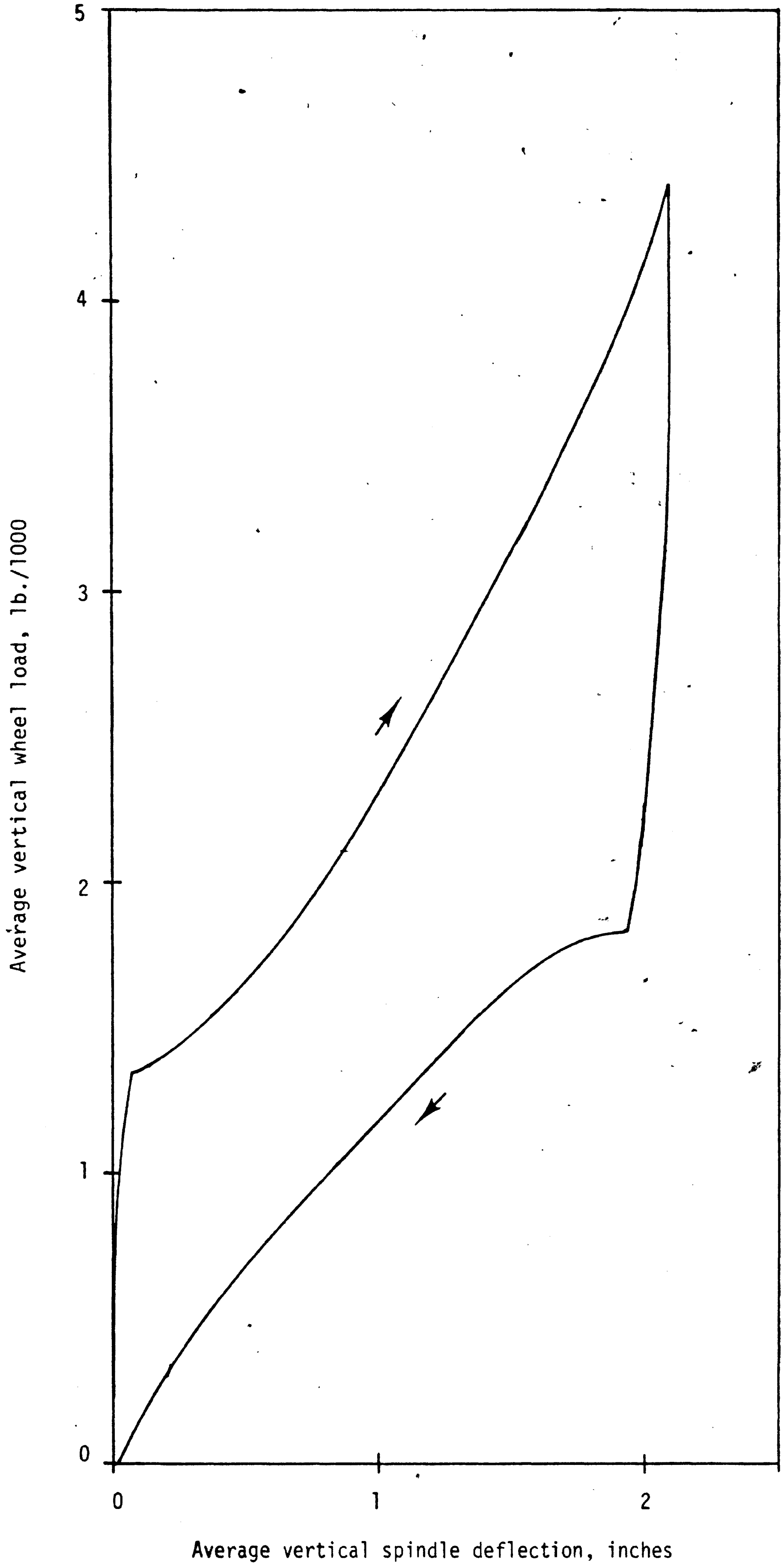

Figure 3.20. Vertical suspension deflection characteristics: trailer E, center axle of three independent axles.

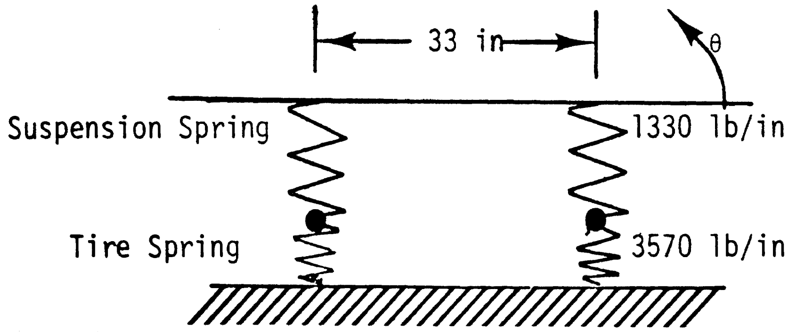

Figure 3.21. Independently suspended two-axle suspension model.

A similar analysis for the three independent-axle suspension of trailer E can be performed. In this case, assuming constant suspension load, load is transferred from the leading to the trailing axle (or vice-versa) while the center axle load remains constant. For this vehicle the sensitivities calculated are:

$$\frac{\Delta F}{\Delta \theta} = 1320 \text{ lb/deg}$$

$$\frac{\Delta F}{\Delta H} = 350 \text{ lb/in}$$

Suspension loads can also be affected during braking both by interaxle load transfer resulting from the application of brake torque and by the effects of Coulomb friction in the suspension. The independent suspensions of trailers C and E preclude inter-axle load transfer due to the application of brake torque, while the geometry of the tandem suspension of trailers B and D result in transfer due to brake torque.

For trailer B, the four spring suspension results in load transfer off the leading axle onto the trailing axle under the actions of brake torque [2]. The opposite is true of trailer D, whose walking beam suspension transfers load from the trailing axle to the leading axle during braking [3].

Coulomb friction, as indicated by the suspension data of Figures 3.16 through 3.20, is fairly low for four of the trailers. On a per axle basis, at rated load, this parameter ranges from about 175 lb. for trailer D to 300 lb. for trailer B. However, for trailer E, Coulomb friction was found to be about 1800 lb. per axle at rated load.

3.1.4 Load Equalizing Hitches. Parameter measurements were not undertaken directly on load equalization hardware, but rather, in conjunction with the vehicle test program, measurements were taken of the resultant effect (on axle loads) of the use of such hitches. In practice, this is a more informative and an easier measurement. However, it is convenient to examine the purpose and nature of load equalization hardware at this point.

The hitch position in a passenger car/trailer combination vehicle is generally far aft of the tow vehicle rear axle. Thus, the imposition of the trailer's vertical tongue load onto the tow vehicle at the hitch position can cause appreciable unloading of the car's front axle accompanied by loading of the rear axle. The distance from the rear wheels of passenger cars to the location of the trailer hitch is typically about half the wheelbase of the car. Using this estimate we can calculate the effect of hitch loading on the loads on the car tires.

Consider Figure 3.22. Summing moments at the front wheels yields

$$\mathrm{FZR} \cdot \mathrm{WB} = \mathrm{W} \cdot \mathrm{A} + \mathrm{FZH} \cdot \frac{3}{2}\,\mathrm{WB} \qquad (3.10)$$

But the static load on the rear tires is W · A/WB, so that

$$\mathrm{FZR} = \mathrm{FZR}_{\mathrm{static}} + \frac{3}{2}\,\mathrm{FZH} \qquad (3.11)$$

and the sum of the vertical loads yields

$$\mathrm{FZF} = \mathrm{FZF}_{\mathrm{static}} - \frac{1}{2}\,\mathrm{FZH} \qquad (3.12)$$

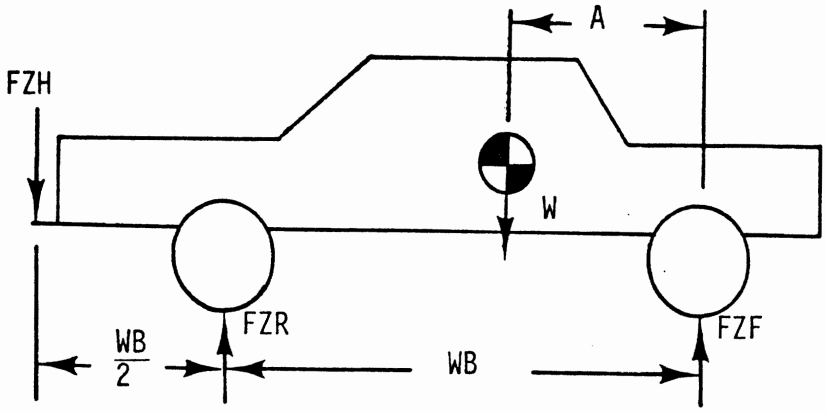

Figure 3.22. Schematic diagram, tow vehicle with hitch load.

In short, on this typical car, the front axle load is reduced by half of the hitch load and one and one-half times the hitch load is added to the rear axle load. Since the relative distribution of vertical load between the front and rear axles is a first-order determinant of tow vehicle braking performance, this redistribution of loads can be a significant problem.

A more readily apparent problem (to the motorist) regards the resulting static trim condition of the car. If the total rear spring rate is KR and the total front spring rate is KF, the front and rear deflections of the suspensions due to the hitch loads are

$$\delta F = \frac{FZH}{2KF} \tag{3.13}$$

$$\delta R = -\frac{3}{2}\,\frac{FZH}{KR} \tag{3.14}$$

where the negative sign indicates compression.

These deflections can be rather formidable, easily on the order of three inches rear and one inch front. This leaves the typical car with a cosmetic problem, in the form of a readily noticeable pitch angle, and a ride problem in that the rear suspension is likely to bottom out on the compression stops.

It is common practice to deal with this situation in either of two ways, viz., (a) the rear suspension trim position can be altered, e.g., with "air shocks," or (b) a "load equalizing hitch" can be used.

The "air shocks" alter the trim position by "expanding" the rear suspension and thus raising the rear end of the car. This is accomplished without change in the hitch load or the loads under the tires and is thus ineffective for dealing with the braking performance problem.

The more common methodology is the use of the load equalizing hitch, which is a spring bar assembly permitting application of a moment through the coupler. Figure 3.23 is a photograph of the hitch assembly just prior to connection of tow vehicle and trailer. Figure 3.24 illustrates the mechanism by which the "load equalization moment" is attained. By adjusting the amount of preset flexture of the spring bar (by the choice of the chain link used at the attachment point between chain and trailer), the amount of moment developed by the hitch is determined.

The moment applied by the hitch is shown in Figure 3.25. Note that the hitch load is now $\overline{FZH}$ rather than FZH as in Figure 3.22. The axle loads are now

$$FZR = FZR_{static} + \frac{3\overline{FZH}}{2} - \frac{M}{WB} \qquad (3.15a)$$

$$FZF = FZF_{static} - \frac{1}{2}\overline{FZH} + \frac{M}{WB} \qquad (3.15b)$$

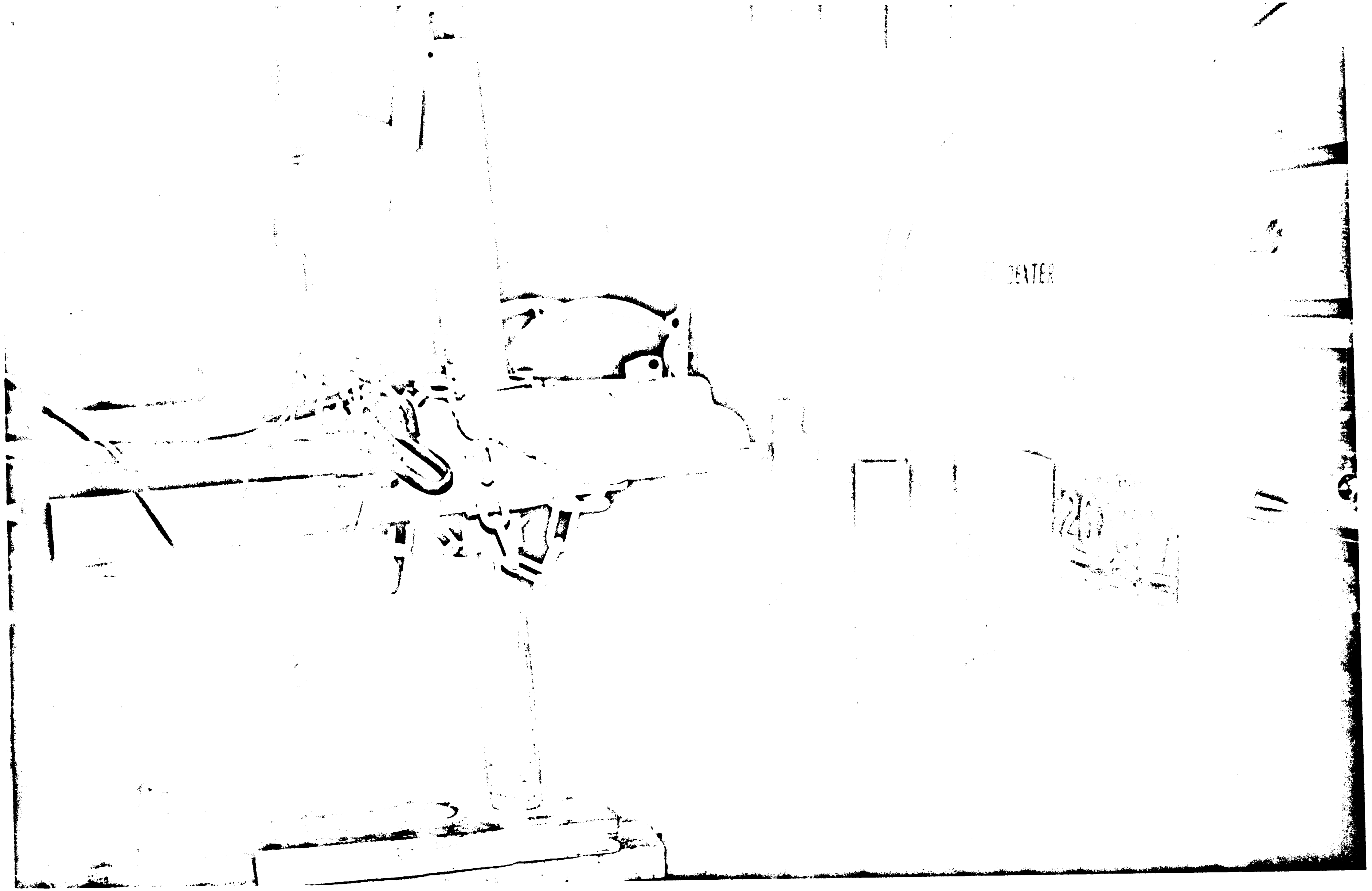

Figure 3.23. Hitch assembly prior to connection of tow vehicle and trailer.

The amount of load equalization is adjusted by the selection of chain attachment link.

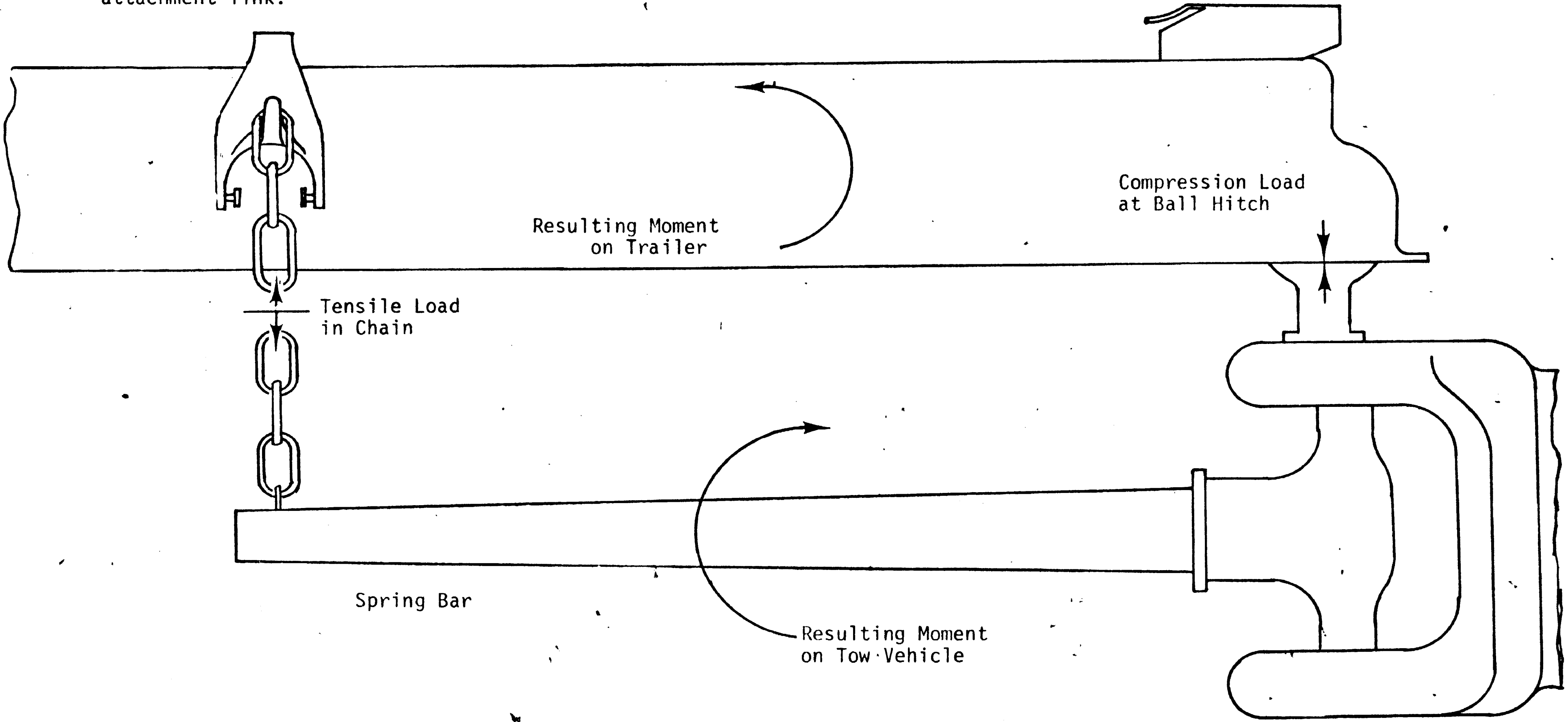

Figure 3.24. The load equalizing trailer hitch.

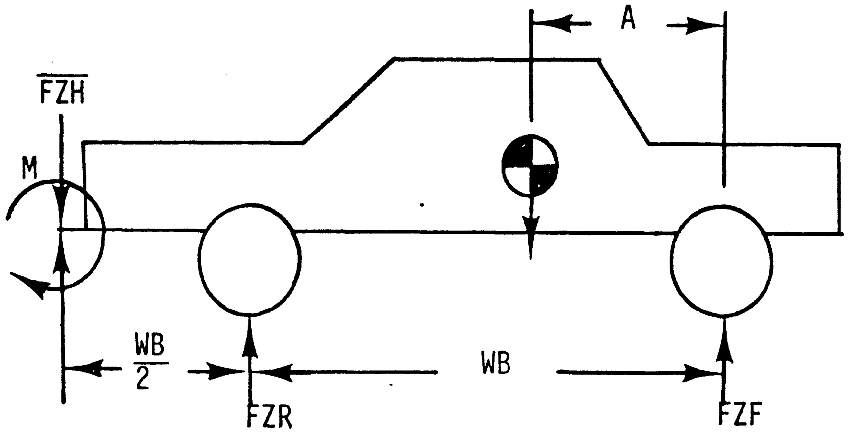

Figure 3.25. Schematic diagram, tow vehicle with load equalization.

Clearly, the moment applied by the load equalizing hitch aids in the solution of both the static trim and brake performance problems by unloading the rear axle and loading the front axle. A further benefit, at least as far as the reattainment of a reasonable trim, is that $\overline{FZH}$ drops with M. This can be shown by the trailer free-body diagram of Figure 3.26.

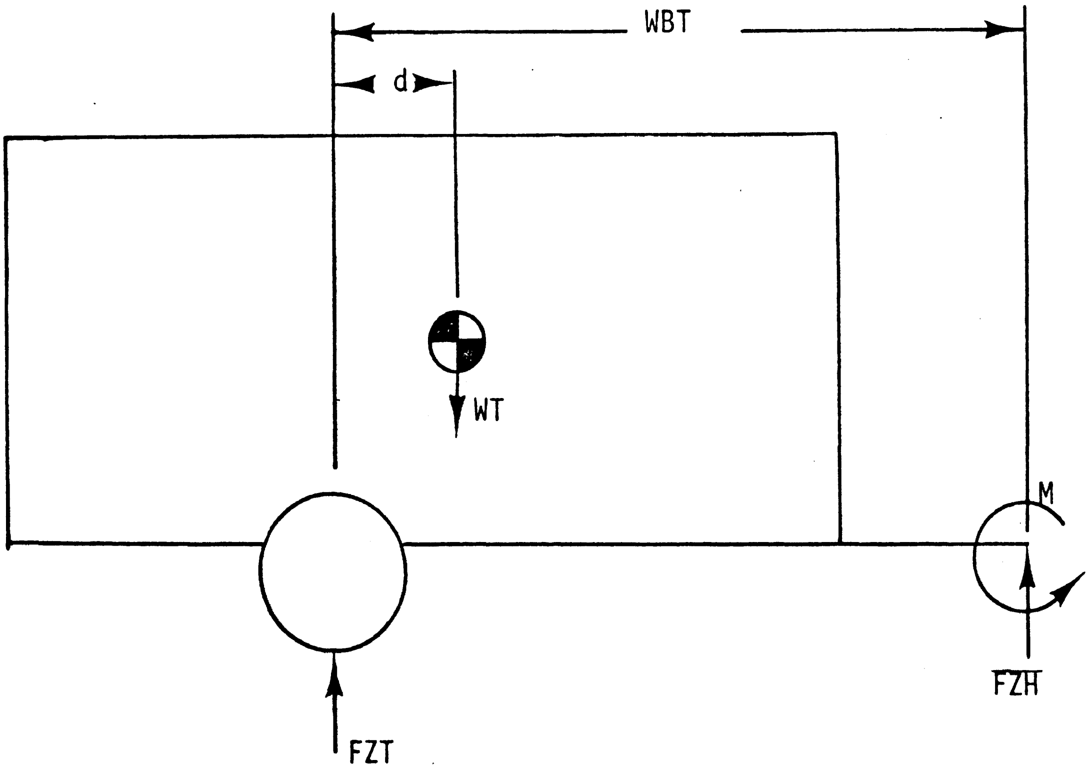

Figure 3.26. Schematic diagram, trailer with load equalization.

The moment sum at the rear wheels yields

$$\overline{FZH} \cdot WBT = WT \cdot d - M \qquad (3.16)$$

Since the hitch load with no equalization is $WT \cdot d/WBT = FZH$,

$$\overline{FZH} = FZH - \frac{M}{WBT} \qquad (3.17)$$

Use of a load equalizing hitch results in an increase in load on the trailer wheels, viz.,

$$FZT = FZT_{static} + \frac{M}{WBT} \qquad (3.18)$$

In summary, Equations (3.15), (3.17), and (3.18) indicate that the load equalizing hitch results in a smaller hitch load, added load on the tow vehicle front axle, decreased load on the tow vehicle rear axle, and increased load on the trailer axle.

It is important to reemphasize that load equalizing hitches and air shocks do not have the same effect on braking performance. Air shocks do not alter the normal load under the tires, thus from Equations (3.11) and (3.12) it is obvious that the hitch load can significantly unload the front tires and load the rear tires. A load equalizing hitch, on the other hand, improves braking performance of car-trailer combinations by increasing the load on the front wheels of the car and thus postponing front lockup. This is not to say that extreme load redistribution cannot degrade braking performance, but for the car-trailer combinations tested, calculations indicate that reasonable use of load equalizing hitches can lead to improved wheels-unlocked stopping capability.

3.2 Vehicle Testing

A detailed explanation of the test procedure used in this study is presented in Appendix B of this report. However, before proceeding to discussion of test results, a brief overview of the test program and its procedures will be presented.

The vehicle testing portion of this study was conducted at the Bendix Automotive Development Center (BADC), New Carlisle, Indiana. The program was structured to examine basic questions addressing combination vehicle braking performance, viz.,

1) What is the braking capability of the tow vehicle alone?
2) What is the inherent braking capability of the trailer alone?
3) What penalty or burden in stopping capability derives from uniting the towing and trailing vehicles into a combination vehicle?

Three distinct test sequences were employed to probe these questions. These were:

1) Tow vehicle alone effectiveness tests
2) Trailer alone effectiveness tests
3) Combination vehicle effectiveness tests

Additional testing was conducted to examine the fade properties of trailer brakes.

The five tow vehicles and five trailers identified in Table 3.1 were tested. With these ten unit vehicles, five "nominal match" combination vehicles, i.e., 1-A, 2-B, 3-C, 4-D, and 5-E, were defined. These five combinations all conform with manufacturers' recommendations for towing combinations except 5-E which violates the pickup manufacturer's recommendation for gross combination vehicle weight (gcvw). Where load leveling hitches were appropriate for use, their adjustment was according to manufacturers' recommendations,* except in a specific case involving trailer A equipped with surge brakes. In the test program, each unit vehicle was subjected to the appropriate "vehicle alone" effectiveness test. Also, combination vehicle tests were conducted on eight combinations, the five "nominal match" plus three mismatch combinations (1-A with no trailer brakes, 1-B and 2-C).

Most of the effectiveness tests were conducted from an initial velocity of 40 mph. This was done to provide acceptable test safety in the combination vehicle tests, particularly those of the "mismatch" combinations, and to enhance the comparative analysis of the results of the three test series. (A limited number of tests were conducted at 60 mph to examine higher velocity effects.)

Except for the initial velocity, tow vehicle alone effectiveness tests were conducted essentially as prescribed by FMVSS 105-75 with the test vehicle loaded to gvw. Trailer alone effectiveness tests consisted of snubs in which the combination vehicle was decelerated through the application of trailer brakes only. The final velocity of these snubs was determined individually for each vehicle such that the trailer brakes were subjected to an energy absorption level equal to that which they would experience in a full stop of the mass equivalent of the trailer axle static load. In these tests, the trailer was fully loaded and the tow vehicle lightly loaded. Application of trailer brakes was accomplished by specially designed equipment capable of precise application level control.

Combination effectiveness tests were conducted based on the specifications of FMVSS 105-75 subject to the altered initial velocity. The results of these tests were intended to indicate the performance of the combination vehicle system in normal use. Thus, standard consumer-available trailer brake application devices were employed.

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*Loaded CV 3-C required full application of equalizer plus air shock assist to obtain good trim.

In all effectiveness tests, the appropriate brake line pressure or electric trailer brake voltage was held steady during the tests, and the test result was characterized by the deceleration of the test vehicle. This methodology was preferred to measuring stopping distance because wheels-unlocked stopping distance measures are a sensitive function of pressure apply rate, and because the trailer-alone tests required a snub rather than a stop. There are drawbacks to the deceleration measure, however.

Consider Figure 3.27 which displays measured data from one run of the combination vehicle 5-E testing. The line pressure and trailer brake voltage are obviously holding constant, yet the deceleration increases significantly during the run because of a general increase in brake effectiveness. The drop in the compressive loading across the hitch during the latter stages of the run indicates that the trailer brakes are <u>increasing</u> in effectiveness relative to the tow vehicle brakes. These changes perhaps are a result of decreasing spin rate and changes in thermal loading.

A single deceleration characterization of this test requires careful consideration. The procedure followed in reducing the data was to read an "average" value, ignoring the rise time and any low speed transients. Figure 3.27 indicates the value used to characterize the example test.

The following subsections will review the results of the vehicle test program.

3.2.1 Tow Vehicle Alone Tests. The five tow vehicles were tested to determine their maximum wheels-unlocked deceleration on the dry asphalt surface at BADC.

The primary purpose of this test was to define the maximum wheels-unlocked stopping ability of the tow vehicle. This baseline performance will be used as a reference in analyzing the "burden" imposed by the trailer in CV braking. Thus, the vehicle was tested in the loaded condition since this condition

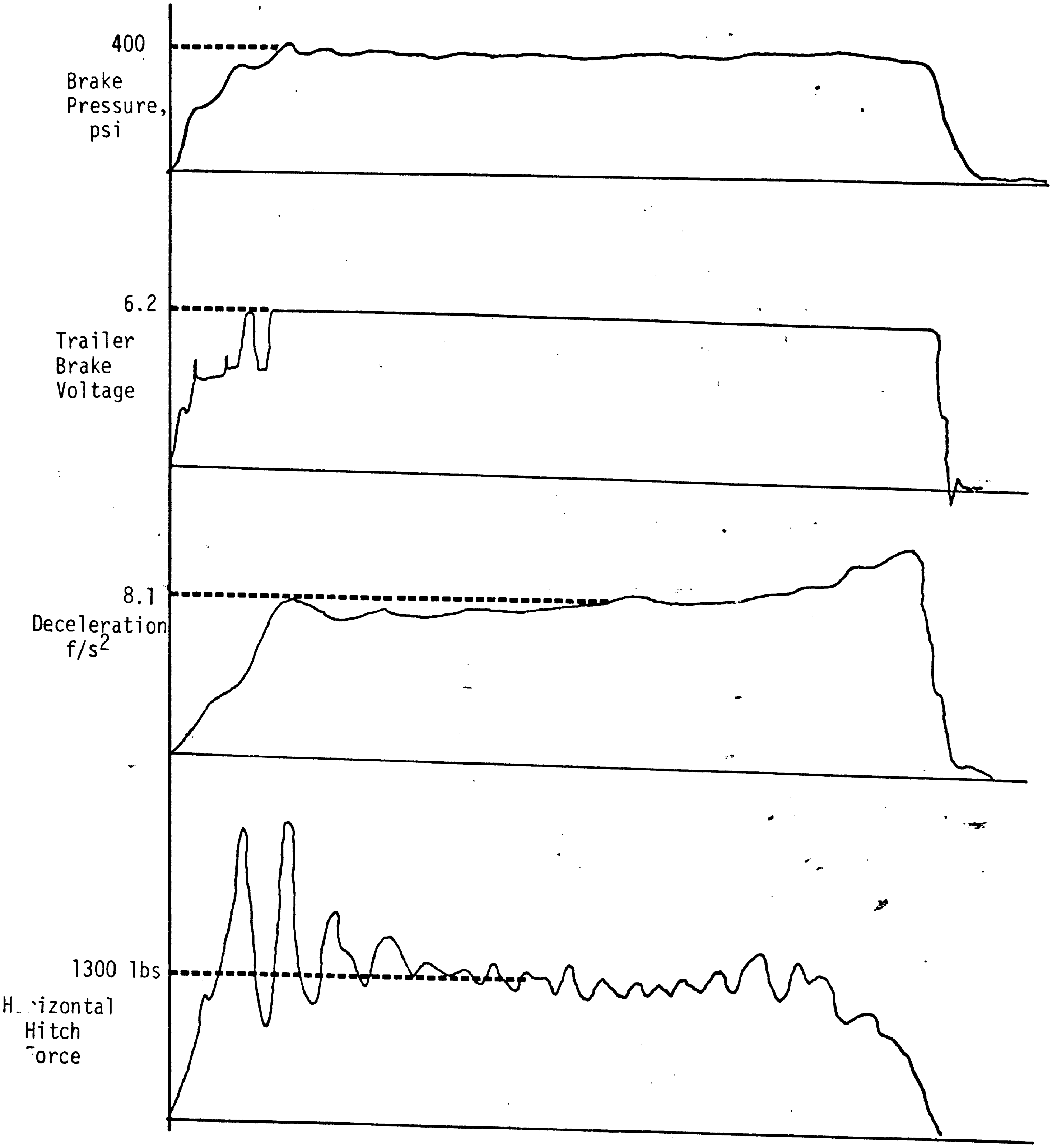

Figure 3.27. A time history of a 5-E CV test vehicle.

was considered as representative of loads commonly carried by CV's on the highway. Forty mph was chosen as the initial velocity to facilitate comparison with CV effectiveness test results. Selected tests were repeated at sixty mph in an attempt to investigate higher speed effects.

The test procedure was as follows:

1) New linings were installed and the brakes were adjusted.
2) A 200-stop burnish was performed as per FMVSS 105-75.
3) The brakes were re-adjusted.
4) Iterative stops were conducted to establish the brake line pressure, P_0, at which maximum wheels-unlocked deceleration occurs.
5) An effectiveness curve was established by conducting additional stops at .8 P_0, .6 P_0, .4 P_0, and .2 P_0.

A summary of the results is presented in Tables 3.5 through 3.9. In each case, effectiveness is listed for the tests from an initial velocity of 40 mph. In addition, results are presented for the 60-mph initial velocity of tow vehicles 1 and 2.

Several facets of these results are of special interest.

1) Four of the test vehicles exhibited remarkable braking performance, surpassing the average deceleration levels now required to meet FMVSS 105-75.
2) The other vehicle, the lighter of the two pickup trucks, exhibited poor wheels-unlocked braking performance resulting from premature rear-wheel lockup. A substantial activity was undertaken

Table 3.5. Tow Vehicle Alone Effectiveness Test Results: Vehicle 1

Brake Line Pressure psi	Deceleration, f/s^2 40 mph test Run #1	40 mph test Run #2	60 mph test Run #1	60 mph test Run #2
160	6.2	6.4	6.4	6.7
320	13.0	13.3	11.5	11.2
440	18.3	19.0	15.4	16.3
590			19.6	18.9
640	24.4	25.5		
720	26.6*	25.5*	21.0*	
760				23.5

*Left front wheel lock

Table 3.6. Tow Vehicle Alone Effectiveness Test Results: Vehicle 2

Brake Line Pressure psi	Deceleration, f/s^2 40 mph Run #1	40 mph Run #2	60 mph
140	3.9	3.4	4.0
320	12.8	12.2	9.0
475	20.2		14.0
620	26.7	29.3	18.3
730	29.3*		22.6
800	29.3*		25.5

*Left front wheel lock

Table 3.7. Tow Vehicle Alone Effectiveness Test Results: Vehicle 3

Brake Line Pressure psi	Deceleration f/s^2 40 mph Run #1	Run #2
130	2.3	3.0
300	8.1	9.2
480	13.9	14.7
580	19.6	19.6
700	25.5*	25.5*

*Rear wheels lock

Table 3.8. Tow Vehicle Alone Effectiveness Test Results: Vehicle 4

Brake Line Pressure psi	Deceleration f/s^2 40 mph Run #1	Run #2
160	3.7	3.7
230	7.5	6.5
280	10.1	10.6
340	12.2*	
360	13.3	14.0
380	14.6*	

*Right rear wheel lock

Table 3.9. Tow Vehicle Alone Effectiveness Test Results: Vehicle 5

Brake Line Pressure psi	Deceleration, f/s^2 40 mph Run #1	Run #2
200	5.0	5.0
390	11.7	11.0
560	17.8	16.8
750	22.6	21.7
850	25.5	
900	25.5*	25.5*

*Left rear wheel lock

to determine the cause of this behavior, but a satisfactory answer was not found. It should be noted that some time following the completion of this study's test program, a brief test series was conducted with this vehicle in which it also surpassed FMVSS 105-75 required deceleration performance.

3) The high decelerations indicate that a substantial amount of braking is being done by the front brakes. (In fact, tow vehicles 1 and 2 exhibited initial front wheel lockup at over two-thirds g.) This factor is of critical importance in the consideration of passenger car CV performances which were invariably limited by front wheel lockup.

3.2.2 Trailer Alone Tests. The term "trailer alone" (TA) as used in this report implies trailer brakes alone. Of course, these tests were conducted with the trailer coupled to a tow vehicle. Each of the five trailers was tested in this fashion on the dry asphalt surface at BADC.

The purpose of the TA effectiveness tests was to determine the trailer's inherent braking capability in its burnished and unburnished conditions. In both pre- and post-burnish effectiveness tests the following procedure was followed:

1) Voltage (for the electric brakes) or line pressure (for the surge brakes) were applied to the trailer brakes by an HSRI controller developed for the TA tests. Incrementally increasing voltage (pressure) levels were applied until wheel lock occurred.*

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*For multiple-axle trailers, it was originally planned to allow one axle of a tandem set to lock and continue until the next axle locked. In practice, this proved untenable due to rapid tire wear on the locked axle.

2) The tests were repeated, again starting at the lowest voltage (pressure) levels and working up to wheel lock.

Most tests were run from an initial velocity of 40 mph. (Selected tests were repeated at 60 mph.) The final velocity was

$$V_f = 40\sqrt{1 - \frac{W_{TA}}{W_{CV}}} \text{ mph} \tag{3.19}$$

where W_{CV} is the weight of the combination vehicle and W_{TA} is the static weight on the trailer axles. Snubs of the combination vehicle from 40 mph to V_f, using the trailer brakes only, resulted in the trailer brakes absorbing energy equivalent to a stop of a vehicle of weight W_{TA} from 40 mph. In these tests the trailer was fully loaded and the tow vehicle lightly loaded.

The trailer burnish procedure was modeled around the burnish prescribed by FMVSS 105-75. The burnish consisted of 200 snub stops from an initial velocity of 40 mph to a final velocity of V_f as prescribed by Equation (3.19) and at a deceleration level of:

$$a = 12\frac{W_{TA}}{W_{CV}} \text{ fps}^2 \tag{3.20}$$

As in the case of the effectiveness tests, V_f was established to provide an appropriate energy absorption level. The deceleration prescribed by Equation (3.20) provided for a trailer brake torque which would decelerate a vehicle of weight W_{TA} at 12 f/s^2. Further details of the test procedures appear in Appendix B.

The pre-burnish and post-burnish trailer-alone test results are summarized in Tables 3.10 through 3.14. In each case the test results include the deceleration of each CV as a function of the voltage (or pressure) applied by the HSRI controller.

Table 3.10. Trailer Alone Effectiveness Test Results: Trailer A, 40 & 60 mph.

	Trailer Brake Line Pressure psi	Deceleration f/s^2	Calculated Total Brake Force, lb	Calculated Total Brake Force from Dyn. Tests, lb
40 mph Pre-Burnish	240	4.0	830	
	260	3.1	650	
	300/300	4.3/4.9	900/1020	
	340	4.5*	940	
	380	5.0*	1040	
	420	5.0*	1040	
40 mph Post-Burnish	180	1.2	250	
	200	1.5	310	
	260/260	1.9/2.5	400/520	380
	340/340	2.5/3.1	520/650	550
	400	4.0	830	700
	420	3.7	770	700
	480	4.7	980	
	500	5.0	1040	930
	520	5.2	1083	
	560	5.6	1170	1100
	600	6.2	1290	1240
	640	5.9	1230	1400
	720	6.8*	1420	1680
	800	6.2**	1290	2050
60 mph Post-Burnish	180/180	1.4/1.2	290/250	
	260	2.8	580	
	340	2.5	520	
	360	3.4	710	
	440	3.7	770	
	520/520	5.0/5.6	1040/1170	
	600	6.2	1290	
	680	6.5/6.5	1350/1350	
	760	6.8*	1420	

*Right Wheel Lock

**Both Wheels Lock

Table 3.11. Trailer Alone Effectiveness Test Results: Trailer B, 40 & 60 mph.

	Trailer Brake Voltage	Deceleration f/s^2	Calculated Total Brake Force, lb	Calculated Total Brake Force from Dyno. Test, lb
40 mph Pre-Burnish	2.4/2.4	5.7/2.9	1740/880	
	4.8/4.8	8.5/7.1	2590/2160	
	7.2/7.2	9.9*/8.5*	3010/2590	
	9.6/9.6	10.7**/9.2*	3260/2800	
	12.0/12.0	11.0**/9.9*	3350/3010	
40 mph Post-Burnish	2.4/2.4	4.2/2.1	1280/640	940
	4.8/4.8	5.7/5.0	1740/1520	1540
	7.2/7.2	7.8/6.4	2370/1950	1880
	9.6/9.6	8.5/7.8	2590/2370	1990
	12.0/12.0	8.5/8.5	2590/2590	2070
60 mph Post-Burnish	2.4	4.3	1310	
	4.8	7.1	2160	
	7.2	8.5	2590	
	9.6	9.9	3010	

*Both lead tandem wheels lock

**Both lead tendem wheels and left rear tandem wheels lock

Table 3.12. Trailer Alone Effectiveness Test Results: Trailer C, 40 mph

	Trailer Brake Voltage	Deceleration f/s^2	Calculated Total Brake Force, lb	Calculated Total Brake Force from Dyno. Test, lb
Pre-Burnish	3.8	1.4	570	
	3.9	1.4	570	
	5.8	3.6	1460	
	5.9	2.5	1010	
	7.8/7.8	5.0/4.3	2030/1740	
	9.7/9.7	7.3*/7.1*	2960/2880	
Post-Burnish	3.9/3.9	2.8/2.1	1130/850	462
	5.8	4.3	1740	980
	5.9	4.3	1740	
	7.8/7.8	6.0/6.4	2430/2590	1560
	9.7/9.7	7.1*/7.1*	2880/2880	2350

*Left lead tandem wheel lock

Table 3.13. Trailer Alone Effectiveness Test Results: Trailer D, 40 mph

	Trailer Brake Voltage	Deceleration f/s^2	Calculated Total Brake Force, lb	Calculated Total Brake Force from Dyno. Tests, lb
Pre-Burnish	2.8/2.8	3.1/2.5	1390/1120	
	4.2/4.2	5.6/5.9	2520/2650	
	5.6/5.6	7.4*/7.4	3330/3330	
	6.5	8.7**	3910	
	7.0	8.7**	3910	
Post-Burnish	2.8	0.9	400	190
	4.2	1.7	760	500
	5.6	2.2	990	680
	7.0/7.0	2.5/2.8	1120/1260	1030
	8.4/8.4	2.8/2.5	1260/1120	1160
	9.8/9.8	3.1/3.3	1390/1480	1220

*Right rear tandem wheel lock

**Right lead tandem and both rear tandem wheels lock

Table 3.14. Trailer Alone Effectiveness Test Results: Trailer E, 40 mph.

	Trailer Brake Voltage	Deceleration f/s^2	Calculated Total Brake Force, lb	Calculated Total Brake Force from Dyno. Tests, lb
Pre-Burnish	4.5	1.9	1510	
	5.0	2.5	1990	
	6.0	3.7	2950	
	6.8	4.7	3750	
	7.0	4.7	3750	
	9.0/9.0	5.9/6.2	4700/4940	
	11.0	7.1*	5660	
	11.3/11.3	7.4*/7.8*	5900/6220	
	12.0	7.8*	6220	
Post-Burnish	3.2/3.2	1.2/1.2	960/960	770
	4.8/4.8	3.1/3.1	2470/2470	960
	6.4/6.4	5.0/4.3	3990/3430	1680
	7.0	4.3	3430	1920
	8.0/8.0	5.9/5.0	4700/3990	2350
	8.5	6.9*	5500	2740

*Left rear wheel lock

Note that for the electric brakes, the table gives voltage across the trailer brakes, and for the surge-braked vehicle, line pressure at the trailer master cylinder is given. In addition to vehicle deceleration, the table gives the calculated total brake force necessary to decelerate the total CV mass at the indicated level. For the post-burnish condition, this figure is compared to the total brake force that the results of the dynamometer test would predict at similar input levels.

Several features of the tables are worth noting.

1) The hydraulic brakes of trailer A were shown by the dynamometer tests to be as effective as the larger electric trailer brakes. The relatively lower maximum values given in the table for the surge brakes indicate wheel lockup limits, not torque limits.

2) The 12" x 2" electric brakes of trailers C and E increased effectiveness slightly with burnish. This trend in the results agrees with the dynamometer tests for trailer E brakes, but not those for trailer C.

3) The 10" x 2" electric brakes of trailer B decreased effectiveness slightly with burnish. This result is generally in agreement with dynamometer test results for this brake.

4) The 12" x 2" electric brakes of trailer D decreased drastically with burnish.* This trend was also apparent in the dynamometer curves.

5) The early lockup of the axle of trailer B in a pre-burnish condition results from interaxle load transfer off the front tandem onto the rear. The trailer D pre-burnish lockup data indicate load transfer from the trailing tandem onto the leading tandem.

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*Note that the maximum brake voltage indicated for post-burnish effectiveness tests is 9.8v, even though wheel lock has not occurred. This voltage was measured at the input to the brake itself while approximately 12v was applied at the input to the trailer wiring harness indicating a voltage drop in the trailer wiring.

In each case, these interaxle load transfers are of the polarity to be expected, given the geometry of the particular suspension. Note that in the post-burnish tests, lockup did not occur because the torque values were not high enough.

6) The occurrence of lock on the left wheel of the lead axle of trailer C is believed to be a result of higher torque generated by this brake. The two axles of trailer C are independent, thus precluding interaxle load transfer. The measured static tire loads of this trailer were quite evenly distributed and the dynamic reactions during deceleration would tend to pitch the trailer forward, thus slightly increasing the load on the lead axle.

7) The occurrence of lockup at the rear axle of trailer E is initially quite surprising considering that the total trailer brake force was approximately 6000 lb, while the total trailer axle load was approximately 18,000 lb. Two factors probably contribute to this premature lockup. First, this trailer was plagued by erratic brake behavior during its burnish indicating wide variance in the effectiveness of individual brakes. With substantial effort, this problem was greatly reduced and burnish successfully completed. However, the presence of some brake imbalance certainly is indicated. Second, the three axles of this trailer suspension are independent, and, in laboratory testing, the suspension was found to have high values of stiffness and Coulomb friction. Although care was taken to provide load and trim conditions resulting in well distributed static wheel loads, these suspension properties combine to provide potential for substantial dynamic load transfer during testing. Thus, it is expected that at the time of lockup the wheels in question were comparatively lightly loaded and experiencing somewhat higher than average brake torque.

8) The level of agreement between brake force calculated from road test results and dynamometer test results varies considerably. (Of course, this comparison is invalid whenever wheel lock occurs in the road test.) Data for trailers A and D compare quite well, while the comparisons get progressively worse for the data from trailers B, C, and E.*

3.2.3 Combination Vehicle Tests. Eight combination vehicle effectiveness tests series were conducted. The subjects of these tests were the five "nominal match" combination vehicles (1-A, 2-B, 3-C, 4-D, 5-E) and three "mismatch" vehicles (1-A with no trailer brakes, 1-B, and 2-C).

The procedure used in conducting the combination vehicle effectiveness tests was:

1) Stops were conducted at low vehicle braking levels of .2 P_0, .4 P_0, .6 P_0, etc., where P_0 was established from the tow vehicle alone tests.

2) This sequence was continued until wheel lockup occurred on the tow vehicle, or an axle locked on the trailer. It was originally planned to proceed past one axle lockup on a multi-axle trailer, but this proved to be largely untenable in practice due to rapid tire wear.

3) Iterations were performed to determine the line pressure for lockup within 50 psi.

4) The entire sequence was repeated.

Tests were conducted with the trailers in both loaded and empty conditions, both with the tow vehicle loaded. Generally, tests were conducted from an initial velocity of 40 mph, although a limited number commenced from 60 mph in order to examine higher

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*Variability in the performance of individual brakes is discussed further in the following technical sections and in the "Conclusions and Recommendations" section of this report.

velocity effects. In general, test conditions (brake temperature, etc.) were controlled as per FMVSS 105-75. Further details appear in Appendix B.

Tables 3.15 through 3.30 summarize the results of the CV tests.

The goal of these tests was to determine the maximum braking performance of these combinations under normal operating conditions. Thus, in conducting these tests, standard consumer-available hardware was used, including trailer brake actuation devices. Whenever possible and reasonable, all manufacturers' usage recommendations were followed. Of most significance here are those recommendations regarding when and how to employ load equalizing hitch equipment and those regarding brake application devices.

For the passenger cars used in this program, and indeed, in general, the manufacturers recommend that load equalizing hitches be employed whenever a trailer weighing more than 2000 lb is towed. This recommendation thus applied to all trailers investigated in this study. The manufacturer of the load equalizing hitches used in this program recommends adjustment of the hitch such that the pitch attitude of the tow vehicle before and after attaching the trailer is the same. (Load equalizing hitches and their operation were covered in some detail in Section 3.1.4.)

Trailer A, as employed in this study, was equipped with hydraulic brakes actuated by the surge hitch mechanism discussed in Section 3.1.2. Largely as a result of the Coulomb friction mechanisms discussed in that Section, the surge hitch used in this study is not compatible with load equalizing hardware, and the manufacturer recommends that load equalizing hardware not be used with this actuator. This incompatibility is not atypical as witnessed by similar findings reported in [4].

Table 3.15. Combination Vehicle Effectiveness Test Results: CV 1-A, Loaded, 40 mph.

	Tow Vehicle Brake Line Pressure psi	Trailer Brake Line Pressure psi	Deceleration f/s^2
Without Load Equalizing	160/160	0/0	3.1/3.6
	320/320	120/120	8.1/9.4
	460/480	240/200	12.4/12.8
	600/600	240/240	17.0/17.0*
	720/700	240/240	17.0*/17.0*
With Load Equalizing	160	0	3.1
	320	0	7.8
	440	120	11.8
	600	160	15.5
	700	160	16.9*

*Tow vehicle left front wheel lock.

Table 3.16. Combination Vehicle Effectiveness Test Results: CV 1-A, Trailer Empty, 40 mph, Without Load Equalizing

Tow Vehicle Brake Line Pressure psi	Trailer Brake Line Pressure psi	Deceleration f/s^2
160/160	0/0	3.6/3.6
320/320	100/100	9.2/8.5
460/440	140/160	12.8/14.2
600/600	180/180	17.0/17.0
720/720	200/200	19.2*/17.8*

*Tow vehicle left front wheel lock

Table 3.17. Combination Vehicle Effectiveness Test Results: CV 1-A, Loaded, 60 mph, Without Load Equalizing.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Line Pressure psi	Deceleration f/s^2
160/160	60/60	3.1/3.6
320/320	160/120	8.5/7.8
440/440	200/200	11.4/11.4
600/600/600	220/220/240	14.2/14.2/14.2
760	260	16.3*

*Tow vehicle left front wheel lock.

Table 3.18. Combination Vehicle Effectiveness Test Results: Mismatch CV 1-A (No Trailer Brakes), Loaded, 40 mph , With Load Equalizing.

Tow Vehicle Brake Line Pressure psi	Deceleration f/s^2
160/160	2.8/3.6
320/320	7.8/7.8
440/480	10.7/12.1
600/600	14.2/14.2
720/720	15.6*/14.2*

*Tow vehicle left front wheel lock

Table 3.19. Combination Vehicle Effectiveness Test Results: CV 2-B, Loaded, 40 mph,

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
140/120	1.8/1.9	3.6/2.8
300/320	3.6/4.3	8.5/9.9
460/480	6.9/7.1	13.5/14.9
600/600	7.1/7.1	17.0/18.5
680/680	7.1/7.1	18.5/19.9
720/720	7.1/7.1	19.2*/18.5*

*Tow vehicle left front wheel lock

Table 3.20. Combination Vehicle Effectiveness Test Results: CV 2-B, Trailer Empty, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
140/160	1.7/1.7	2.8/3.6
300/300	3.3/4.5	10.7/12.1
440/440	4.5/4.5	14.9/14.9*
580/600	6.7/6.7	19.9*/19.9*
720	6.7	24.1*
860	6.9	24.1**
880	6.7	22.7**

*Trailer lead tandem wheels lock

**Tow vehicle front and trailer lead tandem wheels lock

Table 3.21. Combination Vehicle Effectiveness Test Results: CV 2-B, Loaded, 60 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
120	1.3	2.1
320	4.5	11.4
480	6.7	14.2
600	6.7	17.7*
640	6.7	18.0*
680	6.7	19.1**
700	6.7	19.9***

*Trailer left lead tandem wheel lock

**Trailer right lead tandem wheel lock

***Trailer lead tandem wheels lock

Table 3.22. Combination Vehicle Effectiveness Test Results: Mismatch CV 1-B, Loaded, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
160/170	2.0/2.4	5.0/7.8
320/320	4.1/4.4	12.7/12.7
450/460	6.1/6.1	15.6/15.6
600/600	6.1/6.1	17.0/18.4
640/640	6.1/6.1	20.5/19.2
700/720	6.1/6.1	17.0*/17.7*

*Tow vehicle front wheels lock

Table 3.23. Combination Vehicle Effectiveness Test Results: Mismatch CV 1-B, Trailer Empty, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
160/140	2.0/2.0	6.4/7.8
320/320	4.1/4.1	13.5/14.2
480/440	6.1/6.1	17.0/17.0
600/600	6.1/6.1	19.8/19.1
660/660	6.1/6.1	21.2/21.2
700	6.1	19.8*

*Tow vehicle front wheels lock

Table 3.24. Combination Vehicle Effectiveness Test Results: CV 3-C, Loaded, 40 mph

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
120/120	1.4/1.4	
310/310	5.1/5.1	8.5/8.5
440/470	7.4/7.1	13.8/13.9
610/620	7.2/7.1	16.3/17.0*
720/740	7.5/7.4	18.6/18.5*
860/860	7.3/7.1	21.3/20.2*
1160	7.1	18.5**

*Trailer left lead tandem wheel lock

**Tow vehicle front wheels and trailer left lead tandem wheels lock

Table 3.25. Combination Vehicle Effectiveness Test Results: CV 3-C, Trailer Empty, 40 mph

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
120/110	1.4/1.4	
160/160	2.9/2.6	3.6/2.8
300/320	5.1/5.0	9.9/9.2*
440/460	7.1/7.1	14.2*/14.9*
600/620	7.1/7.3	17.0*/17.0*
750/740	7.4/7.3	19.9*/18.5*
860/880	7.1/7.1	20.6*/22.0*
1200/1120	7.1/7.1	19.9**/19.9**

*Trailer left lead tandem wheel lock

**Tow vehicle front wheels and trailer left lead tandem wheel lock

Table 3.26. Combination Vehicle Effectiveness Test Results: Mismatch CV 2-C, Loaded, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
140/140	1.9/1.9	1.4/1.4
320/300	2.1/2.8	4.3/3.8
440/480	7.1/7.1	16.3/17.0
600/600	7.1/7.1	18.5*/19.9
720/720/720	7.1/7.1/7.1	18.5**/18.5**/22.7**
760/760	7.1/7.1	17.8/22.7***

*Trailer left lead tandem wheel lock

**Tow vehicle right front wheel lock

***Tow vehicle front wheels lock

Table 3.27. Combination Vehicle Effectiveness Test Results: Mismatch, CV 2-C, Trailer Empty, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
140/160	1.9/1.9	1.8/2.0
300/320	3.6/3.3	7.1/9.9
480/460/460	7.1/5.2/7.4	18.4/14.2/17.0
520	7.4	19.9
600/600	7.4/7.4	18.6[1]/18.4[2]
640/640/640	7.4/7.4/7.4	20.6[1]/18.5[2]/17.8[2]
680/680/680	7.4/7.4/7.4	19.2[2]/19.9[2,3]/22.0[2,3]
760	7.4	20.6[2,3,4]

[1] Trailer rear tandem wheels lock

[2] Trailer left lead tandem wheel lock

[3] Trailer left rear tandem wheel lock

[4] Tow vehicle front wheels lock

Table 3.28. Combination Vehicle Effectiveness Test Results: CV 4-D, Loaded, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
160/160	1.9/2.1	1.2/1.2
220/220	4.1/4.6	4.3/5.0
270/280	9.6/9.6	8.0/8.0
350	9.6	10.5
420/420	9.6/9.6	11.2/12.1
480	9.6	11.8
500	9.6	11.8*

*Tow vehicle right rear wheel lock

Table 3.29. Combination Vehicle Effectiveness Test Results: CV 4-D, Trailer Empty, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
160/160	1.9/1.9	1.0/1.2
220/220	4.0/4.0	4.3/4.0
280/280	9.5/9.5	7.8/7.5
360/340	9.5/9.5	8.0/8.4
420/420	9.5/9.5	8.6*/10.2*
460/480	9.5	9.9*/9.9*

*Tow vehicle right rear wheel lock

Table 3.30. Combination Vehicle Effectiveness Test Results: CV 5-E, Loaded, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
200	3.3	3.1
400/400	6.2/6.7	7.4/7.7
600/600	6.2/6.5	9.6/10.8
760/800	6.2/6.5	11.1/12.4
900/950	6.2/6.5	12.2/13.6
1100/1100	6.2	12.4*

*Tow vehicle right rear wheel lock

Table 3.31. Combination Vehicle Effectiveness Test Results: CV 5-E, Trailer Empty, 40 mph.

Tow Vehicle Brake Line Pressure psi	Trailer Brake Voltage	Deceleration f/s^2
150/150	1.0/1.0	1.6/1.2
280/280	2.4/1.9	4.0/5.0
420/420	3.3/3.3	9.0/9.0
560/560	3.3/3.8	12.5/12.5*

*Trailer right rear wheel lock

The nature of the problem is illustrated in Figure 3.28. When surge hitch and equalizer hardware are combined, the moment-producing mechanism of the equalizing equipment greatly increases the vertical load acting at the ball of the hitch, for, as the figure shows, one force of the couple which produces the moment is a vertical, compressive load at the ball. Relating this to the earlier analysis of the surge hitch, the force, F_z, as shown earlier in Figure 3.10, is greatly increased relative to its value if load equalization is not used. Thus the over-running force (similar to F_x of Figure 3.10) required to overcome Coulomb friction forces within the hitch can be equal to a very large fraction of the trailer's weight, and the remaining portion of the over-running force available as an actuation force for the trailer brake system may be quite small, or, indeed, zero.

Horizontal components of the tensile chain force can also affect surge hitch performance, but generally to a smaller degree. Assuming that original chain orientation is vertical, if the internal friction of the surge hitch is overcome, motion of the sliding tongue occurs resulting in an inclination angle of the chain. This non-vertical orientation results in the chain tensile force having a horizontal component which serves to partially react the over-running forces, further lessening the level of brake system actuation force.

For our test purposes, this situation meant that for CV 1-A, all manufacturers' recommendations could not be met simultaneously. Thus, tests were conducted using recommended equalization and no equalization.

Table 3.15 presents data for this combination vehicle (1-A) under similar load and velocity conditions, but with and without load equalizing. The high level of trailer braking, as indicated by high trailer brake line pressure, results in improved braking effectiveness for the combination vehicle without load equalizing. Load equalization has the largely counter-balancing effect, in this case, of delaying front wheel lock of the tow vehicle, allowing this unit of the CV to achieve higher braking effort than is possible without equalization.

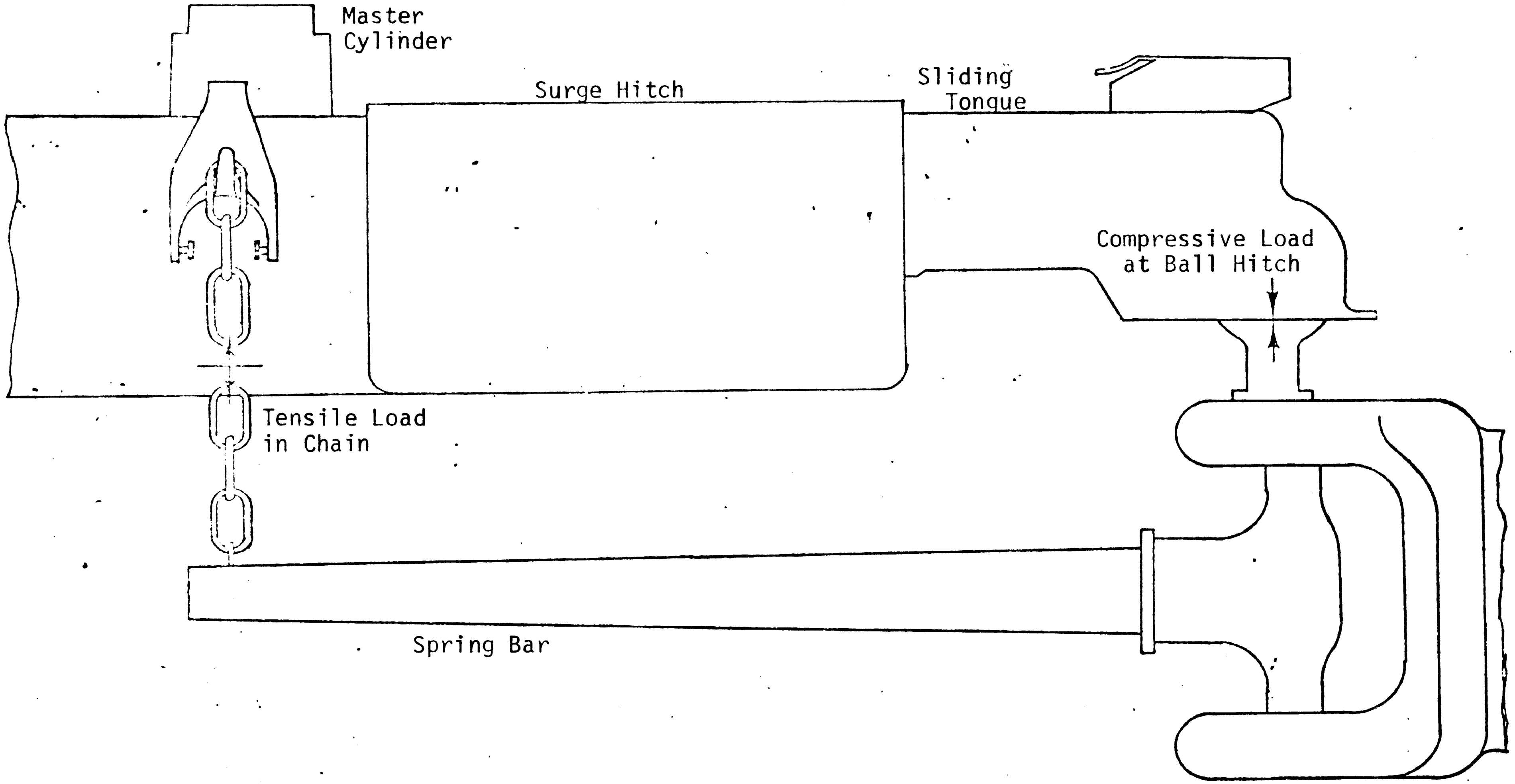

Figure 3.28. Load equalization hardware shown with a surge hitch.

The basic incompatibility of load equalization and surge hitch hardware can present the user with a difficult problem. It would appear that he should, in fact, elect not to use an equalizing hitch, to use air shocks to cure any ride problems due to rear suspension compression, and to then carry on as best he can with the rear and front axle loads biased by the "unequalized" hitch load. This situation can, however, be unacceptable if the hitch loads are high.

Another major concern in CV testing was the proper adjustment of the electric brake application system. This system was described in some detail earlier in Section 3.1.2. The equipment supplied by the manufacturer provides for several possible values for the external gain resistor. The "proper" resistance may be selected through reference to a table based on total trailer weight and the number of trailer brakes and axles, with the added advice to change the setting to obtain "firm braking action just short of skidding on dry pavements" with the controller fully on. Further, it is recommended that the onset rate adjustment "be made to provide for a slight lead of trailer brakes over tow vehicle brakes."

In general, these recommendations were followed in this program. However, unless the gain resistance indicated by the table resulted in an obviously poor adjustment, this setting was not altered. This procedure results from a judgment as to what probably represents the normal in-use situation. First, it was judged that the average user was likely to depend heavily on the table because of a general lack of understanding of the mechanisms of the braking process, and because of limitations either in his willingness to perform tests, or in roadway facilities available on which to perform tests necessary to make further adjustments. Second, if the user were to perform the implied tests, the resultant setting could largely depend upon the chance occurrence of the friction properties of the chosen test surface.

For trailers B and C, this procedure resulted in rather good combination vehicle braking performance. Consider

Tables 3.24 through 3.27, presenting data for 3-C and 2-C combinations. Ignoring the premature lockup of the left wheel of the lead tandem axle of the trailer, these combinations achieved deceleration levels of nearly 20 ft/s^2 or better in both trailer loaded and empty conditions. Tables 3.19 through 3.23 indicate that trailer B performed nearly as well in combination with tow vehicles 1 and 2. In the unloaded condition, however, this vehicle suffered from interaxle load transfer as evidenced by lead axle locking shown in Table 3.20.

Tables 3.28 through 3.31 indicate that CV's 4-D and 5-E did not achieve such good braking performance. Vehicles 4 and D had both demonstrated relatively low performance in their respective effectiveness tests. Thus the results of this combination's effectiveness tests are consistent with earlier results.*

Combination 5-E suffered from the limitations of the standard electric brake application device combined with the previously discussed (Section 3.2.2) problem of interaxle load distribution for this trailer. In the loaded trailer condition and with no external gain resistor used in the trailer brake application system, trailer wheel lockup was experienced at low levels of brake application. Thus, for these tests, the lowest available external gain resistor was used in the brake application system. However, because of the nature of the trailer brake system, this proved in practice to be a very coarse adjustment. Trailer E was equipped with six brakes, thus drawing approximately 50% more current than a four-brake system at a given application level. This higher current draw results in a similarly higher voltage drop across the external gain resistor. This resulted in a voltage drop at the brakes of approximately six and one-half volts. Thus, the trailer brakes probably were not being used to full advantage during these tests.

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*It should be noted again, as was done in reporting the results of trailer alone effectiveness tests for trailer D, that the maximum trailer brake voltage indicated in the table was measured at the input to the brake while approximately 12 volts were input to the trailer wiring harness.

With trailer E in the empty condition, similar adjustment of the external gain resistor was made. In this case, however, a setting could be achieved which prevented trailer wheel lock until relatively high application levels.

3.2.4 Trailer Fade Tests. The trailer fade test procedure was patterned after the first fade and recovery test of FMVSS 105-75 for vehicles in excess of 10,000 lb. gvw. That is, they consisted of baseline, fade, and recovery snubs conducted from initial velocities of 40 mph and subject to temperature, time, and distance constraints as per FMVSS 105-75. Modifications were made to the final velocity of the snubs and to deceleration rates, however. In particular, the final velocity and deceleration rates were prescribed, respectively, as

$$V_f = \sqrt{40^2 - \frac{W_{TA}}{W_{CV}} (40^2 - 20^2)} \text{ mph} \qquad (3.21a)$$

$$a = 10 \frac{W_{TA}}{W_{CV}} \text{ fps}^2 \qquad (3.21b)$$

where

W_{TA} is the total static trailer axle load

W_{CV} is the combination vehicle weight

Snubs from 40 mph to V_f at deceleration, a, using trailer brakes only, result (1) in the trailer brakes absorbing the energy of a 40- to 20-mph snub of a vehicle equal in weight to the trailer axle static load, and (2) in the trailer brakes operating at a torque level which would decelerate the same vehicle at 10 fps^2.

Additionally, trailer A was subjected to a similar program using an initial velocity of 60 mph (requiring that "60" be substituted for "40" in Equation (3.21a)).

In all of the fade tests, trailers were in their loaded condition and tow vehicles were empty. The combinations employed were: 1-A, 1-B, 2-C, 4-D, and 5-E. In the tests, it was intended that the driver would maintain the prescribed constant deceleration through modulation of the trailer brakes only while observing a U-tube decelerometer.

Tables 3.32 through 3.37 summarize the results of the tests. Two points are noteworthy. First, the sustained vehicle decelerations* attained by the driver often varied by significant percentages from the desired deceleration level. At least two factors are contributory to this error. The desired deceleration levels are generally small, thus taxing the useful resolution of the U-tube. This problem would be relieved somewhat by conducting such tests with as light a tow vehicle as possible, thus increasing desired deceleration levels. A more confounding complication derives from the hysteretic and high gain characteristics of trailer brakes, particularly the electric brakes, which make the constant torque mode of operation very difficult to achieve.** This is illustrated in the extreme of Figure 3.29 which presents data gathered in one test run. The figure indicates that once the brake has been applied to a relatively high level, hysteresis in the voltage/torque relationship apparently prevents the brake from reacting to large reductions in input voltage. This not only makes the conduct of a fade test difficult, but also complicates data reduction. In Tables 3.32 through 3.37 sustained brake application levels are indicated.

A second point of interest in these tests concerns the interrelation between aerodynamic and other drags and deceleration. Although the lower deceleration rates experienced in testing do not alter the kinetic energy lost by the vehicle during a snub, they can lower that portion of the energy absorbed due to the braking process while extending the time period of absorption slightly. The remaining portion of the energy

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*Deceleration levels indicated in the tables derive from the electronic accelerometer mounted on a stabilized platform and not from U-tube readings.

**This was also seen in dynamometer testing (Section 3.1.2) wherein servo-controlled constant torque testing was not achievable.

Table 3.32. Trailer Fade Test Results: Trailer A, 40 mph.

Drag Deceleration: 0.6 f/s^2
Target Deceleration: 3.15 f/s^2

Run No.	Trailer Brake Line Pressure psi	Deceleration f/s^2	Average Brake Temperature °F
Baseline 1	260	2.5	166
Baseline 3	270	2.8	188
Fade 1	270	2.5	125
Fade 10	270	2.5	305
Recovery 1	270	2.5	271
Recovery 5	270	2.5	222

Table 3.33. Trailer Fade Test Results: Trailer B, 60 mph

Drag Deceleration: 0.6 f/s^2
Target Deceleration: 3.15 f/s^2

Run No.	Trailer Brake Line Pressure psi	Deceleration f/s^2	Average Brake Temperature °F
Baseline 1	260	2.5	159
Baseline 3	260	2.5	186
Fade 1	260	2.3	142
Fade 10	260	2.1	484
Recovery 1	260	1.9	425
Recovery 5	260	2.5	325

Table 3.34. Trailer Fade Test Results: Trailer B.

Drag Deceleration: 2.1 f/s^2
Target Deceleration: 5.0 f/s^2

Run No.	Trailer Brake Voltage	Deceleration f/s^2	Average Brake Temperature °F
Baseline 1	3.0	5.0	187
Baseline 3	3.0	5.0	193
Fade 1	3.0	5.0	157
Fade 10	3.0	5.0	248
Recovery 1	3.0	5.0	228
Recovery 5	3.7	5.0	185

Table 3.35. Trailer Fade Test Results: Trailer C.

Drag Deceleration: 0.6 f/s^2
Target Deceleration: 5.17 f/s^2

Run No.	Trailer Brake Voltage	Deceleration f/s^2	Average Brake Temperature °F
Baseline 1	2.7	5.0	158
Baseline 3	3.4	5.0	190
Fade 1	3.0	5.0	147
Fade 10	6.2	5.0	341
Recovery 1	6.1	5.0	319
Recovery 5	4.1	5.0	269

Table 3.36. Trailer Fade Test Results: Trailer D

Drag Deceleration: 0.6 f/s^2
Target Deceleration: 5.0 f/s^2

Run No.	Trailer Brake Voltage	Deceleration f/s^2	Average Brake Temperature °F
Baseline 1	9.0	4.3	126
Baseline 3	9.0	4.3	154
Fade 1	9.0	4.3	124
Fade 10	9.7	4.0	342
Recovery 1	9.7	5.6	291
Recovery 5	9.7	5.6	257

Table 3.37. Trailer Fade Test Results: Trailer E

Drag Deceleration: ~0
Target Deceleration: 4.0 f/s^2

Run No.	Trailer Brake Voltage	Deceleration f/s^2	Average Brake Temperature °F
Baseline 1	6.2	3.1	142
Baseline 3	6.2	3.7	182
Fade 1	6.2	3.1	143
Fade 10	6.7	1.3	590
Recovery 1	7.2	1.8	523
Recovery 5	7.2	2.5	485

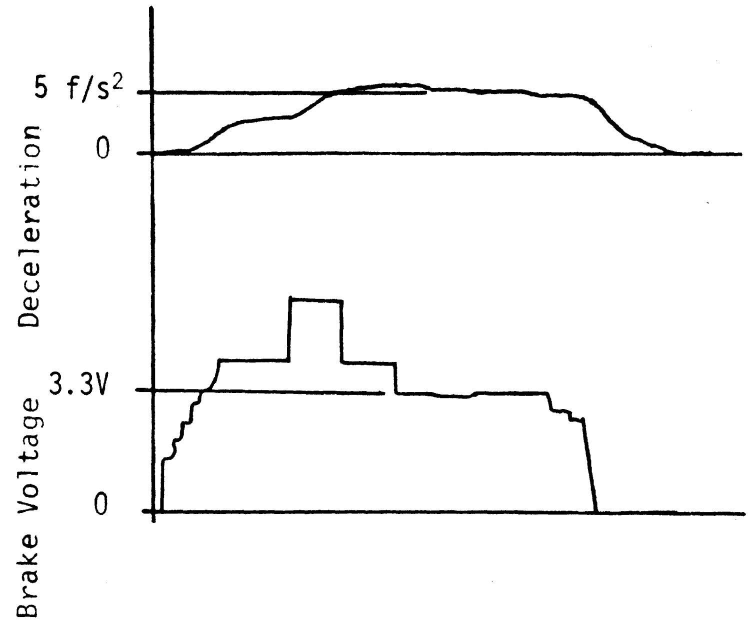


Figure 3.29. An exemplary time history of a trailer fade snub.

loss is attributable to drag forces which can be significant due to the large frontal area of these vehicles relative to their mass. If we assume that the drag forces are constant for a given vehicle across the small velocity change of the snubs, it can be shown that:

$$\frac{E_B}{E_T} = 1 - \frac{A_D}{A_T} \tag{3.22}$$

where

A_D is the portion of the deceleration attributable to drag

A_T is the total deceleration

E_B is kinetic energy loss due to braking forces

E_T is total kinetic energy loss

Equation (3.22) indicates that, as total deceleration decreases and drag deceleration remains constant, the percent of energy absorption attributable to braking decreases.

The data presented in the tables, then, indicates that (a) fade tests of trailers B and C were conducted essentially as desired, (b) the test of trailer E was conducted at a lower deceleration level than desired, but this probably did not significantly disturb the results since deceleration due to drag forces was very small, and (c) tests for trailers A and D were probably less severe than desired because of low acceleration levels. For trailer A, Equation (3.22) would indicate approximately 80% energy absorption due to braking at the proper deceleration level and approximately 75% at the actual level. Similarly, for trailer D, proper deceleration would result in a calculated 88% while actual deceleration results in approximately 86% energy absorption due to braking.

The test results further indicate that for the 40-mph test, trailers A and B exhibited virtually no fade. Trailers C and D exhibited some fade and generally good recovery. Trailer E suffered the most from fade with the least complete recovery. The general ranking between the performance of the sample of trailers is largely in line with their ranking based on average wheel load, and hence, the energy absorption requirement per brake. In the 60-mph test of trailer A, some fade is in evidence, but recovery is good.

4.0 COMPUTER SIMULATION AND ANALYSIS

An appropriate role of computer simulation is to aid in the understanding of vehicle test results by simulating the tests. If the calculations yield results largely in agreement with the measurements, or if the discrepancies between test results and simulated results can be reliably accounted for, the indication is that the tests are well understood.

Much of the success of this exercise depends on one's point of view. In fact, in most simulations of vehicle tests, there are enough important pieces of information that are unknown that one can fit the test data by choosing the input parameters properly. Whether this process entails the science of "fine-tuning" or the art of "fudging" often seems to depend on the eye of the beholder.

Simulation of braking tests is a prime example of this mixture of science and art. This occurs because the brake torque, which is always a key part of the input data, is extremely difficult to determine accurately without resorting to road tests. Thus, although the response of a vehicle to a given brake torque presumably may be accurately computed, it is not reasonable to assume, a priori, that the torque used as input to the simulation is in fact a reasonable analog for the torque actually generated by the vehicle's brakes. To remedy this situation, a few vehicle tests are frequently thought of as laboratory measurements of brake torque designed to determine a reasonable torque versus line pressure relation, and the line pressure is used as input to the computer simulation, as in [5].

This was the procedure used to gather the trailer brake parameters for use in this simulation activity. In particular, the trailer alone test results were reduced to find brake forces corresponding to each voltage (pressure for the surge brakes).

The gathering of data to describe the brake torque of the tow vehicle is potentially more difficult, largely because the five tow vehicles make use of hydraulic valves which alter the front-to-rear proportioning of brake torque distribution and the overall system gain as a function of master cylinder pressure. But since the analytical activity at hand was concerned, in the main, with limit braking performance, the master cylinder pressures to be considered fall within a rather narrow band. Thus, it was reasonable to model the tow vehicle as having fixed proportioning and to employ those brake system parameters descriptive of the real system performance within the limit range of interest. The parameters used were derived from the tow vehicle alone effectiveness test results.

It is important to note here that CV test results were not used to garner brake torque values for use in simulating further CV tests. (In that case, the calculated results would obviously closely match the test results.) Rather, we have used trailer alone results and tow vehicle alone results to procure parameters for CV simulation. The discrepancies between computed and measured results are then indicative of either (a) the measurement errors, or (b) parametric changes during, and possibly as a result of, testing, or (c) simplifications in the analysis.

Another role of simulation is to simulate tests that were not run. (It is, of course, a desirable precondition that the tests that were run are well understood.) In this was, calculations can be substituted for expensive and/or dangerous tests.

Initially, this section will present a short explanation of the quasi-static simulation used to perform the calculations. This will be followed by calculated results for the tests that were run and calculated extensions of the test results.

4.1 The Quasi-Static Simulation.

The quasi-static simulation, BRAKES2 [6], was used throughout this research program to illuminate and extend the test results. The term quasi-static indicates that the pitch and bounce and wheel spin degrees of freedom often associated with braking calculations were neglected—the input is the brake force, the c.g. and axle positions, and tire-road interface data, and the output is the steady-state deceleration of the simulated vehicle.

The straightforward nature of the program allows the user exceptional utility in performing calculations—calculations can be performed interactively at a very rapid rate and at a low cost. This utility is gained at the expense of several simplifying assumptions which are listed below:

1) The brake torque is assumed constant throughout the run.

2) The quasi-static nature of the normal load calculations neglects the time lag required to attain the quasi-static loads. In practice, however, the brakes are applied while the axle is still loaded to approximately its static load—i.e., before the load transfer takes place.

3) Tandem axle dynamics are neglected. Thus the calculations tend to predict initial lockup at higher line pressures than one would expect to find if suspension kinematics lead to appreciable inter-axle load transfer during braking.

4) Changes in the properties of the tire-road interface with load and speed are neglected.

Of these four simplifications, the first turns out to be the most significant. It is eminently apparent from our test data (and, typically, from any data in which severe wheels-unlocked braking plays a role) that, given constant line pressure or voltage, the brake torque cannot be expected to remain constant during the course of a stop. As far as we know, the prediction of torque variations during a stop is beyond the current state of the art.

It is appropriate here to reconsider the example presented in Figure 3.27 which displayed measured data from the 5-E combination vehicle testing. The simulation, of course, cannot predict the effectiveness changes so obvious in the test results and thus must remain a limited, albeit useful, tool in the understanding of the total system.

4.2 Simulation of Test Vehicle Performance

The BRAKES2 simulation was used to calculate the vehicle test results. The comparison between the calculations and the measured data will be presented in this section. These results will be presented in five subsections, with one subsection devoted to each trailer. Further calculations will be presented later which extend the test results.

4.2.1 Trailer C. Braking data for the 12" x 2" electric brakes of trailer C were gathered from the trailer alone tests as shown in Section 3.2.3. These data are repeated here for convenience in Figure 4.1.

The voltage is applied to the trailer brakes as a function of tow vehicle line pressure as determined by the controller used in the combination vehicle tests. Figure 4.2 presents a bilinear fit to the measured trailer brake voltage versus tow vehicle line pressure for the controller, with the gain and limits as set for the CV tests. Note that the controller does not yield such smooth curves in practice. (See, for example, Figure 3.12.) However, our main interest is in the flat limit portion of the curve which is quite repeatable.

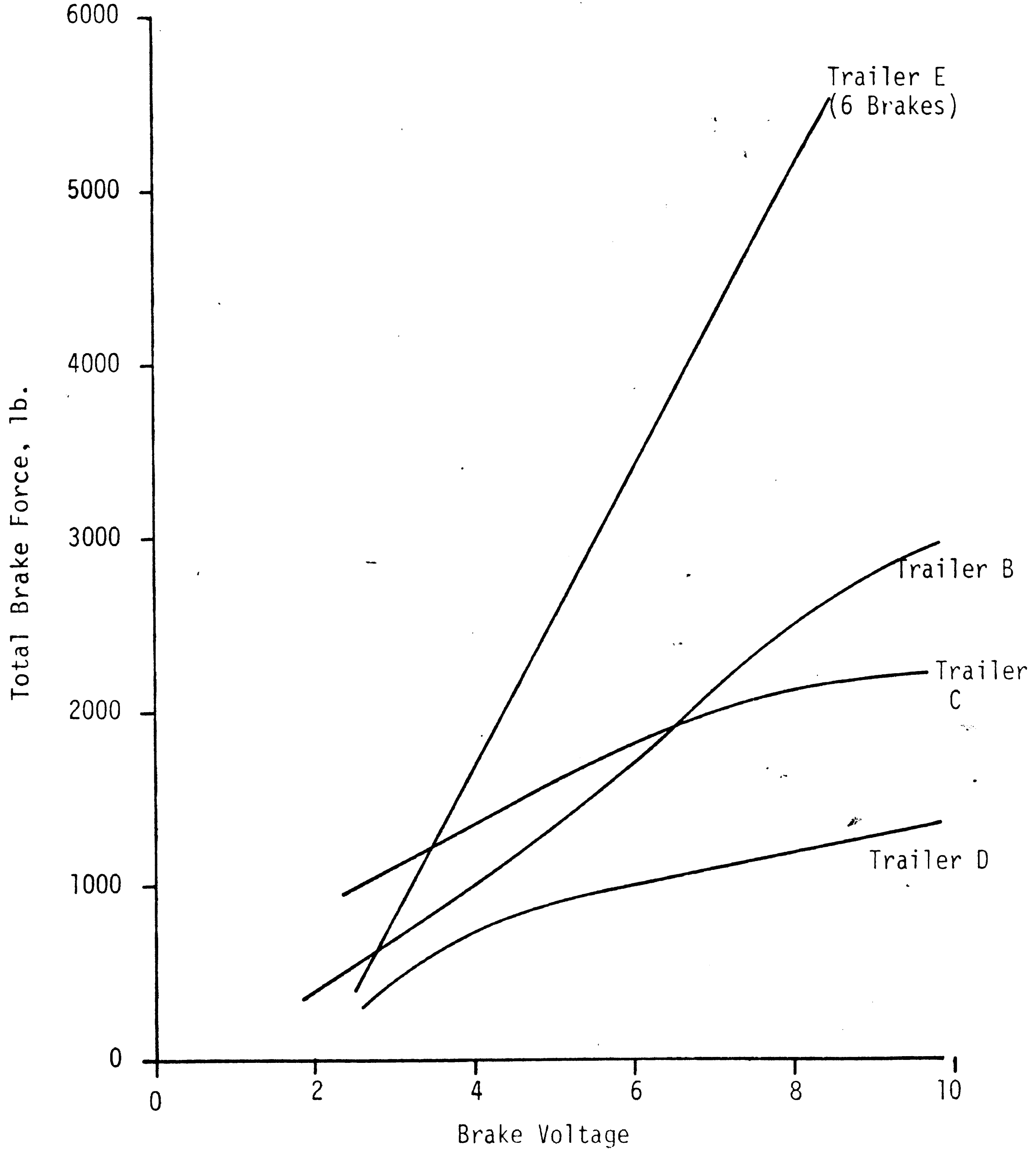


Figure 4.1. Total brake force versus applied voltage.

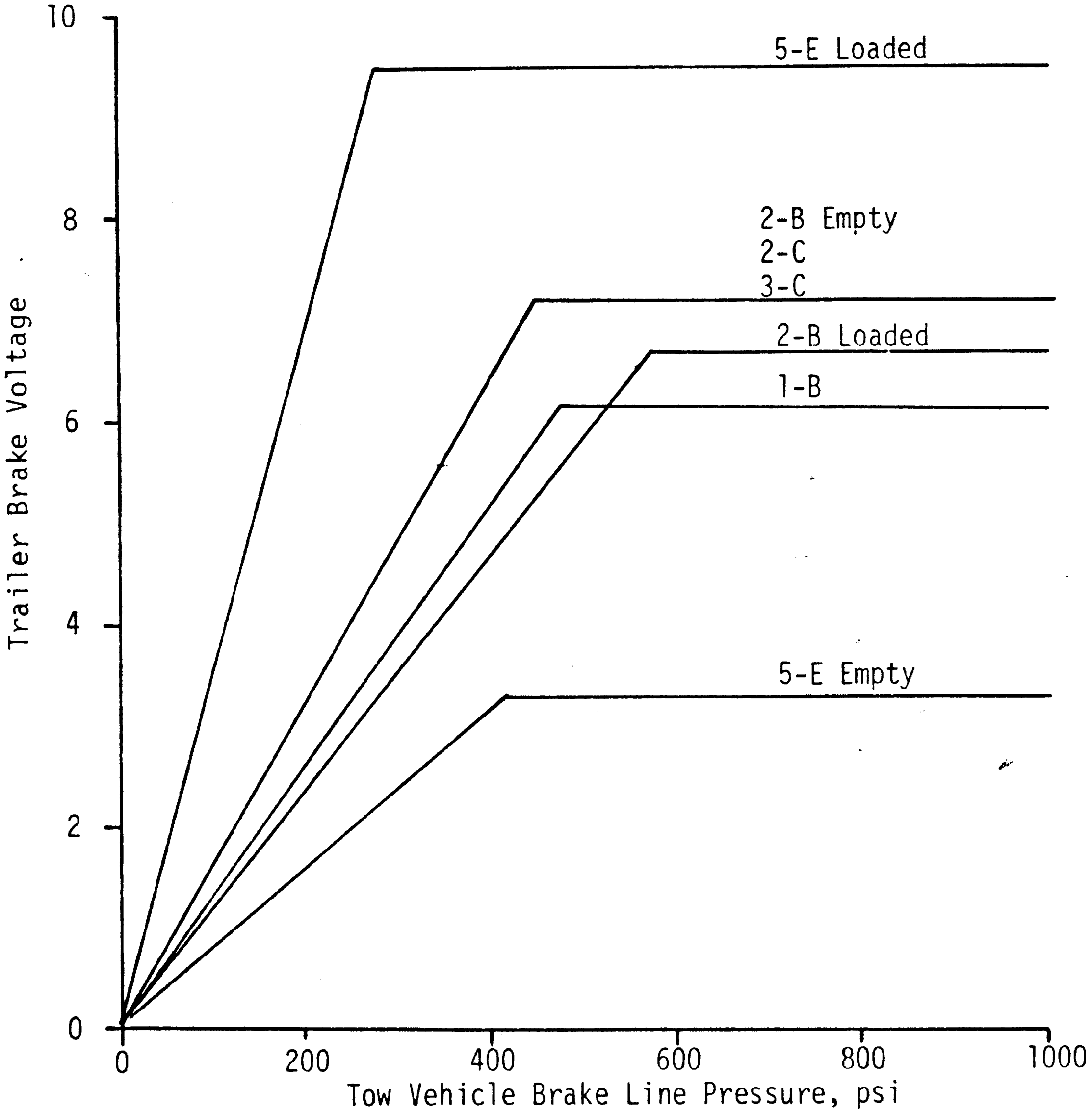


Figure 4.2. Simulated electric brake controllers.

Constant brake proportioning values for each of the tow vehicles was estimated based on the tow vehicle alone tests, and are tabulated in Table 4.1. Note, we estimated 70-30 for vehicles 1 and 2 as they locked front wheels first at very high decelerations. This performance is somewhat surprising, particularly for vehicle 2 which had no rear proportioning valve.*

Table 4.1. Estimated Constant Proportioning for the Tow Vehicle.

Vehicle	Proportioning
1	70-30
2	70-30
3	55-45
4	55-45
5	55-45

Using the assumed proportioning of Table 4.1 in conjunction with the car-alone results of Tables 3.5-3.9, we can estimate the relationship between trailer brake force and the brake force at each axle of the tow vehicle. Trailer brake force is plotted as a function of tow vehicle front-wheel brake force in Figure 4.3.

Most of the data required to simulate trailer C is presented in Figure 4.4 which presents input/output (I/O) for a computer run of the loaded tow vehicle 2 pulling the loaded trailer C.

---

*Vehicle 2 makes use of "metering" or an initial limiting of the front disc brakes for wear reasons, but not variable proportioning, which would limit the rear line pressure at high decelerations.

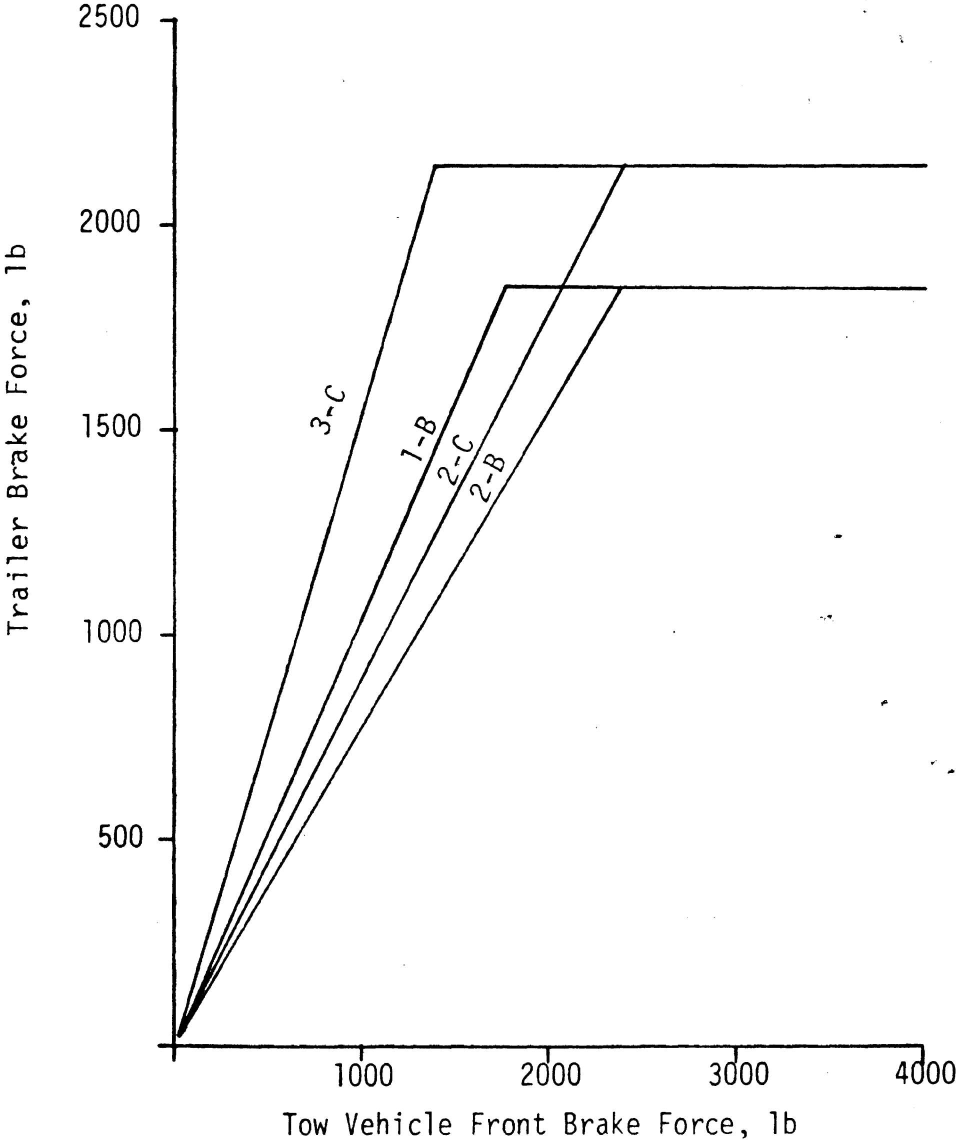


Figure 4.3. Estimated relationship between trailer and tow vehicle brake force.

```
 ♦♦ENTER DATA

01 A1    DISTANCE BETWEEN TRACTOR C.G. AND TRACTOR
            FRONT SUSPENSION (IN)                          55.3

02 A3    DISTANCE BETWEEN TRAILER C.G. AND FIFTH
            WHEEL (IN)                                     134.4

03 A4    DISTANCE BETWEEN TRAILER SUSPENSION AND
            TRAILER C.G. (IN)                              14.6

 4 BB    DISTANCE BETWEEN FIFTH WHEEL AND TRACTOR
           REAR SUSPENSION (IN).  (FIFTH WHEEL LO-
            CATED AFT OF SUSPENSION IS POSITIVE)           69.

05 L     WHEELBASE OF TRACTOR (IN)                        118.

 6 H     HEIGHT OF TRACTOR C.G. ABOVE GROUND (IN)         22.

07 HH    HEIGHT OF FIFTH WHEEL ABOVE GROUND (IN)          18.

 8 HT    HEIGHT OF TRAILER C.G. ABOVE GROUND (IN)         39.2

   GVW1 WEIGHT OF TRACTOR (LB)                            4803.

10 GVW2 WEIGHT OF TRAILER (LB)                            6830.

DO YOU WISH TO INPUT BRAKE DISTRIBUTION (23)? NO


   BRAKE AND TIRE PARAMETERS
TOTAL ATTEMPTED BRAKE TORQUE AT AN AXLE (IN-LB), ROLLING RADIUS
OF TIRE (IN), PEAK FRICTION COEFFICIENT, EFFECTIVE (OR SLIDING)
FRICTION COEFFICIENT: TP,R,MUP,MUE

AXLE 1 (11,14,17,20)      2800.,1.,1.,.1

AXLE 2 (12,15,18,21)      1300.,1.,1.,.1

AXLE 3 (13,16,19,22)      2150.,1.,1.,.1


♦♦♦END DATA INPUT
```

Figure 4.4a. Example input/output for simulation of CV 2-C.

```
USE EQUALIZING HITCH? YES


                                     AXLE 1          AXLE 2          AXLE 3
          STATIC LOADING (LB):       2160.76         3311.49         6160.75

               HITCH LOAD (LB):      669.25

ENTER INCREASE IN STATIC LOAD (LB) FOR AXLE 1
DUE TO EQUALIZING HITCH: 600.


THE MOMENT AT THE HITCH IS   48389.19 IN-LBS.


 THE STEADY-STATE DECEL IS APPROXIMATELY 17.0 FPSPS.


                                     AXLE 1          AXLE 2          AXLE 3
     TOTAL ATTEMPTED
     TORQUE PER AXLE (IN-LB):        2800.00         1200.00         2150.00

          STATIC LOADING (LB):       2760.76         2386.73         6485.51
         DYNAMIC LOADING (LB):       3004.71         2916.26         5712.03

              BRAKE FORCE (LB):      2800.00         1200.00         2150.00
   EFFECTIVE FRICTION (FX/FZ):       0.93            0.41            0.38

 HITCH FORCES (LB)    STATIC:   FX =        0.00     FZ =     344.49
(COMPRESSION POS.)   DYNAMIC:   FX =     1460.80     FZ =    1117.97


     NO AXLES LOCKED (CYCLED)

INITIAL VELOCITY (MPH): 40.

BRAKE DELAY TIME (SEC): .5

THE ESTIMATED STOPPING DISTANCE IS  131. FEET.
```

Figure 4.4b. Example input/output for simulation of CV 2-C.

Some interesting calculations of the trailer C performance are presented in Figures 4.5 and 4.6, where maximum wheels-unlocked deceleration for passenger cars 2 and 3 pulling trailer C are presented. The calculations indicate that the maximum burden of the trailer occurs at high decelerations, a direct result of the high gain and flattening of the trailer C brake force as a function of the applied voltage. In both these figures, the change in slope of the CV curve at about $\mu = .4$ indicates the break point in the controller response curve shown in Figure 4.1.

The CV curves in Figures 4.5 and 4.6, which were based on the data in Figures 4.1 and 4.2, show that the calculated CV deceleration was at least fifteen percent lower than the measured values. Some insight into this discrepancy can be gained from the hitch transducer measurements. In both the 3-C and 2-C combinations the maximum measured compressive force at the hitch was close to 1000 lbs. The calculation in Figure 4.4b, however, shows a far higher compressive force. The indication is that during and perhaps as a result of the trailer alone testing and the CV testing, the trailer brakes increased in effectiveness.

Further calculations verified the obvious—an increase in peak trailer brake force will increase the deceleration and thus move the CV curves on the figures up toward the tow vehicle alone curves. The results of Figure 4.4b, for example, indicate that the trailer brake force could be significantly increased without causing trailer wheel lockup.

In practice, however, the voltage level used in the calculations was the setting recommended by the controller manufacturer for the trailer weight. Further, the 7.1-volt setting shown in Figure 4.2 for trailer C was sufficient to cause occasional lockup of the left lead trailer tandem, indicating an appropriate setting (see Table 3.12). This leads to the conclusion that the rather rough controller resolution and the varying nature of the electric brakes leave little opportunity for the consumer to fine-tune his CV to achieve the potential trailer braking which is suggested by the simulation.

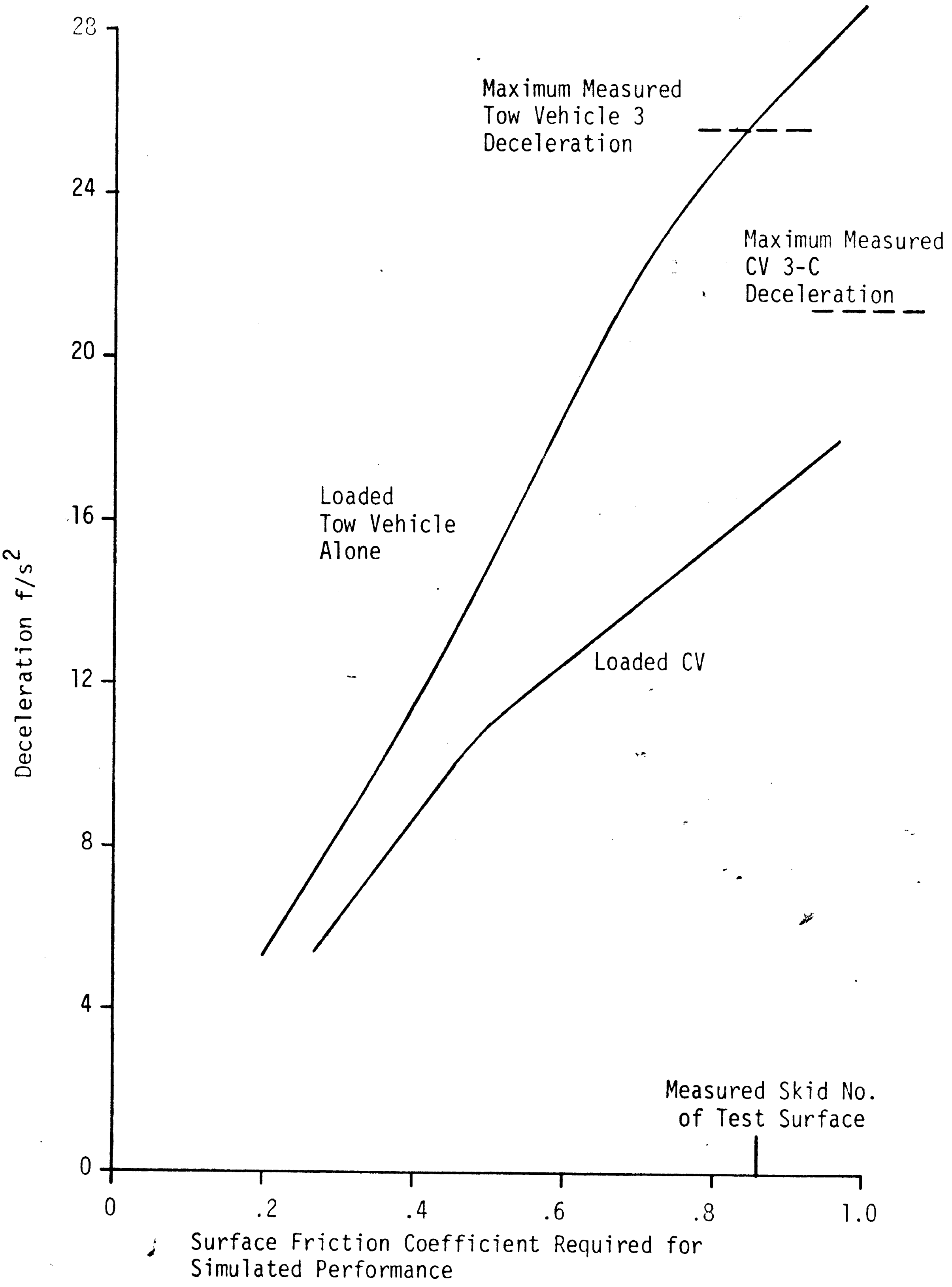


Figure 4.5. Simulated braking performance for loaded 3-C.

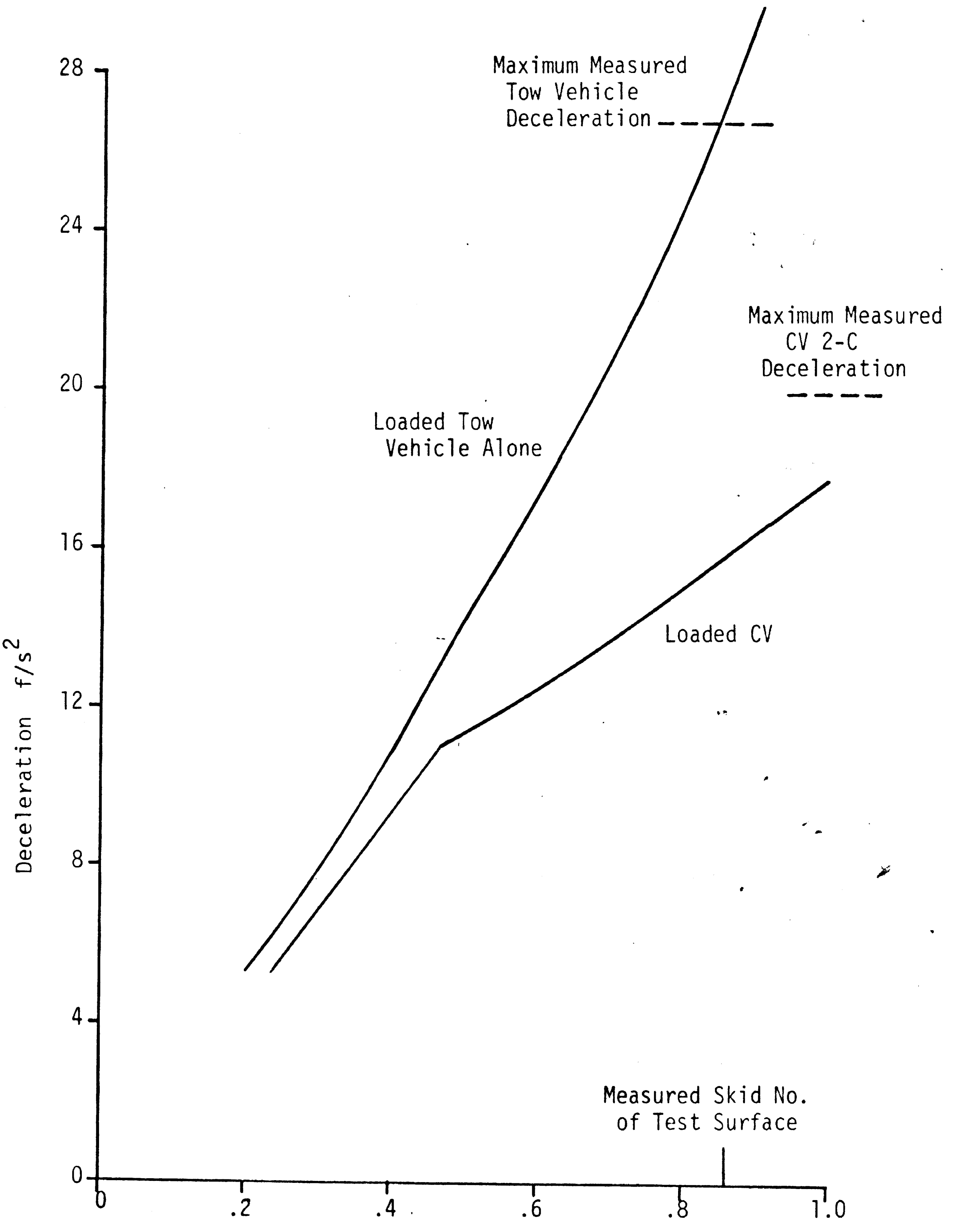


Figure 4.6. Simulated braking performance for the loaded 2-C.

Since both the calculations and tests* indicated that the combinations under study were limited by front wheel lockup on the tow vehicle, it is not surprising that later calculations indicate that hitch load and load equalization are of extreme importance and that many other vehicle parameters are not. These matters will be discussed further in Section 4.3.

4.2.2 Trailer B. The braking data for the four 10" x 2" electric brakes of trailer B were gathered from the trailer alone tests shown in Section 3.2.3. These data were repeated for convenience in Figure 4.1. Measured voltage versus tow vehicle line pressure was presented in Figure 4.2. The constant proportioning assumed for the tow vehicle was presented in Table 4.1.

Much of the data required to simulate trailer B is given in Figure 4.7, which presents I/O for a computer run of loaded tow vehicle 2 pulling loaded trailer B.

Some interesting calculations of trailer B performance are presented in Figure 4.8, where maximum wheels-unlocked deceleration of tow vehicles 1 and 2 pulling the loaded trailer B are presented. As in the case of trailer C, the calculations indicate that lockup occurs first on the front wheels of the tow vehicle on all surfaces. Again, this result is explained by the application of the vertical component of the hitch load behind the rear wheels.

4.2.3 Trailer A. Trailer A is the surge-brake-equipped trailer which, for all the simulation runs, was loaded to 2222 lbs. The gain of the surge brake system, i.e., total trailer brake force per unit over-running force at the hitch, was calculated from trailer geometry and dynamometer curves to be 1.9. Trailer A was coupled to tow vehicle 1, which was assumed, based on tow vehicle alone results, to have 70-30 proportioning. Much of the data required to simulate the 1-A combination is presented in Figure 4.9.

---

*We are ignoring here the occasional measured left-lead tandem lockup, which is more indicative of a "grabby" brake than a bona-fide lockup limit.

```
♦♦♦ENTER DATA

1 A1    DISTANCE BETWEEN TRACTOR C.G. AND TRACTOR
           FRONT SUSPENSION (IN)                                  55.3

2 A3    DISTANCE BETWEEN TRAILER C.G. AND FIFTH
           WHEEL (IN)                                            125.3

3 A4    DISTANCE BETWEEN TRAILER SUSPENSION AND
           TRAILER C.G. (IN)                                      18.7

4 BB    DISTANCE BETWEEN FIFTH WHEEL AND TRACTOR
          REAR SUSPENSION (IN).  (FIFTH WHEEL LO-
           CATED AFT OF SUSPENSION IS POSITIVE)                   69.

5 L     WHEELBASE OF TRACTOR (IN)                                118.

06 H    HEIGHT OF TRACTOR C.G. ABOVE GROUND (IN)                 22.

7 HH    HEIGHT OF FIFTH WHEEL ABOVE GROUND (IN)                  14.

8 HT    HEIGHT OF TRAILER C.G. ABOVE GROUND (IN)                 32.8

09 GVW1 WEIGHT OF TRACTOR (LB)                                   4803.

0 GVW2  WEIGHT OF TRAILER (LB)                                   5000.

DO YOU WISH TO INPUT BRAKE DISTRIBUTION (23)? NO


  BRAKE AND TIRE PARAMETERS
TOTAL ATTEMPTED BRAKE TORQUE AT AN AXLE (IN-LB), ROLLING RADIUS
 F TIRE (IN), PEAK FRICTION COEFFICIENT, EFFECTIVE (OR SLIDING)
FRICTION COEFFICIENT: TP,R,MUP,MUE

 XLE 1 (11,14,17,20)       2800.,1.,1.,.1

AXLE 2 (12,15,18,21)       1200.,1.,1.,.1

 XLE 3 (13,16,19,22)       1850.,1.,1.,.1


 ♦♦END DATA INPUT
```

Figure 4.7a. Example input/output for simulation of CV 2-B.

```
L E EQUALIZING HITCH? Y


                                         AXLE 1          AXLE 2          AXLE 3
           STATIC LOADING (LB):           2172.42         3279.88         4350.69

                HITCH LOAD (LB):           649.30

ENTER INCREASE IN STATIC LOAD (LB) FOR AXLE 1
DUE TO EQUALIZING HITCH: 500.


THE MOMENT AT THE HITCH IS   39887.00 IN-LBS.


 THE STEADY-STATE DECEL IS APPROXIMATELY 19.2 FPSPS.


                                         AXLE 1          AXLE 2          AXLE 3
      TOTAL ATTEMPTED
      TORQUE PER AXLE (IN-LB):            2800.00         1200.00         1850.00

           STATIC LOADING (LB):           2672.42         2502.89         4627.69
          DYNAMIC LOADING (LB):           3008.36         2736.36         4058.28

               BRAKE FORCE (LB):          2800.00         1200.00         1850.00
  EFFECTIVE FRICTION (FX/FZ):             0.93            0.44            0.46

 HITCH FORCES (LB)    STATIC:   FX =        0.00     FZ =     372.31
(COMPRESSION POS.)  DYNAMIC:   FX =    1133.78     FZ =     941.72




           INITIAL VELOCITY (MPH): 40.

           BRAKE DELAY TIME (SEC): .5

           THE ESTIMATED STOPPING DISTANCE IS  119. FEET.
```

Figure 4.7b. Example input/output for simulation of CV 2-B.

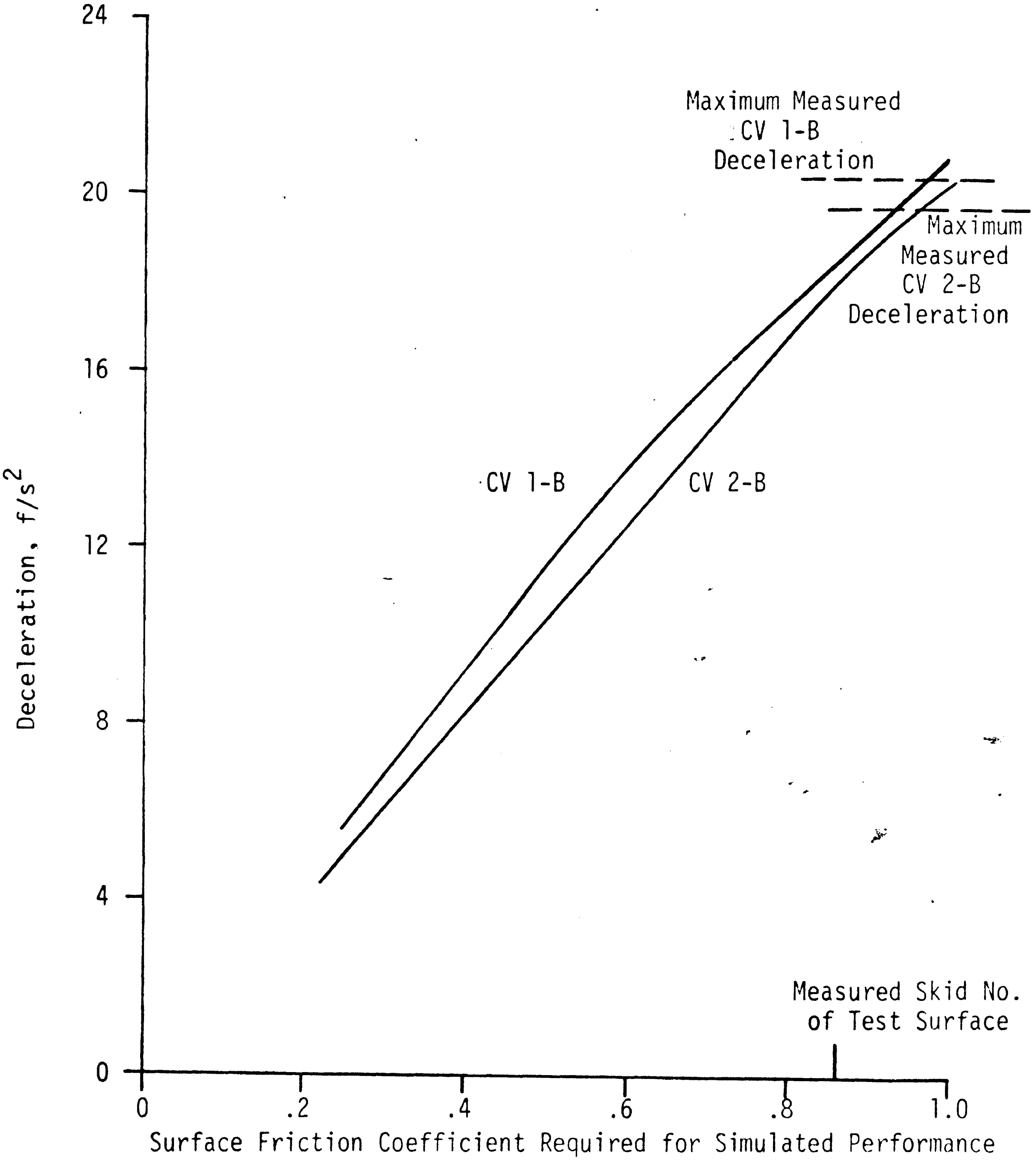


Figure 4.8. Simulated braking performance of loaded CV's 1-B and 2-B

```
***ENTER DATA

01 A1    DISTANCE BETWEEN TRACTOR C.G. AND TRAC
            FRONT SUSPENSION (IN)                              57.7

02 A2    DISTANCE BETWEEN TRAILER C.G. AND FIFT
            WHEEL (IN)                                         88.0

03 A4    DISTANCE BETWEEN TRAILER SUSPENSION AN
            TRAILER C.G. (IN)                                  10.7

04 B1    DISTANCE BETWEEN FIFTH WHEEL AND TRACT
           REAR SUSPENSION (IN).   FIFTH WHEEL
            CATED AFT OF SUSPENSION IS POSITIVE                71.0

05 L     WHEELBASE OF TRACTOR (IN)                            111.0

06 H     HEIGHT OF TRACTOR C.G. ABOVE GROUND (I               24.5

07 H4    HEIGHT OF FIFTH WHEEL ABOVE GROUND (I                15.0

08 HT    HEIGHT OF TRAILER C.G. ABOVE GROUND (I               23.5

09 GVW1 WEIGHT OF TRACTOR (LB)                                4707.

10 GVW2 WEIGHT OF TRAILER (LB)                                2222.

DO YOU WISH TO INPUT BRAKE DISTRIBUTION (23)?


  BRAKE AND TIRE PARAMETERS
TOTAL ATTEMPTED BRAKE TORQUE AT EA AXLE (IN-L        LING RA
OF TIRE (IN), PEAK FRICTION COEFFICIENT, EFFE        OR SLID
FRICTION COEFFICIENT: TP,R,MUP,MUS

AXLE 1 (11,14,17,20)          1056.,1.,1.,.1

AXLE 2 (12,15,18,21)          569.,1.,1.,.1

AXLE 3 (13,16,19,22)          160.,1.,1.,.1


***END DATA INPUT
```

Figure 4.9a. Example input/output for simulation of

```
IS EQUALI    HITC    I


 THE STEA   STATE DE     IS APPRO   ATELY  8.3 FPSPS.

                                     AXLE 1          AXLE 2            LE 3
    TOTAL   TTEMPTED
    TORQU  PER AXLE  IN-LB):        5.00            .00            0.00

          STATIC LOAD    LB):        3.70            5.16             85.14
        DYN   IC LOA     LB):         4.39           32.73             11.38

             BRAKE F     LB):         16.00          369.00           160.00
 EFFECTI     ICTIO       FD):          .44            .33              .09

 HITCH        LB)      ATIO:  F            0.0     FZ =            .36
 COMPRE       FO.      AMIC:  F          412.4     FZ =            .63


    NO      LOCKE      LED)

 ITIAL   CITY       40.

 BRAKE DE    TIME       .5

 HE EST      STOP     DISTANC      237. FE  .
```

Figu   b. Ex   nput/outp   r simulat   of CV 1-

Some informative calculations of 1-[illegible] performance are [illegible] presented in Figure 4.10, where [illegible] vehicle alone and several CV [illegible] combinations are summarized. Note that, in each case, the calculat[illegible] agreed reason[illegible] well with [illegible] measured values [illegible] with the ca[illegible] and measur[illegible] lines intersecting in the area of μ = 0.8.

The calculations serve to illustrate the performance penalty that c[illegible] from

a [illegible] binding of [illegible] surge brakes [illegible] the load equal[illegible]ion hardware (this penalty is indicated by the "[illegible]liza-tion, no trailer brakes" curve

b running without equalization [illegible] this configura[illegible] yields premature tow vehicle front locking [illegible] [illegible]icated in the "no equalization plus trailer brakes" [illegible])

These two curves should be compared to the CV pl[illegible] [illegible]aliza-tion c[illegible], which indicates the performance that would [illegible] expected if th[illegible] [illegible]lization [illegible]ware and surge [illegible]ch were des[illegible] for comp[illegible] operation.

[illegible] Trailer [illegible] Trailer E was [illegible]d by tow ve[illegible] [illegible], a "one-[illegible] pickup tr[illegible] gvw 10000 lbs. Several calc[illegible]s were perfo[illegible] to study [illegible] combination. [illegible] of these [illegible]tions are s[illegible]ized here [illegible] Figure 4.11, wh[illegible] presents c[illegible]ed peak wheel [illegible]cked dec[illegible]ation versus μ [illegible] the tow ve[illegible] alone and v[illegible] CV's. The input data requ[illegible] to simula[illegible] [illegible]-E comb[illegible] is given [illegible] Figure 4.12, along with a sa[illegible]n.

[illegible]ations [illegible] braking perf[illegible]nce of tow [illegible] 5, assu[illegible] [illegible]/45 pro[illegible]oning (see Fig[illegible] 4.11) agree [illegible] well with [illegible]red find[illegible] The additional curves pres[illegible] in Figure [illegible] illust[illegible] the importance [illegible] the level [illegible] [illegible]er braki[illegible]. Three lev[illegible] of trailer brake force are re[illegible] in

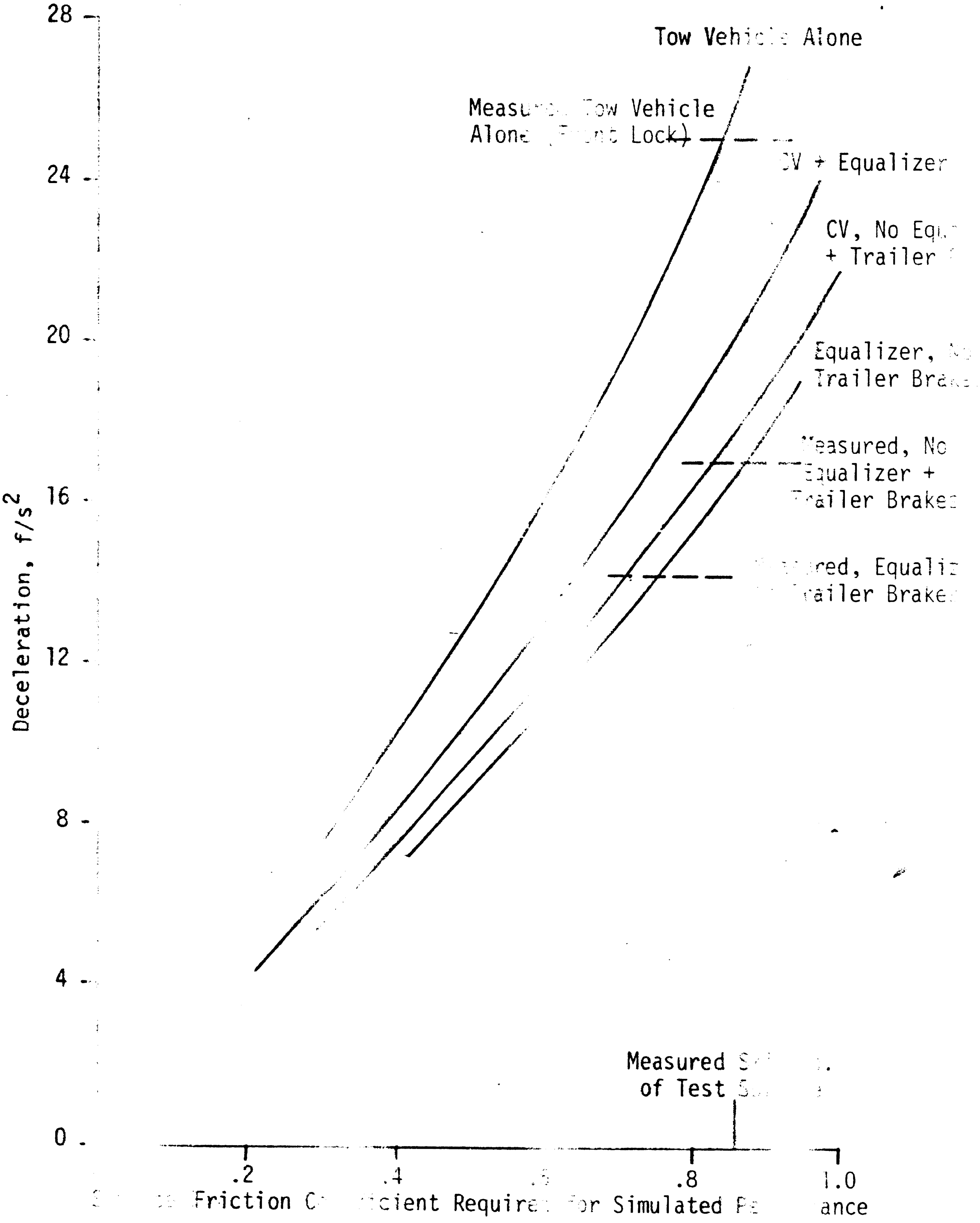


Figure [illegible].10. Simulated braking performance of loaded CV and tow vehicle alone.

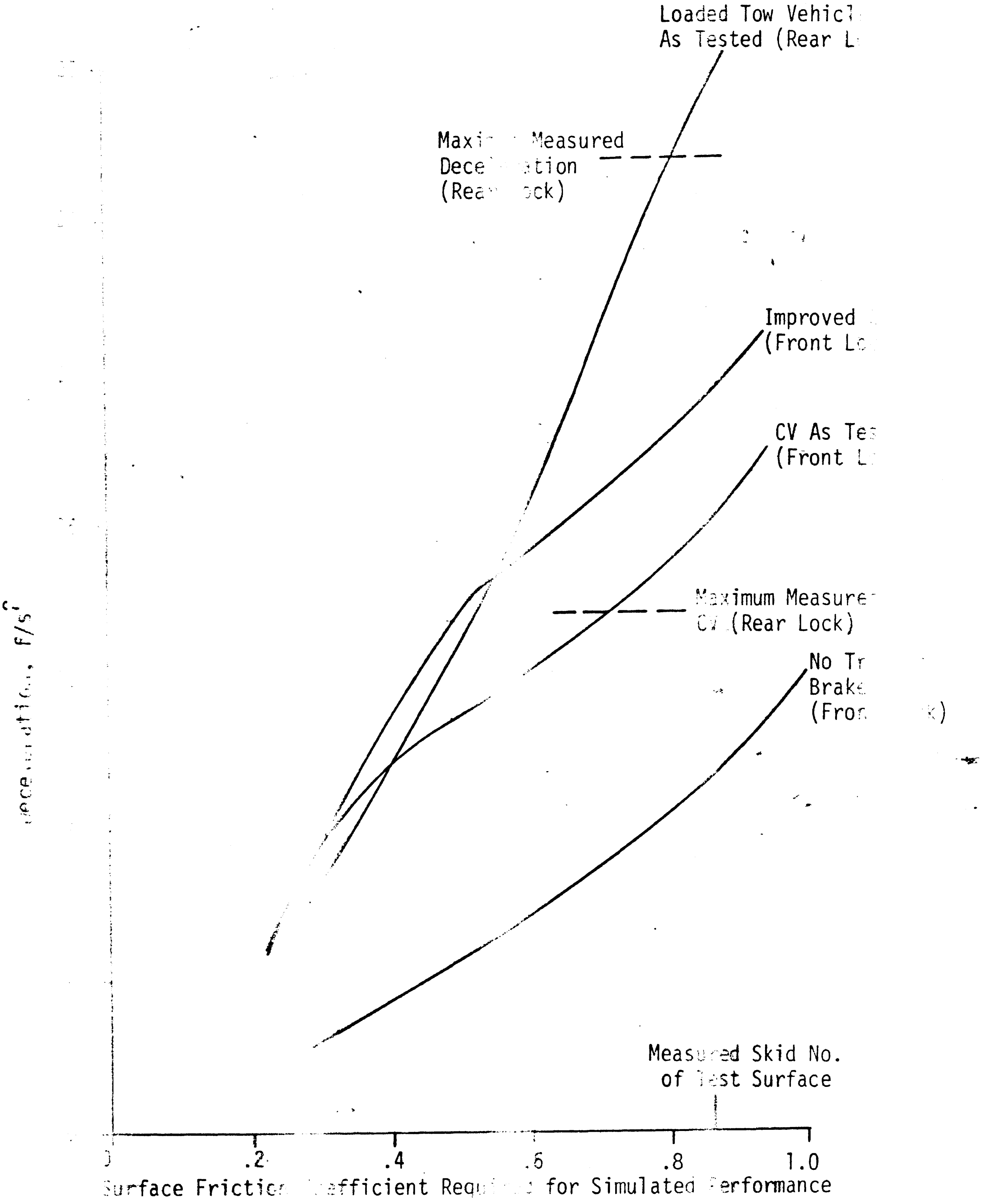


Figure 4.11. Simulated braking performance of CV 5-3 and tow vehic
5 axle.

```
* *ENTER DATA

01 A1   DISTANCE BETWEEN TRACTOR C.G. AND TRACTOR
           FRONT SUSPENSION (IN)                          8

02 A3   DISTANCE BETWEEN TRAILER C.G. AND FIFTH
           WHEEL (IN)                                     1

03 A4   DISTANCE BETWEEN TRAILER SUSPENSION AND
           TRAILER C.G. (IN)                              2

04 BB   DISTANCE BETWEEN FIFTH WHEEL AND TRACTOR
          REAR SUSPENSION (IN).  (FIFTH WHEEL LO-
           CATED AFT OF SUSPENSION IS POSITIVE)           -

05 L    WHEELBASE OF TRACTOR (IN)                       135

06 H    HEIGHT OF TRACTOR C.G. ABOVE GROUND (IN)        33.

07 HH   HEIGHT OF FIFTH WHEEL ABOVE GROUND (IN)         29.

08 HT   HEIGHT OF TRAILER C.G. ABOVE GROUND (IN)        53.

09 GVW1 WEIGHT OF TRACTOR (LB)                          78

10 GVW2 WEIGHT OF TRAILER (LB)                          20

DO YOU WISH TO INPUT BRAKE DISTRIBUTION (Y/N)? NO


  BRAKE AND TIRE PARAMETERS
TOTAL ATTEMPTED BRAKE TORQUE AT AN AXLE (IN-LB), ROLLING RADIUS
OF TIRE (IN), PEAK FRICTION COEFFICIENT, EFFECTIVE (OR SLIDING)
FRICTION COEFFICIENT: TP,R,MU,MUE

AXLE 1 (11,14,17,20)       6500.,1.,1.,.1

AXLE 2 (12,15,18,21)       5500.,1.,1.,.1

AXLE 3 (13,16,19,22)       5500.,1.,1.,.1


***END DATA INPUT
```

Figure 4.12a. Example input/output for simulation CV 5-E.

```
THE STEADY-STATE DECEL IS APPROXIMATELY 13.2 FF

                                    AXLE            AXLE            AXLE 3
    TOTAL ATTEMPTED
    TORQUE PER AXLE      -LB):     6500.  0        550             5500.00

         STATIC LOADING  (LB):     3345.  7        664            18093.05
        DYNAMIC LOADING  (LB):     4345   2        677            16469.6

             BRAKE FOR    LB):      484. .         550             5500.00
   EFFECTIVE FRICTION     FZ):     0.1             0.8             0.33

   HITCH FORCES (LB)        TIC:   FX =        0.00      F        2138.94
  (COMPRESSION POS.)        MIC:   FX =      771.74      F        3762.35

       AXLE 1 LOCKED (C     D)



     INITIAL VELOCITY     PH): 40.

     BRAKE DELAY TIME     EC): .5

     THE ESTIMATED ST     NG DISTANCE      160. FEE
```

Figure 4.12b. Example input/output for simulation 5-E.

the figure: (a) no brakes, (b) 5500 lbs brake force [illegible] measured in the trailer alone tests), and (c) an "imp [illegible] level of 8430 lbs brake force.

The "improved trailer braking results in CV perf[illegible] e in excess of 18 ft/sec on a .8 surface. This perfor[illegible] is obtained in spite of the prevailing la[illegible] over-runnin[illegible] es, because the tongue load which is appl[illegible] in front of [illegible] ow vehicle's rear axle, does not statical[illegible] or dynamical[illegible] found the tow vehicle's proportioning by unl[illegible]ing the tow [illegible] e's front wheels. (This conclusion is supported by the c[illegible] tion that lockup occurred at 900 psi in the [illegible]st performed [illegible] the loaded tow vehicle and [illegible] 1100 psi in [illegible] test perfor[illegible] th the CV, indicating increa[illegible] braking by the tow vehicle [illegible] CV test.) The rationale behind the choice of 8430 lbs [illegible] or the improved trailer will become apparent [illegible] Section 5.0 [illegible] s report.

4.2.5 <u>Trailer D.</u> During the course of this pr[illegible] trailer D was towed by tow vehicle 4, [illegible] three-quart[illegible] pickup truck. Several calculations were performed t[illegible] the braking of this combination.

Testing difficulties precluded a meaningful mea[illegible] of tow vehicle proportioning. Thus, throughout these c[illegible]ons we have used 55/45 for tow vehicle 4, [illegible] reasonable a[illegible]on based on our experience with tow vehicle 5, which has [illegible]king system similar to that of tow vehicle [illegible]

Some of the calculations are summarized in Figu[illegible], which presents peak wheels-unlocked deceleration versus μ [illegible] tow vehicle alone and the various CV's. The input data [illegible]d to simulate the 4-D combination is presented in Figure [illegible] long with a sample run.

---

*Tow vehicle 5 has wider rear linings, otherwise the [illegible] ystem.

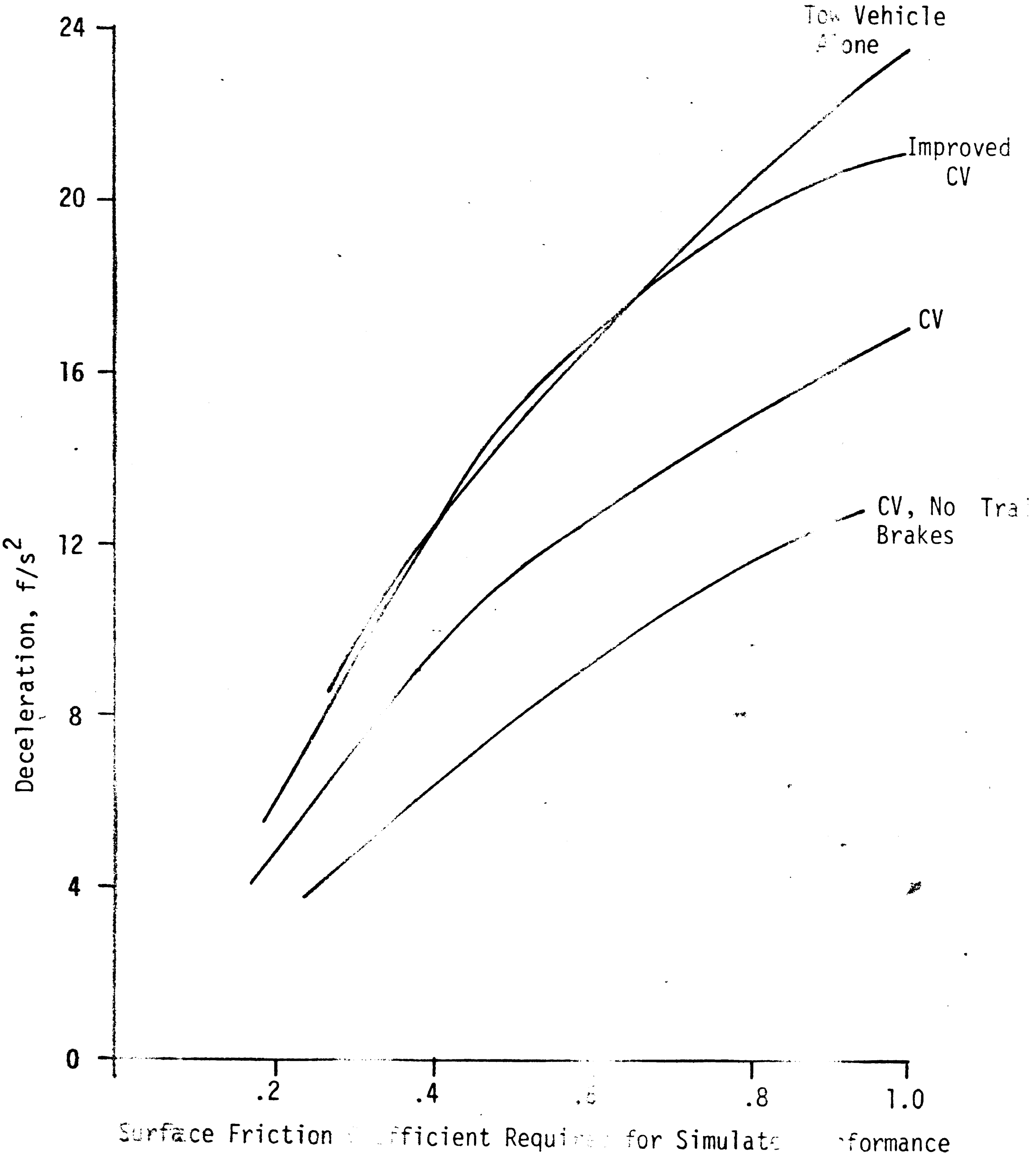


Figure 4.13. Simulated braking performance for CV 4-D and tow vehicle 4 alone.

```
***ENTER DATA

01 A1    DISTANCE BETWEEN TR                D TRACTOR
            FRONT SUSPENSION                                  5.5
02 A3    DISTANCE BETWEEN TR                D FIFTH
            WHEEL (IN)                                        17.
03 A4    DISTANCE BETWEEN TR               ION AND
            TRAILER C.G. (I                                   5.
04 BB    DISTANCE BETWEEN FI                TRACTOR
           REAR SUSPENSION                  WHEEL LO-
            CATED AFT OF SU                 ITIVE)            -4.
05 L     WHEELBASE OF TRACT                                   1.5
06 H     HEIGHT OF TRACTOR                  UND (IN)          .
07 HH    HEIGHT OF FIFTH WHE                ND (IN)           .
08 HT    HEIGHT OF TRAILER C               UND (IN)           .
09 GVW1  WEIGHT OF TRACTOR                                    70.
10 GVW2  WEIGHT OF TRAILER                                    35.
DO YOU WISH TO INPUT BRAKE                  (23)? NO

  BRAKE AND TIRE PARAMETERS
TOTAL ATTEMPTED BRAKE TORQU                (IN-LB), RO      RADIUS
OF TIRE (IN), PEAK FRICTIO                  EFFECTIVE        LIDING)
FRICTION COEFFICIENT: TP,R,

AXLE 1 (11,14,17,20)
AXLE 2 (12,15,18,21)
AXLE 3 (13,16,19,22)

***END DATA INPUT


 THE STEADY-STATE DECEL IS                  14.9 FPSP


                                              AXLE 2          AXLE 3
     TOTAL ATTEMPTED
     TORQUE PER AXLE (IN-LB                    2500.          1450.00

        STATIC LOADING (LB                     4117.          7317.54
       DYNAMIC LOADING (LB                     3172.          6916.93

          BRAKE FORCE (LB                      2500.          1450.00
 EFFECTIVE FRICTION (FX/FZ)                    0.79           0.21

 HITCH FORCES (LB)     STATI               0.00      FZ     1517.46
(COMPRESSION POS.)    DYNAMI              47.26      FZ     1918.07


     NO AXLES LOCKED (CYCLE
```

Figure 4.14. Exampl   or simulatio   4-D.

The loaded truck, as simulated, performs adequately, though not as well as the one-ton pickup whose calculated performance is presented in Figure 4.11. This finding is explained, in part, by the higher c.g. deriving from the four-wheel drive geometry of vehicle 4.

As one would expect with the weight of the trailer being significantly greater than the weight of the tow vehicle, the level of trailer braking is an extremely important determinant of CV braking performance. Three levels of brake force are shown in the figure, namely: (a) no brakes, (b) 1450 lbs (as measured in the trailer alone tests), and (c) an "improved" level of 3115 lbs of brake force.

The "improved" trailer braking results in quite reasonable performance, yielding almost 20 ft/sec^2 on a .8 surface. The rationale behind the choice of 3115 lbs is presented in Section .0.

4.3 Sensitivity Study

A sensitivity study was performed for combinations 2-B, 3- and 4-D to find, via computer simulation, the parameters most important in CV braking performance. Some results from the study are presented in Figures 4.15 through 4.20. In each figure, the vertical axis presents the peak friction coefficient, μ, necessary to prevent wheel lockup on the indicated axle at a vehicle deceleration level of 1/2 g. The vehicle parameter being varied is plotted on the horizontal axis. In each case, the range of parameter variation is judged to be large relative to variations which are likely to occur in use.

Figure 4.15 presents the sensitivity to rear-axle-to-hitch distance. (This is of particular interest here since on vehicles 2 and 3 the hitch was extended about twelve inches in the test program to accommodate the hitch transducer.) Altering this parameter affects the static distribution of axle loads on the tow vehicle. Thus, for CV's 2-B and 3-C, the load equalizer moment was also varied such that the fore/aft distribution of additional (where additional implies those resulting from trailer hitch vertical load and moment) static wheel loads on the tow vehicle remained constant. (This is consistent with recommended hitch adjustment practice.) Note that the CV

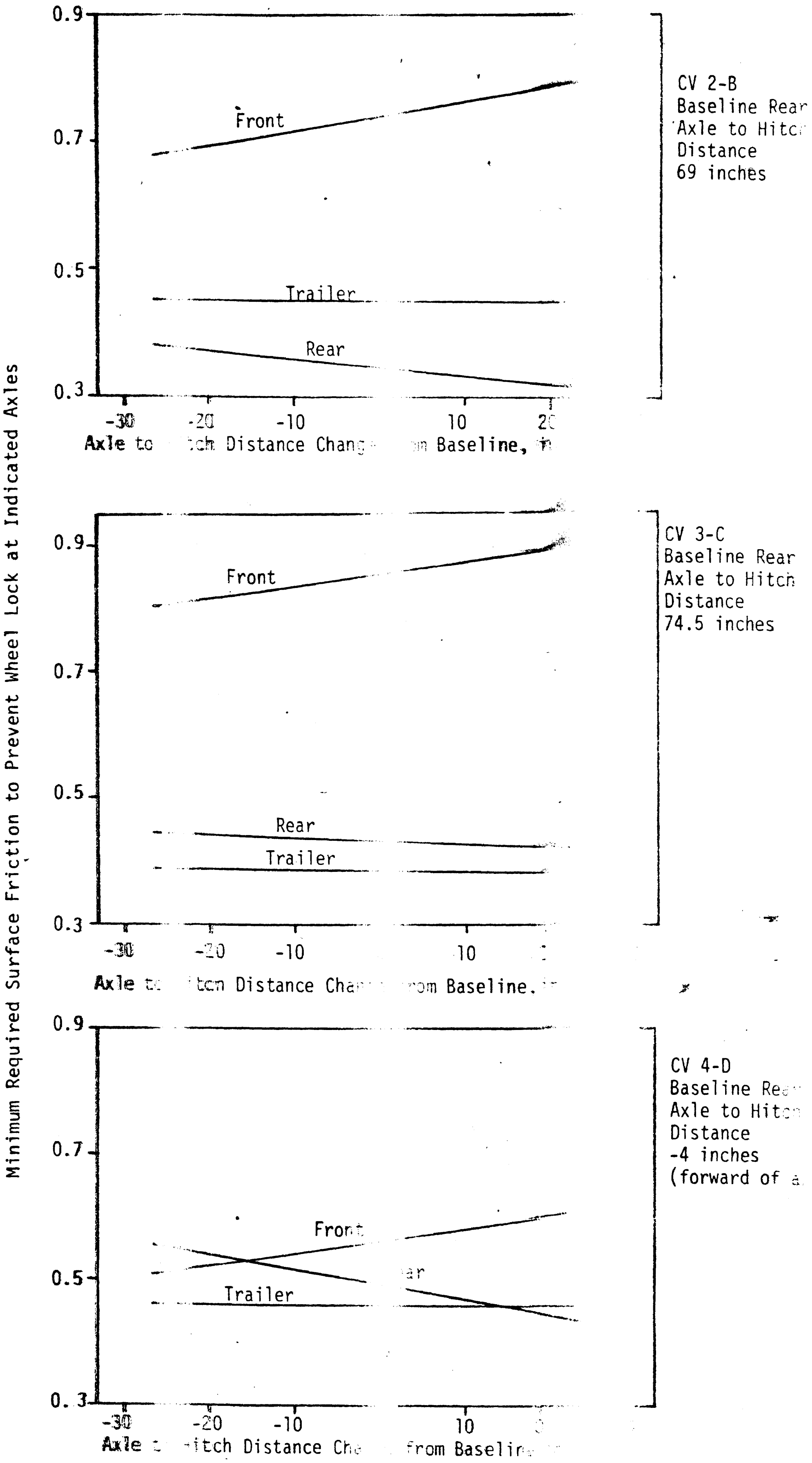


Figure 4.15. Minimum surface friction required for [illegible] ration as a function of rear-axle-to-hitch distance.

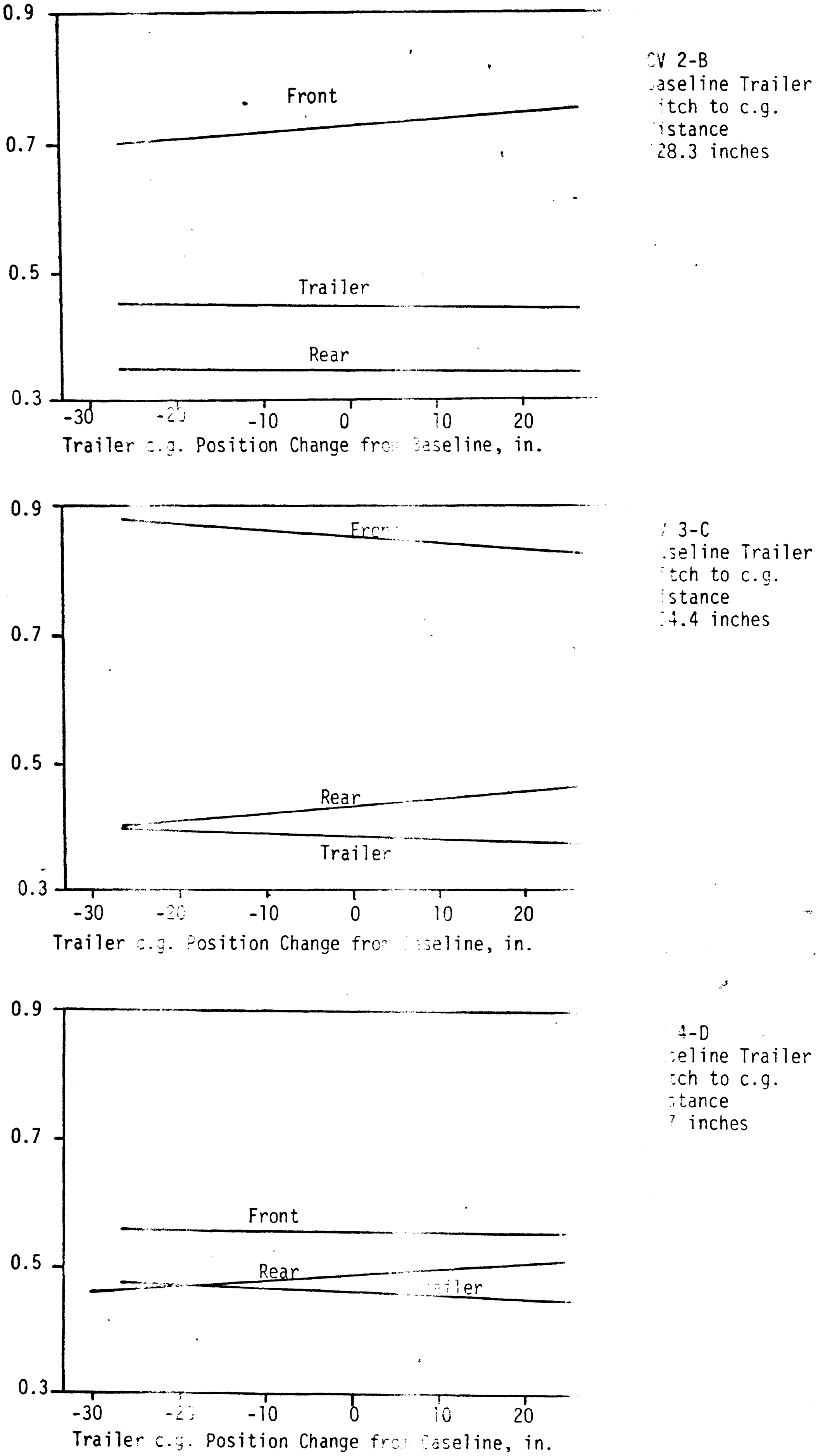


Figure 5.16. Minimum surface friction required for 1/ tion as a function of trailer hitch to c.g. dis

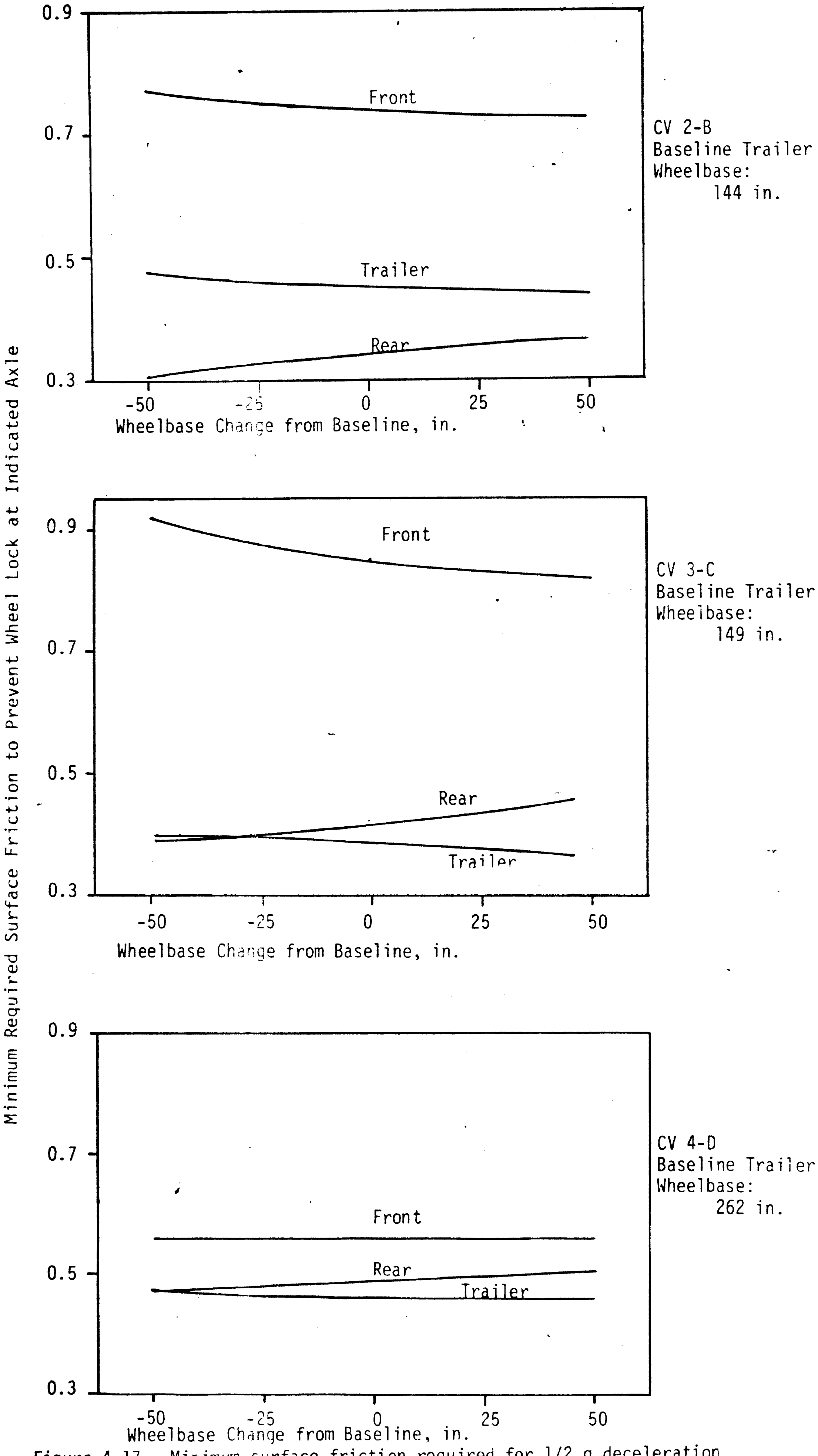


Figure 4.17. Minimum surface friction required for 1/2 g deceleration as a function of trailer wheelbase.

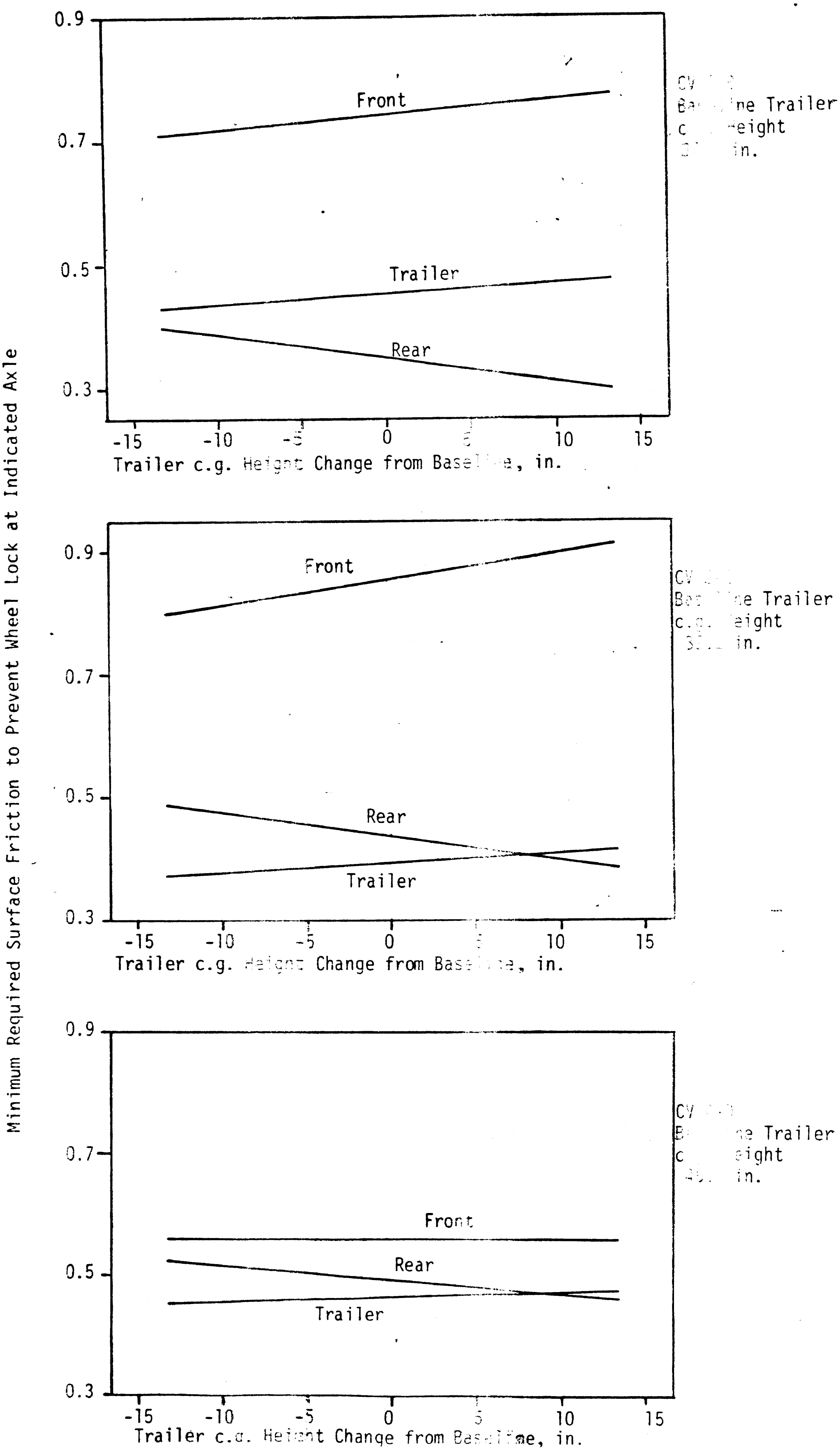
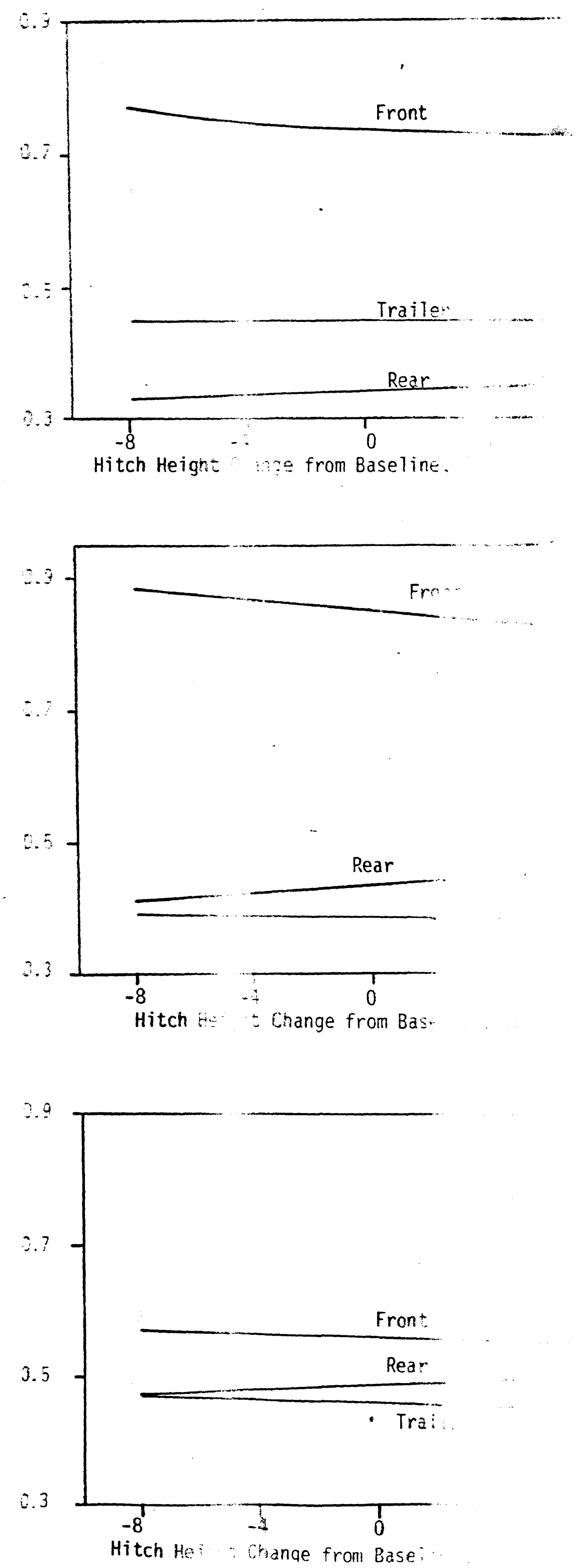


Figure 4.18. **Minimum surface friction required for 1/2 g decelerat**
as a function of trailer c.g. height.



n.

tch
in.

tch
0 in.

Figure 4.19. Minimum surface friction req
as a function of hitch height.

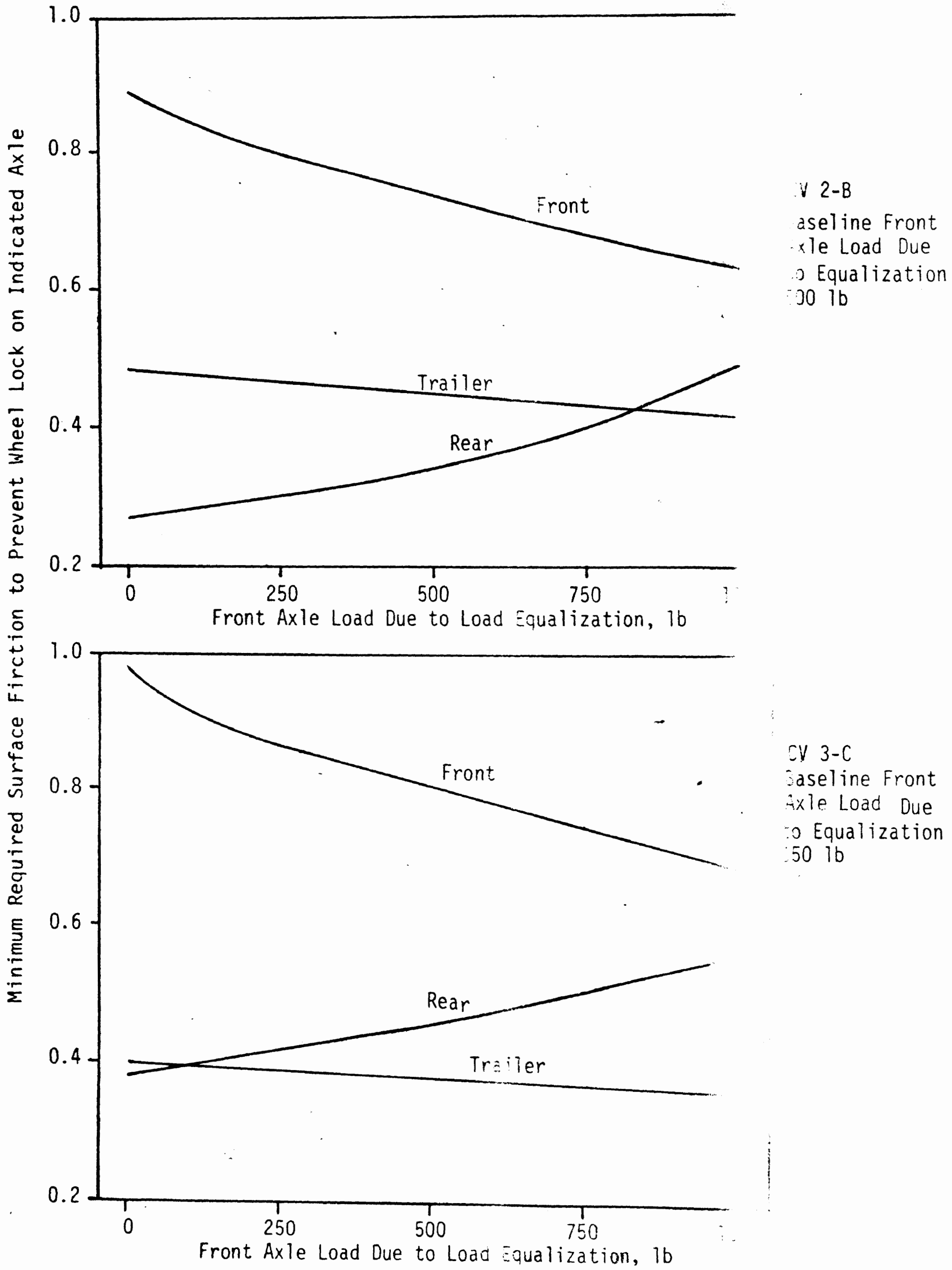


Figure 4.20. Minimum surface friction required for 1/2 g deceleration as a function of load equalization level.

always limited by front wheel lock except for an extreme forward position of the fifth wheel of CV 4-D, and that severe changes, the order of twelve inches, require less than .05 change in fron wheel peak friction coefficient.

Figure 4.16 indicates the sensitivity to the longitudinal location of the c.g. of the trailer (load equalization was agai varied to hold constant fore/aft distribution of additional sta loads on the tow vehicle axles), and Figure 4.17 indicates sensitivity to trailer wheelbase (the trailer c.g. location was also ed to give constant distribution of static trailer hitch and axle l s). In each case, the system was found insensitive to large changes.

Figure 4.18 indicates sensitivity to trailer c.g. height. re 4.19 indicates the sensitivity to hitch ball height. Again, in each case the combination is relatively insensitive to large ch s.

Figure 4.20 presents the sensitivity to the level of load equalization as a function of the static load added to the front tires via load equalization (i.e., zero on the horizontal scale indicates no load equalization moment). Clearly, these findings indicate that load equalization is a most influential variable. CV's shown require an increase of surface friction of about .15 load equalization is decreased from the baseline level to zero

The sensitivity of braking performance to load equalizati changes is obviously a direct result of the redistribution of axle loads. Alteration of other parameters, particularly tow v e hitch position (Figure 4.15) and trailer c.g. position (Figure can also alter static load distribution. As explained earlier, however, this effect was largely negated through compensating -ment of the load equalizing hitch. Such compensation is justi if it is assumed that the user will properly adjust the load equalizing hitch. Figure 4.20 indicates the potential changes performance if this assumption does not hold. It is also impor to note that for CV 4-D, load equalization is never used. Thus, Figures 4.15 and 4.16, the sensitivities demonstrated do include those effects resulting from changes in static axle loads.

5.0 A PROPOSED RULE FORMAT

In the preceding discussion of the simulation activity, the relative unimportance of several combination vehicle parameters, including center of gravity position, wheelbase and hitch position, to maximum CV braking performance was demonstrated. The remaining significant parameters are the weight and brake force capability of the combination plus the in-use factor of load equalizer adjustment. Further, it has been shown that the maximum wheels-unlocked brake force of the tow vehicle remains about the same with or without a trailer, given that the load equalization adjustment is maintained within reasonable bounds. This finding leads us to propose a simplified analysis of combination vehicle braking which will result in a utilitarian methodology for trailer brake performance testing in a standards/guidelines context.

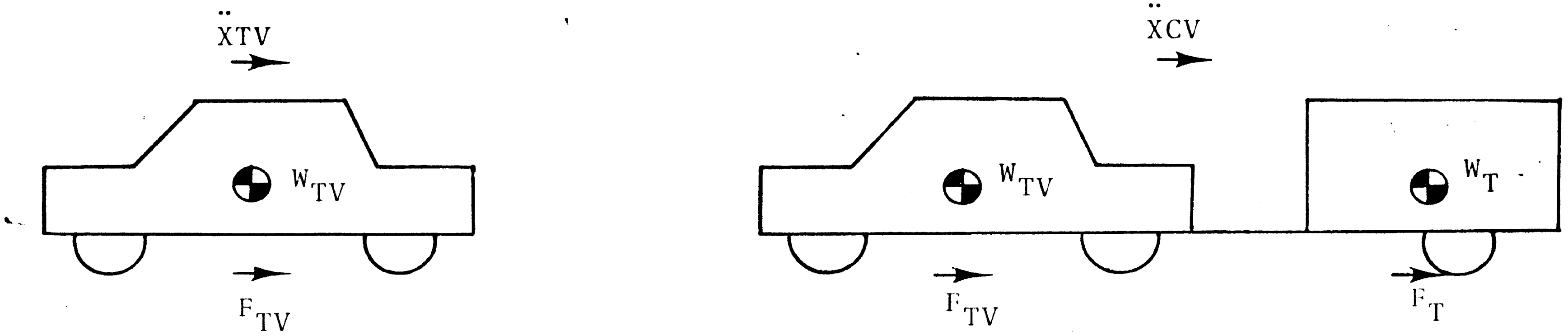
Consider first a combination vehicle using electric trailer brakes. Let us assume a maximum (high μ surface) wheels-unlocked brake force capability of F_{TV} lbs for a given tow vehicle, weighing W_{TV} lbs. Similarly, assume the trailer (weight W_T lbs) has a maximum brake force capability of F_T lbs. Finally, we assume F_{TV} and F_T are not altered by the forming of the combination. Then from the free-body diagrams of Figure 5.1, we find the deceleration capabilities (in g's) to be

$$\ddot{x}_{TV} = \frac{F_{TV}}{W_{TV}} \tag{5.1}$$

$$\ddot{x}_{CV} = \frac{F_{TV} + F_T}{W_{TV} + W_T} \tag{5.2}$$

for the tow vehicle alone and the combination vehicle, respectively. Solving Equation (5.1) for F_{TV} and substituting into (5.2) yields

$$\ddot{x}_{CV} = \ddot{x}_{TV} - \frac{\ddot{x}_{CV}W_T - F_T}{W_{TV}} \tag{5.3}$$



$$\ddot{X}_{TV} = \frac{F_{TV}}{W_{TV}} \qquad \ddot{X}_{CV} = \frac{F_{TV} + F_T}{W_{TV} + W_T}$$

$$\ddot{X}_{CV} = \ddot{X}_{TV} - \frac{\ddot{X}_{CV}W_T - F_T}{W_{TV}}$$

$$P \equiv \frac{\ddot{X}_{CV}W_T - F_T}{W_{TV}}$$

Figure 5.1. A simplified vehicle model which provides the basis for the rule.

Equation (5.3) indicates that in hitching a particular trailer and tow vehicle, a "deceleration penalty," P (in g's), is paid. That is, the combination vehicle deceleration is degraded relative to the tow vehicle alone deceleration by

$$P = \frac{\ddot{x}_{CV} W_T - F_T}{W_{TV}} \tag{5.4}$$

where

$$\ddot{x}_{CV} = \ddot{x}_{TV} - P \tag{5.5}$$

Now, substituting $\ddot{x}_{CV}$ from (5.5) into (5.4) and solving for W_{TV} yields

$$W_{TV} = \frac{W_T \ddot{x}_{TV} - F_T}{P} - W_T \tag{5.6}$$

Equation (5.6) may be used to define a minimum weight tow vehicle appropriate for use with the given trailer. For example, let us define the minimum tow vehicle deceleration as $\ddot{x}_{105}$, i.e., that sustained deceleration generally required by FMVSS 105-75. Further, define the maximum acceptable deceleration penalty to be P_m. Then

$$\ddot{x}_{TV} \geq \ddot{x}_{105} \tag{5.7}$$

$$P \leq P_m \tag{5.8}$$

Substituting (5.7) and (5.8) into (5.6) yields

$$W_{TV} \geq \frac{W_T \ddot{x}_{105} - F_T}{P_m} - W_T \tag{5.9}$$

Thus, if Equation (5.9) is satisfied, and given the assumptions of the analysis, then

$$\ddot{x}_{CV} \geq \ddot{x}_{105} - P_m \tag{5.10}$$

In implementing Equation (5.9), the trailer manufacturer might perform a trailer alone braking test (using virtually any tow vehicle) from which the maximum trailer brake force would be obtained. Using this result and the trailer gvw as W_T, the manufacturer would calculate W_{TV} and publish this figure as a guideline to the consumer, indicating the minimum weight tow vehicle acceptable for use with the trailer.

For trailers equipped with surge hitch braking systems, the actuation level of the brake system is a dependent variable determined by a closed-loop mechanism (as discussed earlier in Section 3.1.2). Thus, the direct measurement of F_T is not reasonable and the above analysis must be modified to be appropriate.

It can be shown that

$$\ddot{x}_{CV} W_T = F_T + F_H \tag{5.11}$$

where F_H is the compressive longitudinal hitch force (in lbs) acting on the trailer. Solving Equation (5.11) for F_H and substituting into Equation (5.3) yields

$$\ddot{x}_{CV} = \ddot{x}_{TV} - \frac{\overline{F}_H}{W_{TV}} \tag{5.12}$$

where the notation $\overline{F}_H$ indicates the value of F_H occurring at a combination vehicle deceleration of $\ddot{x}_{CV}$ g's. Thus, in this case, the deceleration penalty is

$$P = \frac{\overline{F}_H}{W_{TV}} \tag{5.13}$$

If we again specify that

$$P \leq P_m \tag{5.14}$$

and

$$\ddot{x}_{TV} \geq \ddot{x}_{105} \tag{5.15}$$

then from Equations (5.5), (5.14), and (5.15)

$$\ddot{x}_{CV} \geq \ddot{x}_{105} - P_m \tag{5.16}$$

Substituting (5.14) into (5.13) and rearranging yields

$$W_{TV} \geq \frac{\bar{F}_H}{P_m} \tag{5.17}$$

where $\ddot{x}_{CV}$ is limited by Equation (5.16).

In implementing Equation (5.17), the trailer manufacturer might perform a combination vehicle stopping test at a deceleration of $\ddot{x}_{CV} = \ddot{x}_{105} - P_m$.* In this test, the vehicle would be equipped to measure $\bar{F}_H$ directly. The results again would be used to calculate W_{TV} which would be published as a guideline to the consumer. In the test, any tow vehicle capable of attaining $\ddot{x}_{CV}$ when combined with the subject trailer could be used.

Equations (5.9) and (5.17) potentially provide the basic format for a standard or guideline. Their implementation, however, requires an answer to the question, "What constitutes maximum trailer brake force?" In previously promulgated Federal Motor Vehicle Safety Standards, the answer has been, in effect, "That

---

*Using the equality portion of Equation (5.16) would result in the lowest attainable value for $\bar{F}_H$.

att lock," a pos on ba
that sirable due t rection
cons ot clear that is is
answ trailer bra g.

in this pro makes it
pre or more whee an occur
to ability in ric traile
(b) le-axle susp ions commo
tra ng such occu ces,
to er stability not necess
deg a more cost- ective
ma might allow occur
a l er wheels es.

, usage fac ust be
occ at very lo al traile
le te the user djust
to d tire wear ow a
ti ng trailer torque
low e compromise ution is
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rul ke and surg ke (
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on e test data. ble 5

Table 5.1 Application of the Rule to the Electric Brake Trailers Tested.

$$W_{TV} \geq \frac{W_T \ddot{x}_{105} - F_T}{P_{max}} - W_T$$

$$\text{Let} \quad \ddot{x}_{105} = 2/3\ g \qquad\qquad\qquad\qquad$$
$$P_{max} = 1/6\ g \qquad \Rightarrow \qquad \ddot{x}_{CV} \geq 0.5\ g = 16.1\ f/s^2$$

		No Trailer Wheel Lock					Wheel Lock On One Trailer Axle				
				Actual Performance					Actual Performance		
Trailer	Trailer Weight W_T (lb)	Maximum Trailer Brake Force F_T (lb)	Calculated Min. Tow Vehicle Weight, W_{TV} (lb)	CV	Tow Vehicle Weight (lb)	$\ddot{x}_{CV}$ (f/s²)	Maximum Trailer Brake Force F_T (lb)	Calculated Min. Tow Vehicle Weight, W_{TV} (lb)	CV	Tow Vehicle Weight (lb)	$\ddot{x}_{CV}$ (f/s²)
B	5,000	2,584	0	2-B	4,803	19.9					
				1-B	4,707	19.2					
C	6,830	1,742	10,038	3-C	6,216	13.9	2,876	3,234	3-C	6,216	21.3
				2-C	4,803	[illegible]			2-C	4,803	19.9
D	[illegible]	1,440	17,865	4-D	6,270	11.8					
E	20,232	4,329	34,722	5-E	7,858	12.2	5,500	27,696	5-E	7,858	12.2

Table 5.2. Application of the Rule to the Surge Brake Trailer (and No Brakes Trailer) Tested.

$$W_{TV} \geq \frac{\overline{F}_H}{P_{max}} \quad \text{where} \quad \overline{F}_H = F_H @ \ddot{x}_{105} - P_{max}$$

$$\text{Let} \quad \ddot{x}_{105} = 2/3\ g \qquad \Rightarrow \quad \ddot{x}_{CV} \geq 0.5\ g = 16.1\ f/s^2$$

$$P_{max} = 1/6\ g$$

			No Trailer Wheel Lock			
				Actual Performance		
Trailer	Trailer Weight W_T (lb)	Trailer Tongue Force at 1/2 g F_H (lb)	Calculated Min. Tow Vehicle Weight, W_{TV} (lb)	CV	Tow Vehicle Weight (lb)	$\ddot{x}_{CV}$ (f/s^2)
A: with brakes & no equalizing	2,222	665	[illegible]	1-A	4,707	17.9
A: with brakes & equalizing	2,222	1,090	6,544	1-A	4,707	15.5
A: with no brakes & equalizing	2,222	1,111	6,666	1-A no brakes	4,707	14.2

only multiple axle trailers, presents results based on both no-trailer-wheels-locked and one-axle-wheel-lock criterion for F_T.

Several features of Table 5.1 are of interest:

1) With the exception of the 2-C wheels-unlocked combination, every CV wherein the weight of the tow vehicle as tested was less than the calculated W_{TV} exhibited less than 1/2 g measured deceleration, and every CV wherein the weight of the tow vehicle as tested was greater than W_{TV} exceeded 1/2 g measured deceleration.

2) Trailer C apparently exhibits better wheels-unlocked CV performance in combination with the 4808-lb tow vehicle (2) than with the 6216-lb tow vehicle (3). This illustrates two points, namely: (a) the low wheels-unlocked deceleration of combination 3-C is a result of premature lockup of one trailer wheel. This problem was attenuated after the 3-C test activity, apparently as a result of continued usage of the trailer C brakes in intervening tests. Note that with the wheel lockup allowed, as in the right-hand columns of Table 5.1, the performance of trailer C with tow vehicle 3 is excellent. (b) Tow vehicle 2 exhibited as high as 29 ft/sec^2 tow vehicle alone deceleration. Thus it is not surprising that CV's with tow vehicle 2 were able to out-perform the "guideline calculations" which assumed only 2/3 g deceleration for the tow vehicle alone.

3) Trailer B has a calculated W_{TV} of zero pounds, an indication that any tow vehicle is adequate to produce 1/2 g. This is a consequence of the fact that F_T for trailer B is more than half the trailer weight.

4) Because of low brake force capability relative to their weight, trailers D and E require very heavy tow vehicles according to the rule. Accordingly, when combined with the lighter tow vehicles used in this study, they did not meet the 1/2 g deceleration level. It should be noted that in the case of combination 4-D, this failure is partly due to problems with tow vehicle 4, discussed previously in Section 3.2.1 . Note, however, that the trailer braking system could be designed to operate with these tow vehicles. For example, Figures 4.11 and 4.13 have indicated that the use of only 3115 lbs brake force for trailer D and 8430 lbs brake force for trailer E would yield good braking performance for the 4-D and 5-E combinations. These levels of brake force are the minimum required for 4-D and 5-E to conform to Equation (5.9).

The results for trailer A, the surge-braked trailer, also conformed to the predictions of the rule (Table 5.2). (Since combination vehicle testing with this trailer was not conducted at precisely 1/2 g, $\overline{F}_H$ data was derived from interpolation of test results. For the case in which this trailer is considered with no brakes, $\overline{F}_H$ is simply specified at 1/2 the vehicle weight, i.e., the retarding force required to decelerate the trailer at 1/2 g.) Note, however, that in the latter two cases for this trailer, the actual tow vehicle weight is substantially below the minimum weight required by the rule while the actual combination vehicle deceleration is not so far below the 1/2 g level. This is indicative of the capability of tow vehicle number 1. In the tow vehicle alone tests, this vehicle achieved nearly 0.8 g deceleration without wheel lock.

In review, a scheme has been presented, and validated for a number of sample cases, which provides for reasonable assurance of a prescribed minimum braking capability of combination vehicles based on a simple measurement of the trailer's inherent braking capability and the assumption of a minimum braking performance of the tow vehicle alone (as implied by compliance with FMVSS 105-75 and current common design practice). It must be noted, however, that the success of the validation resulted, at least in part, from the fact that the combination vehicle braking performance data was gathered using procedures which adequately control in-use factors, particularly those regarding the use of load equalizing hardware and trailer brake application devices. Given the nature of combination vehicle systems, that is, that such vehicles are not manufactured or marketed as complete systems and that they do not become systems until their various parts are combined by the user, it seems clear that the effectiveness of virtually any rule could be thwarted through improper adjustment of in-use factors. Thus, any rule or guideline should ensure that

- adequate instruction be provided to the user concerning the proper adjustment of load equalizing devices
- an adequate trailer brake application device be provided as well as adequate instructions for its proper use
- the use of incompatible equipment (e.g., load equalizing equipment and certain surge hitches) is eliminated.

A final area of concern which rule-making procedures might deal with involves the consistency of performance of the trailer foundation brake. Electrically-actuated trailer foundation brakes have certain properties which make them quite desirable for use on trailers towed by vehicles with hydraulic brake systems. Nonetheless, electric brakes have been found historically, as well as in this study, to have a propensity for erratic behavior.* This property is demonstrated both in terms of temporal variance in the effectiveness of a single brake sample, as well as variance in the effectiveness of different samples of the same model of brake. Clearly, this property could hamper the effectiveness of any rule, since the representativeness of measured trailer brake performance to in-use performance is in question.

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*It is not our purpose to detail here the workings of the electric brake. Suffice it to say, the sources of this variability are not completely unknown. The basic high gain of the device, as well as the use of two friction surfaces (magnetic-to-drum in addition to lining-to-drum), are two primary sources of the problem.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This study has endeavored to apply the principles of vehicle mechanics to the braking process of combination vehicles on dry surfaces in order that a thorough understanding of the process might result and that those vehicle characteristics which have a major influence on the process might be identified. The study was conducted within a context defined by current passenger car and light truck brake system design practice. (Specifically, subject tow vehicles, both experimental and simulated, were limited to late models whose limit braking performance was generally in compliance with FMVSS 105-75.) The finding of primary importance is that, within this context, the proper hitching of trailer to the tow vehicle does not lead to gross alteration of the brake force capability of the tow vehicle as compared to its capability as a unit vehicle. As a consequence of this finding, and as confirmed by sample vehicle test results, it has been concluded that a practical "rule" can be presented through which the minimum braking performance of combination vehicles can be reasonably assured. The rule would combine a simple test procedure for determining the inherent braking capability of trailers and a guideline for determining acceptable tow vehicles based on the measurement. In addition, the rule must deal with several peripheral points largely concerned with in-use factors.

A number of specific findings derive from the study in support of the above. These findings are summarized below.

6.1 Findings Regarding the Mechanics of Combination Vehicle Braking on Dry Surfaces

1) The passenger cars tested in this program were found to be capable of very high decelerations on dry surfaces in gvw loading conditions, an indication that both front and rear wheels were braked to a point near the limit of adhesion. (Two of the

cars were limited by front lock.) When combined with trailers and making proper use of load equalizing hitches, all passenger car-trailer combinations tested were tow vehicle front-lock limited, and at the limit the tow vehicles supplied about the same level of brake force as they had when running alone.

2) The pickup truck-fifth wheel-trailers tested are in contrast with the passenger car-trailer combinations in that the vertical hitch load is applied slightly ahead of the rear axle rather than significantly aft of the rear axle. Since the hitch loads (vertical and longitudinal) are applied in the nominal load area of the truck, the brake force capability of the tow vehicle when in combination is again comparable to its capability when operating alone (in the loaded condition).

3) Multi-axle trailer suspension systems play an important role in trailer braking capability. Their ability to distribute vertical load equally among trailer wheels determines, in part, what portion of potential brake torque can, in fact, be utilized in producing trailer brake force.

4) The inherent braking capability of a given trailer may be determined by combination vehicle tests employing trailer brakes only.

5) The hydraulic brakes used on the surge-brake-equipped trailer tested in this study were more capable and consistent generators of brake torque than the electric brakes tested in this project.

6) The inherent variability of trailer foundation brakes, particularly electric brakes, puts in question the ability of a test trailer to accurately represent a model line of trailers.

7) Dynamometer tests of trailer brakes have limited usefulness in determining actual trailer braking capability due to suspension effects and brake variability.

8) Ancillary equipment can have an important effect on combination vehicle performance. As implied in (1) above, load equalizing hitch adjustment is important to tow vehicle performance when in combination with a trailer. Electric trailer brake controller adjustment affects trailer performance in the combination vehicle. The coarse resolution of the adjustment plus the testing activity required of the user can hamper good adjustment. For surge brake systems, no adjustment of the actuator is required (since system gain is inherent in design). However, surge brake application hardware may be incompatible with load equalization hardware.

6.2 Conclusions Regarding the Prospects for a "Rule"

1) A practical rule which provides reasonable assurance of a prescribed minimum braking capability of combination vehicles has been presented, and has been validated for a number of sample cases. The rule is based on a simple measurement of the trailer's inherent braking capability and the assumption of a minimum braking performance of the tow vehicle alone (as implied by compliance with FMVSS 105-75 and current design practice). The rule prescribes a minimum weight for the tow vehicle based on the trailer braking measurement.

2) The implementation of the rule requires an answer to the question "What constitutes maximum trailer brake force?" That is, what conditions of trailer wheel lock should be permissible in the conduct of trailer brake performance testing?

3) To be successful, the rule must deal with several in-use factors. It should ensure that

- adequate instruction be provided to the user concerning the proper adjustment of load equalizing devices
- an adequate trailer brake application device be provided as well as adequate instruction for its proper use

- the use of incompatible equipment (e.g., load equalizing equipment and certain surge hitches) is eliminated.

4) The most significant reservation regarding the effectiveness of the proposed rule involves the consistency of performance of trailer foundation brakes. As noted in Conclusion (7) of Section 6.1, test data may not accurately represent the performance of a model line of trailers.

6.3 Conclusions Regarding the Range of Braking Performance of Test Vehicles

1) A wide range of inherent braking capability of test trailers was measured. The ratio of maximum brake force to loaded trailer weight ranged from 0.16 to 0.52.

2) Measured combination vehicle performance demonstrated a similarly broad range. When test trailers were combined with tow vehicles demonstrating a braking capability compatible with FMVSS 105-75, maximum combination vehicle deceleration ranged from 12 f/s^2 to 21 f/s^2.

3) In view of the variance in performance of the trailer brakes tested, the findings of this study should be viewed only as indicative of the performance of the individual test trailer samples used.

6.4 Recommendations

In large measure, Section 5.0, "A Proposed Rule Format," constitutes the recommendations deriving from this study. In addition to the content of this section, the following recommendations are made:

1) The problems associated with various hardware elements, as pointed up in the conclusions, should not be construed as general indictments of any type of trailer brake system. While the variability problems of electric brakes are real, electric brake systems have other desirable features, including low cost and a trailer-to-tow-vehicle coupling which is convenient and relatively secure against contamination. Further, while some specific surge hitch hardware is incompatible with load equalizing hitches and should therefore be restricted to lighter trailers, design modifications in either component might lead to useful systems for heavier trailers. Surge systems do have the advantages of relieving the user of the brake adjustment tasks and allowing the use of hydraulic brakes on the trailer. The rule-making procedure should deal with such problems by promoting advances in design rather than restricting design choice.

2) The "rule" which has been recommended in Section 5.0 is quite simplistic. The price of this simplicity is recognized to be something less than complete assurance that all combination vehicles will be capable of the intended minimum deceleration capability. However, the rule could assure that very poor performers would be eliminated. Further, since it is in the user's hands to perform the final combining of trailers and tow vehicle into a total vehicle system, it would seem that virtually any rule, no matter how complex, would yield something less than full assurance of the desired minimum performance. In this light, and in consideration of the nature of the trailer industry (that is, the reduced level of economic and technical strength of many trailer manufacturers relative to the automobile manufacturer), a recommendation is made that the government strive for simplicity in any rule to be promulgated in the future.

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APPENDIX A

THE TEST VEHICLES

The test vehicles used in this program were chosen to cover a broad range of vehicle types and sizes. In choosing trailers, attention was paid to obtaining vehicles with a broad array of the following properties:

- Size: geometry and weight
- Brakes: number, size, manufacturer, and actuation mechanism
- Suspension: number of axles and tandem suspension types

Table A.1 describes the trailers which were chosen.

The tow vehicles used included compact, intermediate, and full-size passenger cars plus 3/4-ton and one-ton pickup trucks. These vehicles are described in Table A.2.

The ten test vehicles are pictured in Figures A.1 through A.5.

Table A.1. Test Trailers

General:					
Program Designation	A	B	C	D	E
Manufacturer	Starcraft	Fleetwood (Prowler)	Airstream	Holiday Rambler	Donahue
Model	Starmaster 6	20 ft. H	31 ft. Sovereign	32 ft. 5th Estate	20,000-lb Farm Utility
Wheelbase (in) (Hitch to Suspension Center)	98.5	144	149	262	218.5
Test Weight (lb)					
Empty	1440	3210	5760	6950	5961
Loaded	2222	5000	6830	8835	20,232
Hitch to C.G. Distance (in)					
Empty	84.3	128.3	127.8	204.7	183.7
Loaded	88.0	125.3	134.4	217.0	195.4
C.G. Height (in)					
Empty	28.1	38.9	42.4	49.9	34.9
Loaded	23.5	32.8	39.2	45.0	52.6
Brake:					
Manufacturer	Bendix	Fayette	Kelsey-Hayes	Dexter	Kelsey-Hayes
Size	7x1-3/4	10x2	12x2	12x2	12x2
Type	Hyd. Drum	Elec. Drum	Elec. Drum	Elec. Drum	Elec. Drum
Actuation	Bendix SUR Act III Surge Hitch	Kelsey-Hayes No. 81740	Kelsey-Hayes No. 81740	Kelsey-Hayes No. 81740	Kelsey-Hayes No. 81740
Suspension Type	Leaf Spring Single Axle	4-Spring Tandem with Load Leveler	"Duro-Torque" 2 Independent Axle	"MORIRYDE" Modified Walking Beam Tandem	3 Independent Axle

Table A.2. Test Tow Vehicles

Program Designation	1	2	3	4	5
Manufacturer	Chevrolet	American Motors	Chevrolet	GMC	GMC
Model	Nova	Matador	Impala Wagon	K2500 Pickup	C5500 Pickup
Wheelbase (in)	111	118	125	131.5	135.5
Test Weight* (lb)					
Empty	4487	4803	5937	5650	5438
Loaded for Testing Alone	4810	5162	6216	7816	10010
Loaded for Testing with Trailer	4707	4803	5937	6270	7858
Front Axle to C.G. Distance (in)					
Empty	57.1	55.3	73.1	61.3	61.8
Loaded for Testing Alone	57.6	56.2	72.3	69.9	90.0
Loaded for Testing with Trailer	57.7	55.3	73.1	55.0	80.5
C.G. Height (in) (Estimated)					
Empty	24	24	24.5		
Loaded for Testing Alone	24	24	24.5		
Loaded for Testing with Trailer	24	24	24.5		

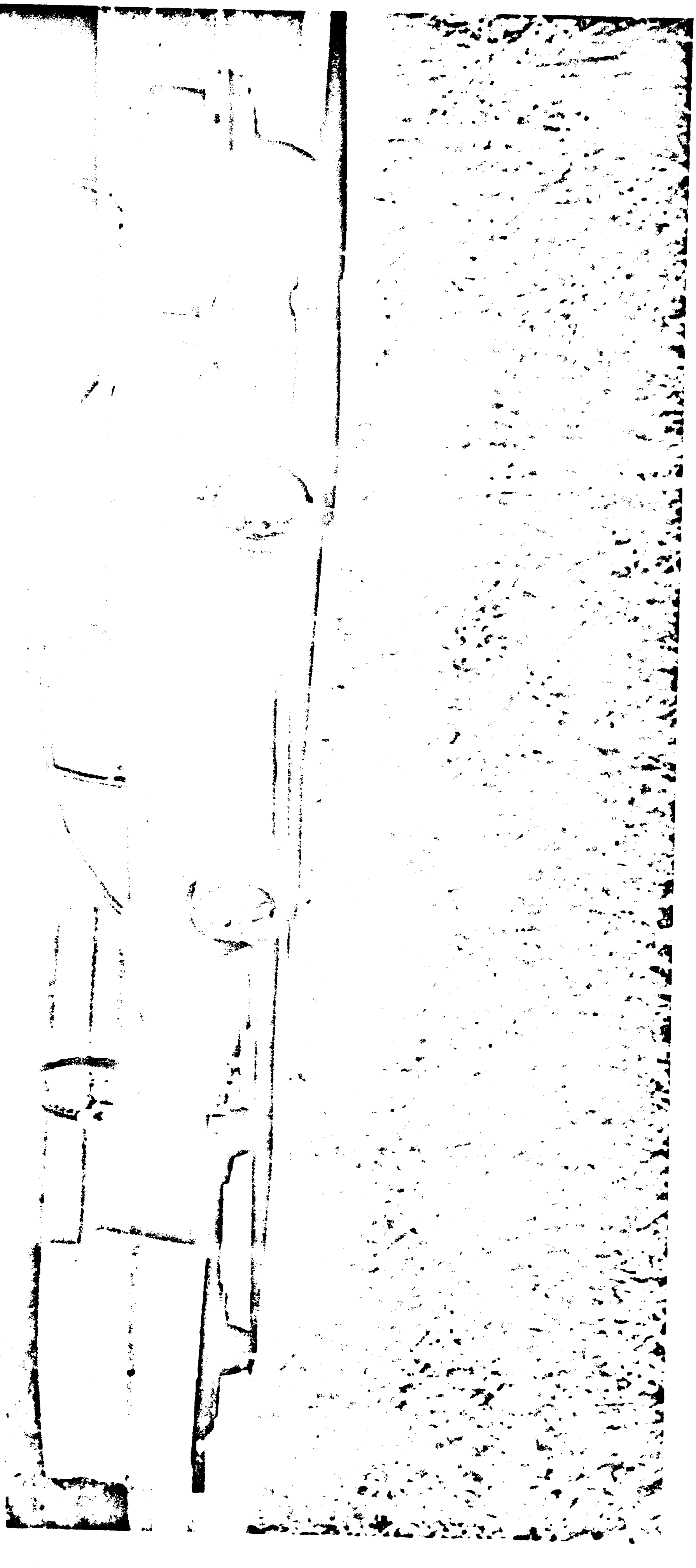


Figure A.2. Tow Vehicle 2 and Trailer B

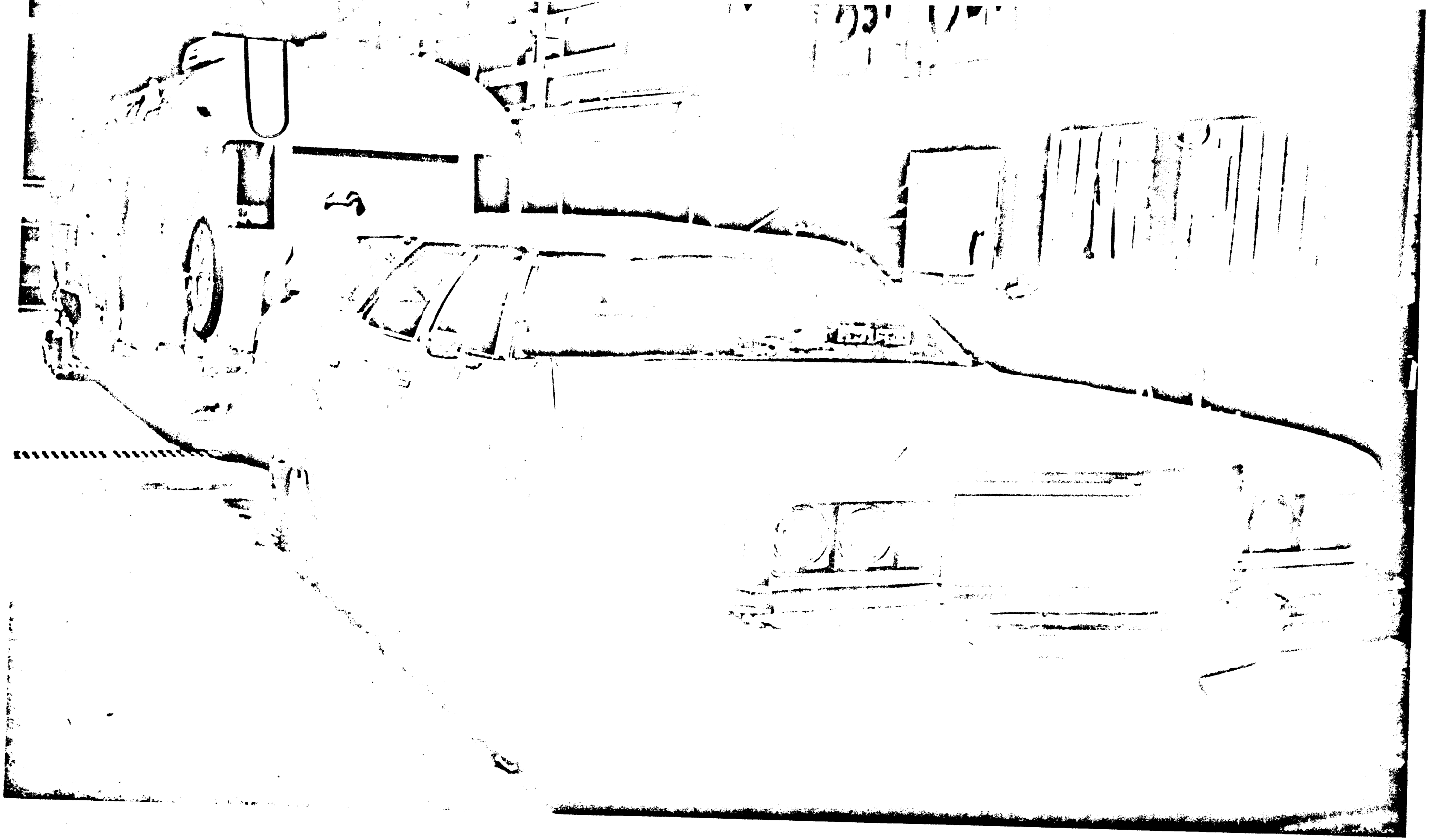
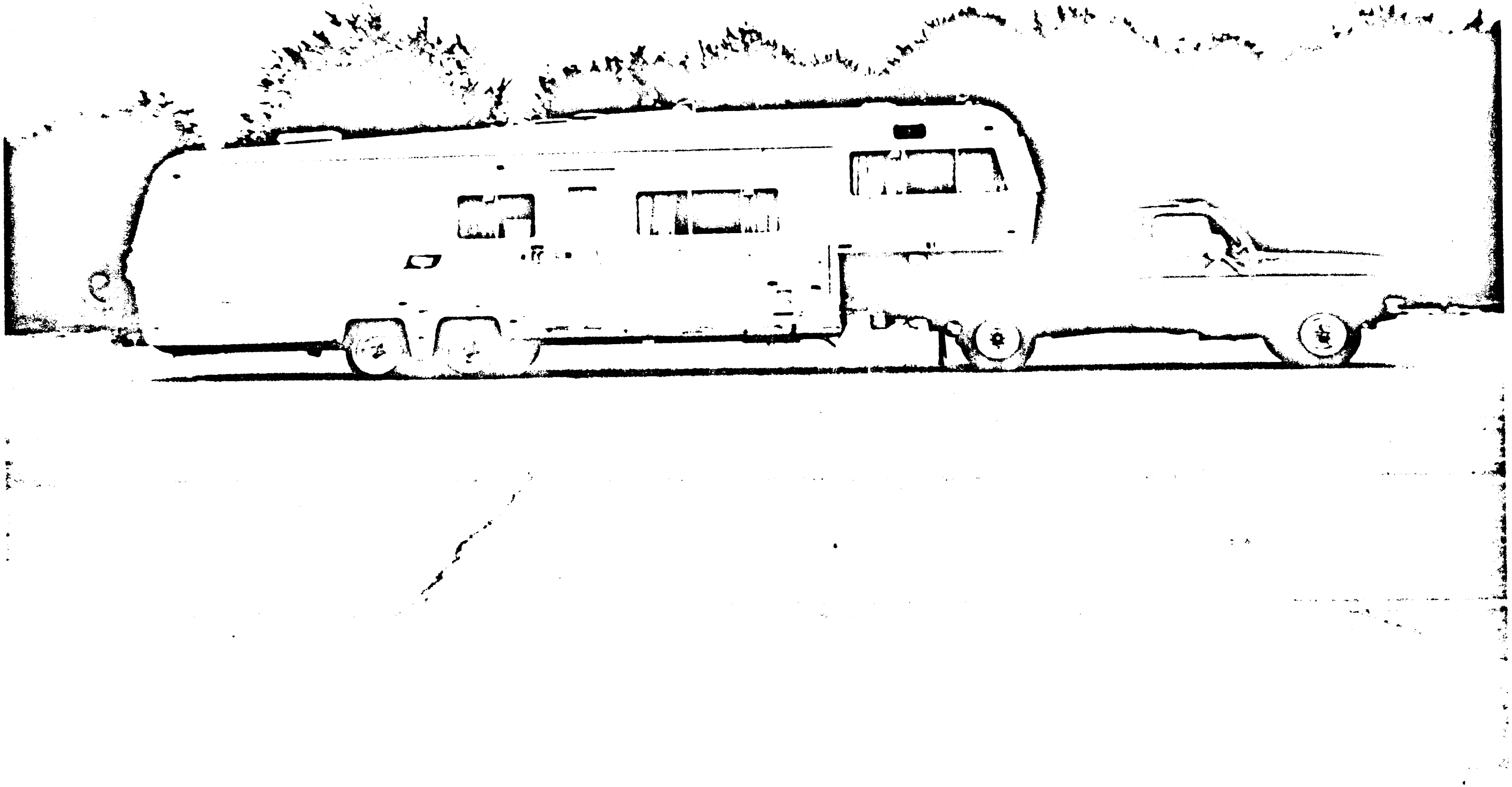


Figure A.3. Tow Vehicle 3 and Trailer C



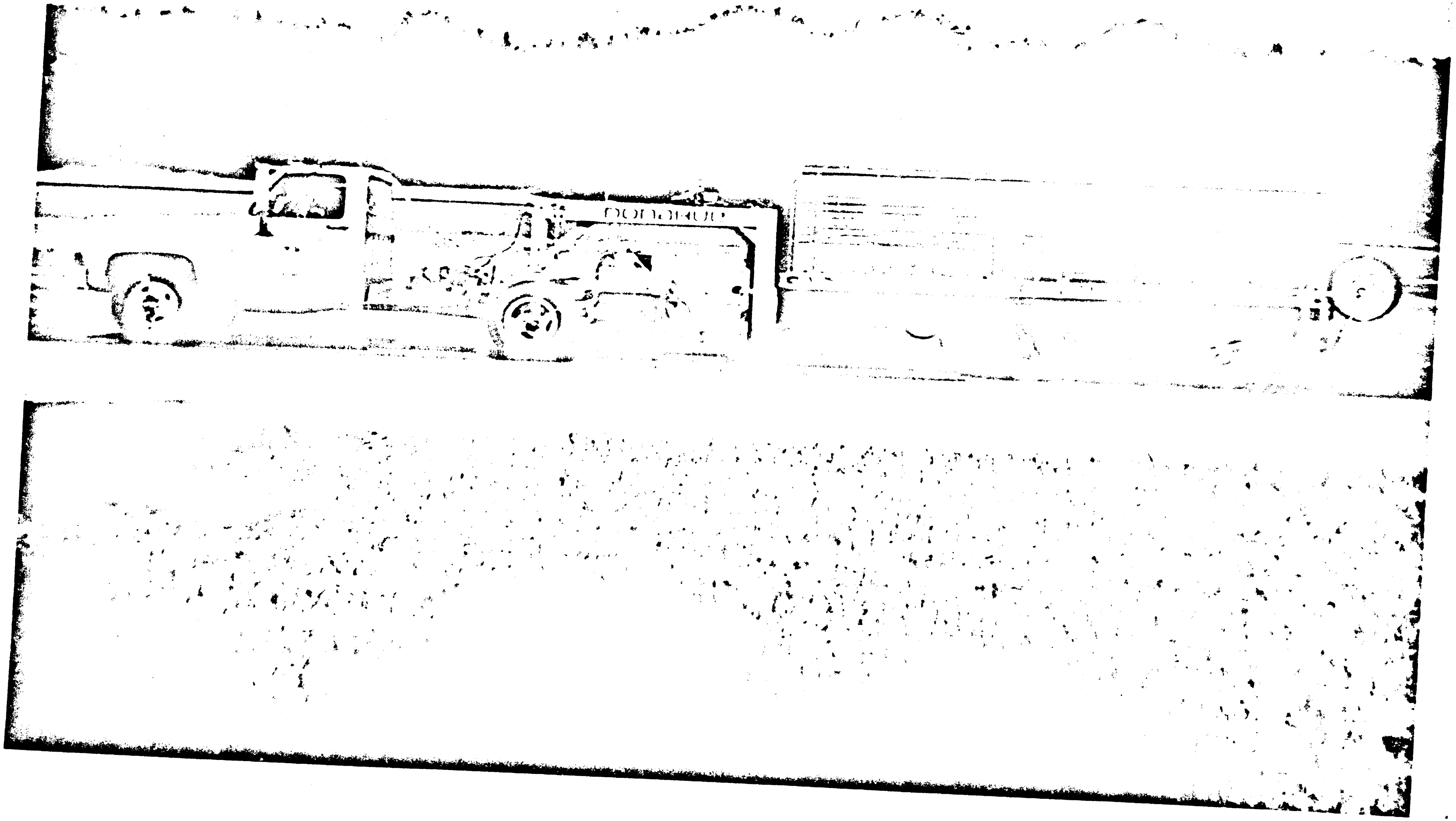


Figure A.5. Tow Vehicle 5 and Trailer E

APPENDIX B

VEHICLE TEST PROGRAM
TRAILER BRAKING PERFORMANCE

B.1 Introduction

The vehicle testing portion of the "Trailer Braking Performance" project was conducted at the Bendix Automotive Development Center (BADC). The program was structured to examine basic questions addressing combination vehicle (CV) braking performance, viz.,

1) What is the stopping performance capability of the tow vehicle (TV)?
2) What is the inherent braking capability of the trailer?
3) What penalty or burden in stopping capability derives from uniting the towing and trailing vehicles into a CV?

Four distinct test sequences were designed to probe these questions, viz.,

1) TV effectiveness tests
2) Trailer alone (TA) effectiveness tests
3) CV effectiveness tests
4) Trailer fade tests

The five tow vehicles and five trailers summarized in Table B.1 were the subjects of the testing program. Note that the tow vehicles are numbered 1 through 5, and the trailers are letters A through E. (These designations will be used throughout this document.) With these ten unit vehicles, five "nominal match" combinations vehicles, i.e., 1-A, 2-B, 3-C, 4-D, and 5-E, can be established. These five combinations all conform with manufacturers' recommendations for towing combinations except 5-E. This last

Table B.1 Test Vehicles

1. Chevrolet Nova
2. AMC Matador
3. Chevrolet Impala Wagon
4. GMC 7500-lb GVW Pickup
5. GMC 10,000-lb GVW Pickup

A.	Starcraft	Starmaster 6
B.	Fleetwood	Prowler H
C.	Airstream	31 ft. Land Cruiser
D.	Holiday Rambler	32 ft. 5th Estate
E.	Donahue	20,000-lb GVW Farm Utility

combination exceeds the pickup manufacturer's recommendation for gross combination vehicle weight (gcvw).

Figure B.1 presents the general test matrix. The following sections present details of the particular tests. Section B.6 deals with general test conditions, including vehicle condition and instrumentation.

Vehicle	Tow Vehicle Alone	Trailer Alone			Combination Vehicle
	Post-Burnish Effectiveness	Pre-Burnish Effectiveness	Post-Burnish Effectiveness	Fade	Post-Burnish Effectiveness
1, 2	GVW Load 40 & 60 mph				
3, 4, 5	40 mph				
		Trailer Loaded-Tow Vehicle Empty			
A		40 mph	40 & 60 mph	40 & 60 mph	
B		40 mph	40 & 60 mph	40 mph	
C, D, E		40 mph	40 mph	40 mph	
					One Each: Trailer Loaded-Tow Vehicle Loaded Trailer Empty-Tow Vehicle Loaded
1-A, 2-B					40 & 60 mph
3-C, 4-D, 5-E 1-B, 2-C					40 mph
					Trailer Loaded-Tow Vehicle Loaded
1-A (No Brakes on A)					40 mph

Figure B.1. Testing Matrix

B.2 Tow Vehicle Alone Tests

The five tow vehicles were delivered to BADC with their brake systems in "as new" condition. Thus a 200-stop burnish, per FMVSS 105-75, was conducted on each vehicle prior to any other activity concerning that vehicle. The brakes were adjusted following burnish.

With the brakes burnished, effectiveness tests were conducted on each vehicle. These tests were conducted on vehicles loaded to gvwr (see Section B.6) on a dry asphalt surface, and from an initial velocity of 40 mph. Vehicles 1 and 2 were also tested from an initial velocity of 60 mph.

Stops were conducted in order to:

1) Establish the maximum wheels-unlocked stopping performance. Iterative stops were conducted to establish the brake line pressure (within at most 50 psi), P_0, at which this performance occurs.
2) Determine an effectiveness curve for the vehicle by conducting additional stops at .8 P_0, .6 P_0, .4 P_0, and .2 P_0.

This test was repeated to examine repeatability of results.

B.3 Trailer Alone Tests

The term "trailer alone" as used in this document implies trailer brakes alone. Of course, these tests were conducted with the trailer coupled to a tow vehicle, but only trailer brakes were used. The purpose of these tests was to establish the inherent braking capability of the trailer.

The trailer alone tests included:

1) Pre-burnish effectiveness
2) Burnish
3) Post-burnish effectiveness

These tests were conducted on a dry asphalt surface, with the tow vehicle empty and the trailer in the loaded condition,* and from initial velocities of 40 mph. Additional tests of trailers A and [illegible] were conducted from 60 mph.

B.3.1 Trailer Effectiveness Tests. The purpose of the effectiveness tests was to determine the trailer's inherent braking capability in its burnished and unburnished condition. These TA effectiveness tests were designed very much like the tow vehicle effectiveness test. For each test, pre- and post-burnish, stops were made to:

1) Establish the maximum deceleration which is obtainable using trailer brakes only within the condition that wheel lock is allowable on only one trailer axle for multiple-axle trailers, and no wheel lock is allowable for single-axle trailers. Iterative snubs from 40 mph to a speed designated by Equation (B.1) below were conducted to define the brake actuation level, L_0, which results in this maximum performance. (L_0 is defined in terms of voltage for the electric brake trailers and line pressure for the hydraulic brake trailer.)
2) Establish an effectiveness curve for the trailer brakes by conducting snubs at brake actuation levels of .8 L_0, .6 L_0, .4 L_0, and .2 L_0. These snubs also occur from an initial 40 mph to a final velocity defined by Equation (B.1).

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*See Section [illegible].

These tests were repeated to examine repeatability of results.

The final velocity of the effectiveness tests snubs is:

$$V_f = 40\sqrt{1 - \frac{W_{TA}}{W_{CV}}} \quad \text{mph} \qquad (B.1)$$

W_{CV} is the total weight of the combination vehicle

W_{TA} is the total static weight on the trailer axles

Snubs of the CV from 40 mph to V_f, using trailer brakes only, result in the trailer brakes absorbing the same amount of kinetic energy as they would if they were to stop a vehicle equal in weight to the static trailer axle loading, from 40 mph.

B.3.2 Trailer Burnish. The trailer burnish procedure was modeled around the burnish prescribed by FMVSS 105-75. The burnish consisted of 200 snub stops from an initial velocity of 40 mph to a final velocity of V_f as prescribed by Equation (B.1) above, and at a deceleration level of:

$$a = 12\,\frac{W_{TA}}{W_{CV}} \quad \text{fps}^2 \qquad (B.2)$$

As previously explained, by snubbing to V_f with trailer brakes only, the trailer brakes will absorb the same amount of energy as they would if they were to stop a vehicle with weight equal to the static trailer axle load.

In the trailer brake burnish, matters regarding brake temperature, distance between snubs, etc., were as per FMVSS 105-75, S7.4.1.

B.4 Combination Vehicle Effectiveness Tests

The purpose of the CV effectiveness tests was to determine the burden suffered in braking performance due to combining the tow vehicle and trailer into a CV. These tests were conducted on a dry asphalt surface from an initial velocity of 40 mph, with 60-mph tests also conducted on CV's 1-A and 2-B. Tests consisted of several full stops as described below.

The CV's tested were the five "nominal match" CV's (see Section B.1), plus three "mismatch" CV's. The mismatch CV's were: 2-C, 1-B, and 1-A in which A was fully loaded and its brakes were inoperative.* (Note that brakes on trailer A are optional equipment.) Except for the mismatch vehicle 1-A, all CV's were tested in two loading conditions, viz., trailer and tow vehicle loaded and tow vehicle loaded, trailer empty (see Section B.6.2.).

In these tests, brake application was accomplished in a normal manner, i.e., the hydraulic brakes of A were actuated by the surge hitch mechanism and all electric brakes by a commercially available electric brake applier. The electric brake appliers were adjusted according to manufacturer's recommendations as described in Section B.6.

The effectiveness tests were performed in the following manner:

1) Stops were conducted at tow vehicle braking levels of .2 P_0, .4 P_0, .6 P_0—etc., where P_0 was established for each tow vehicle by the previous tow vehicle effectiveness tests.

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*It is primarily because of this mismatch CV testing that a 40 mph initial velocity is used in all testing. This speed is seen as reasonable for combinations with larger trailers and smaller cars. It is then used throughout to enhance analysis of results.

2) The above sequence was continued until

   a) any wheel lock occurred on the tow vehicle,

   b) wheel lock on two axles of multiple-axled trailers occurred, or

   c) any wheel lock occurred on a single-axle trailer.

3) Braking level required for wheel lock was determined within 50 psi of tow vehicle line pressure.

4) (1), (2), and (3) were repeated.

B.5 Trailer Fade Tests

The purpose of the trailer fade tests was to examine the fade quality of the brakes with which the trailer is equipped. The fade test procedure was structured similarly to the first fade and recovery test of FMVSS 105-75 for vehicles in excess of 10,000 lb gvw, i.e., S7.11 of FMVSS 105-75.

The fade tests were run as "trailer alone" tests, i.e., only trailer brakes were employed. The initial velocity of all snubs was 40 mph (as per 105-75), the final velocity was

$$V_f = \sqrt{40^2 - \frac{W_{TA}}{W_{CV}}(40^2 - 20^2)} \text{ mph} \qquad \text{(B.3)}$$

where

W_{TA} is the total static trailer axle load

W_{CV} is the total combination vehicle weight.

This final velocity produces an energy absorption per snub equal to that which would occur if the trailer brakes were decelerating a vehicle of a weight equal to the total trailer axle static load, from 40 to 20 mph.

Similarly, the accelerations required in the procedures were not 10 fps^2, but rather

$$a = 10 \frac{W_{TA}}{W_{CV}} \text{fps}^2 \qquad \text{(B.4)}$$

Thus, brake forces were equal to those which would be required to decelerate a vehicle equal in weight to the total trailer axle static load, at 10 fps^2.

B.6 General Test Conditions

General test conditions which have not been covered previously will be detailed in this section. Topics considered will include vehicle equipment, condition, loading, instrumentation, and data collection.

B.6.1 Test Vehicles: Equipment and Condition. The vehicles employed in this test program were listed in Table B.1, above. In preparation for testing, all vehicle brake systems were put in "as new" condition. The three passenger cars were equipped with springs, shocks, and brakes as recommended by their manufacturers for trailer towing.

The three passenger cars were equipped with a frame-mounted trailer hitch capable of using load equalizing hardware. Vehicle 4 was fitted with a fifth wheel kingpin hitch in the bed area for use with trailer D. Vehicle 5 was fitted with a ball-type hitch in the bed area as required for trailer E. All of the tow vehicles were equipped with commercially available Kelsey-Hayes electric brake actuators.

All of this "trailer equipment" was used according to manufacturers' recommendations when possible.* Load leveling hitches were adjusted such that

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*Necessary exceptions due to conflicting recommendations from various manufacturers were discussed in Section 3.2.3.

$$1/2 \text{ inch} \geq \Delta BH_R - \Delta BH_F \geq 0 \qquad (B.5)$$

where

ΔBH_R is the change in the tow vehicle's rear bumper height due to hitching trailer to tow vehicle

ΔBH_F is the change in the tow vehicle's front bumper height due to hitching trailer to tow vehicle.

(In both cases, a downward deflection of the bumper due to hitching trailer is positive.)

A simplified schematic of the commercial electric brake control system is shown in Figure B.2. In operation, the variable resistor (R_1) of the controller is "set" by the action of a small hydraulic piston activated by brake line pressure (P) and working against a spring. The spring is adjustable so that the relationship between P and R_1 is adjustable. In one controller tested by HSRI, this adjustment provided for controller saturation (R_1 = 0) for pressure ranging from 650 to 800 psi. Thus, the controller adjustment can affect the distribution of braking effort in the CV at lower levels, but not at higher application levels where line pressure exceeds 800 psi. A second adjustment

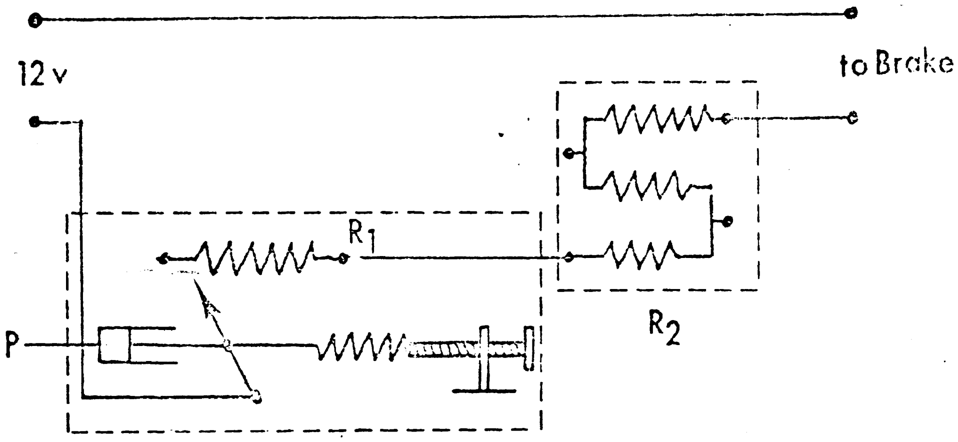

Figure B.2. Electric Brake Control System.

is provided by the selective resistor, R_2. As the figure shows, four connection terminals are provided on R_2 so that various resistance levels may be chosen. The choice of R_2 determines the maximum braking effort available at the trailer.

Manufacturer's recommendations call for selecting R_2 from a table based on total trailer loaded weight and the number of trailer axles and brakes, with the further stipulation that the choice of resistor be modified to obtain "firm braking action just short of skidding on dry pavement" with full controller application. Further, the controller adjustment should be made to "provide for a slight lead of the trailer brakes over the tow vehicle brakes." As per the explanation given in Section 3.2.3, table values for R_2 were used unless this resulted in obviously misadjusted brakes.

Inflation pressure of all vehicle tires was maintained throughout testing as follows: Prior to testing, tires were inflated to the manufacturers' recommended cold inflation pressure for the test loading condition. The vehicle was then driven at 40 mph for 15 miles to establish the "hot" inflation pressure. This inflation pressure was maintained for all tests conducted under the given loading condition.

In addition to maintaining inflation pressures, all tires were "broken in" prior to effectiveness testing. For the tow vehicles, the burnish procedure was adequate for this purpose. For the trailers, at least 15 snubs equivalent to those used for the trailer burnish procedure were required prior to effectiveness testing.*

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*The use of braking snubs, rather than the traditional 100-mile "run-in" for tire break-in, is in line with HSRI's findings as reported to NHTSA in "A Braking Efficiency Test Technique" (DOT-HS-031-765). In this study, it was found that two samples of tires showed significant friction transients of the first 10 to 15 brake applications, regardless of whether they were "run in" or not.

Brake lining temperature conditions for all testing was basically as provided for by FMVSS 105-75, viz.:

- Initial temperatures for all effectiveness stops were 150°- 200°F.
- Burnish stops were conducted at one mile intervals or at the time interval required to reduce initial brake temperatures to 230°- 270°F.
- Initial temperatures for trailer brake fade snubs were 130° to 150°

B.6.2 Vehicle Loading. Trailers were tested in two loading conditions, empty and loaded; the tow vehicles in three, empty, loaded, and gvwr.

The empty conditions for the tow vehicles were curb weight plus driver, passenger, and instrumentation. For the trailers, the empty condition was the "as delivered" condition.

The loaded conditions were defined as follows: For the fifth wheel-type trailers, the total loaded trailer weight (W_{LT}) was brought to the gvwr of the trailer with a distribution between axles and tongue as recommended by the manufacturers.

The loaded condition of the three standard ball hitch trailers was adjusted such that (1) with tow vehicle and trailer load and trailer properly hitched (i.e., with proper load equalization) to its nominal match tow vehicle, the static trailer axle load was equal to the manufacturer's recommended gvwr, and (2) with the trailer unhitched, the distribution of tongue weight to total trailer weight was as per manufacturers' recommendations (where this recommendation was not available, tongue weight was 15% of total trailer weight).

The loaded condition for the tow vehicles was adjusted such that, when properly hitched to their nominal match trailer (in the loaded condition described above), their axle loads were equal to the manufacturers' recommended maximums. When tested alone, tow vehicles were loaded to their gvwr.

When vehicles were tested in "mismatched combinations," their individual loading conditions were maintained at those determined for nominal match vehicles.

Table B.2 lists the loading conditions used in the various tests.

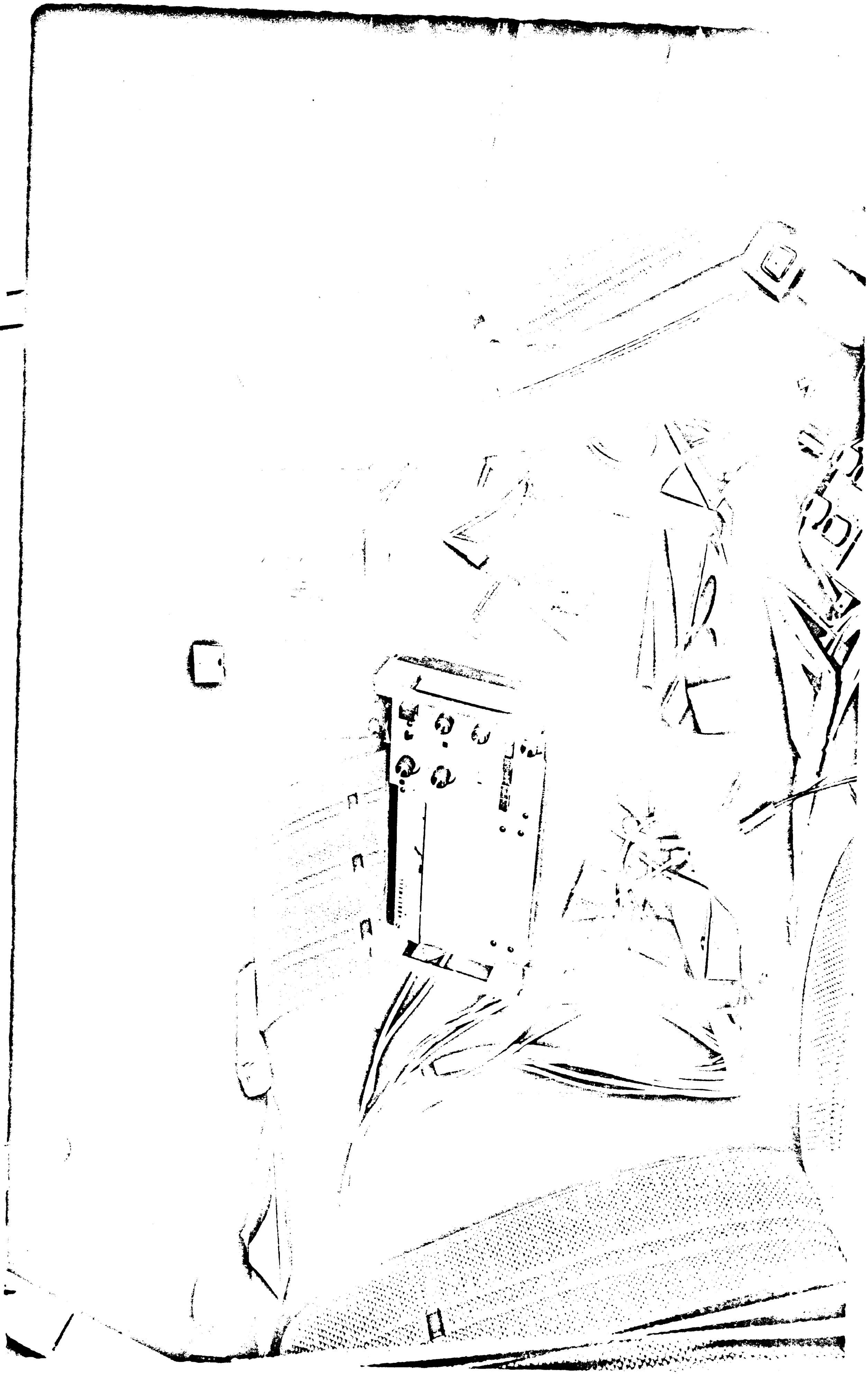
Table B.2

1.	Tow Vehicle Alone	
	Burnish	Tow vehicle loaded to gvwr
	Effectiveness	Tow vehicle loaded to gvwr
2.	Trailer Alone	
	Pre-Burnish Effectiveness	Trailer loaded; Tow vehicle empty
	Burnish	
	Post-Burnish	
3.	Combination Vehicle Effectiveness	
	"Nominal Match" Combinations and Mismatch Combinations 2-C and 1-B	One test with both units of combination vehicle loaded, one test with tow vehicle loaded and trailer empty
	Mismatch Combination 1-A, No Trailer Brakes	Both units of combination vehicle loaded
4.	Fade Tests	Trailer loaded Tow vehicle empty

B.6.3 Instrumentation and Data Collection. An instrumentation package was prepared by HSRI. Table B.3 lists all the data signals which were available. Continuous recording of data was accomplished with a 14-channel light beam oscilloscope. Signals chosen for recording varied between tests dependent on the nature of the test. When appropriate, signals were monitored by driver and instrumentation operator. Figures B.3 through B.8 illustrate certain features of the instrumentation.

Table B.3

A_x	vehicle deceleration, measured by accelerometer mounted on stabilized platform
a_x	vehicle deceleration, measured by U-tube accelerometer
d_s	stopping distance measured by digital fifth wheel
F_B	brake pedal force, measured by electronic load cell
F_x	longitudinal hitch force, measured by strain gauge load cell
P_a	air pressure of air/hydraulic brake actuator, measured by pressure gauge
P_1, P_2	tow vehicle front and rear brake line pressure, measured by electronic pressure transducer
P_2	tow vehicle rear brake line pressure, measured by pressure gauge
P_3	hydraulic trailer brake line pressure, measured by electronic pressure transducer
T_1-T_{10}	up to ten brake shoe temperatures, measured by thermocouple. Brakes numbered 1 through 10 proceeding from left front, right front, left rear, right rear, etc., rearward through all axles of CV
V	vehicle velocity, measured by digital fifth wheel
v	vehicle velocity, measured by tow vehicle speedometer
V_o	initial braking velocity, measured by digital fifth wheel
v_B	electric trailer brake voltage
ω_1-ω_{10}	up to ten wheel speeds, measured by d.c. tach generator system. Wheels numbered as under T_1-T_{10}. Wheel lock, rather than wheel speed, is of primary interest



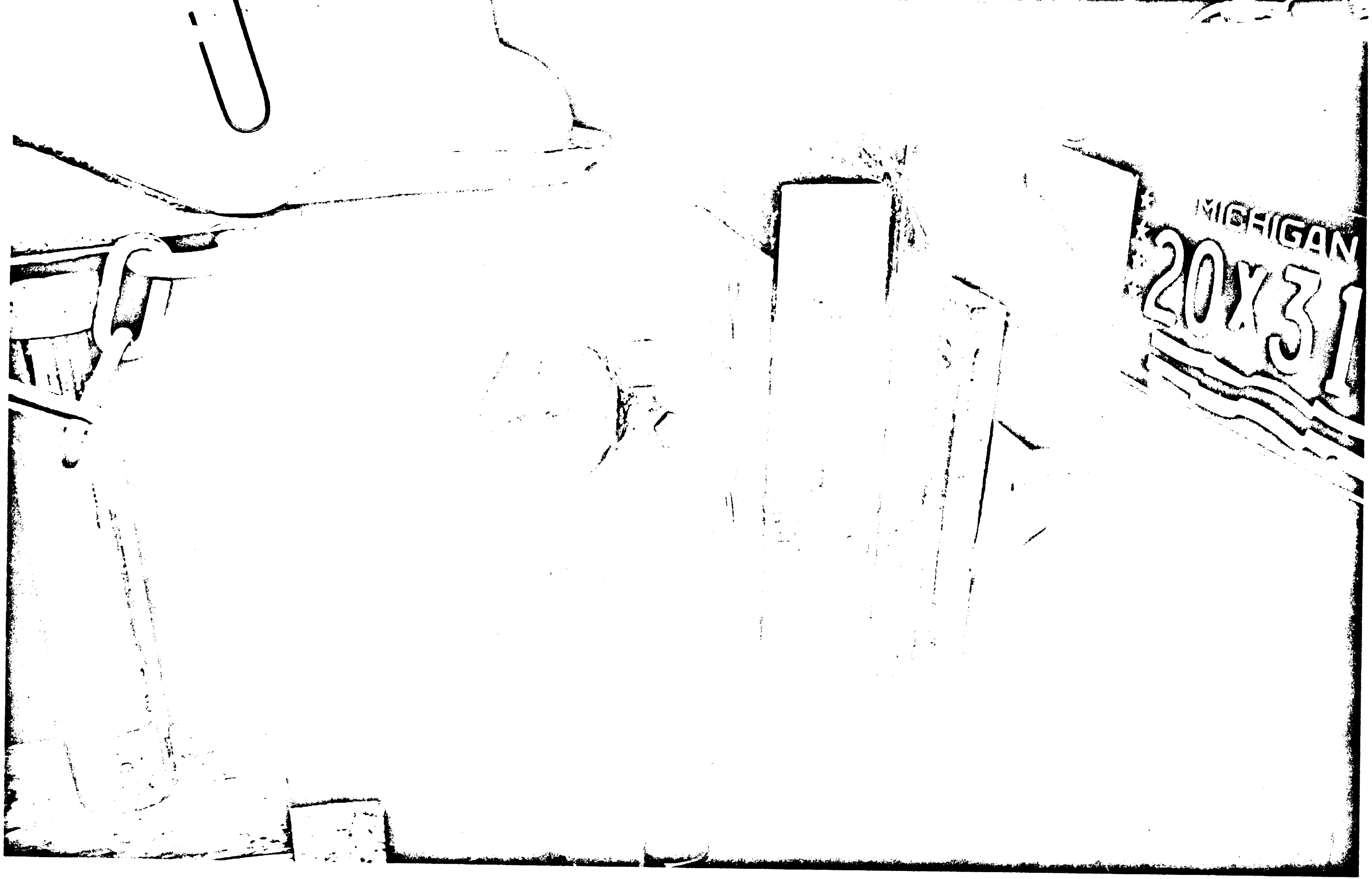


Figure B.5. Ball Hitch Force Transducer.

Figure B.7. Stabilized Platform (Center) and Electric Brake Controller (Left).

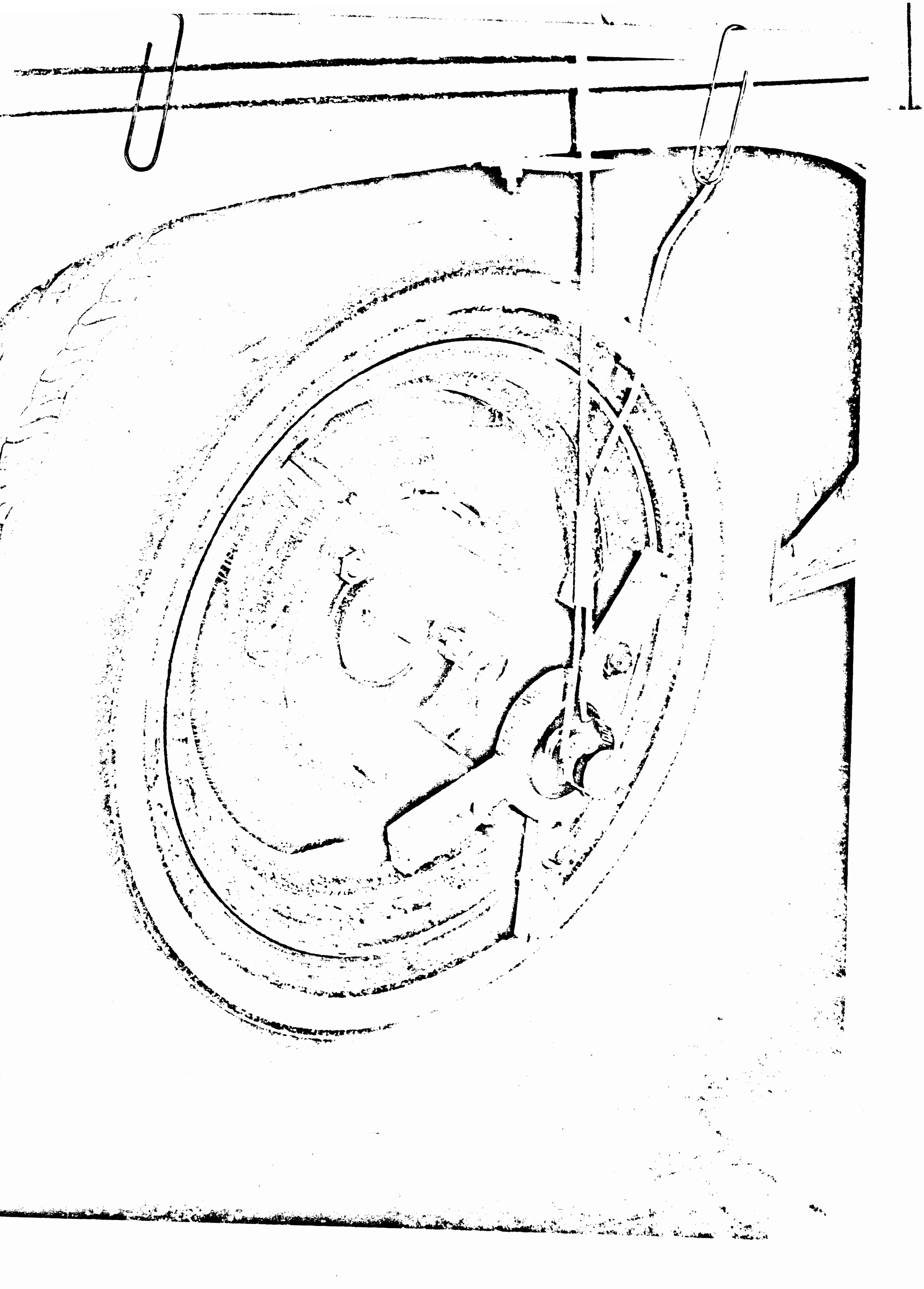


Figure B.8. Wheel Speed Transducer