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Summary Final Report
Contract FH-11-7290
January 1970

BUS, TRUCK, TRACTOR/TRAILER BRAKING SYSTEM PERFORMANCE

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Prepared for
National Highway Traffic Safety Administration
U.S. Department of Transportation

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

BUS, TRUCK, TRACTOR-TRAILER BRAKING SYSTEM PERFORMANCE

5. Report Date

March 1971

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.

PF-101a

9. Performing Organization Name and Address

Highway Safety Research Institute
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Ann Arbor, Michigan 48105

10. Work Unit No.

11. Contract or Grant No.

FH-11-7290

12. Sponsoring Agency Name and Address

National Highway Traffic Safety Administration
U.S. Department of Transportation
Washington, D.C. 20591

13. Type of Report and Period Covered

Summary Final Report
7/69 - 3/71

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The objectives of this study were to determine the range of braking performance currently exhibited by buses, trucks, and tractor-trailers and to establish the maximum braking performance capabilities of these vehicles based upon full utilization of the technology related to brake system design. Both vehicle testing and analytical techniques, including dynamic modeling and simulation, were used to accomplish these objectives. Performance measures were defined which serve to quantify the degree to which a given vehicle-braking system possesses those qualities necessary for adequate braking performance. Using these measures, a braking performance standard is recommended based upon a comparative analysis of (1) current braking performance, (2) the maximum performance achievable by full exploitation of existing technology, and (3) performance as constrained by a host of associated factors.

17. Key Words

brake performance, brakes, brake systems, trucks, buses, tractor-trailers

18. Distribution Statement

Availability is unlimited. Document may be released to the Clearinghouse for Federal Scientific Information, Springfield, Virginia; 22151, for sale to the public.

19. Security Classif. (of this report)

Unclassified

20. Security Classif. (of this page)

Unclassified

21. No. of Pages

22. Price

Form DOT F 1700.7 (8-69)

ACKNOWLEDGMENTS

The authors wish to acknowledge that many individuals and organizations made outstanding contributions to this program, not only by supplying vehicles and technical data, but also by providing technical assistance.

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1.0 INTRODUCTION

This report presents findings, conclusions, and recommendations derived by the Highway Safety Research Institute (HSRI) of The University of Michigan in a research program for the National Highway Traffic Safety Administration (NHTSA) entitled, "Bus, Truck, Tractor-Trailer Braking System Performance Study." The broad objectives of this program are the formulation of techniques and the production of data designed to aid NHTSA in fulfilling its mandate to issue reasonable and desirable safety standards.

1.1 STATEMENT OF THE PROBLEM

The complex relationship between current braking capabilities of commercial vehicles and the frequency of accidents with these vehicles due to deficiencies in braking performance is neither completely understood nor statistically documented. There is, nevertheless, ample intuitive basis to hypothesize that such a relationship exists and, further, that there are certain specific vehicle braking performance characteristics which, during either the normal driving process or emergency situations, cause the potential for loss of control to rise above a threshold beyond which even the skill and experience of the professional driver are of little avail. It is known that the braking performance of buses, trucks, and tractor-trailers varies significantly over a wide range, and is, on the average, less than that for passenger cars, and certainly less than the maximum performance achievable. Thus it can be argued that this performance differential, if great enough, can constitute a significant safety hazard since all vehicle types are subjected to the same traffic and physical environments. The performance demands of these environments and the integration of vehicle types within the environments indicate a need for uniform and higher braking performance levels to be achieved by commercial vehicles. The study described herein addresses this need by focusing on the establishment of braking system performance requirements for buses, trucks, and tractor-trailers.

1.2 OBJECTIVES

The specific objectives of this study are threefold:

- To determine, by means of vehicle testing, the range of braking performance currently exhibited by buses, trucks, and tractor-trailers.

- To establish the maximum braking performance capabilities of these vehicles based on full utilization of the technology related to brake system design.

- To recommend a rational braking performance standard based upon a comparative analysis of (1) current braking performance, (2) the maximum performance achievable by full exploitation of existing technology, and (3) performance as constrained by a host of associated factors.

2.0 SUMMARY OF TASKS

In order to meet the objectives of this program, four major experimental and analytical tasks were carried out.

2.1 LITERATURE REVIEW

The foreign and domestic literature was surveyed with the objective of finding information pertinent to accurate analyses of braking systems, experimental test procedures, and means of measuring and evaluating the braking performance of buses, trucks, and tractor-trailers. Factors considered important in the review were brake system design, braking performance, brake usage, brake testing, brake failure, and performance standards.

2.2 VEHICLE-BRAKE SYSTEM PERFORMANCE TESTS

In order to determine the braking performance capabilities of vehicles equipped with standard braking systems, three integral trucks, three buses, and four tractor-trailer combinations were subjected to a series of effectiveness, fade and recovery, and brake rating tests. So that the improvement in performance through use of more effective brakes and advanced braking systems could be determined, three additional vehicles were tested, namely:

1. An integral truck equipped with disk brakes and a full power hydraulic brake actuation system.
2. A tractor-trailer equipped with proportioning valves, adaptive braking system,* and trailer brake synchronization device.
3. A tractor-trailer equipped with a wheel antilock system.**

The disk brake truck was subjected to effectiveness, fade and recovery, and brake rating tests, while the two tractor-trailer vehicles were tested primarily for effectiveness and minimum stopping capability.

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*Designation used throughout this report for the system developed by Bendix-Westinghouse.

**Designation used throughout this report for the system developed by Eaton, Yale, and Towne.

2.3 ANALYTICAL PROGRAM

The analytical study was directed toward establishing mathematical and computation procedures for predicting braking performance based upon vehicle and braking system design factors. Analysis of the performance of several of the test vehicles demonstrated the feasibility of making accurate predictions of brake effectiveness, braking efficiency, pedal force gain, and thermal response. Dynamic modeling and simulation were employed to determine the extent to which vehicle braking performance can be improved with increased effectiveness, refinements in brake torque distribution, and load and deceleration sensitive proportioning systems.

2.4 RECOMMENDATIONS FOR A SAFETY STANDARD

Based upon the results of the three aforementioned tasks, performance requirements are suggested which would effectively upgrade the braking performance of these vehicles to a level approaching that of passenger cars. Procedures and tests for ensuring compliance with the requirements are also suggested.

The interrelation of the tasks and important subtasks is shown in block diagram form in Figure 1.

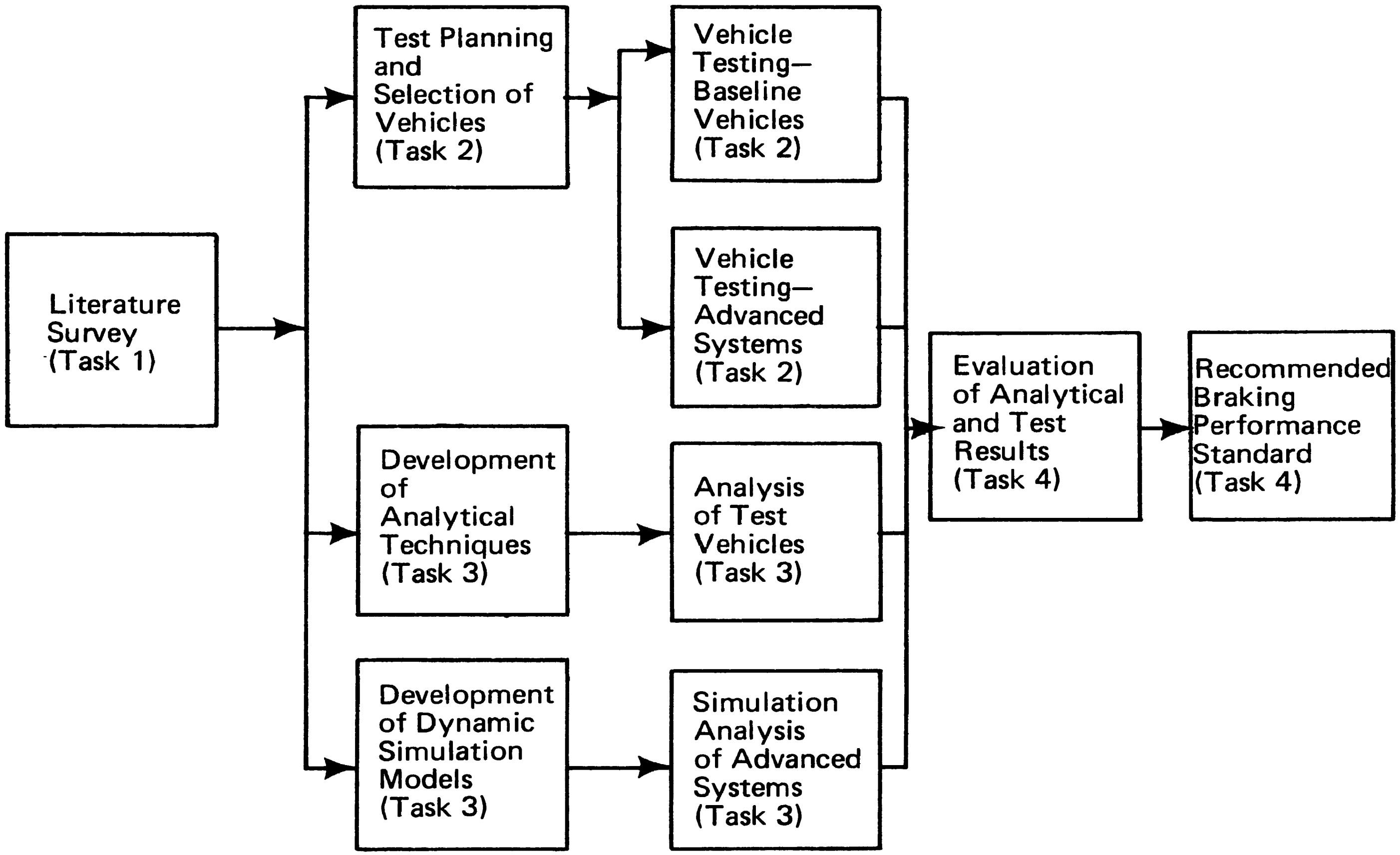

Figure 1. Interrelationship of project tasks and subtasks.

3.0 RESULTS

3.1 TEST RESULTS, BASELINE VEHICLES

The test results for the ten baseline vehicles (vehicles equipped with standard braking systems) are summarized in this section. For specific details on vehicle specifications and the results of each individual test, the reader is referred to the Final Report volume.

3.1.1 Brake Effectiveness Tests

The vehicles were tested for brake effectiveness, in the loaded and empty condition to the point of wheel lockup if the brakes had sufficient torque capacity. If the behicle remained stable beyond the point of first wheel lockup, pedal force was increased to lock up as many wheels as possible. Results for all the effectiveness tests are summarized in Table 1, and a graphical summary of the deceleration capabilities of the baseline vehicles is given in Figure 2.

The average maximum deceleration achieved (without wheel lock occurring) with the tested trucks is 15.5 ft/sec^2 in the empty condition and 17.0 ft/sec^2 in the loaded condition. If wheel locking is permitted, the figures become 19.2 and 17.7 ft/sec^2, respectively. These results show that brake torque capacity has been proportioned to give best performance for the loaded condition.

For the test buses, the average maximum deceleration, wheels unlocked, is 18.5 ft/sec^2 empty and 19.9 ft/sec^2 loaded, with the performance of the empty buses increasing to 21.7 ft/sec^2, when some wheels are locked. It should be noted that it was impossible to lock wheels on any of the buses when fully loaded.

For the tractor-trailers tested, the average maximum deceleration, wheels unlocked, is 15.0 ft/sec^2 empty and 16.5 ft/sec^2 loaded, with the performance empty increasing to 19.4 ft/sec^2 when wheels are locked.

Although the trucks exhibit a wide range in performance, the loaded buses exhibit uniform performance. A rather remarkable variation in performance is noted for the tractor-trailer combinations, notwithstanding the fact that the same tractor was used in two of the combinations (2-S1 and 2-S2) and the same trailer was used in two combinations (2-S2 and 3-S2).

Overall, the ten vehicles achieved an average maximum deceleration, wheels unlocked, of 16.5 ft/sec^2, empty, and 17.7 ft/sec^2, loaded, and 19.4 ft/sec^2,

TABLE 1

EFFECTIVENESS TEST SUMMARY—BASELINE VEHICLES

Vehicles	Nom. V_o, mph	Minimum Stopping Distance, ft				Maximum Deceleration, ft/sec^2			
		Empty		Loaded		Empty		Loaded	
		No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked
Light Truck	60	238	150	219	191	20.0	28.0	23.0	25.0
Medium Truck	60	322	282	307	---	13.0	13.7	12.6	--
Heady Truck	60	316	248	263	262	13.2	15.8	15.5	15.5
School Bus	40	108	84	119	---	19.0	22.0	20.0	--
Intercity Bus	60	290	221	202	---	16.3	21.5	19.5	--
City Bus	40	93	72	89	---	20.5	24.0	20.3	--
Tractor-Trailer 2-S1	60	291	258	292	---	15.5	17.0	15.2	--
Tractor-Trailer 2-S2	60	428	220	222	---	15.0	20.0	20.0	--
Tractor-Trailer 3-S2	60	366	247	376	299	14.0	16.0	14.0	16.1
Tractor-Double Trailer	60	395	294	309	---	15.0	18.8	16.6	--

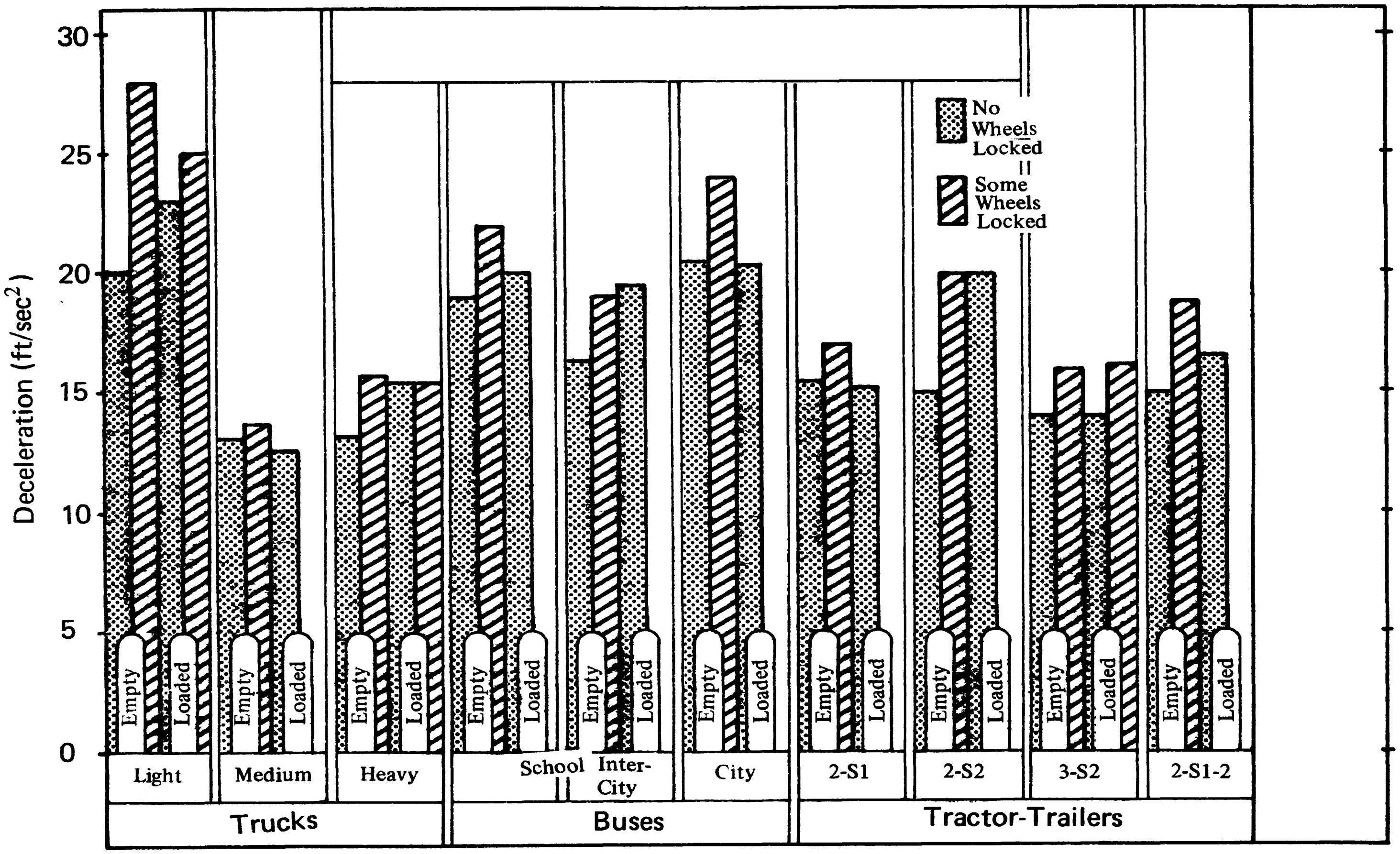

Figure 2. Maximum deceleration capability, baseline vehicles.

empty, and 18.1 ft/sec^2 loaded, if some wheels are permitted to lock during the stop. The measured range of performance is greatest for the trucks (12.6 to 28.0 ft/sec^2) and least for the tractor-trailers (14.0 to 20.0 ft/sec^2). Bus performance ranged from 16.3 to 24.0 ft/sec^2.

It should be noted that seven out of the ten vehicles, when tested in the loaded condition, did not have sufficient torque capacity to lock up any wheels on the surface used in this test program. It should also be pointed out that seven of the ten vehicles, when empty, could not exceed the performance of the loaded vehicle without locking up some wheels, which locking causes either loss of steering control or may lead to lateral instability.

3.1.2 Brake Failure Tests

The brake failure modes selected for test depended upon the design of the brake system. In the light truck, three failure modes were possible: front hydraulic line failure, rear hydraulic line failure, and power boost failure. The medium truck was not designed with separate front and rear brake systems, and thus this vehicle was tested only with the power boost failure. The heavy truck and the city bus, each equipped with air brakes, did not contain an emergency system except for the mechanical hand brake attached to the drive shaft. The school and intercity buses had, however, separate emergency brake systems, which, when actuated under failure of the service brake system, supplied air pressure to the rear brakes. An opening of the rear door of the city bus also actuated the rear brakes through the normal service system. A summary of test results obtained with the trucks and buses in each of the failure modes tested is given in Table 2.

Deceleration performance was measured on tractor-trailer combinations in tests conducted at 20 mph in which brake failure was simulated by opening the trailer emergency air line at the tractor protection valve. It was not considered practical to conduct these tests from 60 mph because of the strong possibility that damage to the suspension and brake supporting structure would result from such a severe brake application at high speed. Two of the tractors were equipped with spring brakes. These brakes were also tested from 20 mph. Results obtained for the combinations in the empty and loaded conditions are given in Table 3.

3.1.3 Fade and Recovery Tests

Table 4 summarizes the findings obtained in the fade and recovery tests conducted on the baseline vehicles. The fade test procedure specified that all vehicles be decelerated from test speed at 15 ft/sec^2 (or the maximum deceleration as determined from the effectiveness test if the vehicle could not

TABLE 2

SUMMARY OF PERFORMANCE OF TRUCKS AND BUSES UNDER FAILURE CONDITIONS

Vehicles	Type of Failure	Brakes Used	V_o, mph	Max. Decel., ft/sec^2		Min. Stopping Dist., ft	
				Empty	Loaded	Empty	Loaded
Trucks							
Light	Front Brakes	Rear Brakes Only	60	11.5*	7.3	380	620
	Rear Brakes	Front Brakes Only	60	15.5	9.0	281	484
	Power Boost	Service Brakes	60	26.0*	17.0	160	238
Medium	Power Boost	Service Brakes	60	13.0*	5.5	352	744
Heavy	Service Brakes	Hand Brake	60	1.5	1.0	1594	2200
Buses							
School	Service Brakes	Emergency	40	9.2	6.0	188	287
Intercity	Service Brakes	Emergency	60	6.8	5.8	571	710
City	Service System	Hand Brake	40	8.1	5.0	212	437
	Rear Door Opening	Rear Brakes	40	8.0	5.1	235	350

*Indicates lock-up of one or more wheels.

TABLE 3

SUMMARY OF PERFORMANCE OF TRACTOR-TRAILERS UNDER FAILURE CONDITIONS

Vehicles	Type of Failure	Brakes Used	V_o, mph	Loading Condition	Maximum Decel., ft/sec^2	Minimum Stopping Dist., ft	Wheel Lockup
2-S1	Opening Trailer Emergency Air Line	Trailer	20	Empty	6.5	94	Both Trailer Wheels
	Opening Trailer Emergency Air Line	Trailer	20	Loaded	7.5	85	None
2-S2	Opening Trailer Emergency Air Line	Trailer	20	Empty	9.5	70	All Trailer Wheels
	Opening Trailer Emergency Air Line	Trailer	20	Loaded	12.0	45	Left Tandem, Right Rear
3-S2	Opening Trailer Emergency Air Line	Trailer	20	Empty	7.0	102	All Trailer Wheels
	Opening Trailer Emergency Air Line	Trailer	20	Loaded	9.0	100	Left Tandem, Right Tandem
	Service System	Tractor Spring Brakes	20	Empty	8.0	83	All Tractor Drive Wheels
	Service System	Tractor Spring Brakes	20	Loaded	6.2	110	None
2-S1-2	Opening Trailer Emergency Air Line	Trailer	20	Empty	13.3	48	Right Front and Left Rear On Full Trailer
	Opening Trailer Emergency Air Line	Trailer	20	Loaded	7.8	91	None
	Service System	Tractor Spring Brakes	20	Empty	5.4	100	Both Rear Tractor Wheels
	Service System	Tractor Spring Brakes	20	Loaded	3.2	155	None

TABLE 4

SUMMARY OF FADE TEST RESULTS

Vehicles	Test Decel., ft/sec^2	Number of Snubs Achieved	Velocity Initial/Final, sec	Average Δt_{2-1}, sec	Average Δt_{1-2}, sec	Highest Lining Temp., °F	Hottest Brake
Trucks							
Light	15	12	60/10	5.9	55	520	Left Rear
Medium	12	3	60/10	7.5	125	335	Right Rear
Heavy	14	5	60/10	5.2	215	405	Left Tandem
Buses							
School	15	9	40/10	3.8	29	445	Left Front
Intercity	15	9	60/10	6.3	85	600	Left Drive
City	15	10	40/10	3.4	48	315	Right Front
Tractor-Trailers							
2-S1	15	10	50/10	5.6	222	390	Left Rear Tractor
2-S2	15	10	45/10	4.3	105	380	Left Rear Tractor
3-S2	14.5	10	50/10	5.3	137	405	Right Rear Tractor
2-S1-2	12.0	10	50/10	7.0	144	460	Left Rear Tractor

Δt_{2-1} is the time from initial brake pedal application at initial velocity to brake pedal release at lower snub velocity.

Δt_{1-2} is the acceleration time from lower snub velocity back to initial test velocity.

achieve 15 ft/sec^2) to 10 mph and accelerated as rapidly as possible back to test speed, the snubs continuing until the specified deceleration level could no longer be maintained. The recovery test as specified in SAE J786 was conducted immediately after the fade test.

In conducting the fade test on the city bus and the tractor-trailers, it soon became obvious that the specified procedure would not fade the brakes even after ten snubs. The tests were terminated at this point. The test procedure also proved impractical in that it was not possible to maintain the required 15 ft/sec^2 deceleration on the 3-S2 tractor-trailer combination or on the doubles combination because of incipient wheel lockup.

3.1.4 Brake Rating Tests

The procedure specified for this test, required that the test vehicle be towed on a flat surface at a constant velocity with brakes applied at a line pressure equivalent to that required to maintain constant vehicle velocity on a 7% descending grade. The vehicle was to be towed with line pressure held constant until the towbar force as measured by a load cell in the towbar decreased (due to fade) by 15%. The towing force over the duration of the test was averaged, the rolling resistance subtracted, and the average braking force calculated, from which the energy absorption rate of the brake (horsepower) and the total energy absorbed were determined. Two measures were formulated for rating the brakes. The first measure is based on horsepower and lining area giving some indication of the rate of energy absorption, the second is based upon total energy absorbed and the weight of the vehicle. A summary of test data for the trucks and buses is given in Table 5 and for tractors and trailers in Table 6.

3.1.5 Brake Response Time Tests

To measure the brake response time of the tractor-trailer combinations pressure transducers were fitted to the output of the brake-control (treadle) valve, and at each axle of the vehicle on which brakes were mounted, except only one transducer was mounted at a tandem axle. Results of the response-time tests are summarized in Table 7 both for application and release.

The brake application times shown in Table 7 were measured from the instant pressure started to rise at the output of the treadle valve to the instant at which the pressure reached 60 psi at a given axle.* Release times were measured

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*This definition is slightly different from that given in SAE J982, which specifies that application time be measured "from the start of pedal movement to a pressure buildup of 60 psi."

TABLE 5

SUMMARY OF BRAKE RATING TEST RESULTS—TRUCKS AND BUSES

Vehicles	Vehicle Weight, lb	Test Velocity, mph	Test Duration, sec	Average Brake Power, hp	Power/ Lining Area, hp/ft^2	Energy/ Weight, ft-lb/lb	Maximum Brake Temp., °F	Hottest Brake
Trucks								
Light	10,732	45	165	66.5	28.7	563	470	Left Front
Medium	25,500	22	85	85.8	20.8	156	275	Right Rear
Heavy	39,000	23	90	146.0	24.4	186	425	Left Tandem
Buses								
School	24,500	25	120	109.0	32.0	293	466	Left Front
Intercity	35,940	23	195	151.0	19.9	451	435	Left Drive
City	32,145	24	240	124.0	20.3	510	425	Left Front

TABLE 6

SUMMARY OF BRAKE RATING TEST RESULTS—TRACTOR-TRAILER

Vehicles	Weight on Test Axles, lb	Test Velocity, mph	Test Duration, sec	Average Brake Power, hp	Power/ Lining Area, hp/ft^2	Energy/ Weight, ft-lb/lb	Maximum Brake Temp., °F	Hottest Brake
2-S1								
Tractor	23,830	22	195	60	14.8	275	550	Right Rear
Trailer	18,010	22	205	78	23.15	476	480	Right Trailer
2-S2								
Tractor	24,930	30	200	150	37.0	660	480	Right Rear
Trailer	31,990	30	280	165	24.5	794	400	Left Rear
3-S2								
Tractor	43,660	21	142	146	23.9	257	405	Right Rear
Trailer	31,990	23	238	123	18.3	463	425	Right Rear
S-S1-2								
Tractor	20.120	23	240	105.4	22.1	524	435	Right Rear
Semi-Trailer	17,940	23.5	229	58.2	17.3	410	325	Left Trailer
Full Trailer	36,205	23	265	134.5	20.0	530	375	Right Front

TABLE 7

SUMMARY OF AIR BRAKE RESPONSE TIME TESTS—TRACTOR-TRAILER COMBINATIONS

Vehicles	Application Time to 60 psi, sec			Release Time to 5 psi, sec		
	Tractor Front	Tractor Rear	Trailer Axle	Tractor Front	Tractor Rear	Trailer Axle
2-S1	0.24	0.23	0.32	0.30	0.40	0.65
2-S2	0.20	0.26	0.29	0.44	0.50	0.75
3-S2	--	0.24	0.24	--	0.75	0.97
2-S1-2	0.40	0.49	0.76	1.30	0.37	1.90
	Full Trailer Front	Full Trailer Rear		Full Trailer Front	Full Trailer Rear	
	0.77	0.79		1.90	1.90	

from the instant pressure began to drop at the output of the treadle valve to the instant at which the pressure at a given axle dropped to 5 psi. These measurements indicate that the average response time for the rear axle of the tractor (when the tractors were tested in combination with a semitrailer) was 0.24 sec. Average response time for the axle on the semitrailers was 0.28 sec. Release times were considerably longer, averaging 0.55 sec for the rear axle on the tractor and 0.79 sec for the axle on the semitrailers. Application and release times were considerably longer on the doubles combination due to the larger volumes of air that had to be moved through the system.

3.1.6 System Failures

Several vehicle suspension and brake system failures occurred during the testing of the baseline vehicles. None of these failures was considered extraordinary since the vehicles and systems were subjected to a series of high level decelerations that generated stresses and cycles of stress not normally encountered in service.

3.2 TEST RESULTS, VEHICLES EQUIPPED WITH ADVANCED SYSTEMS

3.2.1 Truck Equipped with Disc Brakes

The medium truck equipped with Bendix disk brakes and full power hydraulic actuation system was subjected to the same series of tests as the baseline vehicles: effectiveness, brake failure, fade and recovery, and brake rating. The results of the effectiveness test are given in Figure 3. These data point up two important factors:

1. The vehicle has a maximum deceleration capability (with no wheels locked on the given test surface) of better than 21 ft/sec^2, this performance being better than nine of the ten baseline vehicles and considerably better than both the medium or heavy truck.

2. The vehicle has the capability of locking up all four wheels in the loaded condition, demonstrating that it does have brake torque sufficient to utilize the frictional forces in the tire-road interface to a maximum extent.

With separately powered front and rear brake systems, it was possible to fail either system and maintain braking capability on one axle. Table 8 summarizes the minimum stopping distances and maximum decelerations achieved in the brake effectiveness and brake failure tests. Loss of the rear brakes decreases the maximum deceleration capability of the empty vehicle by 35% and

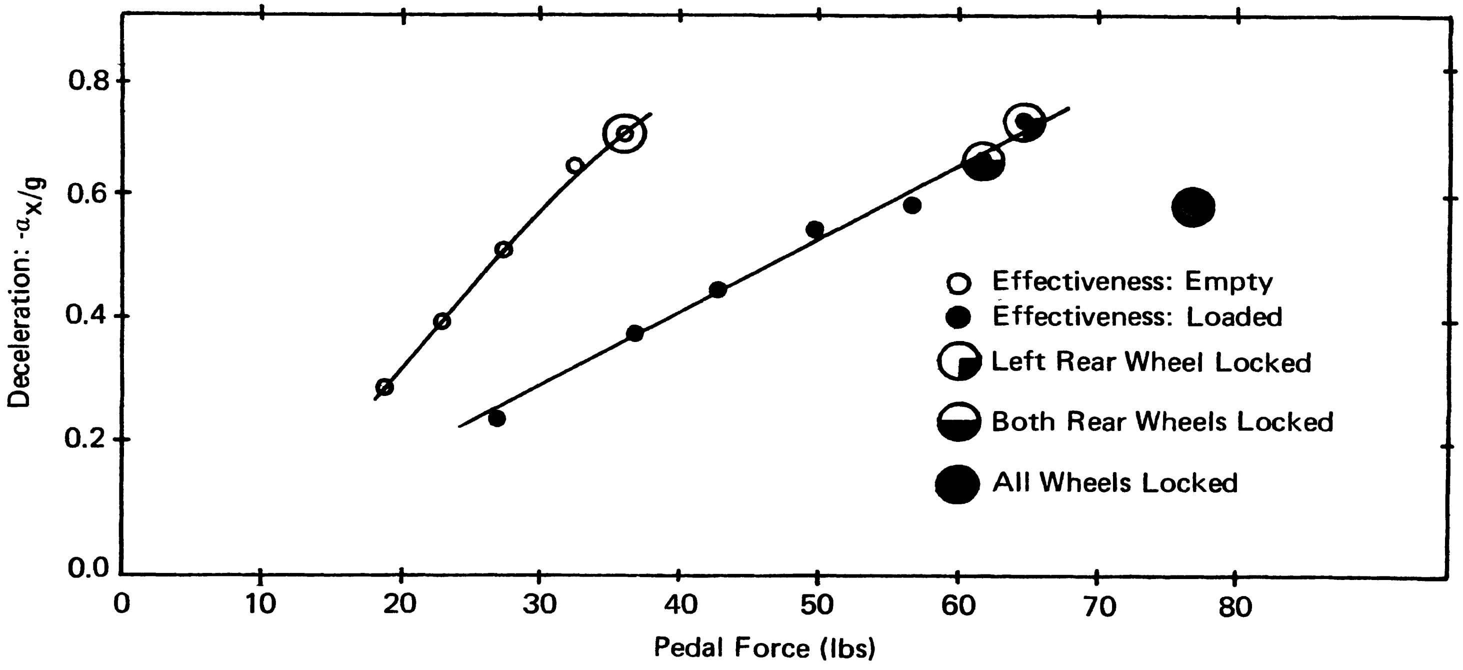

Figure 3. Effectiveness test results, disk brake truck.

TABLE 8

EFFECTIVENESS TEST SUMMARY—DISK BRAKE TRUCK

(Nominal Test Speed to 60 mph)

Systems Operational	Minimum Stopping Distance, ft				Maximum Deceleration, ft/sec^2			
	Empty		Loaded		Empty		Loaded	
	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked
Full System	255	198	204	181	21.8	22.8	21.3	23.8
Front System Only	321	323	438	436	13.2	13.0	9.1	9.1
Rear Systems Only	351	322	345	---	11.5	12.2	12.4	--

of the loaded vehicle by 43%, while loss of the front brakes decreases the maximum deceleration capability by 47% and 43%, empty and loaded, respectively.

Two fade tests were conducted on this vehicle, with the results demonstrating the superior fade resistance of disk brakes. In the first test the pedal force required to maintain 15 ft/sec^2 deceleration from 60-10 mph increased from 47 lb on the first snub to 65 lb on the 15th snub. In the second test the pedal force increased from 47 lb on the first snub to 84 lb on the 15th snub. In both cases the brake temperature, as measured by thermocouples in the lining pads, was in excess of 1270°F. To make a fair comparison with the results of the baseline vehicles, it should be noted that for the two tests the average snub deceleration time was 5.8 sec and 5.7 sec and the average time to accelerate back to test speed was 76.4 sec and 81.8 sec.

In the brake rating test an average power input to the brakes of 91.3 hp was maintained for 670 sec with less than 20% decrease in brake force at a constant pedal pressure. The test was terminated after 670 sec because, by this time, the temperatures of all the brakes exceeded 1200°F. In comparison with the baseline vehicles, this vehicle produced an energy and power rating of 1215 ft-lb of thermal energy absorbed per pound of vehicle weight and 71.4 hp for square foot of lining, respectively.

3.2.2 Tractor-Trailers Equipped with Advanced Systems

For the two tractor-trailer combinations equipped with advanced systems, changes in some of the test procedures were made because the test objectives were different from those of the other eleven vehicles. For example, in testing the While 6 x 4 tractor and the Fruehauf tandem axle platform trailer (hereinafter referred to as Vehicle #12), five different vehicle and loading configurations were used, the effectiveness of the tractor front and rear brakes was varied, and the aforementioned brake control systems, i.e.,: proportioning valves, adaptive braking, and trailer brake synchronization, were employed in various combinations. The purpose in testing Vehicle #12 was to determine the best braking performance which could be achieved using a standard test vehicle, equipped with commercially available brakes, and employing state-of-the-art brake control systems. The effectiveness of the tractor brakes was varied by changing the wedge angles and brake chambers on the front brakes, and the slack adjuster lengths on the rear brakes. Five different vehicle and load configurations were tested using Vehicle #12, namely,

1. tractor-trailer, empty
2. tractor-trailer, loaded, high center of gravity
3. tractor-trailer, loaded, low center of gravity
4. tractor only, bobtail configuration
5. tractor only, loaded to gross axle weight rating

Prior to commencement of tests with Vehicle #12, the following advanced brake control systems were installed:

- Proportioning valves for the tractor rear brakes and trailer brakes, supplied by Borg-Warner.
- Adaptive braking system, with a sensor and controller mounted on each of the ten wheels of the combination to prevent wheel lockup during braking, supplied by Bendix-Westinghouse.
- Trailer brake synchronization (Syncron) system, which effectively applies the trailer brakes as soon as the treadle valve is depressed, supplied by the Berg Manufacturing Company.

During the course of the test program conducted with Vehicle #12, the basic air brake system of both the tractor and trailer was altered by installation of a high capacity brake control (treadle) valve, quick release valves on each trailer brake actuator, larger capacity lines to the front tractor brakes, and replacement of connectors, fittings, and tees which tended to restrict air flow.

To evaluate the braking performance of Vehicle #12 under various conditions of loading and brake effectiveness, as modified by the various brake control systems and combinations of systems, 59 minimum-stopping-distance tests* and five effectiveness tests were conducted.

The last vehicle tested in the program was a tractor-trailer combination, furnished by Eaton, Yale, and Towne. This vehicle (hereinafter designated Vehicle #14), a 4 x 2 Brockway COE tractor with an Arrow lowboy 35 ft trailer, was extensively modified for use in development of the Eaton, Yale, and Towne wheel antilock system, with which the vehicle was equipped. Three effectiveness tests, five minimum-stopping-distance tests, and four brake response time tests were conducted on Vehicle #14.

Summaries of the test results for Vehicles #12 and #14 are given in Table 9 for stops on the dry surface and Table 10 for stops on the low coefficient surface. In Table 9 results from the effectiveness tests are also included, along with results from the disk brake truck. (A complete compilation of the data from the effectiveness and minimum stopping distance tests are included in the Final Report volume.)

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*In the minimum stopping distance test the driver was instructed to apply maximum brake pedal force as rapidly as possible to stop the vehicle in the shortest distance from test speed without locking up any wheels. Tests were conducted on both dry (high coefficient) and wet slippery (low coefficient) surfaces.

TABLE 9

TEST SUMMARY, PERFORMANCE OF VEHICLES EQUIPPED WITH ADVANCED SYSTEMS ON DRY TRACK

(All Stopping Distances Corrected to 60 mph Initial Test Velocity)

Vehicles	Minimum Stopping Distance, ft				Maximum Deceleration, ft/sec^2			
	Empty		Loaded		Empty		Loaded	
	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked	No Wheels Locked	Some Wheels Locked
Disk Brake Truck	255	198	204	181	21.8	22.8	21.3	23.8
Vehicle #12 Tractor-Trailer								
Standard Brakes	346	207	292	---	11.6	19.6	16.2	--
With Proportioning	354	259	---	---	11.3	15.7	--	--
With Adaptive System	216	---	281	---	18.0	--	17.0	--
With Adaptive System and Syncron	---	---	260	---	--	--	15.9	--
With Adaptive System on Tractor and Proportioning on Trailer	289	198	---	---	14.0	19.8	--	--
Vehicle #12 Tractor-Trailer								
Most Effective Brakes	---	---	317	212	--	--	15.1	18.6
With Adaptive System and Syncron	236	---	275	---	20.0	--	16.1	--
Vehicle #12 Tractor								
Standard Brakes	371	---	---	---	11.1	--	--	--
With Proportioning	203	---	---	---	19.8	--	--	--
With Adaptive System	204	---	---	---	19.7	--	--	--
Vehicle #12 Tractor								
Most Effective Brakes	---	---	288	---	--	--	16.9	--
With Adaptive System	---	---	227	---	--	--	19.4	--
Vehicle #14 Tractor-Trailer								
Standard Brakes*	---	---	455	358	--	--	10.0	14.0
With Antilock*	167	---	270	---	14.8	--	15.2	--
Vehicle #14 Tractor								
With Antilock*	210	---	---	---	19.1	--	--	--

*Vehicle #14 was tested on this skid pad approach, which had a lower skid number than the East Straightaway, where all the other dry tests were conducted.

TABLE 10

TEST SUMMARY, PERFORMANCE OF VEHICLES EQUIPPED WITH ADVANCED SYSTEMS ON LOW COEFFICIENT SURFACE

(All Stopping Distances Corrected to 60 mph Initial Test Velocity)

Vehicles	Minimum Stopping Distance, ft		Maximum Deceleration, ft/sec^2	
	Empty	Loaded	Empty	Loaded
Vehicle #12 Tractor-Trailer				
Standard Brakes		749		6.1
With Adaptive System and Syncron		445		11.0
Vehicle #12 Tractor-Trailer Most Effective Brakes with Antilock and Syncron	476	550	9.2	8.7
Vehicle #12 Tractor				
Standard Brakes	874		4.1	
With Proportioning	1194		3.4	
With Adaptive System	510		9.1	
Vehicle #12 Tractor				
Most Effective Brakes	1048	819	4.9	5.4
With Adaptive System	513	517	9.1	8.6
Vehicle #14 Tractor-Trailer				
Standared Brakes	939		5.2	
With Antilock	689	516	7.5	8.2
Vehicle #12 Tractor				
With Antilock	655		7.2	

For Vehicle #12 in the empty condition on the dry surface, using the standard braking system, wheels lockup on the leading axle of the trailer at decelerations as low as 17 ft/sec^2. Maximum deceleration capability of the vehicle was 19.6 ft/sec^2.

When using proportioning valves, wheels started to lockup on the leading axle of the trailer at decelerations as low as 11.8 ft/sec^2. Lockup of wheels on any other axles was prevented by use of the proportioning valves, but at the expense of decreasing the maximum deceleration capability to 15.7 ft/sec^2. It can be shown that load transfer within the two elliptic spring suspensions, such as exists on the trailer of this combination, causes the leading axle to be more severely unloaded than the trailing axle. Since one valve was used to proportion brakes for both axles, the setting of the valve had to be based on the average load carried by the suspension, which allowed premature lockup of the wheels on the leading axle.

Using the adaptive system, the maximum deceleration achieved was 18.9 ft/sec^2, a deceleration that is 96% of the maximum value obtained with the unaugmented vehicle in stops that included wheel lockups. Notwithstanding these moderately high decelerations with the empty vehicle, stability problems were not encountered when the adaptive system was used. When the adaptive system was operational on the tractor with a proportioning valve used only on the trailer, wheel lock on the trailer leading axle was prevented up to a deceleration of 18.1 ft/sec^2. For the empty combination, this scheme proved to be almost as effective in preventing wheel lock as the fully adaptive (antilock) system. A maximum deceleration of 19.5 ft/sec^2 was achieved with lockup of three wheels on the trailer.

The effectiveness test conducted with the loaded vehicle after installing the most effective brakes specified for the program indicated a maximum deceleration capability of 15.1 ft/sec^2 with lockup occurring on some wheels.

The following conclusions can be drawn from an examination of the data from the effectiveness and minimum stopping distance tests on Vehicle #12:

1. For the tractor-trailer combination, best performance (as measured both by stopping distance and maximum deceleration) was obtained when the adaptive system was used with the trailer brake synchronization system. This finding holds for both wet and dry surfaces, and for both the empty and loaded vehicle.

2. Proportioning valves were not as effective on the tractor-trailer combination as would have been the case if braking effort on the tandem axles of the trailer had been proportioned to dynamic axle load, i.e.: less braking effort on the leading axle, and more braking effort on the trailing axle.

3. The dry surface braking performance of the single-element tractor, both loaded and in the bobtail configuration, was improved to an equal degree by use of the proportioning valve or the adaptive system. On the low coefficient surface, however, the deceleration performance of the empty tractor was severely degraded by the proportioning valve, which device set the brake-line pressure ratio (front to rear) at 5 to 1. In these latter tests, the line pressure had to be kept below 30 psi to prevent the front wheels from locking on the low coefficient surface. Since the proportioning valve kept the pressures at the rear brakes below 6 psi, that is, at or near the pushout pressure, the rear brakes did little or no work in these stops, resluting in low decelerations and long stopping distances.

Results from the effectiveness and minimum stopping distance tests on Vehicle #14 indicated that this vehicle was equipped with brakes capable of locking the wheels on a dry surface at relatively low levels of pedal force. In the loaded condition using the standard braking system the left rear tractor wheel locked at a deceleration of 14.0 ft/sec^2 on the dry surface. For the same test conducted with the antilock system operational, the vehicle achieved a maximum deceleration of 15.2 ft/sec^2. The empty combination was able to achieve 14.8 ft/sec^2 with the antilock system operational, while the tractor (bobtail configuration) was able to achieve 19.0 ft/sec^2. On the low coefficient surface, use of the antilock system improved braking performance considerably.

A summary of results from brake response time tests for Vehicles #12 and #14 is given in Table 11. Averaged results for the three baseline tractor-trailer combinations are included for comparison.

TABLE 11

SUMMARY OF BRAKE RESPONSE TIMES

Vehicles	Application/Release Time, sec Tractor Rear Axle	 Trailer Rear Axle
Average Baseline Vehicles	0.24/0.55	0.28/0.79
#12 Standard System	0.27/0.30	0.40/0.70
#12 with Syncron	0.27/0.30	0.30/0.40
#14 Standard System	0.23/0.36	0.36/0.64
#14 with Antilock	0.23/0.44	0.27/0.60

It should be noted that on Vehicle #12, use of proportioning valves and/or the adaptive system did not significantly change the response times of the standard system. Syncron however improves (i.e., decreases) trailer brake application time by about 25% and release time by better than 40%. On Vehicle #14, when the antilock system is used, little change is noted in application response time, except on the rear axle where the response time is decreased significantly, i.e., from 0.36 to 0.27 sec. Little change is noted in release times, except that the rear axle brakes on the tractor are somewhat improved in this regard.

3.3 TEST SURFACES AND TIRE-ROAD INTERFACE TESTS

All vehicle brake performance testing reported herein was accomplished at the Bendix Automotive Development Center, New Carlisle, Indiana, during the time period September 1969 to October 1970. Tests requiring a surface with a high coefficient of friction were conducted on the high speed oval track and the approach road to the skid pad, while those tests requiring a surface with a low coefficient of friction were conducted on a portion of the skid pad in which the asphalt surface had been treated with a sealant and wetted using a sprinkler truck.

The skid number of the test surfaces was measured twice during the program using a skid trailer equipped with ASTM-249 tires, and checked each week during which tests were conducted using an instrumented passenger car also equipped with the ASTM-249 tires. An investigation was also made using special instrumentation in the disk brake truck to determine the peak and sliding coefficients for a typical truck tire.* Results are given in Table 12.

TABLE 12

SKID NUMBERS AND PEAK/SLIDING TIRE-ROAD COEFFICIENTS FOR TEST SURFACE

Surface	Skid No.	Tire-Road Coefficient for Typical Truck Tire	
		Peak	Sliding
Oval Track (asphalt—dry)	87	0.75	0.60
Approach Road to Skid Pad (asphalt—dry)	87	0.72	0.57
Skid Pad (sealed asphalt—wet)	21—24	0.35	0.26

3.4 ANALYTICAL RESULTS

The purpose of the analytical study was to establish mathematical procedures for predicting vehicle braking performance, specifically: brake effectiveness,

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*Remington Premium Highway Universal, 10.00 x 20, tube type, load range F.

braking efficiency, pedal force gain, and thermal response. Analytical methods found in the literature were evaluated and extended for use in the study.

The test results indicated that the loaded vehicles experienced considerable brake fade when being decelerated from speeds of 60 mph. The test data also showed that wheel lockup occurred prematurely on axles of a tandem-axle pair mounted on either a tractor or trailer. The analysis developed to predict maximum deceleration capability necessarily had to include fade effects as well as dynamic load transfer occurring on tandem-axle suspensions. Since this analysis resulted in a rather extensive set of algebraic and differential equations, digital, analog, and hybrid computer techniques were developed to perform the calculations.

3.4.1 Braking Performance

For eleven of the thirteen vehicles tested, braking performance diagrams were constructed, in which by use of analytical expressions, relationships between pedal force, brake line pressure, vehicle deceleration capability (loaded and unloaded) and tire-road friction coefficient required to prevent wheel lockup on a given axle are depicted.* Figure 4 shows the brake performance diagram for the 2-S1 combination tested, wherein the experimental points are denoted by small circles. Curves for braking efficiency for this vehicle are given in Figure 5. In these diagrams good agreement is shown between theoretical and test results which are generally typical of the results for the other vehicles tested. The major conclusion that can be drawn from this phase of the analytical program is that accurate predictions of braking performance can be made based upon vehicle and brake system design data for buses, trucks, and tractor-trailers.

The relationship between brake force distribution and braking efficiency was also considered in assessing the braking performance of vehicles tested. It was demonstrated that those vehicles which exhibited the best performance, as measured by maximum deceleration achievable, were those whose brake force distribution was at or near optimum, whereas those vehicles showing lesser performance capabilities could have achieved better performance with a different brake force distribution. For example, the 2-S1 combination had a brake force distribution given by

$$\phi_{1F} : \phi_{1R} : \phi_{2R} = 0.11 : 0.44 : 0.45$$

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*Exceptions were the heavy truck and the city bus, for which diagrams could not be constructed because necessary design information was not available from the vehicle manufacturers.

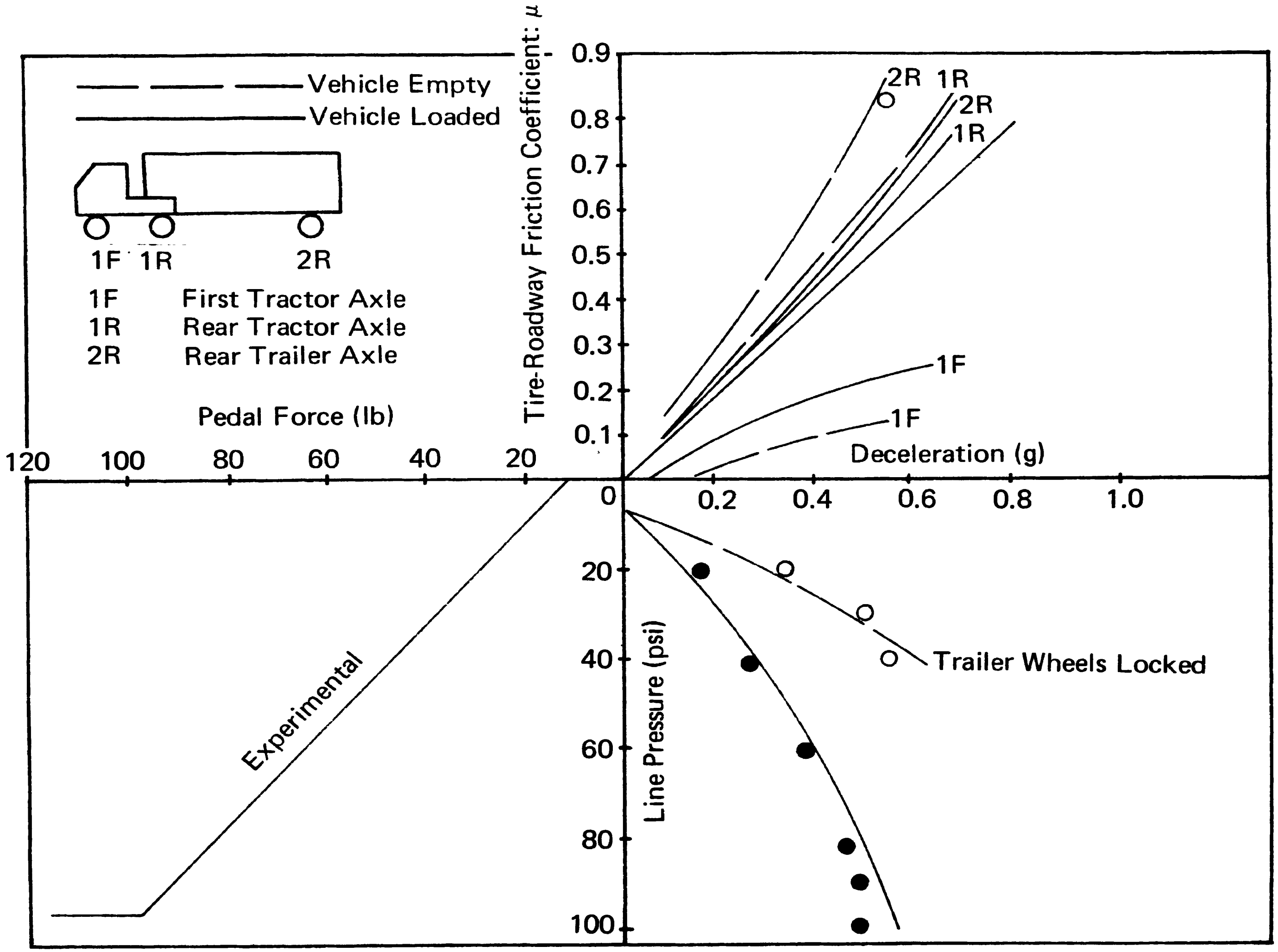

Figure 4. Braking performance diagram for 2-S1 tractor-trailer.

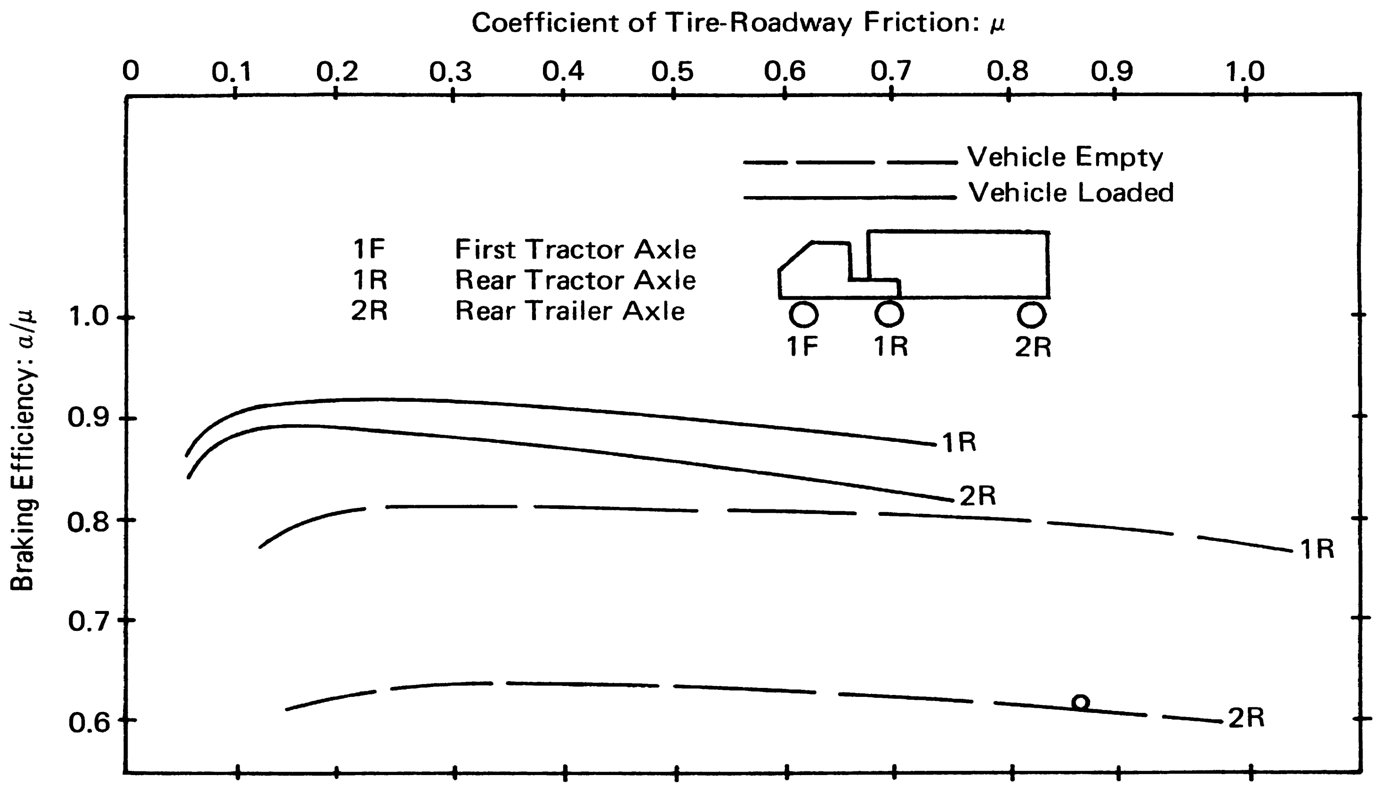

Figure 5. Braking efficiency for 2-S1 tractor-trailer.

where

ϕ_{1F} = brake force on front axle/total brake force

ϕ_{1R} = brake force on rear axle/total brake force

ϕ_{2R} = brake force on trailer axle/total brake force

The optimum brake force distribution for this vehicle was determined to be 0.20 : 0.42 : 0.38 indicating insufficient braking effort on the front axle and too much on the trailer axle. Test data support this analysis in that one tractor rear wheel and one trailer wheel approached wheel slide when the empty vehicle decelerated at 17 ft/sec^2. Although better performance can be achieved by modifying the brake force distribution, a fixed distribution should not be expected to produce braking efficiencies for combination vehicles much higher than 75%.

Also included in this study are efforts that have been directed towards developing techniques to predict brake thermal response. The analysis was hindered by several factors, namely: (a) the instrumentation used in the experimental program did not lend itself to an accurate correlation of calculations and experimental results, (b) lining material parameters such as thermal conductivity, specific heat, and density, could not be measured and thus had to be estimated, (c) the location of the thermocouples installed in the brake lining was not known with sufficient accuracy, and (d) the convective heat transfer coefficient could be neither accurately computed nor accurately determined from experiment. Notwithstanding these difficulties, calculations were made to predict brake temperatures as functions of time.

Finite difference methods were employed to compute the temperatures as a function of time at various points in the lining, $T = f(x,t)$, that would ensue in three of the test procedures, namely, the fade test, the recovery test, and the brake rating test. This procedure was dictated by the necessity to introduce the convective heat transfer coefficient, h, as a variable dependent upon vehicle speed. The thermal properties needed for the analysis were obtained from published data and a digital computer program was written to facilitate the numerical work involved. Although reasonably good agreement was obtained between theory and test for one of the vehicles, agreement between theory and test was less satisfactory for other vehicles, there being, in general, discrepancies of the order of 20%. It can be concluded from these results that in order to develop techniques for predicting brake thermal response based upon vehicle and brake system design data, further analytical work supported by carefully instrumented tests will be required.

3.4.2 Proportioning Schemes

Dynamic modeling and simulation were employed in this study to investigate the effectiveness of load and deceleration-sensitive brake proportioning schemes in improving braking performance over a wide range of loadings and test surfaces.

The dynamic simulation developed for this study is based on a model that represents either a two-axle truck or tractor, or a three-axle tractor-trailer combination. Motions are constrained to the plane of symmetry (vertical plane). Specifically the wheels can bounce and spin, the chassis can heave and pitch, and the vehicle can accelerate (decelerate) in straight-line motion. The braking system is modeled in a manner such that variable time lags and delays in torque response can be introduced. Any desired brake force distribution can be specified.

To determine the improvement in performance that could be expected for a three-axle tractor-trailer combination (2-S1) using static load-sensitive proportioning valves, a typical two-axle tractor and 27 ft van trailer were used as a basis for the study. Brake torque for each axle was calculated from typical design information. In this preliminary investigation, no account was taken of the loss of brake effectiveness that is caused by fade during a single stop. The following findings were obtained:

1. Without proportioning the loaded vehicle achieves a maximum deceleration of 16.7 ft/sec^2 before the trailer wheels lockup.

2. The empty vehicle without proportioning achieves a maximum deceleration of 16.9 ft/sec^2 before the trailer wheels lockup.

3. The empty vehicle with the brakes proportioned to the static loads on the axles can achieve a maximum deceleration of 23.8 ft/sec^2 without encountering wheel lockup, an improvement in stopping capability of about 40%.

A second study was conducted to determine if a feasilbe proportioning scheme could be developed which would distribute the brake forces for maximum braking efficiency over a wide range of loadings and surface conditions. The 2-S1 combination vehicle tested in the program, namely, the Ford F-7000 tractor in combination with the Trailmobile 35 ft van trailer, was selected as the prototype for this study. Parameter data defining the vehicle and brake system were determined and introduced into the simulation. The effects of brake response time, fade, and pushout pressures were included. Preliminary runs were made to check that the simulation results matched test results obtained for the vehicle in the empty and loaded condition.

Simulated braking runs were made for the baseline and ideally proportioned vehicles for a variety of loading conditions and two tire-road interface conditions: $\mu_{peak}/\mu_{sliding}$ = 0.76/0.70 and 0.325/0.3. Results indicated that by means of this idealized proportioning scheme it is possible to achieve better than 90% braking efficiency for a tractor-trailer on the 0.7 and 0.3 surfaces, except for two cases on the dry surface, namely, the fully-loaded vehicle and the bobtail. The study also showed that changing the height of the center of gravity from 16 in. to 48 in. from the trailer deck had a negligible effect on straight-line braking performance.

4.0 RECOMMENDATIONS

In order to evaluate the findings obtained in the experimental and analytical phases of this study, and to formulate recommendations for improving the braking performance of commercial vehicles, it appeared desirable to categorize braking performance into a number of distinct facets or qualities.

The mechanics of the braking process suggest that there are at least five facets of braking performance that are deserving of consideration for commercial vehicles. These facets (or measures of braking performance) shall be referred to as "effectiveness," "thermal capacity," "controllability," "efficiency," and "response" and are defined below.

4.1 PERFORMANCE MEASURES

Brake "effectiveness" is a measure of the gain of a brake in terms of torque output per unit input of line pressure at the brake chamber. When the braking level is low such that the tires are not being forced to operate near their adhesion or friction limit, the total braking force acting on a vehicle is linearly related to the total torque being generated by all of the brakes. Under these conditions, deceleration per unit value of brake line pressure serves as an overall measure of the braking effectiveness of the vehicle. For pneumatic systems characterized by a limit value of line pressure, a finite value of effectiveness for a given brake means that there is an upper limit to the brake torque that can be generated. If this maximum torque is insufficient to produce wheel lock, during the braking process, the maximum value of wheels-unlocked deceleration that can be achieved by the vehicle is degraded.

The thermal efficiency of a brake can be characterized by the ability of the brake to absorb heat generated in a single stop and to conduct or convect away heat generated in a series of stops. The combination of this thermal efficiency (which is mostly a characteristic of the brake drum) with the lining properties determines the fade resistance of the brake. With the instrumentation used in the tests, thermal efficiency could not be measured directly, and so thermal capacity or resistance to fade is measured in terms of the level of braking effectiveness that can be maintained during a series of rapidly repeated snubs (as specified in the fade test procedure for this program) or the number of snubs which can be accomplished in a given time interval (SAE J880), or the decrease in tow bar force in a towing test (as specified in this program for the brake rating test). The fade test as conducted was not successful for the large commercial vehicles tested in this program because brake fade could not be induced. However, if the requirements for the initial and final snub velocities are changed to correspond with those of SAE J786, that is, 40 mph to 20 mph instead of 60 or 50 mph to 10 mph, fade can be induced and a measure of thermal capacity could be obtained. One such performance measure is the number of snubs that can be produced at a specified level of deceleration with the time to accelerate back to test speed between snubs not to exceed a specified period. From the point of view of safety, a thermal capacity test should be based upon the most severe duty cycle that a vehicle might encounter in general use.

Brake controllability is used here in the sense of the driver being able to modulate brake force under a wide variety of loading and road surface conditions to minimize stopping distance while preventing wheel lockup. Deceleration/pedal force gain is a performance measure that can be used to characterize brake controllability.

Braking efficiency is a measure of the ability of a vehicle to utilize the friction forces available at the tire-road interface. Strictly speaking, it is defined as the ratio of the maximum wheels-unlocked deceleration capability of the vehicle on a given surface to the peak tire-road friction coefficient of that surface. When braking efficiency is determined experimentally, the surface on which the vehicle is tested must be measured to determine the peak tire-road friction coefficient. At the present time, adequate means do not exist for making such a measurement with large truck tires. Therefore, as an alternative, it is proposed that braking efficiency be determined by calculating this measure, using vehicle and brake system design data as was accomplished for the test vehicles in this program.

Brake response time is defined as the time required for a brake to reach a given level of effectiveness from the time that the brake control (pedal) is activated. Measurements of response time in an actual stop would therefore require torque sensors on each braked wheel. Consequently, a more common means for determining the response time of pneumatic brake systems is to measure the time from the instant of pedal application (resulting in a full, fast opening of the treadle valve) to the instant a given pressure level is reached in the brake chamber. Measurements show that the response times typically exhibited by air-brake systems are sufficient to influence the braking performance of commercial vehicles, as measured either by average deceleration or stopping distance. Synchronization of brake timing is important for preventing instabilities in articulated vehicles. Brake-release time is significant when the driver is attempting to modulate the brake force to prevent wheel lockup. Therefore it is apparent that brake response is a significant measure of commercial vehicle brake system performance.

The performance measures defined above are summarized in Table 13.

TABLE 13

PERFORMANCE MEASURES

Quality Measures	Performance Measure	Symbol	Technique
1. Effectiveness	Maximum Deceleration (wheels unlocked)	a_x	Effectiveness Test
2. Thermal Capacity	Number of Snubs Achieved at a Given Deceleration	n	Fade Test
3. Efficiency	Braking Efficiency	$-a_x/\mu$	Calculation of Efficiency and Tire/Road Interface Test
4. Controllability	Deceleration/Pedal Force Gain	$-a_x/F$	Effectiveness Test
5. Brake Response	Application and Release Times (air brake systems only)	T_a, T_R	Static Response Time Test

4.2 MAXIMUM ACHIEVABLE PERFORMANCE

The maximum braking performance that can be achieved by a vehicle on a given test surface is limited by five factors:

1. the frictional forces available at the tire-road interface,
2. the effectiveness of the vehicle's brakes, that is, the maximum torque capacity of the brakes,
3. the braking efficiency of the vehicle, that is, how well the brake torque is balanced axle to axle such that the tire/road frictional forces are best utilized,
4. the ability of the driver to modulate the pedal force such that maximum deceleration and minimum stopping distance are achieved without loss of directional control and stability, and
5. the time response of the brake system to an applied pedal force.

Tire-road interface tests conducted for this program indicate that the friction coefficient of truck tires, both peak and sliding, is significantly less than that of passenger car tires. The effectiveness tests point up considerable variation in tire-road friction coefficient among the various types of truck tires. For example, the light truck was capable of locked wheel decelerations of as high as 28 ft/sec^2, while the disk brake truck was capable of only 22 ft/sec^2 with the wheels locked. Since tests with both the Michigan Department of State Highways' skid trailer and an instrumented car indicated that the friction coefficient of the test track varied only slightly over the entire period of testing, the difference in locked wheel deceleration must be attributed to difference in tire traction. The importance of this observation cannot be overemphasized since it is pointless to increase the effectiveness of brakes if frictional forces corresponding to the increased brake torque capabilities cannot be produced at the tire-road interface. The reader is therefore cautioned to judge the performance capabilities of the larger trucks and tractor-trailers tested in this program in light of these findings on truck tire traction.

The maximum wheels unlocked deceleration achievable, as determined either from an effectiveness test or a minimum stopping distance test, is a measure of not only the torque capacity of the brakes, but also of how well the vehicle utilizes the friction available at the tire-road interface. The maximum deceleration obtained on the dry surface is summarized in Figure 6 for all of the vehicles tested. With performance depicted in this fashion, it is immediately obvious that the vehicles equipped with advanced brake and brake-control systems did not exhibit braking performance that was significantly better than was achieved by the baseline vehicles. In fact it can be argued that a truck, bus, or tractor-trailer with brakes balanced for maximum braking performance can exceed the performance achieved on a dry surface by advanced brake control systems. For example, the light truck, all the buses, and the 2-S2 tractor-trailer combination, exhibited performance on the dry surfaces as good as Vehicle #12 and considerably better than Vehicle #14. The disk brake truck, however, was outperformed only by the light truck, and this result may stem from a difference in tire traction. Figure 7 perhaps better depicts the improvement in performance that can be expected by use of advanced brake-control systems. Since wheel lockup is viewed as undesirable, only the maximum decelerations obtained up to the point of wheel lockup are presented in this figure. Considerable improvements in performance are achieved for Vehicle #12 through use of the adaptive braking system, especially in the test conducted on the low coefficient surface, and in the tests conducted with the empty vehicle on the dry surface. It should be noted that the effectiveness of the brakes on Vehicle #12 was insufficient to lock up all the wheels on the dry surface in the loaded condition.

Vehicle #14 did not perform as well as Vehicle #12, either on the dry surface (even after making allowance for the slightly lower tire-road friction coefficient of the surface upon which Vehicle #14 was tested) or the

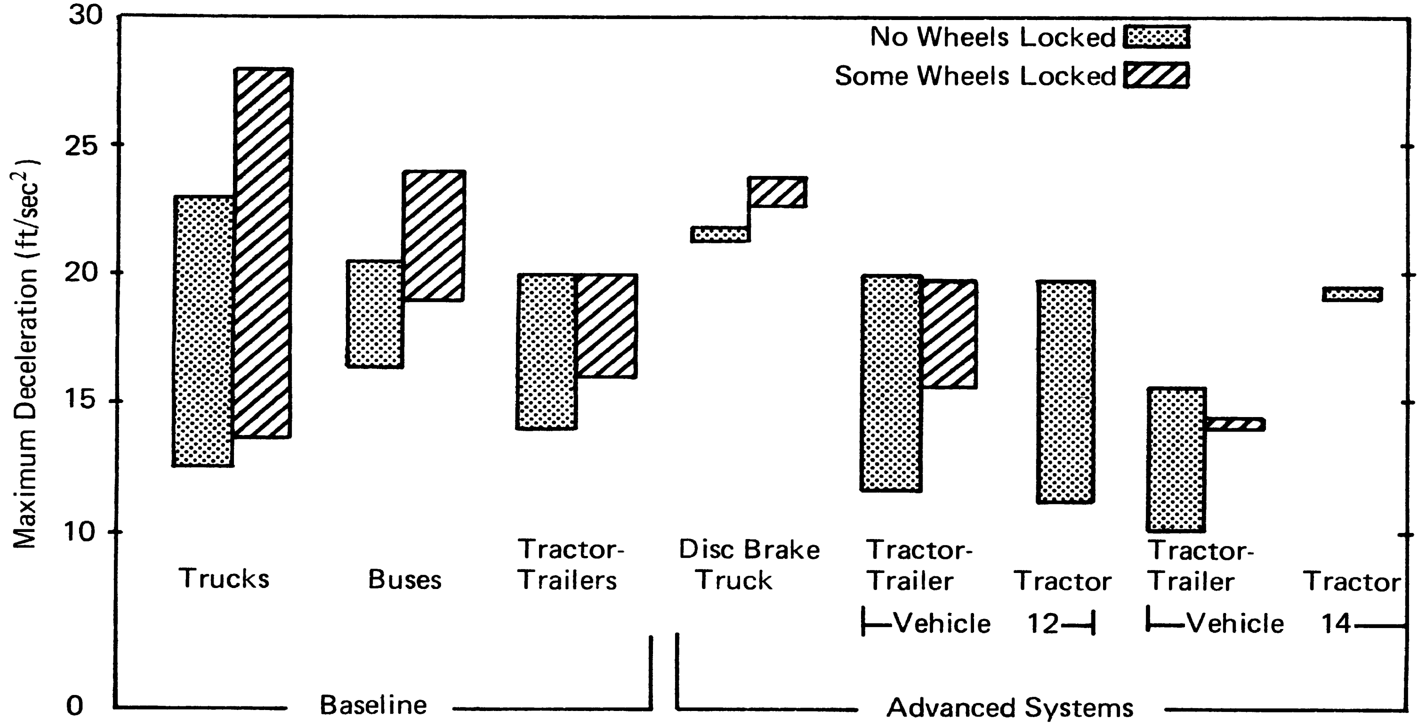

Figure 6. Maximum deceleration performance ranges, baseline and advanced systems.

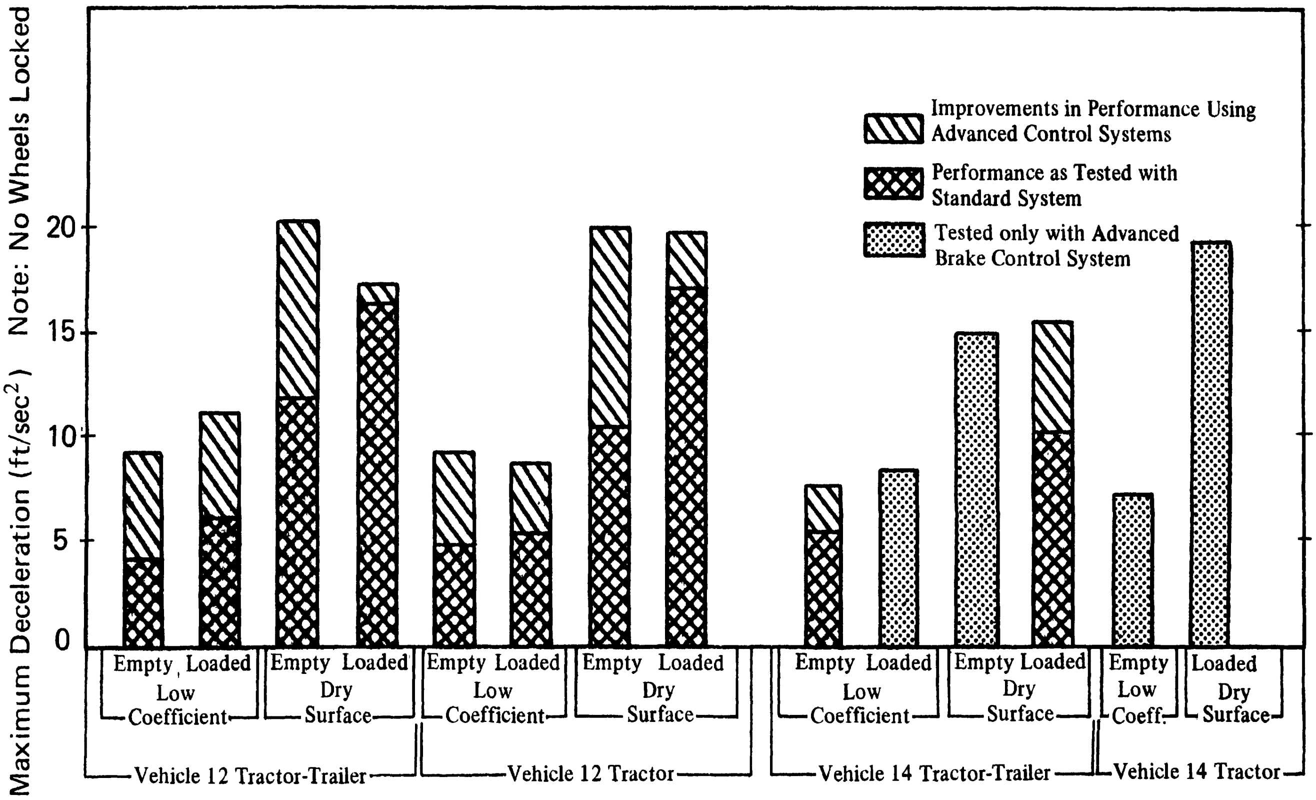

Figure 7. Improvement in maximum deceleration performance with advanced systems.

wet surface. The empty tractor (bobtail) of Vehicle #14 produced a maximum deceleration of 19 ft/sec^2 on the dry surface while the combination, empty or loaded, produced 15 ft/sec^2. Although the antilock system did improve performance of the combination as measured by the maximum deceleration achievable without wheel locking, the improved performance was considerably less than that which could have been achieved by better utilization of the forces in the tire-road interface.

Using the experimental data at hand, it is impossible to calculate exactly the braking efficiency of the tested vehicles since the peak values of tire-road friction coefficient, upon which efficiency calculations must necessarily be based, have been determined in an approximate manner. However, using these approximate coefficients, the efficiency exhibited by each vehicle and system tested is tabulated in Table 14. Using efficiency as the criterion, the disk brake truck showed best performance on the dry surface. The system which produced the best overall efficiency measure was the adaptive braking system installed on Vehicle #12. Next best was the antilock system installed on Vehicle #14. The smallest performance gains were achieved with the proportioning system. As pointed out earlier, minor adjustments in the proportioning valves, plus design steps that prevent premature lockup of the wheels on the leading axle of the trailer would have markedly improved the performance obtained with the proportioning system. The simulation study described earlier has indicated the magnitude of performance improvements that can be expected from use of proportioning systems.

TABLE 14

OVERALL BRAKING EFFICIENCIES FOR ADVANCED SYSTEMS TESTED

Vehicles	System	Dry Surface		Low Coefficient	
		Empty	Loaded	Empty	Loaded
Disk Brake Truck	--	90	88	--	--
#12 Tractor-Trailer	Standard	48	67	--	54
	Proportioning	47	67	--	--
	Adaptive	83	70	81	96
#12 Tractor	Standard	46	70	43	47
	Proportioning	82	70	30	47
	Adaptive	82	80	80	75
#14 Tractor-Trailer	Standard	--	45	46	--
	Antilock	66	68	66	72
#14 Tractor	Antilock	86	--	63	--

If a vehicle is equipped with an adaptive or wheel antilock brake system, the driver does not have to modulate the pedal force to prevent wheel lock. However, for vehicles not so equipped, a recent study at HSRI showed that the driver's ability in modulating the brake-pedal force to prevent wheel lockup is directly dependent upon the deceleration-pedal force characteristic of the vehicle.* Of all the vehicles tested, the disk brake truck achieved the greatest maximum deceleration without lockup of wheels. Figure 8 shows the deceleration-pedal force gain characteristics of the disk brake truck along with the recommended upper and lower limits derived from the HSRI study. It is interesting to note that those baseline vehicles in which the driver was able to modulate the pedal pressure such that a high deceleration was possible without wheel lockup all had deceleration-pedal force characteristics which were within the limits suggested by the HSRI study. These vehicles included the light truck, the three buses, and the 2-S2 tractor-trailer combination. It therefore appears reasonable to conclude that these limits may also serve as a guideline in selecting the deceleration-pedal force characteristics for buses, trucks, and tractor-trailers.

Measurements of brake response time given in Table 11, show that the standard braking systems of Vehicles #12 and #14 had application/release times that were approximately the same or slightly longer than those of the baseline tractor-trailers. However when using Syncron on Vehicle #12 and the antilock system on Vehicle #14, the response times of the trailer brakes were improved considerably.

4.3 RECOMMENDATIONS FOR A STANDARD

The above discussed findings, as derived both from analysis and test, indicate that three major steps will have to be taken to significantly upgrade the maximum braking performance of commercial vehicles.

First. The basic braking systems of the majority of these vehicles will have to be improved by use of more effective brakes, better balance, and faster system response on air braked vehicles.

Second. The traction characteristics of tires used on the majority of medium and heavy commercial vehicles will have to be improved so that the advantage of improved brake effectiveness can be fully utilized at the tire-road interface.

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*R. G. Mortimer, et al., Brake Force Requirement Study: Driver-Vehicle Braking Performance as a Function of Brake System Design Variables, Contract No. FH-11-6972, prepared for the National Highway Safety Bureau, U. S. Department of Transportation, by the Highway Safety Research Institute, The University of Michigan, April 10, 1970.

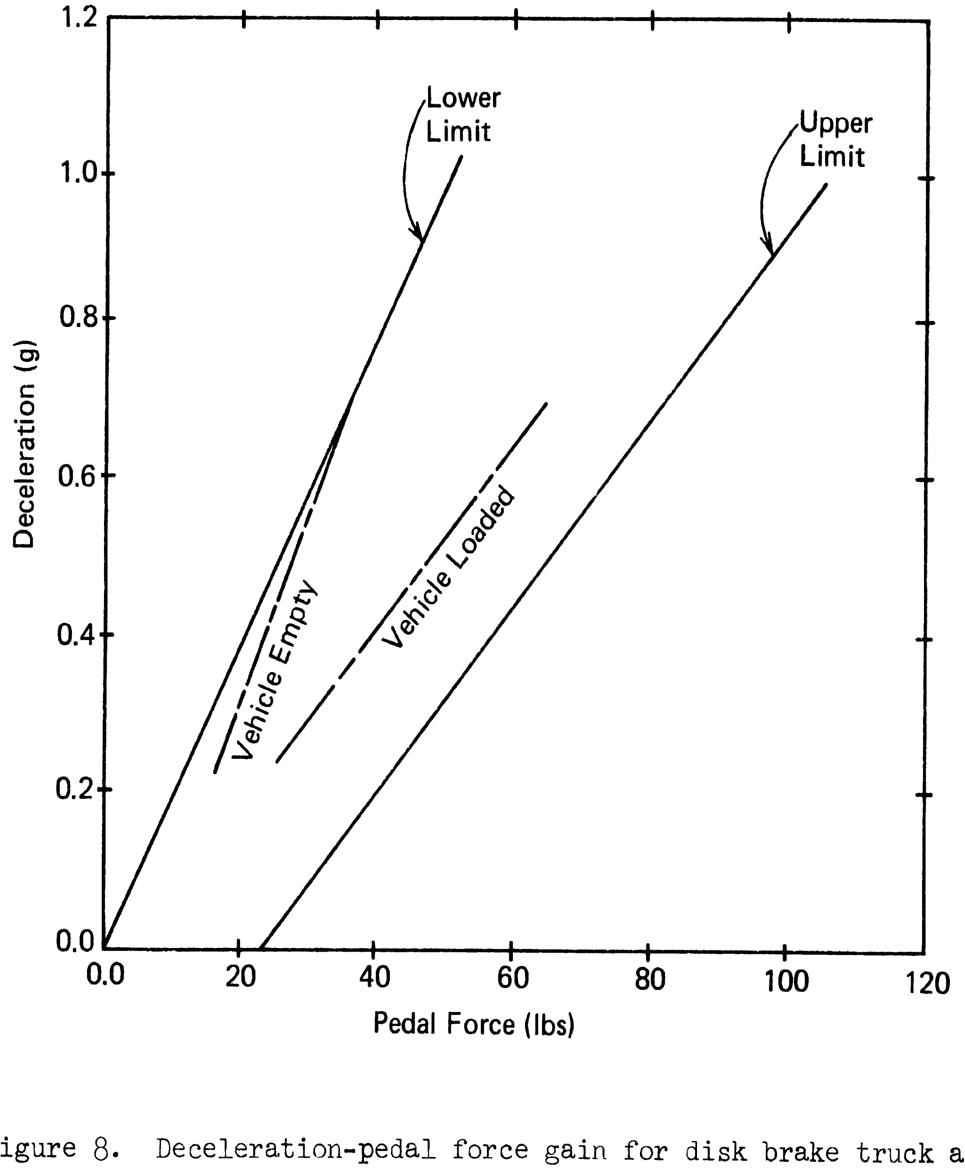

Figure 8. Deceleration-pedal force gain for disk brake truck and HSRI recommended limits.

Third. Advanced brake control systems will have to be employed to allow rapid brake applications without instigating vehicle instability whether the vehicle be loaded or empty, and operating on a dry or slippery surface.

A number of design alternatives exist for achieving these objectives:

1. The effectiveness and fade resistance of the braking systems on medium and heavy trucks can be improved significantly by use of disk brakes, powered either by a vacuum assist unit or a full power hydraulic system.

2. The effectiveness of the braking systems of tractors can be improved by use of large brakes on the front axle of tractors with tandem rear axles (a design configuration in which front brakes are generally absent) and by use of larger brakes on the front axle of two-axle tractors.

3. The braking efficiency of many trucks and tractor-trailer can be improved by careful distribution of braking effort among the axles of the vehicle.

4. The brake response time of air braked systems can be improved significantly through use of larger hoses, improved connectors and fittings, quick release valves, relay valves on tractors, and trailer brake synchronization.

5. Braking performance can be improved significantly on trucks, buses, and tractor-trailers through use of the advanced brake control systems, which were evaluated by test and/or simulation in this program. These systems, ranked in order of potential for improving braking performance, are:

    a. wheel antilock system
    b. dynamic load sensitive proportioning system
    c. static load sensitive proportioning system.

In considering any of the above design alternatives, one must bear in mind that the commercial vehicle has evolved over the years as a design compromise. The vehicle structure, suspension, and brake system have been designed for a given level of average braking performance, with a capability of accepting a certain amount of overload in emergency situations. The pneumatic tires are part of this design compromise, since there isn't much point in designing high tractive capability into truck tires, at the expense of increased rolling resistance and higher wear rates, if that tractive capability cannot be matched by brake torque capabilities as constrained by brake size and brake design practice. The aim of this design compromise has been to produce vehicles which are safe and reliable within their performance range, and which are characterized by high payload/vehicle weight ratios and minimal operating and maintenance costs. To introduce a requirement for severely increased braking capability into the commercial fleet, as it has evolved, will necessarily require a reevaluation of the design of the entire system. The following points are suggested for serious consideration.

1. More effective brakes will require stronger suspensions and stronger adjacent vehicle structures.

2. Large brakes on the front axles of tractors could require new front axle and steering system designs, and, in many cases, the use of power steering.

3. With increased deceleration capability, methods of cargo restraint will have to be reevaluated. On buses, passenger restraint systems may have to be utilized.

4. The relatively high ratio of center of gravity height above roadway to truck width, that is common to straight trucks, caused vehicle stability problems to be encountered at moderate decelerations in this test program. It is expected that the problem will be worse at higher decelerations. This problem may be alleviated by use of antilock systems. However, at this point in time, the problem is not clearly defined and requires much more study before a definite solution can be suggested.

5. If proportioning and/or antilock systems are to be widely used, cognizance should be taken of maintenance and reliability problems associated with each system. Load sensitive proportioning systems require mechanical, pneumatic, or other means of sensing changes in load. Due to wear, corrosion, and other degrading factors, the level of coulomb friction in the suspension system may change, thus requiring periodic inspection and adjustment of the linkage. Since antilock systems for air braked vehicles are still in the developmental stage, reliability problems with both mechanical and electronic components were encountered in the test program. It is mandatory that antilock systems have a high degree of reliability because of the human factors involved. The test program has pointed out that regardless of load or surface condition, the driver will make rapid, high-level brake applications if he knows the antilock system is operational, whereas he will be extremely sensitive to load and surface conditions when applying the brakes without the antilock system in operation. Serious stability problems are possible if the driver applies the brakes rapidly thinking that the antilock system is operational where, indeed, it

is not, due to a component failure.

In making specific recommendations for a standard, careful consideration has been given to the necessity to upgrade commercial vehicle braking performance as quickly as possible to acceptable levels. Careful consideration has also been given to those points discussed in the paragraph above. Taking into account the system design problems which will result from increased performance requirements, and the state of development of advanced systems, it is recommended that rules be promulgated which require upgrading the performance of trucks, buses, and tractor-trailers in three discrete steps, separated by appropriate periods of time.* As a first step, it is recommended that the rules require immediate action to upgrade braking performance to a level achievable by current design practice, that is, the best performance already demonstrated by baseline vehicles tested. For the second step, it is recommended that the rules require performance to be improved to the limit of the tire-road interface tractive capabilities of truck tires now available with due regard to realistic braking efficiencies. The second step may require use of load sensitive proportioning systems on certain vehicles, and therefore sufficient lead time should be allowed for further development and testing of these devices. After an appropriate time interval to allow for development and testing of a reliable antilock system, the development of truck tires with better tractive characteristics, and the necessary design modifications of vehicle brake, suspension, and structural systems, it is recommended as a third step that performance equal to or approaching that of passenger cars be required along with use of an antilock system to insure vehicle stability over a wide range of vehicle loadings and road surface conditions. Summaries of the suggested performance requirements for each step are given as follows:

<u>Step #1</u>

- Maximum deceleration capability - 16 ft/sec^2**
- Minimum braking efficiency - 65% for surfaces having peak truck tire-road friction coefficients between 0.2 and 0.8

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*Recommendations for a specific time frame or schedule to implement these steps cannot be made since information on lead times for introduction of design changes, development of new hardware and necessary manufacturing techniques is not generally available from vehicle, brake, and brake component manufacturers.

**It is presumed that this deceleration would be measured on a surface having a peak truck tire-road friction coefficient of at least 0.75.

- Thermal capacity - same as requirements of SAE J786 fade and recovery test except that 15 ft/sec^2 deceleration is required for fade snubs

- Deceleration/pedal force gain - HSRI recommendations as given in Figure 8

- Air brake response time - application: 0.25 sec tractor, 0.35 trailer; release: 0.50 tractor, 0.70 trailer

- Special systems required - none

Step #2

- Maximum deceleration capability - 20 ft/sec^2*

- Minimum braking efficiency - 75% for surfaces as in Step #1

- Thermal capacity - test upgraded to correspond with heaviest duty cycles experienced in class of service

- Air brake response time - application· 0.25 sec tractor, 0.30 sec trailer; release: 0.30 tractor, 0.40 trailer

- Special systems required - static load proportioning (if necessary)

Step #3

- Maximum deceleration capability - 24 ft/sec^2 with upgraded tires such that peak tire-road surface coefficient is at least 0.85

- Minimum braking efficiency - 85% for surfaces having peak truck tire-road friction coefficient between 0.2 and 0.9

- Special systems required - antilock system

- Improved tires also required

Test procedures similar to those used in the test program are recommended for determining brake effectiveness, fade resistance, deceleration/

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*It is presumed that this deceleration would be measured on a surface having a peak truck tire-road friction coefficient of at least 0.75.

pedal force gain characteristics, and static response time of air brake systems. If stopping distance tests are required, they should be made in conjunction with the effectiveness tests to ensure maximum unlocked wheel decelerations are achieved. Compliance with braking efficiency requirements can be made by requiring design calculations similar to those outlined in the Final Report volume, and by validating the calculations by effectiveness tests on high coefficient and low coefficient surfaces.

Testing of tractor-trailer combinations presents a special challenge. Because of brake balance problems, a tractor which may perform very well with one trailer may perform poorly with another. Conversely, a trailer whose brakes were tested on a brake dynamometer and deemed adequate may perform well with one tractor but perform poorly with another. Also a tractor could perform well as a loaded straight truck, but poorly in combination with a trailer. For this reason it is recommended that tractors be certified to pull only those trailers with which it has been demonstrated by design calculation and test that performance of the combination vehicle is adequate.