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HSRI Report No. HuF-6a

Brake Force Requirement Study: Driver-Vehicle Braking Performance as a Function of Brake System Design Variables

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April 10, 1970

Summary Final Report

Contract FH-11-6952

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

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Brake Force Requirement Study: Driver-Vehicle Braking Performance as a Function of Brake System Design Variables

5. Report Date
April 10, 1970

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
HuF-6a

9. Performing Organization Name and Address
Highway Safety Research Institute
University of Michigan
Ann Arbor, Michigan 48105

10. Work Unit No.

11. Contract or Grant No.
FH-11-6952

12. Sponsoring Agency Name and Address
Federal Highway Administration
National Highway Safety Bureau
Washington, D.C. 20591

13. Type of Report and Period Covered
Summary Final Report
July 1, 1968-April 10, 1970

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract The objective of this study was to define those brake characteristics, within the space bounded by the relationship between brake pedal force and vehicle deceleration, which lead to acceptable driver-vehicle performance. A driver-vehicle braking test was performed in which the deceleration/pedal force ratio, the pedal displacement, the surface-tire friction, and driver characteristics (age, weight) were systematically varied in order to determine the influence of these variables upon minimum stopping distance and other performance variables. The tests that were performed on a low coefficient of friction surface showed that high values of deceleration/pedal force gain result in large number of wheel lockups and lower mean deceleration in bringing the vehicle to a stop, compared to intermediate or low deceleration/pedal force gain levels. Tests conducted on intermediate and high coefficient of friction surfaces showed that high and intermediate deceleration/pedal force gains produced greater mean decelerations and greater frequencies of wheel lockups than lower gain systems. The frequency of loss of lateral control was significantly greater with the high deceleration/pedal force gain brakes on all surfaces than with lower gains. There were minor benefits of 2.5 inch pedal displacement compared to zero inches. Potential brake failures and their effects upon pedal force requirements were analyzed. The implications of the findings for a vehicle braking standard were shown in terms of deceleration/pedal force gain and pedal force.

17. Key Words
BRAKING, DECELERATION, STOPPING DISTANCE, DRIVER BRAKING, PEDAL FORCE, PAVEMENT FRICTION, BRAKE FAILURE.

18. Distribution Statement
Availability is unlimited. Document may be released to the Clearinghouse for Federal Scientific and Technical Information, Springfield, Va. 22151 for sale to the public

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
unclassified	unclassified	22 + i-v	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

OBJECTIVE

The major objective of this study was to define the envelope enclosing the relationship between vehicle deceleration and brake pedal effort which gives rise to good driver-vehicle braking performance. Having derived a suitable set of limiting conditions upon the deceleration/pedal force gain, as a function of pedal displacement, it was also desired to recommend an appropriate set of objective testing and compliance procedures. The effect of various types of brake failures upon the brake pedal force required to obtain a given level of deceleration was also investigated in order to derive a methodology by which deceleration/pedal force ratios may be recommended for a brake failure mode.

SUMMARY OF TASKS

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

LITERATURE REVIEW

A review of the literature was carried out pertinent to an analysis of the deceleration/pedal force characteristics of an automotive vehicle. The factors considered important in the review were brake system design, brake usage, skidding, brake testing, and driver characteristics and brake modulation.

FOOT FORCE CAPABILITY OF DRIVERS

The brake pedal on conventional vehicles is actuated by the foot or both feet of the driver. For this reason it is important to know the foot force capabilities of individuals comprising the driving population. A procedure was developed by which left and right foot maximum force exertion could be measured for a sample of female and male drivers. The pedal force measuring buck shown in Figure 1 was used in these tests. Male and

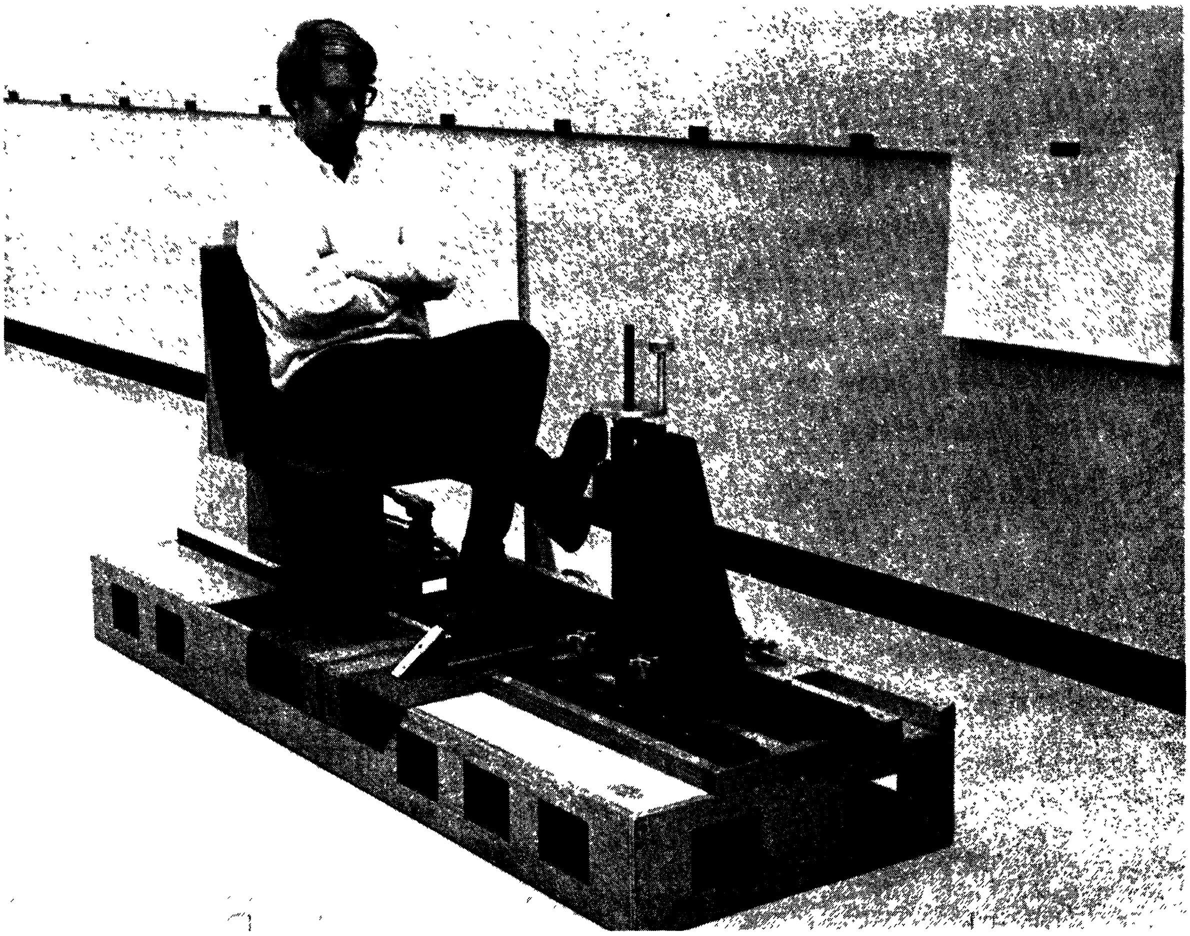

Figure 1. Foot pedal force measurement buck.

female subjects were selected at random from individuals in a local shoe store and a driver licensing office. Two measurements of maximum foot force were taken with the right and the left foot, each. The instructions on the first and second trials were varied such that in the second trial the subject was asked to exert the absolute maximum effort. Maximum foot force for the right and left foot, weight and age for each subject were obtained.

DRIVER BRAKING PERFORMANCE AS A FUNCTION OF PEDAL-FORCE AND PEDAL-DISPLACEMENT

An experimental test vehicle was constructed in which variations in deceleration/pedal force gain and pedal displacement could be readily made. A braking test was devised in which a driver was required, upon a signal, to bring the car to a stop as rapidly as possible within a lane ten feet wide delineated by rubber traffic cones (Figure 2). The test was conducted on three surfaces: a dry asphalt, wet asphalt and a wet-painted surface. The rolling tire friction coefficients of these surfaces were, respectively: .86, .71 and .40. Stops were made from 35 mph and 50 mph. The 28 test subjects were randomly selected on the basis of three weight categories and five age groupings, with an upper limit of 60 years.

Measurements taken from the start of braking consisted of the braking distance, braking time, number of wheels locked, duration of wheels locked, number of loss of control runs, pedal force and speed.

DRIVER BRAKING PRACTICE

The deceleration levels that drivers used in normal driving conditions were measured by means of an instrumented vehicle. The vehicle was driven by personnel engaged on University business. Measurements were made of the deceleration levels that were used by drivers and the maximum deceleration in each appli-

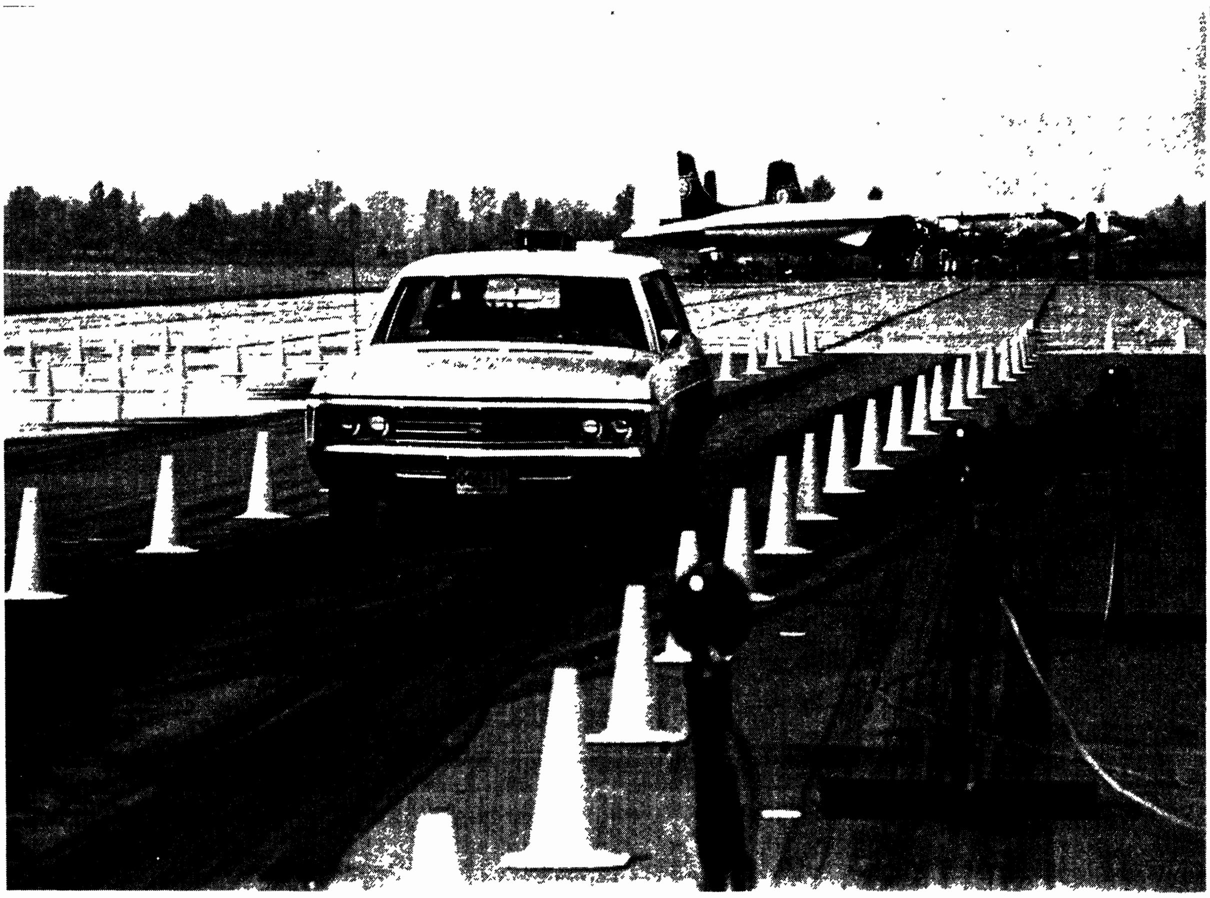

Figure 2. Brake test in progress

cation of the brakes was recorded. By this means a frequency distribution of the peak decelerations employed in everyday driving, on city, rural roads and expressways, were obtained. Such data were required in order to provide information of demands imposed upon the service brake and the probability with which a given level of deceleration is desired by drivers. The latter data were required for application in the failure analysis phase of the project.

FAILURE ANALYSIS

An analysis was conducted to determine the effect of various failures in the braking system, such as front and rear brake circuit failure, booster failure and brake fade upon the pedal force required to decelerate the vehicle.

FINDINGS

MAXIMUM FOOT FORCE

The maximum force exerted with the right foot for 276 female drivers in the "standard" motivation (trial-1) and the "induced" motivation (trial-2) conditions are shown in the form of a cumulative percent distribution of force in Figure 3. The analogous data for the 323 male subjects are shown in Figure 4. The 5th percentile force for females was 70 and 100 lbs in the two trials, and for males 140 and 185 lbs.

These data could be considered to be over-estimates of force levels that may be attained in a vehicle seat, which has considerable compliance, because a hard seat was used in the test fixture. On the other hand the stress of an emergency situation has been argued to enable drivers to exert high pedal forces. An intermediate level between the "standard" motivation and "induced" motivation pedal force levels for the 5th percentile female would appear to be a reasonable maximum force level that drivers should be expected to exert to derive a high

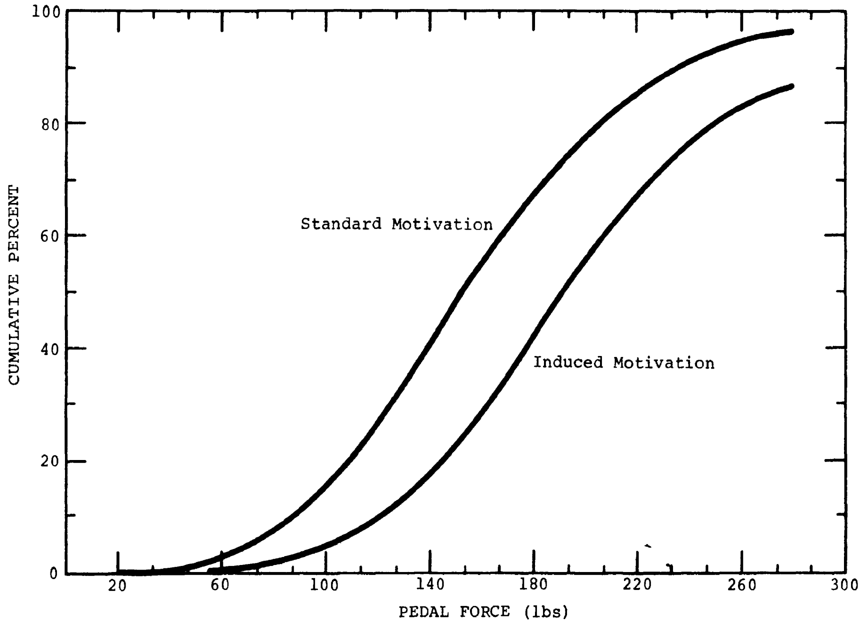

Figure 3. Cumulative percent pedal force for 276 females.

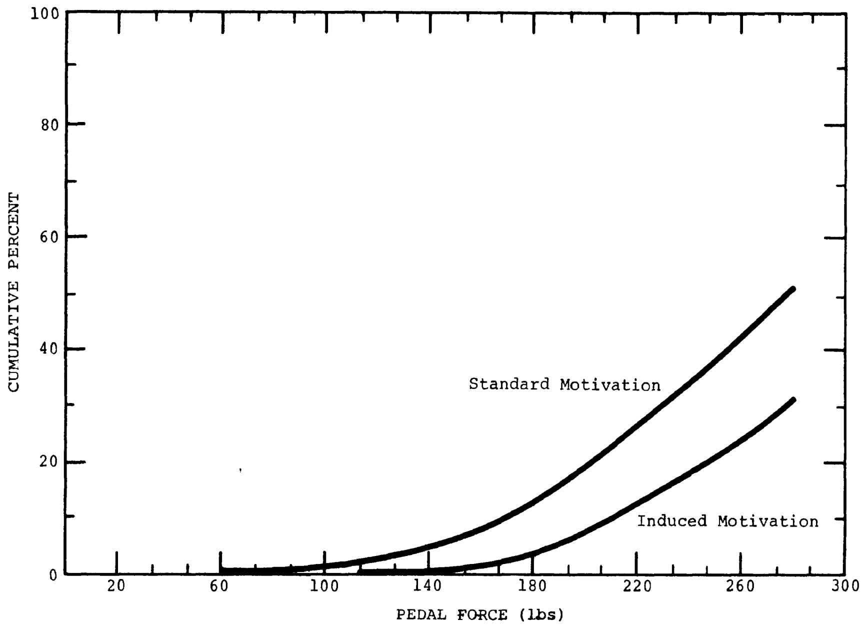

Figure 4. Cumulative percent pedal force for 323 females.

level of deceleration from the vehicle. A force of 85 lbs is therefore suggested by these data as the maximum brake pedal effort for a vehicle deceleration in the order of 0.75 g.

DRIVER-VEHICLE BRAKING TEST

The major interest in the braking test was to determine the effect of the relationship between deceleration and pedal force and pedal displacement upon the ability of drivers to minimize stopping distances, while retaining control of the vehicle.

The stopping distances achieved in each run during the test were converted to the average deceleration. An analysis of variance carried out upon the average deceleration data showed that there were no significant effects due to the pedal displacement variable. Thus, performance was similar for a pedal having a maximum displacement of 2.5 inches, at about 1000 psi in the brake line, and one which had zero inches displacement. Mean decelerations were slightly favorable to the pedal which displaced during braking. Statistically significant effects were found due to the deceleration/pedal force gain. The mean decelerations on each of the three surfaces, at the two initial speeds, for the deceleration/pedal force gain levels are shown in Figure 5. The highest gain (defined as high deceleration/pedal force in g/lb, or as pedal force/deceleration in lbs/g) configuration did not provide optimum performance in any of the surface x speed combinations. On the dry and wet surfaces performance was also poor at low gains. On the wet-painted surface the low and intermediate gain configurations provided best performance.

Table 1 shows the findings of Newman-Keuls tests conducted in each of the surface and speed conditions across the deceleration/pedal force gain levels. Values which are in parentheses indicate those levels of control gain which provided superior

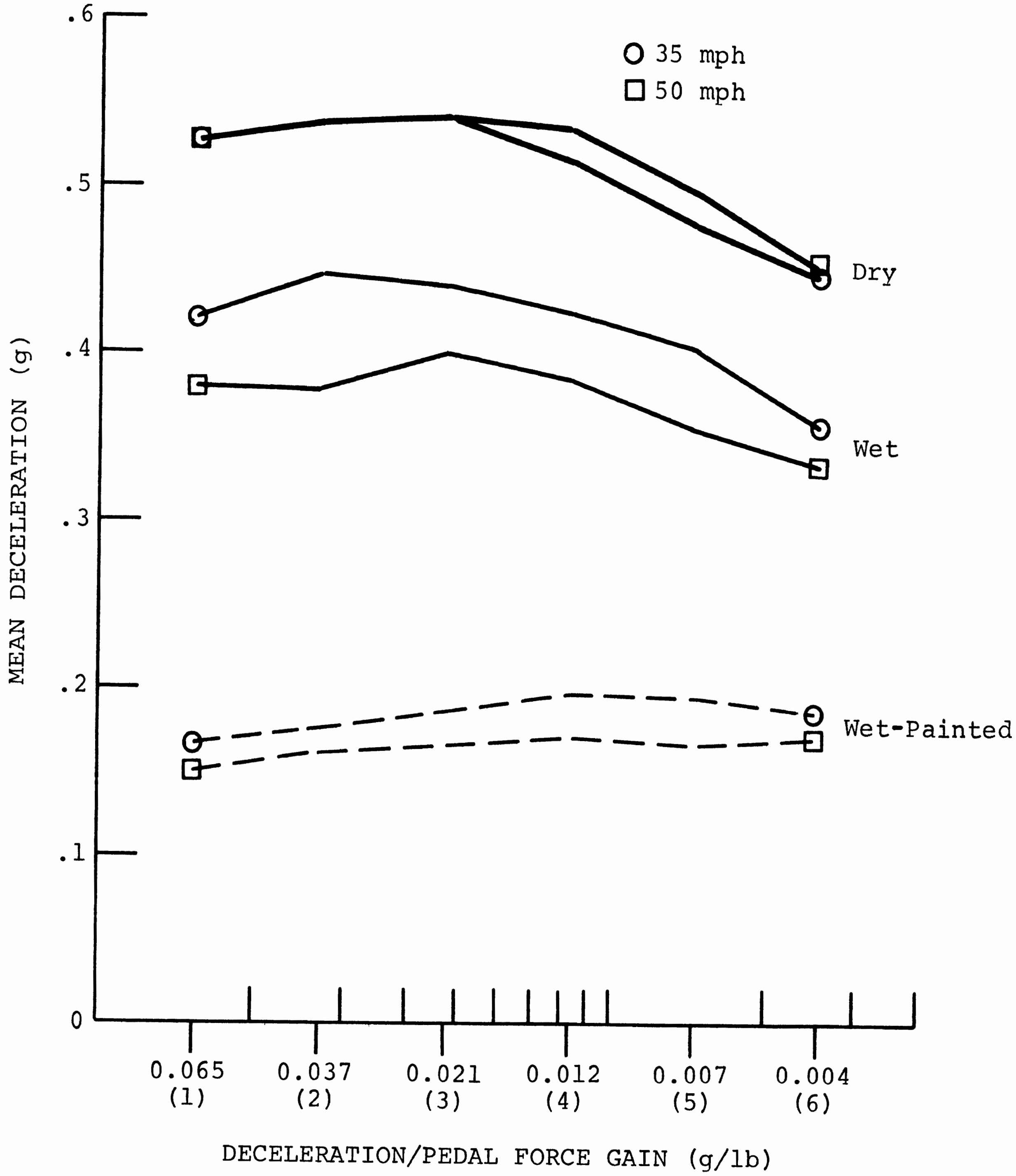

Figure 5. Geometric mean deceleration as a function of deceleration/pedal force gain, speed and surface.

TABLE 1. RANK ORDER OF DECELERATION/PEDAL FORCE GAINS DIFFERING SIGNIFICANTLY IN DRIVER VEHICLE BRAKING DECELERATION

Level	PFG (g/lb)	Dry 35 MPH	Dry 50 MPH	Wet 35 MPH	Wet 50 MPH	Wet-Painted 35 MPH	Wet-Painted 50 MPH	Rank Sum
(1)	0.065	3	4	3.5	3	6	6	25.5
(2)	0.037	[1.5]	[2]	[1.5]	3	5	5	17.5
(3)	0.021	[1.5]	[2]	[1.5]	[1]	3.5	3.5	14.0
(4)	0.012	4	[2]	3.5	3	[1.5]	[1.5]	15.5
(5)	0.007	5	5	5	5	[1.5]	3.5	24.5
(6)	0.004	6	6	6	6	3.5	[1.5]	29.0
		21	21	21	21	21	21	126.0

[Those values blocked off indicate the pedal force gains providing significantly greatest mean deceleration under each surface-speed condition].

performance to other levels. The numbers within the table indicate the rankings of each of the deceleration/pedal force gain levels in terms of significant differences with other levels.

The mean frequency with which wheels were locked up during each run as a function of the initial speed and the pedal force gain is shown in Figure 6. There is a clear reduction in wheel lockup frequency as the gain is decreased. There were slightly less wheel lockups with the 2.5 inch maximum displacement pedal than the 0 displacement on some of the pedal force gain levels. There was a considerable effect upon mean number of wheel lockups of the pavement surface, with far greater frequency of wheel lockups occurring on the wet-painted surface than on either the wet and the dry which incurred similar frequencies (Figure 7).

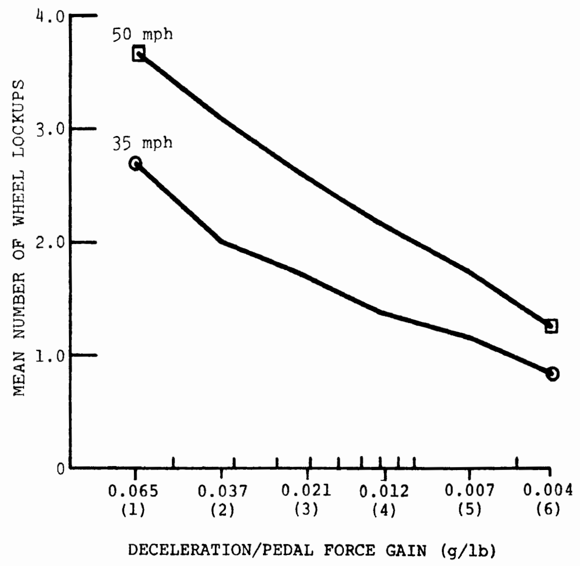

Figure 6. Mean number of wheel lockups as a function of deceleration/pedal force gain and speed.

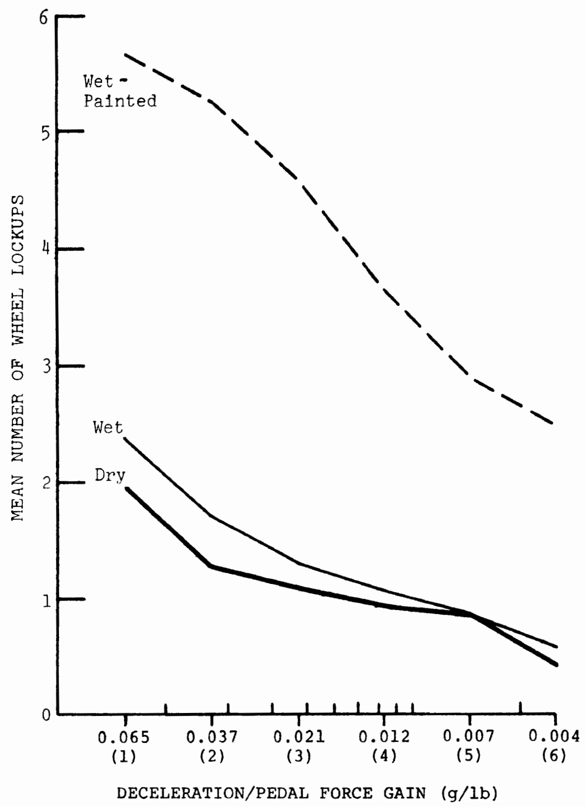

Figure 7. Mean number of wheel lockups as a function of deceleration/pedal force gain and surface.

The mean time for which wheels were locked up as a function of the pavement surface and the pedal force gain is shown in Figure 8. The mean time of wheel lockup is greatest on the wet-painted surface. There is a consistent reduction in wheel lock-up time as the pedal force gain is reduced. The proportion of the braking time during which one or more wheels were locked on each of the three surfaces is shown in Figure 9, indicating that for as much as 60 percent of the braking time, on the wet-painted surface, one or more wheels were locked.

Loss of control trials (Table 2) occurred most often with the highest brake pedal gain. There are small differences attri-

TABLE 2. PERCENT[1] OF TRIALS INVOLVING LOSS OF LATERAL CONTROL AS A FUNCTION OF BRAKE SYSTEM, SPEED AND SURFACE

Pedal Displacement	Surface	MPH	Deceleration/Pedal Force Gain (g/lb) 0.065	0.037	0.021	0.012	0.007	0.004
0	Dry	35	3	0	0	12	0	0
		50	6	6	3	9	3	0
	Wet	35	3	3	0	0	0	0
		50	28	12	9	3	0	3
	Wet-Painted	35	16	0	6	0	0	0
		50	48	22	25	21	10	6
2.5	Dry	35	3	6	9	0	6	3
		50	12	12	0	3	3	6
	Wet	35	12	3	12	12	3	0
		50	17	6	6	6	0	0
	Wet-Painted	35	12	3	12	12	3	0
		50	39	26	28	17	24	20
	Mean		19.0	9.2	9.7	8.0	5.1	3.7

[1]Percent = $\frac{\text{Loss of Control Trials in a Test Condition}}{\text{Total (Successful \& Loss of Control) Trials in a Test Condition}} \times 100$

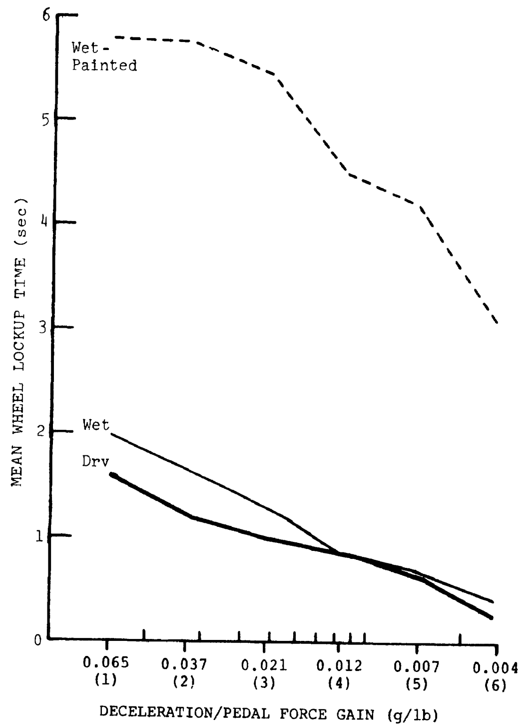

Figure 8. Mean wheel lockup time as a function of deceleration/pedal force gain and surface.

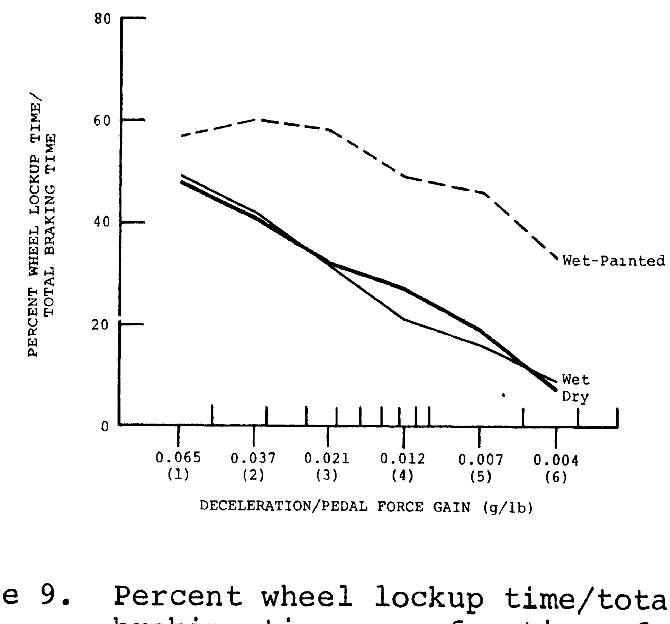

Figure 9. Percent wheel lockup time/total braking time as a function of deceleration/pedal force gain and surface.

butable to the pedal displacement variable in the percent of loss of control trials. Clearly, most such events occurred with the highest deceleration/pedal force gain brake configuration on the wet-painted surface, though they were also quite frequent on the wet surface.

Ratings made by the subjects of the controllability of the vehicle during the braking test for each of the gain and displacement conditions showed (Figure 10) that they did not perceive differences due to the displacement variable, but the highest gain was undesirable. The ratings made by subjects of the magnitude of the force required to operate the brake (Figure 11) showed that gain levels 1 and 2 required too little force and levels 5 and 6 required too much force. The intermediate gains used in the test, levels 3 and 4, were clearly preferred.

Based upon these data a set of limiting pedal force gain values was established within which good driver performance, on all three surfaces used in this test, was obtained. Figure 12 shows the slopes of the functions relating deceleration to pedal force for each of the levels of the gain factor used in the test. The results of the statistical analyses of the average deceleration data, which are shown in Table 1, were used to define limiting pedal force gain values. The table shows that on the dry surface levels 2 and 3, at both speeds, provided significantly superior performance to level 1. For this reason pedal force gain level 1 was taken as a gain which should not be exceeded in order to retain good driver performance when braking on the dry surface ($\mu_{peak} = 0.86$). This is shown by A^1 in Figure 12 at a deceleration level of 0.86 g. However, pedal force gain level 1 incurs significantly high frequencies and durations of wheel lockup and loss of control. For these reasons, and those shown by the subjective data, a

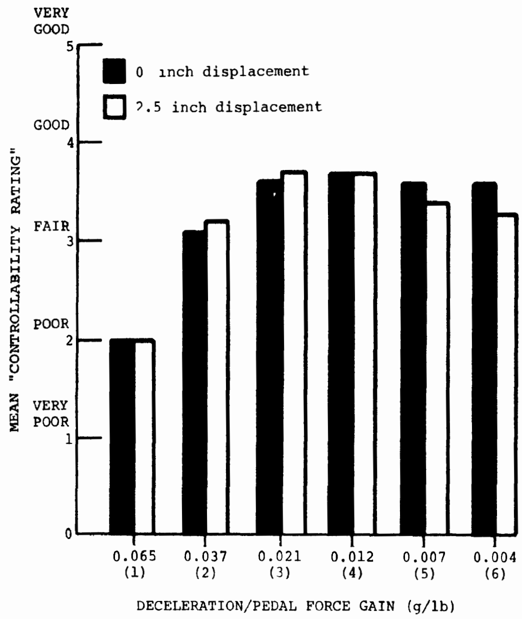

Figure 10. Mean controllability rating for 28 subjects as a function of deceleration/pedal force gain and pedal displacement.

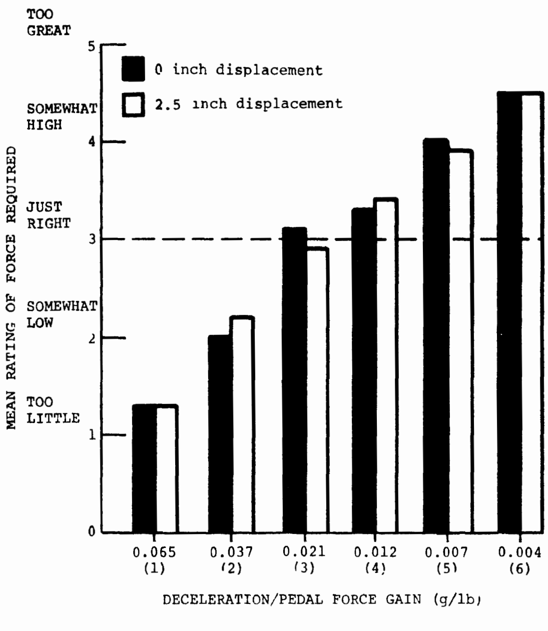

Figure 11. Mean rating of force required for 28 subjects as a function of deceleration/pedal force gain and displacement.

lower gain was desired for the limiting value. Therefore, the limiting value of maximum deceleration/pedal force gain was taken as that found with gain level 2 and is shown as A in Figure 12. The mean deceleration data on the wet surface show that gain level 3 provided superior performance to levels 1 and 2 and for this reason pedal force gain level 2 was taken as the maximum limiting value. This is shown as B in Figure 12. Similarly, C was selected at a deceleration of 0.40 g as the maximum deceleration/pedal force gain. Minimum PFG values were selected, using a similar rationale, by the data shown in Table 1. In this way points D, E and F were found as the minimum gain levels to which brake system performance should be limited at the corresponding deceleration levels.

DECELERATION MAGNITUDE FREQUENCY DISTRIBUTION

The peak deceleration on each brake application was recorded for 8934 miles of driving by 44 drivers. The brake was non-power (manual) in the initial phase of the test for 4254 miles and then converted to a power brake for the remainder. There were an average of 1.4 brake applications per mile traveled. Figure 13 shows the cumulative percent distribution of peak decelerations in manual and power brake modes, which produced almost identical results. About 80 percent of all peak brake decelerations were below 0.20 g, 96 percent were below 0.3 g, and 99.9 percent were below 0.5 g.

FAILURE ANALYSIS

Analyses were made of the effects upon pedal effort of front or rear brake circuit failure, brake booster failure and brake fade. These analyses were carried out for various front-rear brake force distributions. The increments in pedal force that were required in each of these conditions were noted, and in many instances clearly required pedal forces that could not be attained by a substantial proportion of the driving public.

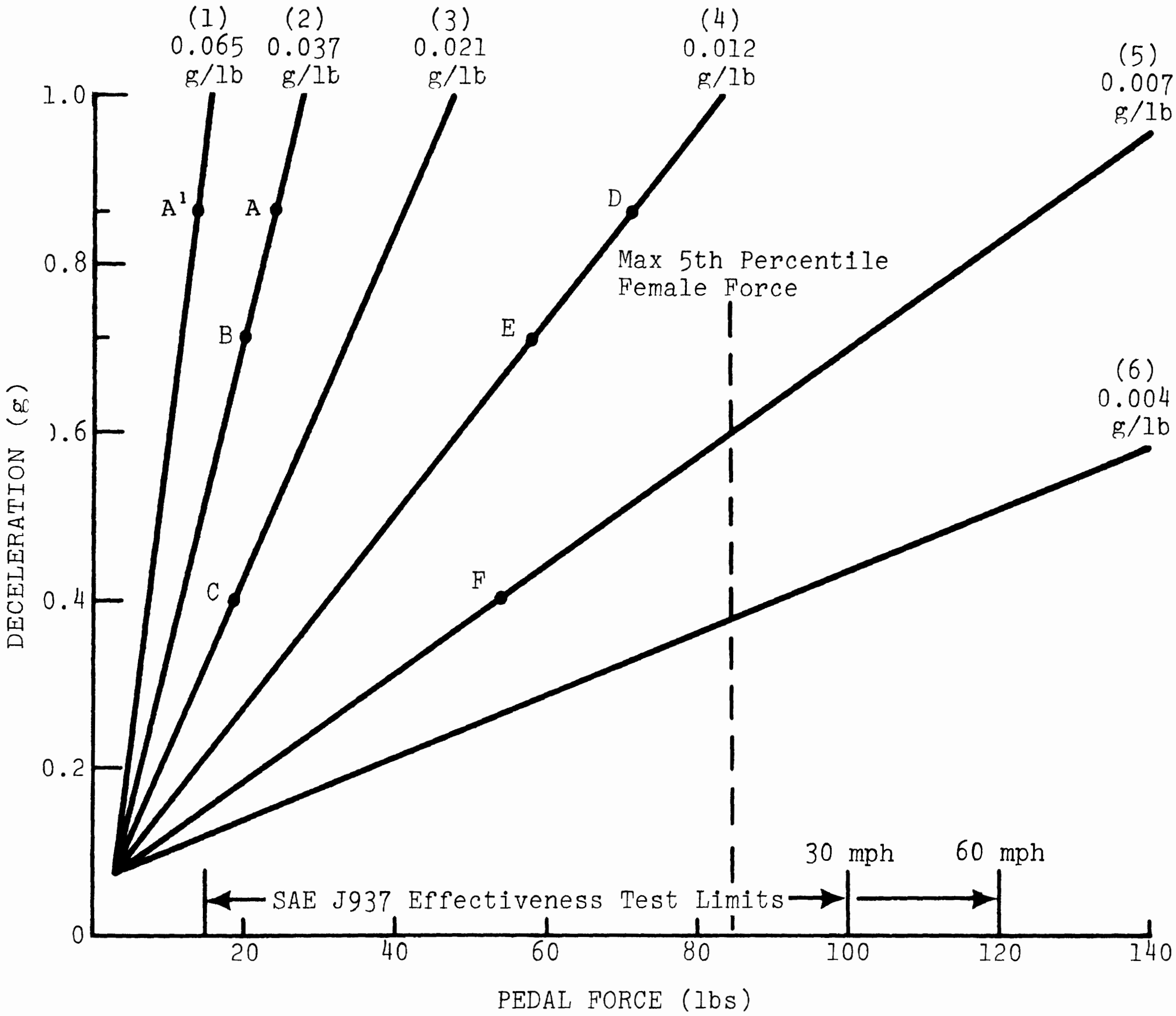

Figure 12. Cut-off PFG values for satisfactory driver-vehicle braking performance.

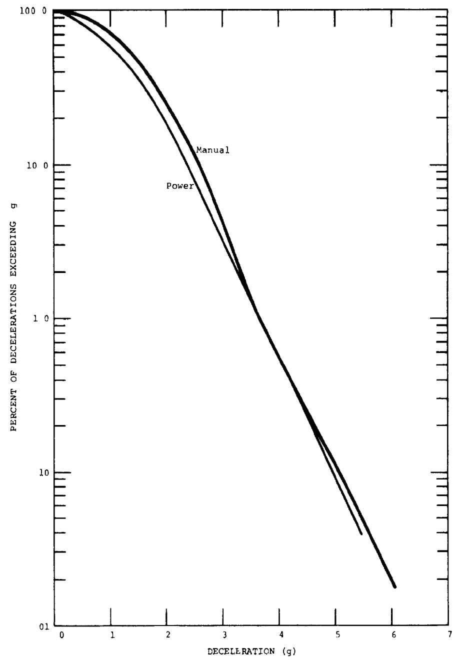

Figure 13. Cumulative percent of decelerations for manual and power brakes.

Front brake circuit failures resulted in higher pedal effort requirements than rear brake circuit failures, as expected. Similarly, the effect of loss of power boost and the effects of lining temperature were investigated in terms of deceleration/ pedal force relationships. The results of compliance tests on a number of vehicles equipped with drum, disc, and disc/drum brakes were summarized. The clear differences in the pedal force gain levels between manual and power brakes are apparent (Figures 14 and 15).

A technique was derived to show the effect of a failure in terms of the probability that a desired deceleration will be achieved. The method used the data representative of the effects of various brake system failures upon pedal force requirements, the distributions of driver force capabilities and the distribution of decelerations incurred in everyday driving. Figure 16

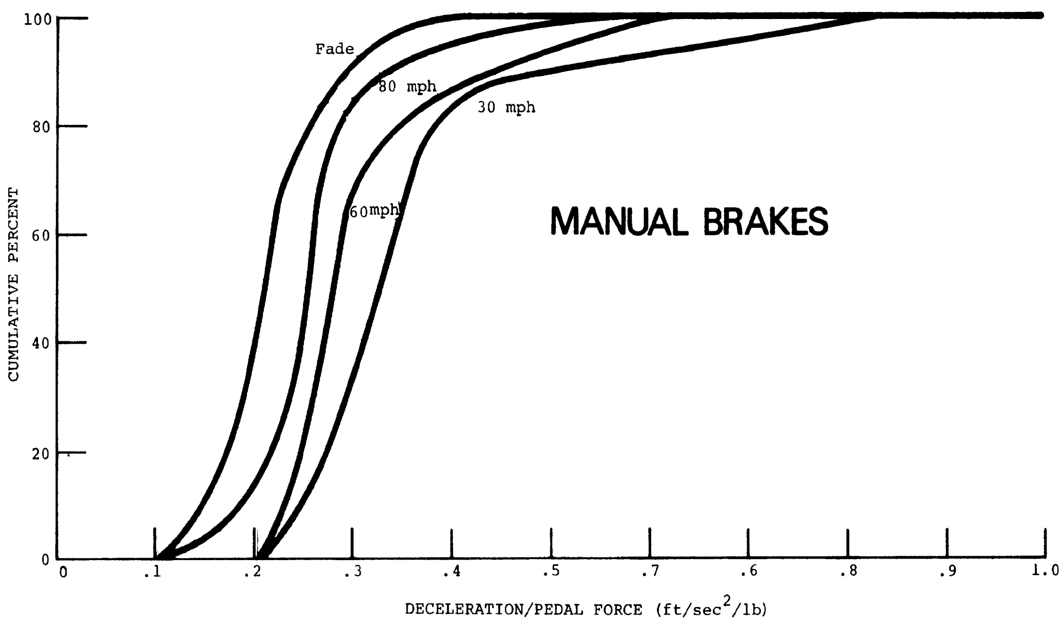

Figure 14. Cumulative percent of vehicles with lower gain: Manual brakes.

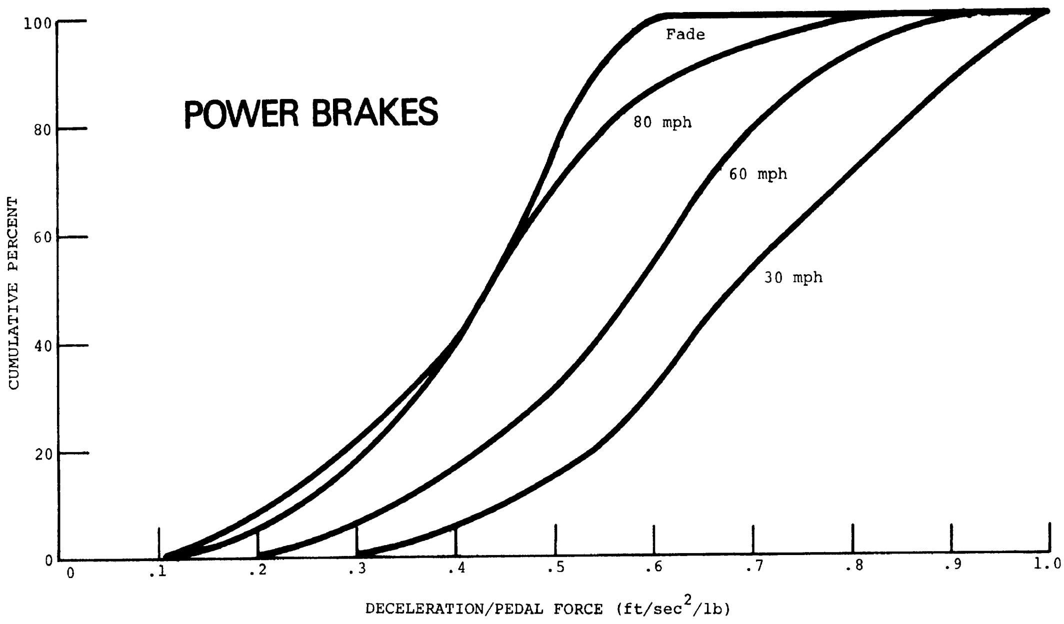

Figure 15. Cumulative percent of vehicles with lower gain: Power brakes.

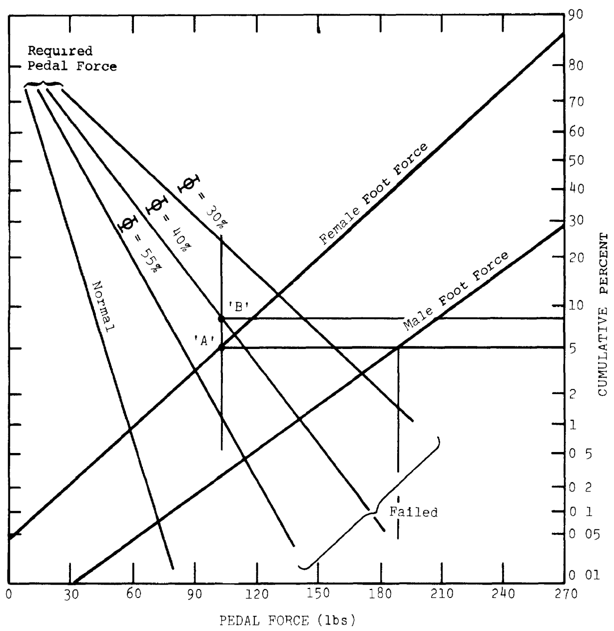

Figure 16. Cumulative pedal force distributions for front axle brake circuit failure in a loaded sedan with manual brakes.

shows the relationship between the distributions of driver pedal force, the decelerations used by drivers, and the front-rear brake effort of a hypothetical vehicle in a normal and in a front brake circuit failure condition. This diagram can be used to determine the probability that a 5th percentile female, for example, driving a manual brake vehicle with a 60/40 front-rear brake effort distribution, fails to achieve a probably desired deceleration during a stop following a front brake circuit failure. Using the right-hand scale of Figure 16, the 5th percentile line intersects the female foot force capability line at A. Proceeding vertically to the $\Phi = 40\%$ line, point B, and then again horizontally back to the right-hand scale, it is found that the probability of the 5th percentile female foot force driver failing to achieve her desired deceleration level is 8 percent. This means that there is a probability of 8 percent that the deceleration that the driver may perceive as being required will need a pedal force equal to or greater than she is capable of exerting. The curves shown in the report can be used with specific vehicle brake configurations, failure modes and selected pedal force and deceleration requirements in order to define pedal force requirements in a failed condition.

CONCLUSIONS

The analytical and experimental studies have shown that boundary values of maximum and minimum deceleration/pedal force gain can be derived which could be used in order to set recommended limitations upon these brake system characteristics. The data are augmented by those obtained by measurements of the maximum foot force capability of males and females in the driving population. A maximum brake pedal effort of 85 lbs has been selected, being within the capability of 5 percent of female drivers, at which near to the practical maximum deceleration should be attainable from a passenger car. For this reason 85 lbs is suggested as the pedal force at which a deceleration of 0.75 g should be attained.

The braking tests showed that the highest deceleration/ pedal force gain resulted in sub-optimal mean deceleration on all pavement surfaces used in the test, resulted in high frequency of wheel lockup, wheel lockup duration, loss of steering control, and was down-graded in the subjective ratings. High gain and intermediate gain configurations provided best performance in terms of mean deceleration on the dry and wet surfaces, while lower gains were required on the wet-painted surface. This is what would have been expected, but the data also showed those deceleration/pedal force gains that could be used as boundary conditions, such that the gain levels should not be greater than nor less than indicated values.

The limiting points have been shown in Figure 12. With respect to this figure a number of recommendations can be made which are described in Figure 17:

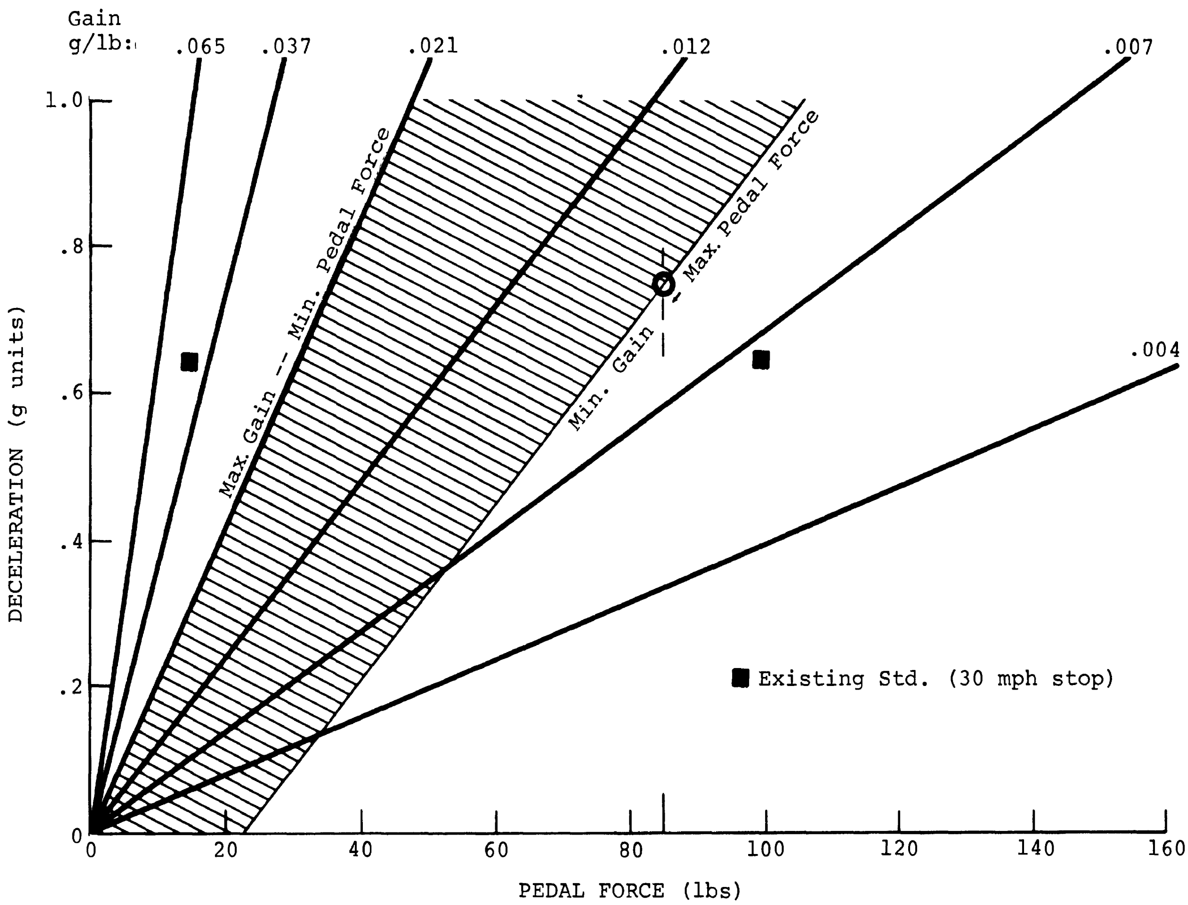

Figure 17. The recommended deceleration/pedal force space.

1. The limiting maximum deceleration/pedal-force gain should be 0.21 g/lb because:

   a. In Figure 12, C is the most critical limit and falls on this function;

   b. Higher pedal force gains incurred greater frequencies of loss of control and wheel lockup, wheel lockup duration and were downgraded in subjective ratings of force requirement and controllability;

   c. Practical restrictions on brake performance currently preclude a deceleration/pedal force curve in which the gain increases with pedal force.

Therefore, Figure 17 shows a line of slope 0.021 g/lb as the maximum gain and the bound on minimum pedal force in the deceleration/pedal force space.

2. The low gain limit in the deceleration/pedal force space is obtained as follows:

   a. The minimum gain at which effective braking performance was obtained on all surfaces that were used is 0.012 g/lb.

   b. The female 5th percentile foot force (85 lbs) should be sufficient to attain a deceleration of 0.75 g.

Therefore, the minimum bound on pedal force and gain is described (Figure 13) by a line of slope of deceleration/pedal force of 0.012 g/lb passing through the point 0.75 g/85 lbs.

3. In the event that a recommendation such as that shown above is adopted, it will be necessary to employ a brake test procedure to obtain pedal force values at a number of deceleration levels less than 0.2 g and up to a maximum attainable prior to wheel locking on a dry, smooth, Portland cement concrete surface as described in SAE J-843. In this way the curve relating pedal force and vehicle deceleration can be obtained and compliance with the limitations recommended in Figure 17 can be measured.