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THE FRICTION OF RAILWAY BRAKE SHOES AT HIGH SPEED AND HIGH PRESSURE

BY

HERMAN J. SCHRADER

PUBLISHED BY THE UNIVERSITY OF ILLINOIS

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THE FRICTION OF RAILWAY BRAKE SHOES AT HIGH SPEED AND HIGH PRESSURE

BY

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CONTENTS

		PAGE
I.	INTRODUCTION	7
	1. Previous Experiments	7
	2. Purpose of Investigation	7
	3. Test Program and General Results	7
	4. Acknowledgment	9
II.	TESTING EQUIPMENT	9
	5. Brake Shoe Testing Machine	9
III.	BRAKE SHOES AND TEST WHEEL	9
	6. Brake Shoes Used in Tests	9
	7. Car Wheel Used in Tests	11
IV.	GENERAL TEST PROCEDURE	11
	8. Preliminary Test Procedure	11
	9. Method of Conducting Test	12
	10. General Treatment of Wheel and Shoes During Tests	12
	11. Method of Calculating Results	13
V.	MAIN RESULTS OF TESTS	14
	12. Coefficient of Friction	14
	13. Stopping Distance	19
	14. Brake Shoe Wear	19
VI.	SECONDARY RESULTS OF TESTS	23
	15. Effect on Wheel and Shoes	23
	16. Relative Merits of Shoes	32
VII.	SUMMARY AND CONCLUSIONS	34
	17. Summary of Results	34
	18. Conclusions	35

PAGE

Appendix A. Variation of Coefficient of Friction During the Stopping Period 36
1. Purpose 36
2. Method of Calculating Results 36
3. Results 36
4. Conclusions 39

Appendix B. Variation of Coefficient of Friction With Shoe Thickness 40
1. Purpose of These Tests 40
2. Test Program 40
3. Procedure 40
4. Results of Tests 42
5. Conclusion 43

Appendix C. Relation Between Shoe Bearing Area and Coefficient of Friction 44
1. Purpose 44
2. Procedure 44
3. Results of These Tests 46
4. Conclusion 48

Appendix D. Temperature of Wheel and Shoe . . 49
1. Object of Temperature Tests 49
2. Procedure 49
3. Results of Temperature Tests 50
4. Conclusions 51

LIST OF FIGURES

NO.		PAGE
1.	Relation Between Coefficient of Friction and Brake Shoe Pressure, for All Tests	15
2.	Relation Between Stopping Distance and Brake Shoe Pressure, for All Tests	18
3.	Relation Between Brake Shoe Pressure and Brake Shoe Wear, for All Tests	19
4.	Relation Between Work per Second and Brake Shoe Wear per 100 Million Foot-Pounds of Work, for All Tests	22
5.	Wheel and Shoe During a Stop	23
6.	Condition of Wheel After One Stop	24
7.	Cracks in Wheel Tread	25
8.	Cracks in Wheel Near Thermocouple No. 2	27
9a.	Condition of Shoes After Tests	30
9b.	Condition of Shoes After Tests	31
10.	Variation of Coefficient of Friction During Stopping Period	38
11.	Variation of Coefficient of Friction and Bearing Area With Shoe Thickness	42
12.	Changes in Shoe Bearing Area	50

LIST OF TABLES

NO.		PAGE
1.	Test Program Showing Stops Made at Various Combinations of Shoe Pressure and Wheel Speed	8
2.	Brinell Hardness and Weight of Shoes Before and After Tests	10
3.	Results of Tests	16
4.	Sequence of Occurrence of Wheel Tread Cracks, and Test Conditions Which Immediately Preceded Their Appearance	28
5.	Average Work-Rate Performance, for Tests at 18 000 and 20 000 Pounds Shoe Pressure	29
6.	Number of Stops Made by Each Shoe	32
7.	Results of Tests Made to Determine Relative Merits of Shoes	33
8.	Variation of Coefficient of Friction During Stopping Period	37
9.	General Results of Test No. 3442, Run With Shoe Pressure of 8000 Pounds and Initial Wheel Speed of 80 Miles per Hour	43
10.	Relation Between Bearing Area of Shoe and Coefficient of Friction	45
11.	Average Bearing Area of Shoe for Tests at 7000 to 10 000 Pounds Pressure	47
12.	Maximum Shoe Temperature During Stops Made in Tests 3419 and 3425	51

THE FRICTION OF RAILWAY BRAKE SHOES AT HIGH SPEED AND HIGH PRESSURE

I. Introduction

1. *Previous Experiments.*—From 1880 until 1930 a large amount of experimental work was done in determining the coefficient of friction of railway brake shoes. In general these experiments covered the range of operating conditions which existed on the railroads during that time, the maximum brake shoe pressure being about 15 000 pounds, and the maximum speed about 65 miles per hour. The results of some of these investigations have been published by the University of Illinois* and the Pennsylvania Railroad, and in the Proceedings of the former Master Car Builders Association.† In a few cases tests were run with pressures as high as 18 000 pounds and speeds as high as 80 miles per hour, but the data available from these tests are meagre or poorly coördinated.

2. *Purpose of Investigation.*—The tests here described were undertaken because of the recent revival of interest in brake shoe friction. A general increase in the speed of all trains, climaxed by the development of the high-speed streamlined trains, has shown the necessity of supplementing the existing test data in order to be able to predict their stopping distance.

The chief purpose of the tests was to determine the values of the coefficient of friction of railway brake shoes under conditions similar to those which prevail on the road, in stopping trains traveling at high speed by means of high pressures of the shoe upon the car wheel.

3. *Test Program and General Results.*—During this investigation 432 stops were made. The tests were run at shoe pressures ranging from 4500 to 20 000 pounds and under each of these pressures stops were made from initial speeds of 60, 80, and 100 miles per hour. Table 1 shows the shoe pressure, initial speed, the number of stops made for each combination of pressure and speed, and the identification number or letter of the shoe used.

The results of the tests are given in detail in Chapters V and VI,

*"An Investigation of the Properties of Chilled Iron Car Wheels, Part III, Strains Due to Brake Application, Coefficient of Friction and Brake-Shoe Wear," Univ. of Ill. Eng. Exp. Sta., Bul. No. 135, 1923.

"The Friction of Railway Brake Shoes, Its Variation With Speed, Shoe Pressure, and Wheel Material," Univ. of Ill. Eng. Exp. Sta., Bul. No. 257, 1933.

†The Proceedings of the Master Car Builders' Association between 1896 and 1915, Vols. 30 to 49, contain the results of numerous tests made by the Committee on Brake Shoes, on the Master Car Builders' testing machine which is deposited at Purdue University.

TABLE 1
TEST PROGRAM SHOWING STOPS MADE AT VARIOUS COMBINATIONS OF SHOE PRESSURE AND WHEEL SPEED

Shoe Pressure lb.	Initial Speed m.p.h.	Number of Stops Made	Identification Number of Shoe Used
4500	60	5	8
	80	5	8
	100	5	8
6000	60	5	8
	80	5	8
	100	5	8
7000	60	5	8
	80	5	8
	100	5	8
8000	60	5	9
	80	5	9
	80	70	5
	80	5	4
	100	5	9
9000	60	5	9
	80	5	9
	100	5	9
10 000	60	5	9
	80	5	9
	100	5	9
12 000	60	5	8
	80	5	8
	100	3	8
	100	5	4
14 000	60	5	12
	60	2	B
	80	5	12
	80	1	B
	100	7	A
	100	1	B
	100	3	52
	100	5	102
	100	6	102
15 000	60	5	12
	60	2	B
	80	5	12
	80	1	B
	100	2	11
	100	1	B
	100	1	1
	100	5	122
16 000	60	7	12
	60	2	B
	80	5	10
	80	1	B
	100	1	11
	100	2	B
	100	1	1
	100	5	122
18 000	60	5	12
	60	2	B
	60	5	50
	60	5	70
	60	5	100
	60	5	120
	80	3	10
	80	1	B
	80	5	50
	80	5	70
	80	5	100
	80	5	120
	100	1	11
	100	1	B
	100	1	1
	100	2	4
	100	3	50
	100	5	70
	100	4	100
	100	5	120
20 000	60	6	51
	60	6	71
	60	6	101
	60	5	121
	80	5	51
	80	5	71
	80	5	101
	80	5	121
	100	3	51
	100	5	71
	100	5	101
	100	5	121

and they are summarized in Chapter VII. They are in accord with the results of previous experiments in which the maximum shoe pressure was about 15 000 pounds, and the maximum speed about 65 miles per hour. Beyond these limits there is a definite change in the trend of the results. This variation is caused by the drastic change in the behavior of the shoe material which occurs when shoe pressures above 15 000 pounds are combined with speeds above 60 miles per hour.

4. *Acknowledgment.*—The investigation has been carried on as a part of the work of the Engineering Experiment Station, of which DEAN M. L. ENGER is the director, and of the Department of Railway Engineering, of which PROF. EDWARD C. SCHMIDT is the head. The author is indebted to Prof. Schmidt for many helpful suggestions and for his interest and encouragement in carrying out the tests.

II. TESTING EQUIPMENT

5. *Brake Shoe Testing Machine.*—All the tests were made on the University of Illinois brake shoe testing machine, which in all fundamental features of its design is like the original testing machine of the Master Car Builders' Association.* The machine consists essentially of a car wheel keyed to a main shaft which carries also a heavy flywheel. This system may be rotated at any desired speed by means of a steam engine which drives the shaft through a pulley and clutch. The shaft, flywheel, and car wheel constitute a revolving unit whose kinetic energy, at any given rim speed of the wheel, is equal to one-eighth of the kinetic energy of a car of 100 000 pounds gross weight moving at this same speed.

The shoe to be tested is held in a brake-shoe head of special design, and is suspended above the wheel from one of a system of levers, by means of which the shoe may be applied to the wheel at any desired pressure up to 20 000 pounds. The tangential pull of the shoe which develops when it is thus applied to the rotating wheel is transmitted through a horizontal yoke to a dynamometer which draws a continuous graphical record of the pull. This pull record is drawn on a moving chart whose travel is proportional to the travel of the wheel rim. A record of the time in half seconds is also drawn on this chart. From the information on this chart, speed–pull, speed–distance, and time–distance curves may be drawn and the coefficient of friction may be calculated.

III. BRAKE SHOES AND TEST WHEEL

6. *Brake Shoes Used in Tests.*—During the tests 21 brake shoes were used. They were all unflanged "Diamond S" reinforced steel-back shoes, and were made by the American Brake Shoe and Foundry Co. Shoes A and B were chosen by a representative of the University from the brake shoe stock of a western railroad; all other shoes were obtained from the maker. With the exception of shoes 70, 71, 120,

*This machine is illustrated and described in the Proceedings of the Master Car Builders' Association Vol. 28, 1894, pages 154-161. For a detailed description of the University of Illinois' machine see Bulletin 257 of the University of Illinois Engineering Experiment Station, pages 11-14.

TABLE 2
BRINELL HARDNESS AND WEIGHT OF SHOES BEFORE AND AFTER TESTS

Type of Shoe	Shoe No.	Average Brinell Hardness of Shoe				Weight of Shoe lb.	
		Before Tests		After Tests		Before Tests	After Tests
		Ends	Body	Ends	Body		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Diamond S Pattern C-40 Chilled ends	1	481	262	217	280	17.97	13.56
	4	484	257	363	253	17.72	12.90
	5	472	244	278	238	17.67	10.89
	8	479	233	302	217	16.36	11.80
	9	488	250	265	230	18.31	14.60
	10	490	248	309	248	17.70	15.61
	11	482	254	367	289	17.92	12.04
	12	470	248	333	234	17.82	14.74
	50	398	218	383	261	18.59	13.66
	51	438	246	285	282	19.10	14.20
	52	469	228	461	274	17.35	14.21
Diamond S Pattern C-51 Chilled ends	A	426	262	...	295	22.48	16.94
	B	459	300	277	224	24.26	16.63
	100	477	300	378	353	24.16	18.70
	101	481	305	256	304	23.92	17.63
	102	477	278	374	303	24.43	15.90
Diamond S Pattern C-40 Plain ends	70	261	229	243	296	18.47	11.47
	71	270	221	228	284	18.73	11.41
Diamond S Pattern C-51 Plain ends	120	385	298	325	380	23.56	17.65
	121	370	274	296	308	23.73	17.83
	122	402	234	292	280	24.03	17.26

121 and 122 all the shoes had chilled ends. Embedded within the cast iron body of the shoe are mild steel plates which are slotted and expanded to form a mesh with diamond-shaped openings. Several layers of these plates are placed in the mold before the shoe is cast.

Upon arrival at the laboratory about $\frac{1}{8}$ inch of material was ground from the face of each shoe in order to remove the surface hardness. The hardness was then determined at 3 points on the longitudinal center line of the shoe face—one at the middle, and one $2\frac{1}{2}$ inches each way therefrom. The averages of these values of the hardness before and after the tests are presented in columns 4 and 6 of Table 2. The average hardness values for the ends of the shoes are shown in columns 3 and 5. These values are the averages of 4 determinations made about $1\frac{1}{2}$ inches from the ends of the shoe. Table 2 shows also the weight of the shoes before and after the tests.

The shoes from Pattern C-40 were $1\frac{1}{2}$ inches thick, and shoes from Pattern C-51 were 2 inches thick, when new. All the shoes were $3\frac{1}{4}$ inches wide and $14\frac{1}{4}$ inches long—measured on the arc—and conform in all respects to the specifications for standard passenger car brake shoes adopted by the Association of American Railroads.

7. *Car Wheel Used in Tests.*—All tests were made upon a "multiple-wear" rolled steel wheel. This wheel was of the American Railway Association Standard design, 33 inches in diameter, for use on 6-inch by 11-inch axles. It was made during July 1930, and was chosen by a representative of the University from the wheel stock of a western railroad. The contour of the tread was the standard adopted in 1919 and modified in 1923, as shown on page 18 of the American Railway Association's "Wheel and Axle Manual of December 1928." This tread contour, which is the double-taper contour, was maintained during all the tests. Prepared for the tests the wheel weighed 773 pounds and was 8.66 feet in circumference at the gage line.

The wheel was tested for tread hardness before and after the investigation. On both occasions the hardness was determined at twenty spots on the tread. Four lines parallel to the wheel axle were marked on the tread, 90 degrees apart; and, by means of a Shore scleroscope, hardness was measured at five spots along these lines. The maximum and minimum values and the average of these twenty measurements, taken before and after the tests, are as follows:

Before Tests			After Tests		
Maximum	Minimum	Average	Maximum	Minimum	Average
43	32	37.3	48	36	42.3

The chemical composition of the wheel, as taken from the heat analyses made at the time it was rolled, is as follows: carbon 0.73 per cent, manganese 0.83 per cent, phosphorus 0.022 per cent, sulphur 0.038 per cent and silicon 0.19 per cent.

IV. General Test Procedure

8. *Preliminary Test Procedure.*—After calibrating the dynamometer of the testing machine, the car wheel was mounted on the machine shaft and there ground to within 0.0005 of an inch of a true circle, care being taken to maintain the original tread contour.

The shoes used were next ground to an approximate fit on the wheel by means of a special grinding machine. The shoe to be used was weighed and then mounted in the brake-shoe head of the machine. The weights on the lever system were then adjusted to produce the desired shoe pressure. If the testing machine had been idle for any length of time before a test was made, the machine was run, with the brake shoe released, until the machine bearings had sufficient time to reach their normal operating temperatures. After standing over night this usually required about 30 minutes with the machine running at a constant speed of 200 revolutions per minute.

9. *Method of Conducting Test.*—All tests of this investigation were so-called stop tests, in which the test conditions simulate those which prevail in service when the brakes of a train are applied to bring it to a stop. In making such a test from a speed of, say, 60 miles per hour, the rotating element of the machine is brought up to a speed slightly greater than 60 miles per hour, the clutch is then disengaged, and the rotating parts allowed to run free until the speed falls to the desired 60 miles. At this instant the shoe is applied, and under its action the wheel and other rotating parts are gradually brought to rest. Under these conditions the pressure remains constant; but the tangential pull and the coefficient of friction vary somewhat during the period of the stop.* The coefficient of friction value reported for the stop is its average value during this period. In this investigation five such stops, under the same pressure and initial speed, constitute a test at that pressure and speed; and the values of coefficient of friction here presented are, with some exceptions, the average values derived from five such stops. The term "speed" as here used is the linear speed of a point on the wheel tread; and is, of course, equivalent to the speed of the train in service.

The data recorded during each stop provide means for determining (in addition to the average coefficient just described) the coefficient of friction, the elapsed time, and the distance run, for various intervals from the beginning to the end of the stop. During some of the tests the temperature of the brake shoe and of the wheel tread were measured by means of inserted thermocouples. The results of these temperature tests are presented in Appendix D.

10. *General Treatment of Wheel and Shoes During Tests.*—The shoe wear was found by weighing the shoe before and after the test. For the lower pressures and speeds the shoe was weighed after each series of five stops; at the higher pressures and speeds, which produced severe wear, the shoe was weighed after each stop. In replacing the shoe in the head of the testing machine after weighing, care was taken to have it in the same position relative to the wheel tread during each stop. No work was done on the shoe between stops.

During the tests at the lower pressures and speeds only a small amount of brake shoe material was deposited on the tread of the

*A detailed discussion of the variation of the coefficient of friction during the stopping period is given in Appendix A.

wheel. This was not removed. During test No. 3433 (14 000 lb., 80 m.p.h.) a large amount of shoe material was deposited on the wheel tread, and in order to remove it the wheel was subjected to a brake application with a sand filled shoe, and was further polished by means of an abrasive block held by hand against the revolving wheel tread. This polishing procedure was used after each stop from test No. 3433 until the end of the investigation.

The shoe and the wheel were cooled after each stop, by means of an air blast, to about the temperature of the air in the laboratory. The air blast was not used while the brake shoe was applied to the wheel.

11. *Method of Calculating Results.*—As explained in Chapter II, the paper chart drum of the dynamometer recording mechanism is geared to the main shaft of the testing machine. The drum surface and the paper consequently travel at a speed proportional to the speed of a point on the tread of the test wheel. A record of the tangential pull of the brake shoe is drawn on the paper chart together with a record of the time in one-half second intervals. In all previous tests made at the University of Illinois the coefficient of friction was determined from the dynamometer record. The area under the tangenital pull curve was measured by means of a Coradi rolling planimeter, and the average height of the record was found by dividing this area by the length of the chart. From the calibration curve of the dynamometer the average tangential pull was found, and the coefficient of friction determined by dividing this average tangential pull by the brake shoe pressure.

In all the tests of this investigation a simpler and more accurate method of determining the coefficient of friction was used. The aggregate kinetic energy of the car wheel, fly wheel, and shaft was calculated for any speed; and all calculations necessary in determining the coefficient of friction were based on the kinetic energy existing in the revolving unit at the time the brake shoe was applied. This method presupposes that the friction of the bearings which carry the revolving unit is small and that it is constant.

Calibration tests made to determine the bearing friction of the revolving unit show that, after the machine has run for a time sufficient to warm all the bearings, the friction is constant, and is equal to an equivalent average tangential pull of 25 pounds on the tread of the wheel.

For the car wheel tested the kinetic energy (ft.-lb.) present in the revolving unit may be found from the formula*

$$\text{Kinetic energy} = 427.64S^2$$

where S is the initial speed in miles per hour. The initial speed is the speed at the instant the shoe is applied, and is calculated from the graphical time record on the dynamometer chart.

Two records of the stopping distance are available. The first is made by a revolution counter which automatically engages as the brake shoe is applied, and which records the number of revolutions of the car wheel in stopping. The second is the length of the paper chart which is proportional to the distance the car wheel travels in stopping. All the calculations were based on the revolution counter readings with an occasional check on the stopping distance by means of the dynamometer chart record.

The average tangential pull is found by dividing the kinetic energy in foot-pounds by the stopping distance in feet; and the average coefficient of friction is based on the average tangential pull thus found.

V. Main Results of Tests

The main results of the tests are presented in Table 3. The values there shown are averages based on the number of individual stops indicated in column 6. All discussion of the results in this section of the report is based upon these average values.† In order to facilitate discussion, some of these results are reproduced in graphical form in Figures 1, 2, 3, and 4.

12. *Coefficient of Friction.*—The values of coefficient of friction are given in column 8 of Table 3. For each of the three initial speeds these coefficient-of-friction values are plotted in Fig. 1, for all the various shoe pressures.

As in previous experiments, the coefficient of friction decreases as the initial speed is increased. At speeds of 60 and 80 miles per hour, there are no exceptions to this decrease with speed throughout the entire pressure range. At the speed of 100 miles per hour, however, there is a recovery of the coefficient at shoe pressures above 14 000 pounds, such that at 15 000 and 16 000 pounds the coefficient at 100 miles per hour is greater than at 80 miles per hour. At shoe pressures of 18 000 and 20 000 pounds, the coefficient at 100 miles per hour

*This formula was derived from calculations based on the dimensions of the main shaft, flywheel, and car wheel, which constituted the revolving unit.

†A detailed discussion of the variation of the coefficient of friction among the five stops which constitute a test is given in Appendix C.

FIG. 1. RELATION BETWEEN COEFFICIENT OF FRICTION AND BRAKE SHOE PRESSURE, FOR ALL TESTS

is not only greater than at 80 miles per hour, but it is also greater than the coefficient at 60 miles per hour.

Previous experiments have shown a general decrease in coefficient of friction as the shoe pressures are increased. In general, these tests show a similar decrease except at the higher pressures used. The actual variations of coefficient with pressure are shown in Fig. 1. With one exception (at 7000 lb. and 60 m.p.h.), the coefficient decreases at all three speeds until the shoe pressure reaches 8000 pounds. From this point, however, it rises again until the shoe pressure becomes 10 000 pounds. This temporary rise in the coefficient may, perhaps, be due to the better seating of the shoe on the wheel under pressures of 7000 and 10 000 pounds, or to inherent frictional qualities of the shoes Nos. 8 and 9. Beginning at a pressure of 10 000 pounds, there is, under all three speeds, a definite and rapid decrease in the coefficient of friction until the shoe pressure reaches 14 000 pounds. From this point, at speeds of 60 and 80 miles per hour, with

Table 3
Results of Tests

Brake Shoe Pressure lb.	Initial Speed m.p.h.	Test No.	Identification Number of Shoe	Number of Stops	Number of Stops Used in Determining Average Calculated Results	Average Calculated Results							
						Tangential Pull lb.	Coefficient of Friction per cent	Stopping Distance ft.	Duration of Stop sec.	Foot-Pounds of Work Done per Stop	Shoe Wear per Stop [Loss in Weight] lb.	Shoe Wear per 100 Million Ft-lb. of Work lb.	Work Performed [and Dissipated] per Second ft. lb.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
4 500	60	3404	8	5	5	582.0	12.93	2570.1	50.7	1 492 683	0.016	1.072	29 442
	80	3406	8	5	4	575.6	12.79	4600.6	71.5	2 647 052	0.038	1.436	37 017
	100	3408	8	5	5	527.3	11.72	7645.6	96.6	4 028 834	0.074	1.837	41 702
6 000	60	3409	8	5	5	765.0	12.74	1949.4	38.7	1 490 690	0.022	1.476	38 520
	80	3410	8	5	5	734.8	12.25	3624.1	56.2	2 661 015	0.044	1.654	47 349
	100	3411	8	5	4	685.4	11.42	5969.0	74.5	4 090 382	0.086	2.102	54 904
7 000	60	3412	8	5	5	906.0	12.94	1647.3	33.6	1 490 707	0.026	1.744	44 366
	80	3413	8	5	5	834.3	11.92	3156.8	49.3	2 632 705	0.048	1.823	53 402
	100	3414	8	5	5	739.3	10.56	5583.7	68.7	4 125 781	0.084	2.036	60 055
8 000	60	3418	9	5	5	975.0	12.19	1523.1	29.7	1 481 624	0.028	1.890	49 886
	80	3419	9	5	5	809.2	10.12	3260.8	50.1	2 633 954	0.056	2.126	52 573
	80	3442	5	70	70	794.8	9.91	3329.0	50.7	2 637 550	0.084	3.196	51 982
	80	3428	4	5	5	866.9	10.84	3131.3	48.0	2 697 544	0.082	3.040	56 199
	Average Values for 3419-42-28					823.6	10.29	3240.4	49.6	2 656 349	0.074	2.787	53 585
	100	3420	9	5	5	723.1	9.04	5633.0	68.9	4 062 045	0.150	3.693	58 956
9 000	60	3421	9	5	4	1127.9	12.53	1355.8	26.3	1 524 209	0.028	1.837	58 021
	80	3422	9	5	5	939.8	10.45	2792.0	42.8	2 623 280	0.066	2.516	61 292
	100	3423	9	5	5	828.3	9.20	4986.8	61.2	4 127 329	0.156	3.780	67 429
10 000	60	3424	9	5	5	1278.1	12.78	1146.3	22.9	1 460 558	0.030	2.054	63 891
	80	3425	9	5	5	1070.0	10.70	2469.5	38.0	2 642 002	0.066	2.498	69 600
	100	3426	9	5	5	958.0	9.58	4267.0	52.3	4 075 533	0.158	3.877	77 926
12 000	60	3415	8	5	5	1362.0	11.35	1042.0	20.4	1 416 331	0.042	2.965	69 428
	80	3416	8	5	5	1169.9	9.75	2251.3	33.5	2 630 130	0.076	2.890	78 511
	100	3417	8	3	1	1216.2	10.14	3274.4	40.5	3 982 349	.....	.....	98 330
	100	3427	4	5	5	869.8	7.25	4737.8	57.2	4 107 769	0.252	6.135	71 814
	Average Values for 3417-27					1043.0	8.70	4006.1	48.9	4 045 059	0.252	6.135	85 072
14 000	60	3429	12	5	5	1290.0	9.21	1128.9	22.4	1 439 607	0.038	2.640	64 268
	60	3443	B	2	2	1083.6	7.74	1253.6	25.5	1 358 026	.....	.....	53 256
	Average Values for 3429-43					1186.8	8.48	1191.3	23.9	1 398 817	0.038	2.640	58 762
	80	3433	12	5	4	1168.7	8.35	2232.0	32.2	2 574 408	0.160	6.215	84 407
	80	3444	B	1	1	939.5	6.71	2728.5	40.8	2 561 930	.....	.....	62 870
	Average Values for 3433-44					1054.1	7.53	2480.3	36.5	2 568 169	0.160	6.215	73 638
	100	3437	A	7	4	904.8	6.46	4367.9	53.0	3 943 380	.....	.....	74 572
	100	3483	52	3	3	1140.0	8.14	3678.1	45.4	4 107 458	0.943	22.958	90 473
	100	3484	102	5	4	819.4	5.85	5044.0	62.9	4 130 325	0.414	10.023	65 686
	100	3487	102	6	6	1025.6	7.33	4046.1	50.1	4 089 776	0.308	7.539	81 665
	Average Values for 3437-83-84-87					972.5	6.95	4284.0	52.8	4 067 735	0.555	13.507	78 099

TABLE 3—(CONCLUDED)
RESULTS OF TESTS

Brake Shoe Pressure lb.	Initial Speed m.p.h.	Test No.	Identification Number of Shoe	Number of Stops	Number of Stops Used in Determining Average Calculated Results	Average Calculated Results: Tangential Pull lb.	Coefficient of Friction per cent	Stopping Distance ft.	Duration of Stop sec.	Foot-Pounds of Work Done per Stop	Shoe Wear per Stop [Loss in Weight] lb.	Shoe Wear per 100 Million Ft-lb. of Work lb.	Work Performed [and Dissipated] per Second ft. lb.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
15 000	60	3430	12	5	5	1269.2	8.46	1159.9	22.5	1 459 600	0.048	3.289	64 871
	80	3434	12	5	5	1131.9	7.55	2334.6	34.0	2 620 705	0.190	7.250	77 080
	80	3447	B	1	1	1188.5	7.92	2217.3	....	2 635 271	.....	.....	......
	Average Values for 3434-47					1160.2	7.74	2276.0	34.0	2 627 988	0.190	7.250	77 080
	100	3448	B	1	1	1230.0	8.20	3325.5	39.5	4 090 329	.....	.....	103 553
	100	3455	1	1	1	1324.9	8.83	2993.3	36.5	3 965 842	1.420	35.806	108 653
	100	3485	122	5	5	1061.1	7.08	4011.1	50.0	4 166 536	0.554	13.296	83 331
	Average Values for 3448-55-85					1205.3	8.04	3443.3	42.0	4 074 236	0.987	24.551	98 512
16 000	60	3431	12	7	5	1524.4	9.53	958.4	18.6	1 438 637	0.061	4.240	77 346
	60	3449	B	2	1	1627.0	10.16	878.1	17.5	1 428 673	.....	.....	81 638
	Average Values for 3431-49					1575.7	9.85	918.3	18.1	1 433 655	0.061	4.240	79 492
	80	3435	10	5	5	1150.5	7.19	2270.2	33.6	2 587 725	0.152	5.874	77 130
	80	3450	B	1	1	1310.2	8.19	1910.1	29.0	2 502 701	.....	.....	86 300
	Average Values for 3435-50					1230.4	7.69	2090.2	31.3	2 545 213	0.152	5.874	81 715
	100	3440	11	1	1	1151.0	7.19	3360.1	40.0	3 867 612	1.300	33.612	96 690
	100	3451	B	2	1	1360.0	8.50	2873.9	33.5	3 908 410	1.630	41.705	116 669
	100	3456	1	1	1	1289.4	8.06	3146.4	39.0	4 056 973	1.330	32.783	104 025
	100	3486	122	5	5	1219.6	7.62	3475.8	43.5	4 092 382	0.770	18.875	94 077
	Average Values for 3440-51-56-86					1255.0	7.84	3214.1	39.0	3 981 344	1.258	31.729	102 865
18 000	60	3432	12	5	5	1584.2	8.80	902.3	17.9	1 406 119	0.066	4.694	78 554
	60	3452	B	2	1	1634.6	9.08	853.0	17.0	1 394 290	.....	.....	82 017
	60	3459	50	5	5	1371.3	7.62	1164.8	23.3	1 593 986	0.052	3.262	68 411
	60	3463	70	5	5	1818.4	10.10	799.9	17.0	1 453 758	0.042	2.889	85 515
	60	3466	100	5	3	1530.5	8.50	960.8	19.9	1 470 368	0.016	1.088	73 814
	60	3469	120	5	5	1461.9	8.12	980.9	20.2	1 427 400	0.026	1.821	70 663
	Average Values for 3432 to 69					1566.8	8.70	943.6	19.2	1 457 653	0.040	2.751	76 496
	80	3436	10	3	3	1404.7	7.80	1870.6	29.2	2 608 885	0.443	16.993	89 437
	80	3453	B	1	1	1365.9	7.59	1841.8	28.5	2 515 787	.....	.....	88 273
	80	3460	50	5	5	1152.5	6.40	2343.0	36.8	2 640 147	0.254	9.621	71 743
	80	3462	70	5	5	1383.2	7.68	1939.2	31.5	2 642 426	0.308	11.656	84 020
	80	3465	100	5	5	1264.7	7.02	2186.5	34.3	2 732 885	0.274	10.026	79 676
	80	3468	120	5	5	1256.1	6.98	2155.7	33.3	2 677 259	0.158	5.902	80 398
	Average Values for 3436 to 68					1304.5	7.25	2056.1	32.3	2 636 232	0.287	10.840	82 258
	100	3441	11	1	1	1582.3	8.79	2413.6	30.0	3 818 989	1.580	41.372	127 299
	100	3454	B	1	1	1472.2	8.18	2643.8	32.0	3 892 074	1.630	41.880	121 627
	100	3457	1	1	1	1568.5	8.71	2549.5	32.5	3 998 856	1.660	41.512	123 042
	100	3458	4	2	2	1611.9	8.95	2472.9	31.6	3 983 419	1.335	33.514	125 938
	100	3461	50	3	3	1818.8	10.10	2183.0	28.0	3 961 734	1.083	27.345	141 490
	100	3464	70	5	5	1807.5	10.04	2190.0	28.0	3 956 818	1.050	26.536	141 315
	100	3467	100	4	3	1754.5	9.75	2291.1	29.8	4 018 599	1.095	27.248	135 079
	100	3470	120	5	5	1486.2	8.26	2708.5	33.8	4 014 669	0.998	24.859	118 777
	Average Values for 3441 to 70					1637.7	9.10	2431.6	30.7	3 955 645	1.304	33.033	129 321
20 000	60	3471	51	6	6	1758.3	8.79	808.7	17.5	1 417 383	0.067	4.704	80 809
	60	3474	71	6	6	1834.6	9.18	780.3	16.9	1 427 319	0.065	4.554	84 557
	60	3477	101	6	6	1654.7	8.28	882.6	18.5	1 452 913	0.033	2.294	78 536
	60	3480	121	5	5	1823.5	9.12	801.6	17.0	1 459 677	0.048	3.288	85 863
	Average Values for 3471 to 80					1767.8	8.84	818.3	17.5	1 439 323	0.053	3.710	82 441
	80	3472	51	5	5	1543.7	7.72	1725.9	28.2	2 612 589	0.212	8.115	92 810
	80	3475	71	5	5	1477.9	7.39	1782.3	29.1	2 586 032	0.262	10.131	88 867
	80	3478	101	5	5	1485.5	7.43	1782.3	28.7	2 614 033	0.172	6.580	91 081
	80	3481	121	5	5	1344.2	6.72	1968.1	31.3	2 593 832	0.174	6.708	83 003
	Average Values for 3472 to 81					1462.8	7.32	1814.7	29.3	2 601 622	0.205	7.884	88 940
	100	3473	51	3	3	2267.3	11.33	1756.7	23.7	3 963 205	1.143	28.933	167 436
	100	3476	71	5	5	2063.8	10.32	1899.8	24.8	3 900 678	1.036	26.559	157 285
	100	3479	101	5	5	2125.5	10.63	1884.5	24.1	3 981 272	0.928	23.091	165 198
	100	3482	121	5	5	1872.0	9.36	2177.8	28.1	4 035 462	0.958	23.740	143 611
	Average Values for 3473 to 82					2082.2	10.41	1929.7	25.2	3 970 155	1.016	25.581	158 382

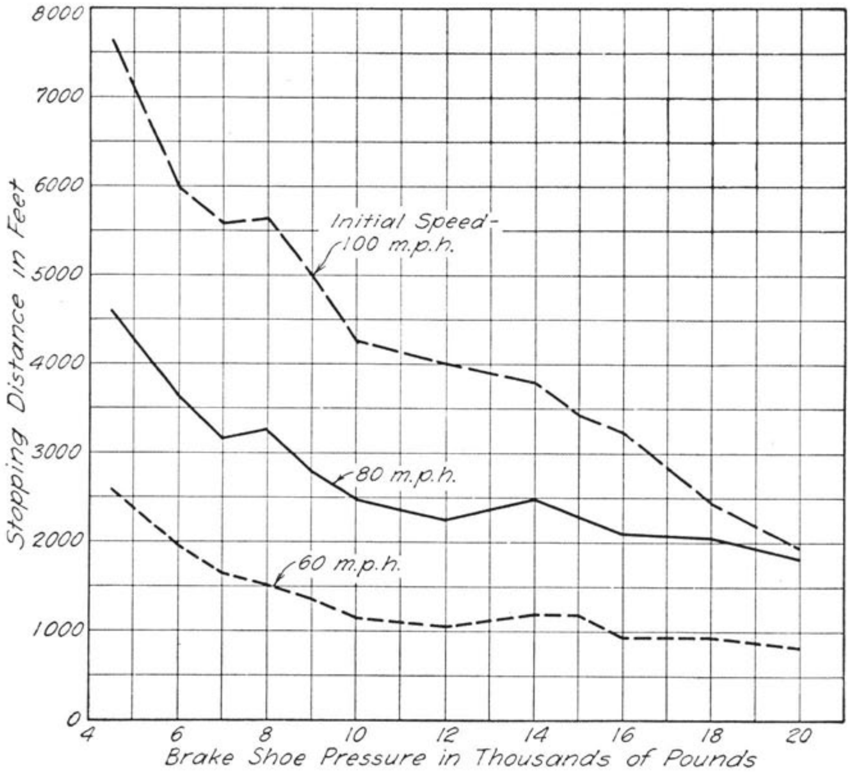

FIG. 2. RELATION BETWEEN STOPPING DISTANCE AND BRAKE SHOE PRESSURE, FOR ALL TESTS

one exception (16 000 lb. and 60 m.p.h.), the coefficient remains practically constant. At 100 miles per hour, however, the coefficient increases rapidly for pressures above 14 000 pounds (which gives a coefficient of friction of only 6.95 per cent), becoming 8.04, 7.84, 9.10 and 10.41 per cent at pressures of 15 000, 16 000, 18 000 and 20 000 pounds, respectively.

The reason for this recovery in coefficient of friction at shoe pressures in excess of 14 000 pounds probably lies in the fact that under these higher combinations of speed and pressure the rate of heat generation is so high that the shoe material begins to soften at the surface of contact. Such a surface softening of the shoe would result in more intimate contact between shoe and wheel, and in more rapid tearing away of the shoe material; and both of these changes would account for the increase in the coefficient of friction. This view is well supported by the recorded rise in shoe temperature under these severe conditions, by the fact that a continuous stream of particles of molten metal issues from beneath the shoe during most of its period of application, and by the very marked increase in the shoe wear which occurs at these combinations of high speed and high pressure.

13. *Stopping Distance.*—Stopping distance, since it combines the effects of both coefficient of friction and shoe pressure, provides a means for more direct comparisons of the effectiveness of various combinations of speed and pressure than is provided by the coefficient alone. The average values of stopping distance are given in column 9 of Table 3, and they are plotted for all pressures and each of the three speeds in Fig. 2. At each of the three test speeds the stopping distance decreases fairly regularly as the shoe pressure is increased. At both 60 and 80 miles per hour the rate of decrease diminishes, however, at the higher pressures, so that at neither of these speeds was very much gained by increasing the pressure above 12 000 pounds. At speeds of 60 miles per hour the increase in pressure from 12 000 to 20 000 pounds produced a decrease in stopping distance of only 224 feet. At speeds of 80 miles per hour the corresponding change in pressure produced a decrease in distance of 437 feet. During the tests from an initial speed of 100 miles per hour, however, an important decrease in distance was attained by increasing the pressure from 12 000 to 20 000 pounds. At the former pressure the average stopping distance was 4006 feet, whereas at the higher pressure the distance was only 1930 feet—a decrease of 2076 feet. Unfortunately, however, at both 80 and 100 miles per hour, pressures much in excess of 12 000 pounds produce an excessive shoe wear; and apparently at these two speeds an increase in shoe pressure above about 14 000 pounds will prove, on this account, to be impracticable. As indicated in the discussion following, the tests at high speed and high pressure also caused serious damage to the wheel tread.

14. *Brake Shoe Wear.*—The loss of weight of the brake shoe during the tests—the shoe wear—is presented in two forms in Table 3; first in column 12, as the pounds of wear per stop, and second in column 13, as the weight lost per hundred million foot-pounds of work performed. The latter is the unit usually employed to define shoe wear. Figure 3 shows the wear in terms of this unit, plotted with respect to shoe pressure for each of the three test speeds.

Inspection of Table 3 and Fig. 3 discloses the fact that during the tests at 60 miles per hour the shoe wear was of moderate and

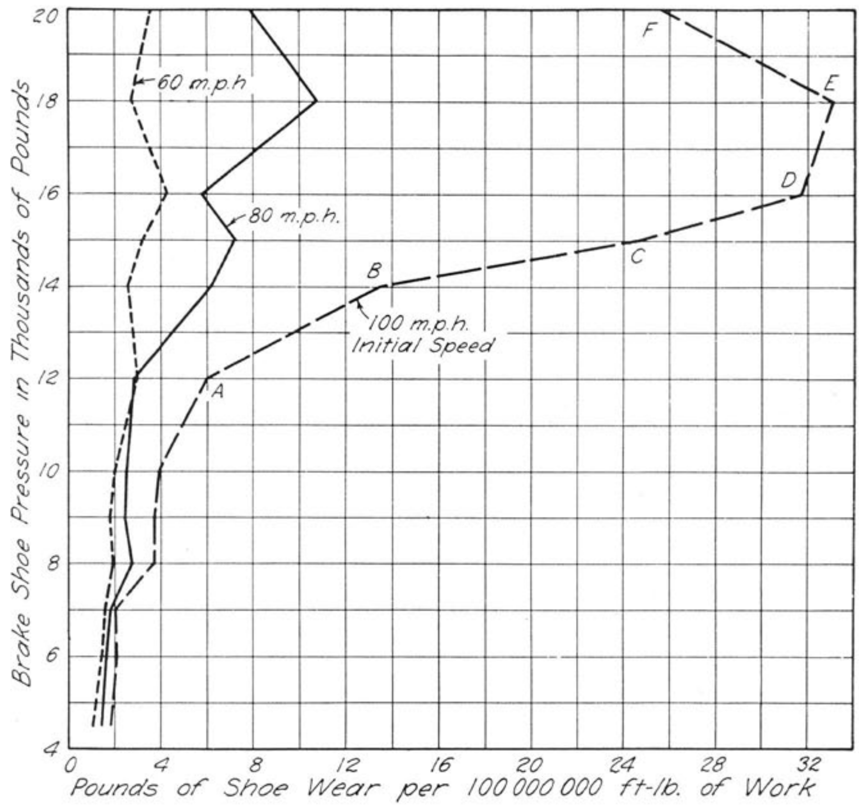

FIG. 3. RELATION BETWEEN BRAKE SHOE PRESSURE AND BRAKE SHOE WEAR, FOR ALL TESTS

tolerable amount throughout the entire pressure range, although there was a fourfold increase in the wear between pressures of 4500 and 20 000 pounds. No further attention need here be given to the shoe wear at this speed.

Considering the results for speeds of 80 miles per hour as plotted in Fig. 3, it is apparent that for pressures from 4500 to 12 000 pounds the shoe wear is very moderate. With pressures higher than 12 000 pounds the wear increases, until at 18 000 pounds the wear is ten times that at 4500 pounds. Although this increase in the wear is of a considerable magnitude, it is not intolerable, and it is likely that the higher pressures can be used to advantage in train service where the maximum speed is about 80 miles per hour.

As shown in Fig. 3, during tests at 100 miles per hour a radical change in the rate of shoe wear begins at point *A*, corresponding to a pressure of 12 000 pounds. At points *A*, *B*, *C*, *D*, *E* and *F* the average wear per stop is, respectively, 0.25, 0.56, 0.99, 1.26, 1.30 and 1.02 pounds. Obviously, at point *A* some fundamental change in the behavior of the shoe material begins. The test records show that at pressures beyond this point a marked rise in shoe temperature occurs, and that there is a softening of the shoe material as evidenced by the continuous ejection of molten particles from the shoe surface. Furthermore, the shoes are not only rapidly worn away under these severe test conditions, but even a new shoe after one or two applications may be so badly cracked as to render it unfit for further service. Evidently the point *A* marks the beginning of conditions which cause a breakdown in the shoe material, which at pressures beyond that prevailing at this point become so serious as probably to render the use of higher pressures impracticable. The shoes of pattern C-40 and C-51, when new weigh respectively 20 and 25 pounds, and when worn to the thickness at which they would usually be discarded they weigh about 11 pounds; there is available, therefore, about 9 pounds and 14 pounds of wearable metal, respectively, on the two shoes. Consequently, at the rate of wear prevailing during stops from 100 miles per hour and at pressures above 14 000 pounds, the thin shoe would have to be rejected from service after from 6 to 9 stops, and the thick shoe after from 10 to 14 stops. Disregarding any damage done to the wheel by the combinations of high speed and high pressure, the shoe wear alone may render these high pressures impracticable.

Evidently there are, at high speeds, limits to the pressures which may practically be used in train brakes if this general breakdown in shoe material is to be avoided. These limits are imposed by the overheating of the shoe, and they cannot, therefore, be defined by setting a limit to the number of foot-pounds of work to be performed by the shoe without regard to the time within which the work has to be performed. The limits must be defined in terms of the time-rate of work performance, instead of in terms of its mere magnitude. The time-rates at which the various shoes performed their work during these tests and dissipated it as heat are shown in column 14 of Table 3. They range up to a maximum of about 167 000 foot-pounds of work performed and dissipated per second (Test No. 3473). The relations between the foot-pounds of work performed and dissipated per second and the pounds of shoe wear per 100 million foot-pounds of

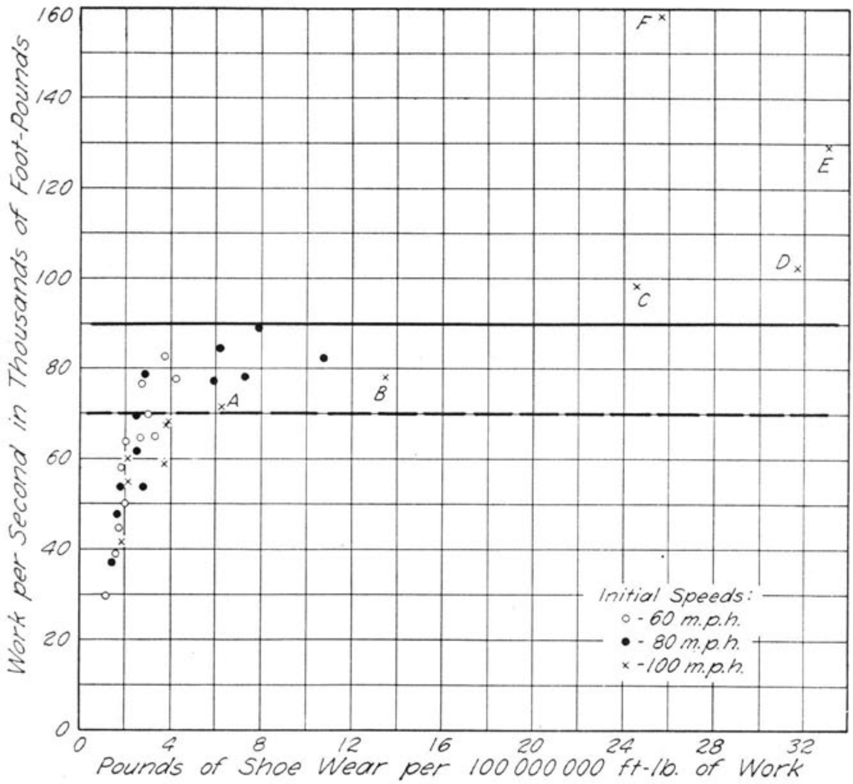

FIG. 4. RELATION BETWEEN WORK PER SECOND AND BRAKE SHOE WEAR PER 100 MILLION FOOT-POUNDS OF WORK, FOR ALL TESTS

work done are plotted in Fig. 4, for all combinations of pressure and speed. On this graph the points lettered *A, B, C, D, E,* and *F* correspond to the same combinations of speed and pressure as the points so lettered on Fig. 3.

Since the difficulties arising from the change in behavior of the shoe begin to be acute under the conditions prevailing at points *B* and *C*, the limiting rates of work performance ought not be greater than the rates which prevailed at those points, namely 78 000 and 98 500 foot-pounds per second. The suggestion is offered that the limiting rate of work performance ought to be set at about 90 000 foot-pounds per second. This limit is shown on Fig. 4 by the heavy horizontal line. If this suggestion is accepted then the test results are to be interpreted as meaning that, if excessive wear and deterioration of brake shoes are to be avoided, no brake shoe of the types

FIG. 5. WHEEL AND SHOE DURING A STOP

tested should be subjected to braking conditions which will require it to perform and dissipate more than 90 000 foot-pounds of work per second.

VI. SECONDARY RESULTS OF TESTS

The discussion of the secondary results of the tests is limited to the presentation of data covering the effect of high speed and high pressure on the wheel and shoes, the relative merits of the shoes of pattern numbers C-40 (light) and C-51 (heavy), and the advantage and disadvantage of the shoes with unchilled ends.

15. *Effect on Wheel and Shoes.*—The combination of high speed and high pressure causes a softening of the shoe surface, as evidenced by the continuous ejection of molten metal particles. Figure 5 is from a photograph showing the fire, sparks, and molten particles coming from beneath the shoe surface. This photograph was taken with two seconds exposure during a stop from 100 miles per hour with 18 000 pounds shoe pressure. The speed of the wheel was approximately 75 miles per hour while the picture was being taken; the fire and molten metal supplied all the necessary light.

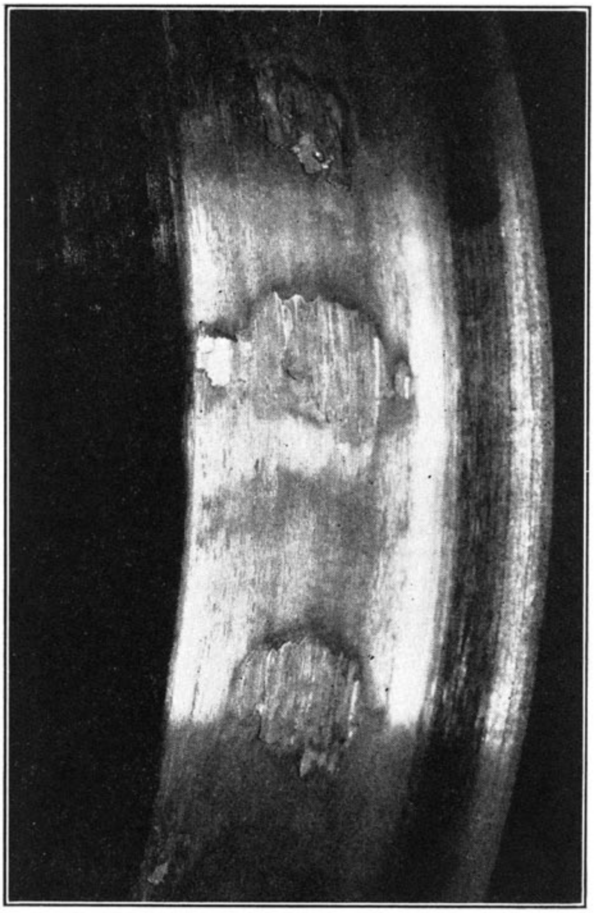

FIG. 6. CONDITION OF WHEEL AFTER ONE STOP

The molten metal was not only scattered over the laboratory but a large amount of it was welded to the surface of the wheel. Figure 6 shows the shoe material welded to the wheel during one stop from 100 miles per hour with 18 000 pounds pressure. Although this figure reproduces only a small section of the wheel tread, it is characteristic of the general condition of the tread.

As stated in Section 10 under "General Test Procedure," this welding of the shoe material to the wheel was not apparent until Test 3433 (14 000 lb., 80 m.p.h.); and from this test on to the end of the investigation the wheel was polished after each stop. If this material

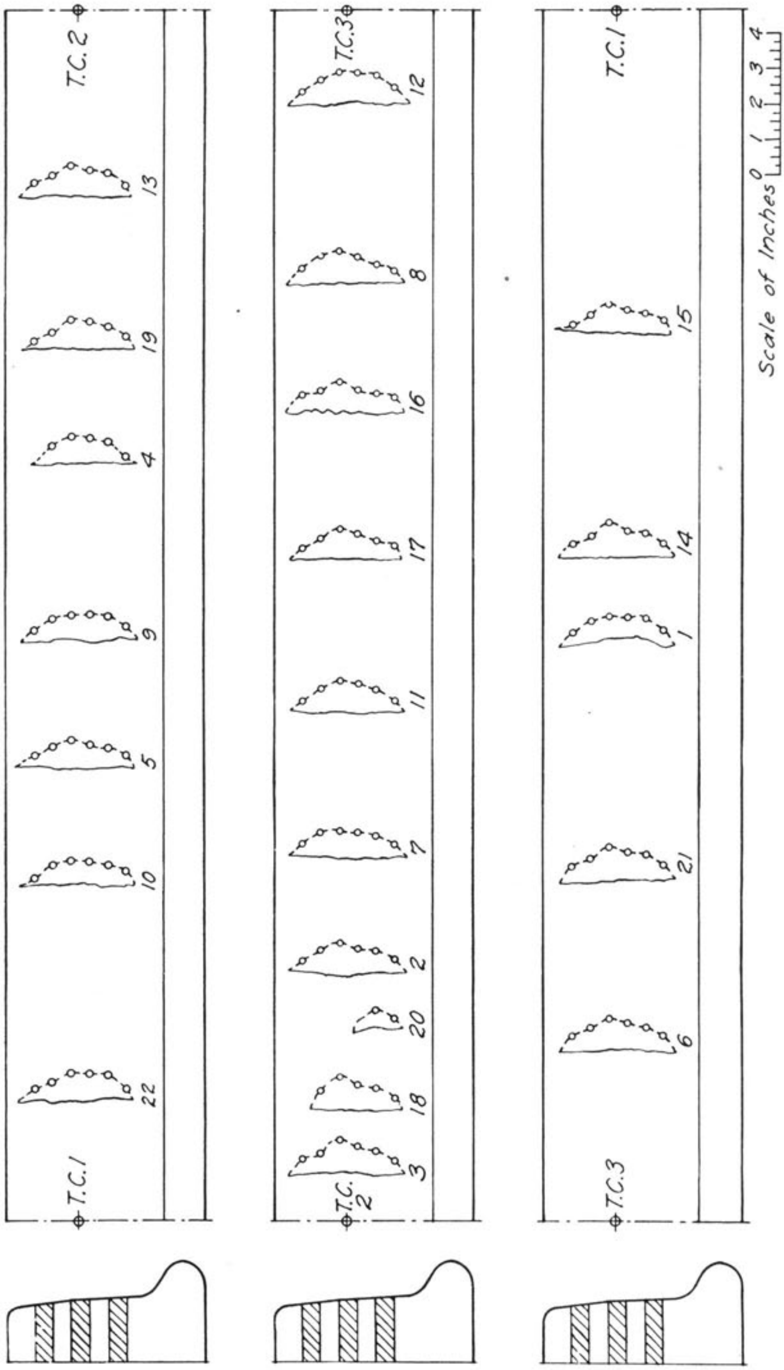

Fig. 7. Cracks in Wheel Tread

is not removed from the tread, the building up of the spots is cumulative since during the next stop the shoe, bearing only on these spots, will deposit an additional layer of metal. About ¼ inch of material around the edge of these areas may be removed with a knife but a substantial portion of the area forms a perfect weld. In train service, this building up of shoe material on the wheel tread may be a cause of hard riding cars. In some cases this welded material is hard enough to make indentations in the rails.

In general the shoe material was not welded to the wheel surface until the pressure exceeded 16 000 pounds in the 60 miles per hour stops, and 12 000 and 10 000 pounds, respectively, in the 80 and 100 miles per hour stops.

Since this difficulty occurred at combinations of speeds and pressures which required the shoe to perform and dissipate work at a rate of 70 000 foot-pounds (or more) per second, it might be desirable, in some classes of service, to limit the rate of work performance to about 70 000 foot-pounds per second. This limit is shown in Figure 4 by the heavy broken line.

The cracks, which developed in the wheel tread during the progress of the investigation, are shown in Fig. 7. In this figure, which is a scaled drawing of the wheel tread, the cracks are shown numbered in the order in which they occurred. The wheel tread was divided into three sections in order to shorten the drawing. All the cracks occurred during the cooling of the wheel, and most of them occurred after the temperature had dropped to about room temperature. The formation of the crack was accompanied by a loud ringing sound similar to the sound caused by a sharp blow with a light hammer on the rim of the wheel. The cracks, as they first appeared on the tread, were about full length and only a few became longer on additional tests. The maximum amount of the gradual increase in length was ¾ inch. None of the cracks extended into the throat or flange, or to the outside of the wheel rim. Figure 8 is from a photograph of a short section of the wheel tread near Thermocouple No. 2. Reading from top to bottom the cracks shown are Nos. 2, 20, 18, and 3 of Fig. 7. With the exceptions of Nos. 18 and 20, all the twenty-two cracks were from 3 to 3⅜ inches long.

At the end of the investigation four circular rings were cut from the wheel rim and the depth of all the tread cracks was measured on the six faces of these rings. These faces were ¾, 1¼, 1¾, 2¼, 2¾, and 3¼ inches, respectively, from the outside edge of the wheel rim. Before determining the depth of the cracks a short section of the

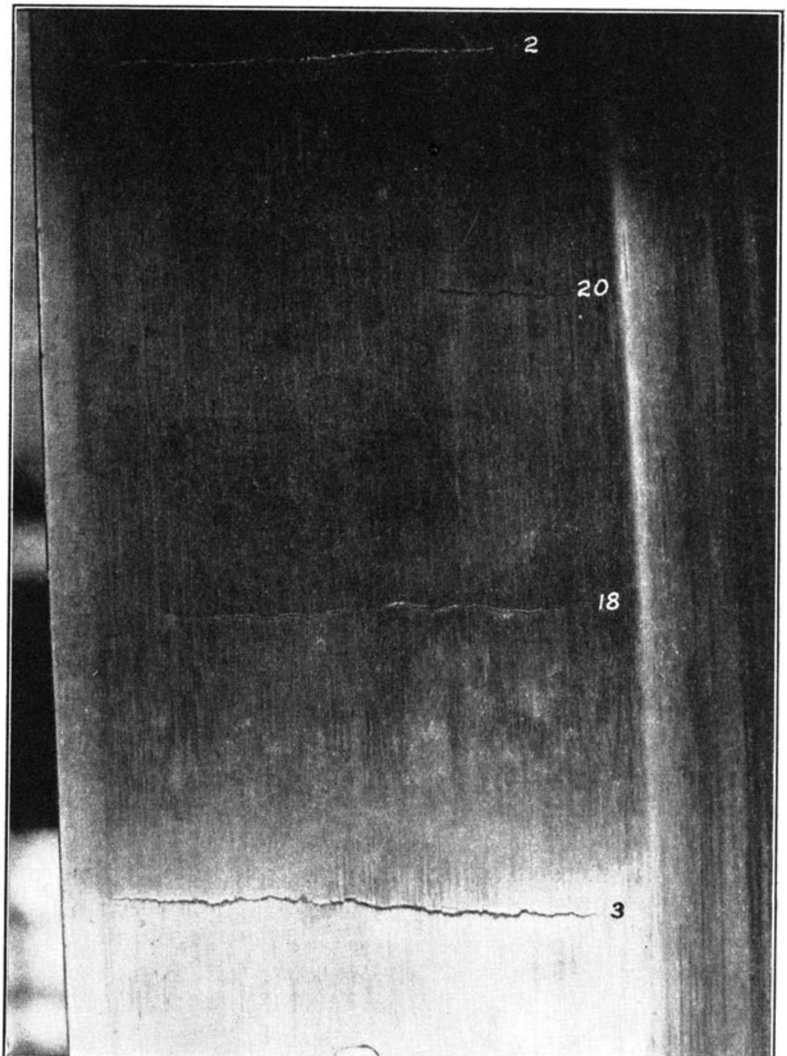

FIG. 8. CRACKS IN WHEEL NEAR THERMOCOUPLE NO. 2

rings in the immediate vicinity of each crack was finished on a milling machine. This finishing process gave a smooth surface upon which the cracks could be seen very clearly by the naked eye. The depth of the cracks thus found is plotted to scale in Fig. 7, and the bottom of each crack is shown by the broken line.

Three typical cracks, (Nos. 1, 11 and 22), were deep etched in a

TABLE 4
SEQUENCE OF OCCURRENCE OF WHEEL TREAD CRACKS, AND TEST CONDITIONS WHICH IMMEDIATELY PRECEDED THEIR APPEARANCE

Crack No.	After		Brake Shoe Pressure lb.	Initial Speed m.p.h.
	Test No.	Stop No.		
1	3459	5	18 000	60
2	3472	2	20 000	80
3	3476	3	20 000	100
4	3479	2	20 000	100
5	3479	3	20 000	100
6	3479	5	20 000	100
7	3480	1	20 000	60
8	3480	2	20 000	60
9 and 10	3480	5	20 000	60
11 and 12	3481	3	20 000	80
13	3482	1	20 000	100
14, 15, 16 and 17	3482	3	20 000	100
18 and 19	3482	4	20 000	100
20, 21 and 22	3482	5	20 000	100

50-per-cent solution of hydrochloric acid, and the depth of these cracks again measured on all six faces of the rings. The etching showed that the cracks extended into the wheel rim only 0.02 to 0.04 of an inch deeper than could be seen on the unetched rings.

Table 4 shows the sequence in which the tread cracks developed. The first crack, for example, occurred upon the completion of the fifth stop of Test No. 3459. Previous to this test the wheel had made 294 stops. The second crack occurred upon the completion of the second stop of Test No. 3472, and after a total of 354 stops had been made.

Eight stops immediately preceding the occurrence of the second crack were made with a shoe pressure of 20 000 pounds; all the other stops were made with pressures below 20 000 pounds. During the next 53 stops, all of them with shoe pressures of 20 000 pounds and speeds of 60, 80, and 100 miles per hour, the remaining 20 cracks were produced in the tread. These facts indicate that a brake shoe pressure of 20 000 pounds should not be used on wheels like the one in this investigation.

Table 5 shows the average rate of work, (foot-pounds per second), done by the shoe upon the wheel, for the tests at 18 000 and 20 000 pounds shoe pressure, and it includes all stops made during Tests 3457 to 3482, inclusive. The work-rate exceeded 100 000 foot-pounds per second in seven stops not shown on this table, and in one stop, (Test No. 3441 at 127 299 foot-pounds per second), exceeded 125 000 foot-pounds per second.

TABLE 5

AVERAGE WORK-RATE PERFORMANCE, FOR TESTS AT 18 000 AND 20 000 POUNDS SHOE PRESSURE

This table is arranged in the order in which the tests were made, and shows the sequence in which the wheel tread cracks developed

Test No.	Brake Shoe Pressure lb.	Initial Speed m.p.h.	Number of Stops	Average Work per Second ft-lb.	Number of Cracks Formed
(1)	(2)	(3)	(4)	(5)	(6)
3457	18 000	100	1	123 042	
3458	18 000	100	2	125 938	
3459	18 000	60	5	68 411	One
3460	18 000	80	5	71 743	
3461	18 000	100	3	141 490	
3462	18 000	80	5	84 020	
3463	18 000	60	5	85 515	
3464	18 000	100	5	141 315	
3465	18 000	80	5	79 676	
3466	18 000	60	5	73 814	
3467	18 000	100	4	135 079	
3468	18 000	80	5	80 398	
3469	18 000	60	5	70 663	
3470	18 000	100	5	118 777	
3471	20 000	60	6	80 809	
3472	20 000	80	5	92 810	One
3473	20 000	100	3	167 436	
3474	20 000	60	6	84 557	
3475	20 000	80	5	88 867	
3476	20 000	100	5	157 285	One
3477	20 000	60	6	78 536	
3478	20 000	80	5	91 081	
3479	20 000	100	5	165 198	Three
3480	20 000	60	5	85 863	Four
3481	20 000	80	5	83 003	Two
3482	20 000	100	5	143 611	Ten

In determining the maximum rate of work which can be performed on a wheel without causing cracks on the tread, it is necessary to investigate a number of stops preceding the test during which the crack was formed. For example, the first crack appeared after Test No. 3459, in which the average rate of work, for the five stops, was only 68 411 foot-pounds per second; however, during the two preceding tests the work-rate was about 125 000 foot-pounds per second. Cracks Nos. 2 and 7 to 12, inclusive, were also formed during tests in which the work-rate was relatively low, but immediately preceding the tests in which these cracks were formed the wheel had been subjected to stops in which the work-rate was very high. A study of Table 5 indicates that cracks may or may not be formed by stops made at such combinations of speed and pressure as require the shoe to do work on the wheel at a rate of 125 000 foot-pounds per second,

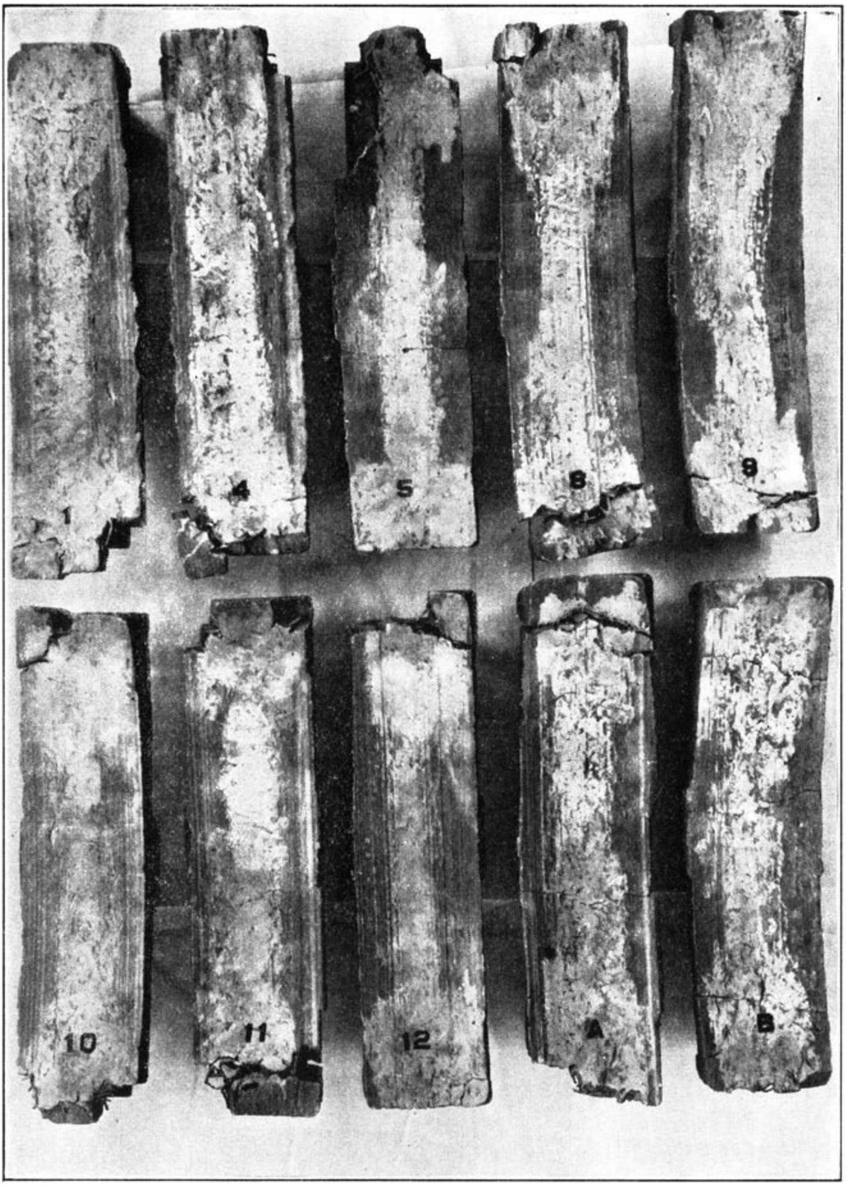

FIG. 9a. CONDITION OF SHOES AFTER TESTS

FIG. 9b. CONDITION OF SHOES AFTER TESTS

TABLE 6
NUMBER OF STOPS MADE BY EACH SHOE

Shoe No.	Number of Stops	Shoe No.	Number of Stops	Shoe No.	Number of Stops
1	3	12	32	71	16
4	12	A	7	100	14
5	70	B	17	101	16
8	89	50	13	102	11
9	45	51	14	120	15
10	8	52	3	121	15
11	4	70	15	122	10

but when this work-rate is exceeded cracks will almost certainly be formed.

Figures 9a and 9b show the condition of all shoes after the tests. The number of stops made by each shoe are shown in Table 6, and the combinations of speed and pressure under which the stops were made are shown in Table 1. From the photographs it is evident that the characteristic failure of all the shoes is the cracked and broken ends. In a few cases this did not occur until the shoe was worn to about the allowable minimum thickness; very many shoes were rejected, however, on account of the ends failing, long before they reached this minimum thickness. Combinations of speed and pressure which gave low shoe wear did not crack or break the ends until the shoe was near the allowable minimum thickness. In all tests where the work-rate was over 90 000 foot-pounds per second this failure occurred, and in some cases the ends gave way after only two or three stops.

16. *Relative Merits of Shoes.*—As stated in Chapter III, four types of shoes were used in the tests. Although some types of shoes were used on tests at various combinations of speed and pressure, the tests to determine their relative merits were all made with pressures of 18 000 and 20 000 pounds, and speeds of 60, 80, and 100 miles per hour. In these tests two new shoes of each type were used. They are grouped as follows:

(a) Shoes Nos. 50 and 51 of pattern C-40, with chilled ends
(b) Shoes Nos. 70 and 71 of pattern C-40, with plain ends
(c) Shoes Nos. 100 and 101 of pattern C-51, with chilled ends
(d) Shoes Nos. 120 and 121 of pattern C-51, with plain ends.

All were "Diamond S" reinforced steel-back shoes. The shoes of pattern number C-40 were 1½ inches thick and weighed 20 pounds each when new, while those of pattern number C-51 were 2 inches thick and weighed 25 pounds.

TABLE 7

RESULTS OF TESTS MADE TO DETERMINE RELATIVE MERITS OF SHOES

Average values for the four types of shoes for tests at 60, 80 and 100 miles per hour and 18 000 and 20 000 pounds shoe pressure

Type of Shoe	Number of Stops Upon Which the Average Values Are Based	General Average Values			
		Coefficient of Friction per cent	Stopping Distance ft.	Shoe-Wear per 100 Million Foot-Pounds of Work lb.	Work per Second ft-lb.
Pattern C-40 Shoes Nos. 50-51 Chilled ends	27	8.66	1663.7	13.663	103 783
Pattern C-40 Shoes Nos. 70-71 Plain ends	31	9.12	1565.3	13.721	106 927
Average for Pattern C-40	58	8.89	1614.5	13.692	105 355
Pattern C-51 Shoes Nos. 100-101 Chilled ends	27	8.60	1664.6	11.721	103 897
Pattern C-51 Shoes Nos. 120-121 Plain ends	30	8.09	1798.8	11.053	97 053
Average for Pattern C-51	57	8.35	1731.7	11.387	100 475
Average for chilled-end shoes	54	8.63	1664.2	12.692	103 840
Average for plain-end shoes	61	8.61	1682.0	12.387	101 990

Table 7 presents a summary of the results of these tests, in which only the general average values are shown. From this table two general comparisons may be drawn:

(1) The relative merits of the light shoes of pattern C-40, and the heavy shoes of pattern C-51

(2) The relative merits of the plain and the chilled-end shoes.

Considering the light and the heavy shoes, it is found that the coefficient of friction and the shoe wear is lower for the heavy shoes than for the light shoes; and that the stopping distance is greater for the heavy shoes than for the light ones. The main advantage of the heavy shoes is that in them an increase of 55 per cent of wearable metal is attained by an increase of only 25 per cent in weight. Except under conditions where the minimum stopping distance is of paramount importance, this fact may be regarded as offsetting the small deficiency in coefficient of friction of the heavier shoes.

Considering the plain and the chilled-end shoes, Table 7 shows that the coefficient of friction, the stopping distance and the shoe wear are practically the same for these two types of shoes. The tendency for the ends of the shoes to crack and break was more pronounced on the chilled than on the plain shoes.

All four types of shoes wore away unevenly under the tests at high speeds and high pressures, and on some shoes the difference in thickness at the ends was as much as ½ inch after the tests. In this respect the chilled-end shoes were slightly superior.

VII. Summary and Conclusions

The main purpose of the tests was to determine the coefficient of friction of brake shoes, the stopping distance, and the brake shoe wear under conditions which simulate those that prevail on the road in stopping trains traveling at high speeds. Secondary purposes were to determine the effect of high speed and high pressure on the wheel and shoes.

17. *Summary of Results.*—During this investigation 21 brake shoes were used, and 432 stops were made. The shoe pressures ranged from 4500 to 20 000 pounds, and under each of these pressures stops were made from initial speeds of 60, 80, and 100 miles per hour.

The results of these tests are in general accord with those of previous experiments in which the maximum shoe pressure was about 15 000 pounds and the maximum speed about 65 miles per hour. Below this speed and pressure the average coefficient of friction for a stop decreases as the initial speed increases and as the shoe pressure increases. Beyond the pressure range of the previous experiments there is a definite change in the trend of the results. The coefficient of friction, at speeds of and below 80 miles per hour, remains practically constant. At 100 miles per hour the coefficient increases rapidly so that with shoe pressures of 18 000 and 20 000 pounds the coefficient is greater than at 60 and 80 miles per hour.

The variation in the trend of the results is caused by the drastic change in the behavior of the shoe material which occurs when shoe pressures above 15 000 pounds are combined with speeds above 60 miles per hour. There is a softening of the shoe surface under these conditions which allows the shoe to fit itself better on the wheel, with a corresponding decrease in unit bearing pressure and an increase in coefficient of friction. This softening of the shoe surface accounts also for the high shoe wear per stop under combinations of very high speed and high pressure. The summarized results of the tests are shown in Table 3, and they are presented in graphical form in Figs. 1, 2, 3, and 4.

18. *Conclusions.*—The following conclusions seem warranted by the test results. They are applicable only to the types of shoes and the kind of wheel tested.

(1) If excessive wear and deterioration of brake shoes are to be avoided, no cast iron brake shoe should be subjected to braking conditions which will require it to perform and dissipate more than 90 000 foot-pounds of work per second.

(2) The building up of the welded brake shoe material on the wheel tread may be avoided by limiting the braking conditions to combinations of pressure and speed such that the work-rate performance of the shoe is kept below 70 000 foot-pounds per second.

(3) Shoe pressures of 20 000 pounds combined with high speeds, cracked the wheel tread at a very rapid rate, and the rate of performing work on the wheel should be kept below 125 000 foot-pounds per second in order to avoid this type of failure.

(4) Under the conditions of shoe pressure and speed prevailing in these tests the heavy shoes of pattern C-51 are more economical than those of the lighter pattern C-40; and are preferable, unless the service conditions are such as to make minimum stopping distance of paramount importance.

(5) The chilled-end shoes were not superior to the plain-end shoes when tested at high speeds and high pressures.

APPENDIX A

Variation of Coefficient of Friction During the Stopping Period

1. *Purpose.*—The values of the coefficient of friction presented in the body of this bulletin are average values for the entire stopping period. Frequently it is desirable to know how the coefficient of friction varies during the progress of a stop. In this appendix the variation of the coefficient of friction during the stopping period is shown for typical tests with 6000, 12 000 and 20 000 pounds shoe pressure at the three test speeds.

2. *Method of Calculating Results.*—As explained in Section 11, all calculations necessary in determining the coefficient of friction were based on the kinetic energy present in the revolving unit of the machine. The kinetic energy may be calculated at any speed and the foot-pounds of work necessary to change the speed of the car wheel determined. From the length of the dynamometer chart and the time record which appears thereon, the speed at any point and the distance which the car wheel travels during any speed change may be found. The average tangential pull during any speed interval is found by dividing the difference in the kinetic energy at the start and at the end of the speed interval by the distance the car wheel travels during that time. The average coefficient of friction is found by dividing the average tangential pull by the brake shoe pressure.

3. *Results.*—The results of nine typical tests are given in Table 8, which shows the average coefficient of friction values for each successive decrease in speed of ten miles per hour. These average values are derived from the number of stops shown in the second column. The number, under each coefficient of friction value, is the relative magnitude of the coefficient, expressed as a percentage of the coefficient developed during the 10 to 0 miles per hour speed interval.

The variation of the coefficient of friction during the stopping period is shown in Fig. 10. The heavy lines are the average, and the light lines the maximum and minimum values of the coefficient of friction. A study of this figure reveals that at pressures of 6000 and 12 000 pounds there is, during all tests, a definite increase in the coefficient of friction, beginning at a point where the speed has decreased to about 35 miles per hour, and continuing until the wheel stopped. During the tests with 20 000 pounds pressure at initial

TABLE 8
VARIATION OF COEFFICIENT OF FRICTION DURING STOPPING PERIOD

Test No.	No. of Stops	Shoe Pressure lb.	Average Values of Coefficient of Friction for Speed Intervals of 10 Miles per Hour									
			100-90	90-80	80-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0
3409	5	6 000	......	......	......	......	12.70	12.40	12.41	14.19	16.90	17.58
	Relative Magnitude		......	......	......	......	72	71	71	81	96	100
3410	5	6 000	......	......	13.12	12.60	11.98	10.97	12.02	13.03	16.78	15.89
	Relative Magnitude		......	......	83	79	75	69	76	82	105	100
3411	4	6 000	11.22	11.47	10.67	11.27	11.24	11.80	11.92	14.08	16.44	16.12
	Relative Magnitude		70	71	66	70	70	73	74	87	102	100
3415	5	12 000	......	......	......	......	9.90	12.20	12.14	12.50	16.19	21.16
	Relative Magnitude		......	......	......	......	47	58	57	59	77	100
3416	5	12 000	......	......	9.42	10.37	9.75	9.05	9.93	11.84	14.44	18.47
	Relative Magnitude		......	......	51	56	53	49	54	64	78	100
3427	5	12 000	7.84	6.58	6.81	7.03	6.95	8.12	8.12	9.45	11.99	14.79
	Relative Magnitude		53	44	46	48	47	55	55	64	81	100
3471	6	20 000	......	......	......	......	10.11	8.39	8.16	8.79	10.03	9.87
	Relative Magnitude		......	......	......	......	103	85	83	89	102	100
3472	5	20 000	......	......	9.16	7.82	7.32	7.01	7.34	8.19	9.31	9.21
	Relative Magnitude		......	......	99	85	80	76	80	89	101	100
3473	3	20 000	12.30	10.77	10.51	11.20	13.44	11.88	11.67	10.66	11.98	10.47
	Relative Magnitude		117	103	100	107	128	113	112	102	114	100

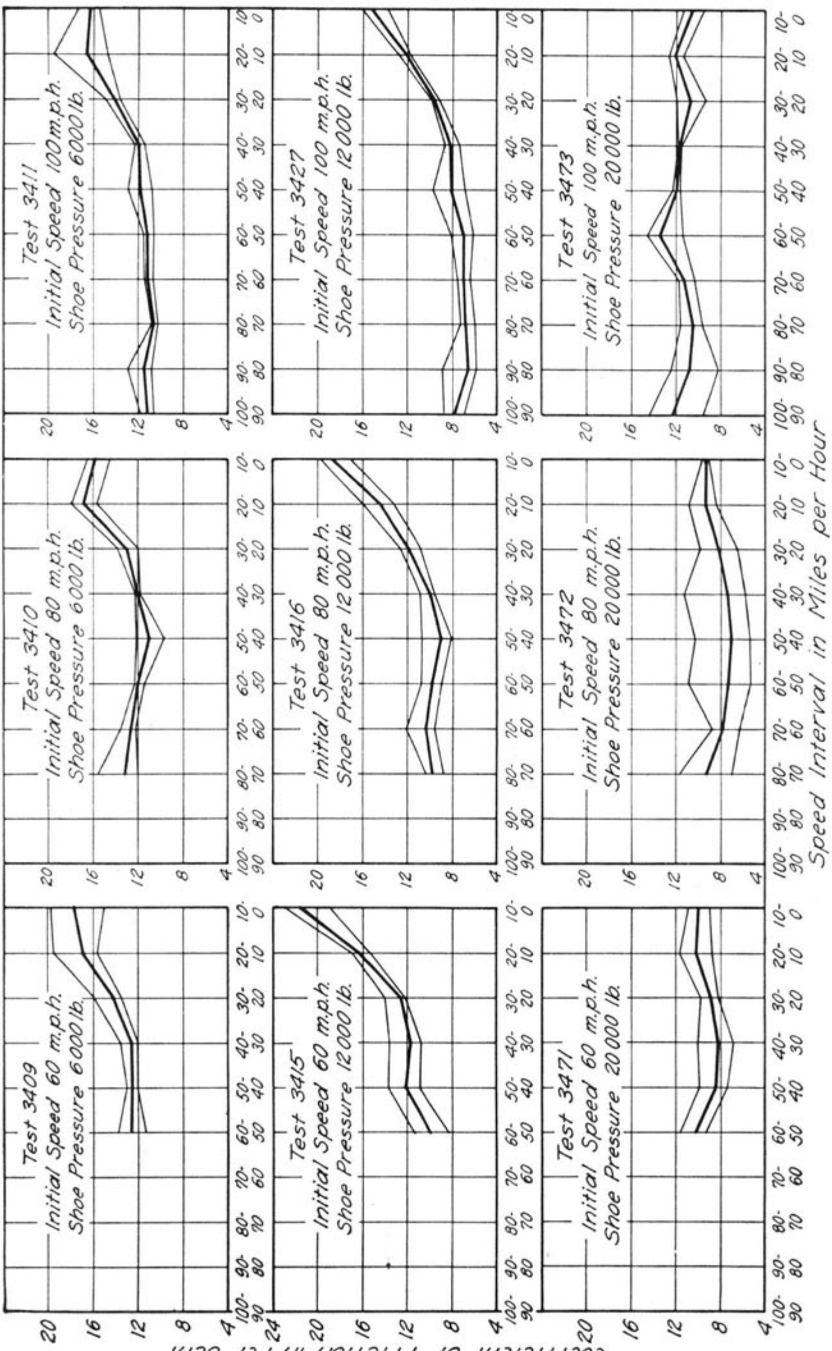

FIG. 10. VARIATION OF COEFFICIENT OF FRICTION DURING STOPPING PERIOD

speeds of 60 and 80 miles per hour, the coefficient of friction was about the same during the initial and the final speed interval, with a small decrease during the middle portion of the stop. At speeds of 100 miles per hour with 20 000 pounds pressure the coefficient is high during the initial speed interval, gradually falls off until the speed decreases to about 75 miles per hour, from this speed until about 50 miles per hour increases slightly, and from this point until the car wheel stops the coefficient is about uniform.

4. *Conclusions.*—A study of these typical tests together with a study of all the dynamometer chart records shows that with shoe pressures below 16 000 pounds there is a definite increase in the coefficient of friction beginning at a point where the speed has decreased to about 35 miles per hour, and continuing to the end of the stop.

At pressures above 16 000 pounds the coefficient is fairly uniform during the entire stopping period, with the exception that during stops from an initial speed of 100 miles per hour the coefficient of friction is high at the beginning, and again high when the speed has decreased to about 60 miles per hour.

APPENDIX B

Variation of Coefficient of Friction With Shoe Thickness

1. *Purpose of These Tests.*—The general results presented in Chapter V are based on averages of five stops; however, considerable variation in the coefficient of friction occurs in making stops under the same test conditions. In order to define more clearly this variation of the coefficient of friction from stop to stop under exactly the same test conditions, the tests described in this appendix were made.

Before stating the program for these tests it may be well to discuss the variables which change the coefficient of friction of brake shoes. These variables are as follows:

- (a) Speed
- (b) Brake shoe pressure
- (c) Type of brake shoe
- (d) Kind of wheel
- (e) Wheel tread condition
- (f) Shoe fit to the wheel tread
- (g) Bearing area of shoe
- (h) Character of the surface of shoe
- (i) Thickness of shoe as affecting rigidity
- (j) Thickness of shoe as affecting the proportion of the chilled material on the surface
- (k) Changes in hardness of the body of shoe
- (l) Changes in hardness of chilled material at the ends of shoe.

It should be borne in mind that, although in making stop tests it is impossible to make two stops exactly alike in all respects, in this series of tests an attempt was made to have all the conditions as nearly alike as possible.

2. *Test Program.*—The program for these tests comprised 70 stops by one shoe on one wheel, from an initial speed of 80 miles per hour with 8000 pounds brake shoe pressure. This combination of pressure and speed was chosen in order to wear away the shoe with a reasonable number of stops, and at the same time avoid warping and roughening the surface of the shoe to any great extent.

3. *Procedure.*—Throughout the tests precautions were taken to eliminate as far as possible the variables which cause variations in

the coefficient of brake shoe friction. The stops were made in the same manner as the stops which are recorded in the body of this report.

Of the twelve variables listed on page 40 the first four (a) speed, (b) brake shoe pressure, (c) type of shoe, and (d) kind of wheel, were eliminated in this series of tests.

A small amount of shoe material was deposited on the wheel tread during each stop. The wheel tread was therefore polished after each stop, by means of an abrasive block held by hand against the wheel tread while the wheel was revolving. This eliminated variable (e), wheel tread condition.

In order to eliminate variable (f), shoe fit to the wheel tread, the shoe was removed for weighing only upon the completion of each ten consecutive stops; and care was exercised, in replacing the shoe in the head, to have it resume each time the same position relative to the wheel tread.

The conditions of the tests, together with these precautions, served to eliminate six of the twelve variables which may cause variations in brake shoe friction. The remaining variables, all of which are due either directly or indirectly to shoe thickness, cannot be controlled.

Variable (g), the bearing area of the shoe, changes from stop to stop, and causes large fluctuations in the brake shoe pressure, when expressed in pounds per square inch of bearing area. A more complete discussion of the effect of bearing area is given in Appendix C.

The "Diamond S" shoe used in these tests is composed of layers of soft steel mesh embedded in cast iron. The proportion of the steel mesh exposed on the surface of the shoe is constantly changing, and the surface of the shoe, variable (h), cannot be kept constant.

As the brake shoe becomes thinner due to wear it also becomes more flexible, due to its reduced moment of inertia, and to the cracks which develop in it. This increased flexibility allows the shoe to fit better on the wheel, and generally produces a correspondingly larger bearing area.

The effect of shoe thickness in changing the proportion of the chilled material on the shoe surface, variable (j), cannot be controlled. The cross section of the chilled volume at the ends of the shoe, in the longitudinal plane, is roughly triangular, and the chilled area in contact with the wheel is the base of this triangle multiplied by the shoe width. As the shoe becomes thinner, the base of the triangle becomes shorter, and the chilled area in contact, smaller.

As the shoe wears, the material in the body of the shoe changes,

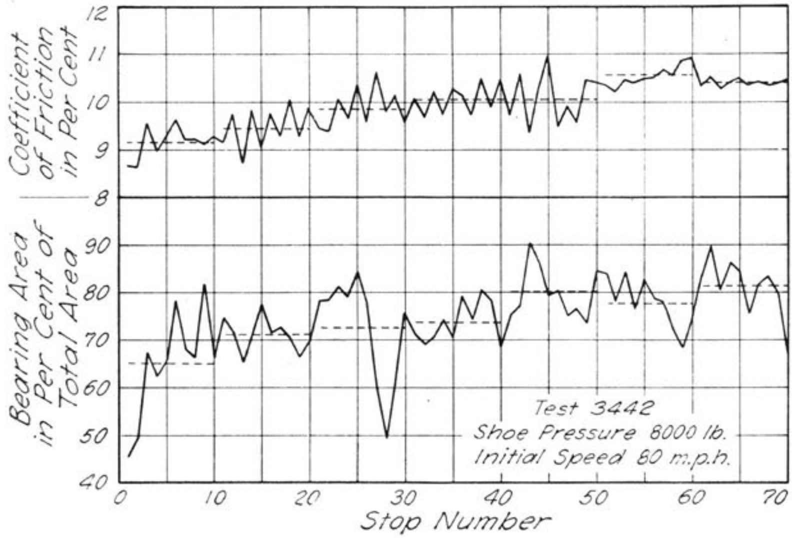

FIG. 11. VARIATION OF COEFFICIENT OF FRICTION AND BEARING AREA WITH SHOE THICKNESS

the hardness of its original surface being different from the hardness of the material in the interior of the shoe. Both the body and the chilled ends of the shoe are subjected by its service to an annealing process which may change the hardness.

The chilled ends of the shoe, in addition to the changes in the proportion of chilled material, as explained in the foregoing, change in hardness as the shoe wears and exposes material which was farther away from the chilling block in the mold.

4. *Results of Tests.*—The results of these tests show the influence of brake shoe thickness on brake shoe friction. The variation of friction, due to changes in shoe thickness, is caused by combinations of the last five variables cited on page 40. No attempt has been made to separate the effects of these variables, all of which are functions of shoe thickness.

Shoe No. 5 used in these 70 stops was a Diamond S shoe of pattern C-40 with chilled ends. At the start its average thickness was $1\frac{9}{64}$ inches, and its weight 17.67 pounds. During the 70 stops the shoe lost 5.9 pounds due to wear, and the average thickness was $\frac{19}{32}$ inch after stop No. 70.

The general results of these 70 applications of the shoe are shown

TABLE 9

GENERAL RESULTS OF TEST NO. 3442, RUN WITH SHOE PRESSURE OF 8000 POUNDS AND INITIAL WHEEL SPEED OF 80 MILES PER HOUR

The values shown are the averages of the results from successive groups of ten stops each

Stops	Coefficient of Friction per cent	Bearing Area in Percentage of Total Area	Shoe-Wear in Pounds per 100 Million Foot-Pounds of Work	Change Based on Stops 1 to 10		
				Coefficient of Friction Increase per cent	Bearing Area Increase per cent	Shoe-Wear in Pounds per 100 Million Foot-Pounds of Work Decrease per cent
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1 to 10	9.16	64.99	3.449	.....	.....	.....
11 to 20	9.46	71.12	3.419	3.28	9.43	0.87
21 to 30	9.86	72.60	3.313	7.64	11.71	3.94
31 to 40	10.06	73.78	3.063	9.83	13.53	11.19
41 to 50	10.06	80.07	2.835	9.83	23.20	17.80
51 to 60	10.54	77.87	3.044	15.07	19.82	11.74
61 to 70	10.41	81.28	3.248	13.65	25.07	5.83

in Fig. 11, in which the upper section shows the value of the coefficient of friction for each of the successive stops. The broken lines represent the average coefficient of friction for each group of ten stops. The results of these tests are summarized in Table 9. In this table the average values for ten stop intervals may be compared in column 2; this shows, in general, a steady increase of the coefficient of friction with the number of stops. As shown in column 4 the brake shoe wear per 100 million foot-pounds of work done decreases with the number of stops. In columns 5 and 7 these changes, based on the average values of stops 1 to 10, are shown in per cent. It should be noted that the average value of the coefficient of friction for stops 51 to 60 is 15.07 per cent greater than the average values for stops 1 to 10; and that the brake shoe wear per 100 million foot-pounds of work is 11.74 per cent less than for stops 1 to 10.

When individual stops are considered, the maximum variation between successive tests occurs in stops 45 and 46, for which the coefficients of friction are 10.94 and 9.49 per cent, respectively—a 13.25 per cent decrease. This change must be attributed to changes in the bearing area of the shoe or in the character of its surface.

5. *Conclusion.*—The results of this series of tests show definitely that, under the test conditions outlined in the program, the coefficient of friction increases and the brake shoe wear per 100 million foot-pounds of work decreases as the brake shoe becomes thinner.

APPENDIX C

Relation Between Shoe Bearing Area and Coefficient of Friction

1. *Purpose.*—Early in this investigation a variation in the coefficient of friction values for two successive stops under the same conditions was noted. At the same time it was evident, from a study of the action of the shoe on the wheel during the progress of the stop, that the bearing area of the shoe in contact with the wheel was not the same during one stop as it was in the next. The bearing area not only changed in amount, but also in position on the surface of the shoe. In order to determine the bearing area of the shoe in contact with the wheel during each stop the following method was used.

2. *Procedure.*—Immediately following each stop the brake shoe was released and a piece of white paper, about six inches longer and two inches wider than the shoe face, was inserted between the shoe and the wheel. The brake shoe was then applied for one second. The sections of the face of the shoe which were in contact with the wheel during the stop were hot enough to scorch the paper brown. This method could not be used on tests combining low brake shoe pressure and low speed, nor high brake shoe pressure and high speed. In the first case the surface of the shoe was not hot enough to scorch the paper, while in the second case the paper caught on fire when inserted.

The tests to determine the influence of bearing area upon coefficient of friction were run under various combinations of shoe pressure and initial speed of the wheel tread. The following tabulation shows these combinations:

Shoe Pressure pounds	Wheel Speeds miles per hour	Number of Stops Made	Shoe Pressure pounds	Wheel Speeds miles per hour	Number of Stops Made
6000	60	5	10 000	60	5
	80	5		80	5
	100	5		100	4
7000	60	5	12 000	60	5
	80	5		80	5
	100	5		100	4
8000	60	5	15 000	60	5
	80	10		80	5
	100	5			
9000	60	5	16 000	60	5
	80	5		80	5
	100	5	18 000	60	5

TABLE 10

RELATION BETWEEN BEARING AREA OF SHOE AND COEFFICIENT OF FRICTION

Test No.	Stop No.	Bearing Area in Percentage of Total Area	Coefficient of Friction per cent	Test No.	Stop No.	Bearing Area in Percentage of Total Area	Coefficient of Friction per cent	Test No.	Stop No.	Bearing Area in Percentage of Total Area	Coefficient of Friction per cent
3409	1	15.1	12.85	3428	1	66.5	9.76	3415	1	18.4	12.11
6000	2	24.0	12.49	8000	2	47.4	9.93	12000	2	14.9	10.59
lb.	3	11.9	12.82	lb.	3	38.9	10.84	lb.	3	38.1	11.23
60	4	59.5	13.16	80	4	51.3	10.75	60	4	33.0	11.08
m.p.h.	5	56.4	12.40	m.p.h.	5	29.6	11.90	m.p.h.	5	31.3	11.73
3410	1	43.2	11.73	3420	1	75.6	9.51	3416	1	79.6	9.57
6000	2	53.4	12.22	8000	2	85.1	8.48	12000	2	75.5	9.65
lb.	3	63.3	11.96	lb.	3	86.1	8.43	lb.	3	71.6	9.29
80	4	54.8	12.62	100	4	81.2	9.25	80	4	67.3	10.41
m.p.h.	5	60.1	12.70	m.p.h.	5	68.7	9.53	m.p.h.	5	77.5	9.83
3411	1	73.9	.....	3421	1	21.4	.....	3427	1	79.7	7.92
6000	2	74.5	11.17	9000	2	29.1	11.85	12000	2	92.9	7.23
lb.	3	75.3	11.59	lb.	3	19.7	13.47	lb.	3	95.8	7.18
100	4	83.3	11.36	60	4	19.8	11.78	100	4	94.9	7.04
m.p.h.	5	77.7	11.56	m.p.h.	5	14.7	13.03	m.p.h.	5	....	6.86
3412	1	34.7	12.56	3422	1	58.6	10.60	3430	1	21.6	7.84
7000	2	29.1	12.97	9000	2	44.1	10.26	15000	2	19.2	9.39
lb.	3	17.7	13.37	lb.	3	40.4	10.16	lb.	3	21.7	7.68
60	4	22.6	12.30	80	4	48.9	10.68	60	4	16.2	9.29
m.p.h.	5	27.6	13.52	m.p.h.	5	44.7	10.51	m.p.h.	5	25.8	8.11
3413	1	60.4	11.97	3423	1	87.9	9.25	3434	1	54.0	8.92
7000	2	44.0	12.51	9000	2	93.6	9.19	15000	2	79.3	7.17
lb.	3	45.5	11.65	lb.	3	80.0	8.81	lb.	3	83.2	7.50
80	4	38.7	11.66	100	4	85.0	9.64	80	4	97.8	7.01
m.p.h.	5	43.6	11.80	m.p.h.	5	93.0	9.13	m.p.h.	5	94.0	7.14
3414	1	94.4	10.66	3424	1	32.7	11.80	3431	1	29.6	10.27
7000	2	94.5	10.80	10000	2	22.2	12.08	16000	2	26.6	7.67
lb.	3	96.4	10.50	lb.	3	29.2	13.41	lb.	3	18.1	10.09
100	4	91.5	10.01	60	4	32.7	12.89	60	4	20.8	8.77
m.p.h.	5	84.8	10.84	m.p.h.	5	8.6	13.73	m.p.h.	5	13.3	10.83
3418	1	4.2	12.56	3425	1	62.0	10.81	3435	1	60.2	7.69
8000	2	12.6	11.51	10000	2	46.8	10.76	16000	2	83.6	7.12
lb.	3	10.8	11.47	lb.	3	63.8	10.50	lb.	3	89.4	6.35
60	4	4.5	12.51	80	4	57.8	10.82	80	4	85.2	8.07
m.p.h.	5	15.4	12.89	m.p.h.	5	51.1	10.62	m.p.h.	5	95.9	6.73
3419	1	41.3	8.29	3426	1	93.5	10.47	3432	1	25.9	8.01
8000	2	42.2	10.25	10000	2	98.7	9.56	18000	2	20.4	10.70
lb.	3	46.6	10.40	lb.	3	95.9	9.81	lb.	3	22.0	7.68
80	4	32.7	10.33	100	4	91.7	9.16	60	4	48.3	9.47
m.p.h.	5	40.8	10.31	m.p.h.	5	....	8.90	m.p.h.	5	21.8	8.15

In addition to these tests the bearing area was determined after each of the 70 stops of Test No. 3442.

3. *Results of These Tests.*—Table 10 shows the results of the tests. The bearing area there presented is expressed in terms of percentage of the total area. All the brake shoes were 3¼ inches wide and 14¼ inches long—measured on the arc. This gave a gross potential bearing surface of 46.3 square inches. The actual bearing area of the shoe indicated by the brown spots on the paper was measured by means of a planimeter, and this area divided by the 46.3 square inches is shown in the table under the heading "Bearing Area in Percentage of Total Area." In order to facilitate comparisons of the bearing area of the shoe and the coefficient of friction developed during each stop, the coefficient of friction values are also shown in the table.

Figure 12 (page 50) is a scaled drawing of the imprints made on the paper by the brake shoe after each of five stops of two tests (Nos. 3419 and 3425). This drawing shows the change in bearing area of the shoe in proportion to the total area, and also the shift in the positions of the bearing area in successive stops. On this figure the areas of the shoe actually in contact with the wheel are shown in black. Tests 3419 and 3425 were both made from an initial speed of 80 miles per hour with 8000 and 10 000 pounds shoe pressure, respectively.

In all the tests summarized in Table 10, no attempt was made to distinguish the frictional qualities of the various bearing surfaces. Each square inch of bearing area on any section of the face of the shoe was assumed to have the same frictional qualities as the others.

Comparing the highest and lowest coefficient of friction with the highest and lowest bearing area for all five stops of each test individually, and summarizing the results obtained from all 24 tests presented in Table 10, the following relations are revealed:

(a) In three tests the highest coefficient is developed on stops where the bearing area is highest.

(b) In six tests the lowest coefficient is developed on stops where the bearing area is lowest.

(c) In five tests the lowest coefficient is developed on stops where the bearing area is highest.

(d) In nine tests the highest coefficient is developed on stops where the bearing area is lowest.

(e) Five tests show no relation; that is, the highest or lowest coefficient is not developed on stops where the bearing area is either the highest or the lowest.

TABLE 11
AVERAGE BEARING AREA OF SHOE FOR TESTS AT 7000 TO 10 000 POUNDS PRESSURE

Test No.	Brake Shoe Pressure lb.	Initial Speed m.p.h.	Average Bearing Area in Percentage of Total Area	Average Coefficient of Friction per cent
3412	7 000	60	26.3	12.94
3418	8 000	60	9.5	12.19
3421	9 000	60	20.9	12.53
3424	10 000	60	25.1	12.78
3413	7 000	80	46.4	11.92
3419	8 000	80	40.7	10.12
3422	9 000	80	47.3	10.45
3425	10 000	80	56.3	10.70
3414	7 000	100	92.3	10.56
3420	8 000	100	79.3	9.04
3423	9 000	100	87.9	9.20
3426	10 000	100	95.0	9.58

In discussing the results of the tests in Section 12, it was suggested that the rise in the coefficient of friction, shown in Fig. 1, at all speeds and at pressures of 9000 and 10 000 pounds, was perhaps due to the better seating of the shoe on the wheel under these pressures. Table 11 is a summary of the tests at pressures from 7000 to 10 000 pounds, in which the average bearing area and the average coefficient of friction for the five stops are presented. It should be noted that during all tests at 7000 pounds pressure the bearing areas follow the general trend of the bearing area values, and the coefficient of friction values developed during these tests follow the general trend of the points plotted on Fig. 1. Under pressures of 8000 and 9000 pounds the bearing areas are low at all speeds, and the coefficients are lower than expected. At 10 000 pounds pressure both the bearing area and the coefficient of friction are again normal.

In the lower section of Fig. 11 the bearing area in percentage of the total area of the brake shoe is shown for the 70 stops of Test No. 3442. The broken lines in this figure show the averages for each series of ten stops. When individual stops are considered, there seems to be no definite relation between the bearing area and the coefficient of friction. This may be expected, for the bearing area is but one of the six variables which cause variations in the coefficient of friction. When, however, the averages of the results from successive groups of ten stops each are considered, the general trend shows that low bearing area gives low coefficient, and high bearing area high coefficient.

In Table 9 the bearing areas in percentage of total area, for each successive group of ten stops in Test No. 3442, are shown in column 3, and in column 6 the increase in bearing area is expressed in per cent change based on the average bearing area of the first ten stop series.

4. *Conclusion.*—From a study of Table 10 and Fig. 11, it is found that no definite relation exists between the bearing area of the shoe and the coefficient of friction developed during individual stops. This is not surprising, in view of the fact that the values of coefficient of friction here used are average values throughout the duration of each stop, whereas the corresponding bearing area could be determined only at the end of the stop; and it is known that this area generally fluctuates during the stopping period. The *average* area is consequently not definitely known; it must occasionally differ from the area here used. Such discrepancies as appear in the discussion must be due, in part at least, to this variation.

When, however, we deal with the values of coefficient of friction and bearing area from groups of stops, as in Table **9**, some of these discrepancies disappear, and we find a fairly regular increase in coefficient as the area increases.

APPENDIX D

TEMPERATURE OF WHEEL AND SHOE

1. *Object of Temperature Tests.*—The desirability of obtaining reliable temperature data on the shoe and wheel during the progress of a stop has been suggested by several previous investigators. As yet no method is available whereby the surface temperature of the revolving wheel may be measured with any satisfactory degree of accuracy.

An accurate determination of the temperature of the wheel surface would be valuable in investigating the cause of "heat-checks" and "shell outs" on the tread. A relation between the coefficient of friction and the temperature of the brake shoe could also be determined. During the tests described in Appendix C an attempt was made to determine the temperature of three points near the surface of the wheel, and of two points on the surface of the shoe.

2. *Procedure.*—The temperatures on the wheel and shoe were measured by means of No. 23 gage Chromel and Alumel thermocouples. On the wheel the thermocouples were located on the gage line at three points 120 degrees apart. These were numbered 1, 2, and 3. On the shoe, thermocouples 4 and 5 were located on the longitudinal center line $3\frac{1}{2}$ inches to the right and left of the vertical center of the shoe.

All the thermocouple ends consisted of cylindrical plugs $\frac{5}{16}$ inch in diameter and $\frac{5}{16}$ inch long. The chemical composition of the plugs was approximately the same as that of the material they replaced in the wheel and shoe. The two thermocouple wires were inserted into small holes drilled into one end of the plugs and peened into place by a special tool. The plugs together with the wires were then screwed into the wheel and shoe and ground down to the surface. The six wires from the wheel were led out to the end of the shaft of the brake shoe machine through a slip ring connection to the recording table; the four wires from the shoe passed through the back of the shoe directly to the recording table. Located at the recording table were the cold junction, individual switches for each couple, a clock, and a Leeds and Northrup indicating type potentiometer.

This method of inserting the thermocouple in the wheel gave the temperature at points $\frac{5}{16}$ inch below the surface. When the plugs in the shoe were new the indicated temperature was that of points

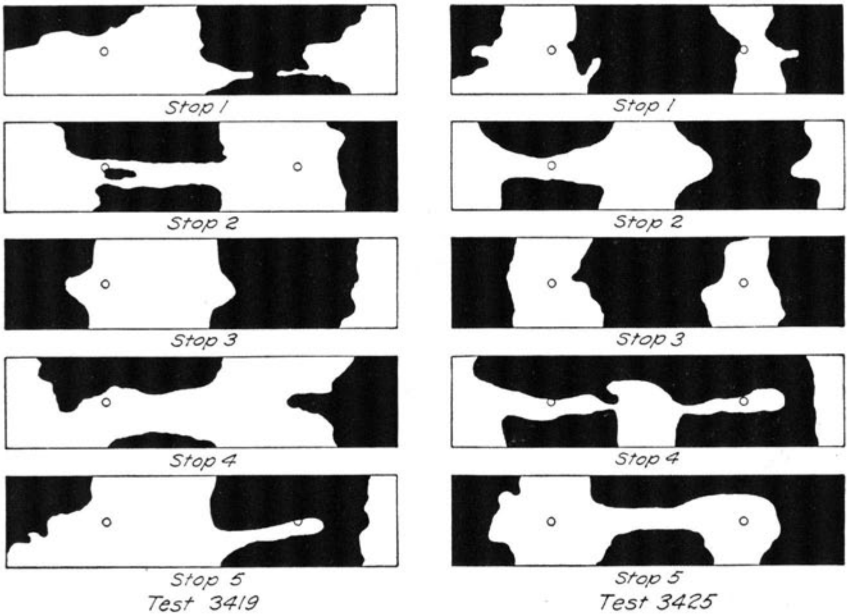

FIG. 12. CHANGES IN SHOE BEARING AREA

$\frac{5}{16}$ inch below the surface. As the surface of the shoe and the plug wore away, due to brake applications, the indicated temperature gradually became that of material closer and closer to the shoe surface. Finally a break in the thermocouple circuit would indicate that the plugs were all worn away and they were then replaced.

The wiring allowed each couple to be read separately, or the average of thermocouples 1, 2, and 3, or 4 and 5, to be taken at the same time. During the early tests one thermocouple was read during each stop. However, in the majority of the tests, during the first and fifth stop the average of thermocouples 1, 2, and 3 were recorded. Thermocouple 4 was recorded during stop 2, thermocouple 5 during stop 3, and the average of 4 and 5 during stop 4. In general, the temperature was recorded every ten seconds during the stop, and a final reading was taken at the time the wheel came to rest. The temperature readings were taken during all the 24 tests summarized in Table 10 of Appendix C.

3. *Results of Temperature Tests.*—As stated, no accurate method is available for measuring the surface temperature of the revolving

TABLE 12
MAXIMUM SHOE TEMPERATURE DURING STOPS MADE IN TESTS 3419 AND 3425

Test No.	Stop No.	Thermo-couple No.	Maximum Tempera-ture deg. F.	Test No.	Stop No.	Thermo-couple No.	Maximum Tempera-ture deg. F.
3419	1	4, 5	1130	3425	1	4, 5	470
	2	4	225		2	4	1155
	3	5	470		3	5	165
	5	4, 5	730		5	4, 5	340

wheel. The temperature measured and recorded during these tests was that of points $\frac{5}{16}$ inch below the surface of the wheel. During a large number of stops the surface of the wheel was hot enough to change its color to a dark red, plainly visible in the well-lighted laboratory. In some of the tests at high speed and high pressure the surface was bright red. This red color on the surface appeared in the form of circumferential streaks which moved back and forth across the wheel. At times the streak would divide, forming two or more shifting streaks.

In spite of the fact that the surface of the wheel was occasionally red hot, the maximum temperature indicated by the thermocouples in the wheel was only 380 degrees Fahrenheit. This is no doubt due to the short duration of these tests—the maximum stop requiring only 75 seconds and the minimum, 18 seconds.

The temperature measured in the brake shoe depended entirely on the location of the thermocouple relative to the areas bearing on the wheel during the stop. In Fig. 12 the location of the thermocouples is indicated by small circles, No. 4 being at the right and No. 5 at the left. From a study of this figure together with Table 12 it may be noted that on stop 1 of Test 3419 thermocouple 4 was near the center of a bearing area, while thermocouple 5 was not in contact with the wheel. It should also be noted that the temperature of thermocouple 4 recorded during stop 2 of Test 3425 indicated a maximum of 1155 degrees; while thermocouple 5 during the next stop indicated a maximum temperature of only 165 degrees. This difference can also be explained by a study of Fig. 12.

4. *Conclusions.*—Some accurate method of measuring the surface temperature of a revolving wheel must be developed before any reliable conclusions can be drawn as to the relation of the surface temperature of the car wheel and car wheel failures. The tempera-

ture of a point $\frac{5}{16}$ inch below the surface is no indication of the surface temperature.

The average temperature of the surface of a brake shoe cannot be measured by two thermocouples. A minimum of about ten thermocouples would probably be required to give a reliable average temperature of the surface of the shoe.

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